Title

The Material and Industrial Ecologies of Excavated Sediment: Insights for Climate Change Adaptation Planning

Author

Kauffman, Nate

Publication Date

2022

The Material and Industrial Ecologies of Excavated Sediment: Insights for Climate Change Adaptation Planning

by

Nate Kauffman

A dissertation submitted for partial satisfaction of the
requirements for the degree of

Doctor of Philosophy

in

Landscape Architecture and Environmental Planning

in the

Graduate Division

of the

University of California, Berkeley

Committee in charge:

Professor Kristina Hill, Chair
Professor Louise Mozingo
Professor Arpad Horvath

Summer 2022

Abstract

The Material and Industrial Ecologies of Excavated Sediment: Insights for Climate Change Adaptation Planning

by

Nate Kauffman

Doctor of Philosophy in Landscape Architecture and Environmental Planning

University of California, Berkeley

Professor Kristina Hill, Chair

Global warming is producing countless changes in the biogeophysical world, and will increasingly force human responses to them. These challenges are evident everywhere: in all manner of resource use, growth and development processes; in the intensification of climate risks, hazards and natural disasters; and in the sociopolitical and socioeconomic systems that must confront this paradigm shift in earnest during the 21st century. This dissertation seeks to situate prominent and emergent issues of how this confrontation and the changes induced by it—adaptation--function and matter in the context of environmental design and planning. In particular, and because of the global scale and widespread socioenvironmental issues involved, the work focuses on sea level rise (SLR) and issues stemming from its impacts on developed shorelines and the ecological complexes and structures evident therein. Human beings have deep roots in the manipulation of landscapes, especially as they concern the role and resources that coastal waterbodies and waterways represent, through the active design and physical defining of topography: how the shape and elevational contours of land affect flows and functions of water. Accordingly, the introduction herein frames the roles of landform as an elemental aspect of the construction and spatial planning of urban coastal and shoreline zones, and focuses on the physical materials, including actively-gathered geomaterial resources called *sediment* that compose the basic building blocks of constructed landforms. In chapter one, the interplay of various terms and concepts involved in climate change adaptation that matter in the context of spatial planning are articulated and clarified to frame ways in which challenges and opportunities of the era may be described. Chapter two then works to establish areas of much-needed consideration for the fields of landscape architecture and environmental planning to enfold into its professional practice milieu: namely tools and techniques from industrial ecology, which has been traditionally applied almost exclusively to climate mitigation (as opposed to adaptation). The third and final chapter discusses the application of modeling methods to an *excavated sediment budget* in an approach designed to assess aspects of the climate change future of a case study region. The work helps illustrate several insights and critical questions that are discussed in the final conclusion section.

Table of Contents

Dedications

We drink from wells we did not dig;
we are warmed by fires we did not kindle.

Devarim 6:11
625 BCE

~ - ~

To ply their labor: some extend the wall; Some build the citadel; the brawny throng
Or dig, or push unwieldly stones along. Some for their dwellings choose a spot of ground,
Which, first designed, with ditches they surround. Some laws ordain; and some attend the choice
Of holy senates, and elect by voice. Here some design a mole, while others there
Lay deep foundations for a theater; From marble quarries mighty columns hew,
For ornaments of scenes, and future view.

Publius Vergilius Maro
25 BCE

~ - ~

It is hard to follow one great vision in this world of darkness and of many changing shadows.
Among those, men get lost.

Heȟáka Sápa
1920

~ - ~

Is this concrete all around, or is it just in my head?

David Robert Jones
1972

~ - ~

Hope is not a lottery ticket you can sit on the sofa and clutch, feeling lucky.
It is an axe you break down doors with in an emergency.
Hope should shove you out the door, because it will take everything you have
to steer the future away from endless war, from the annihilation of the earth's treasures
and the grinding down of the poor and marginal…
To hope is to give yourself to the future – and that commitment to the future
is what makes the present inhabitable.

Rebecca Solnit
2004

Preface

Dissertation, taken from Latin *dissertātiō* or "path" may have etymologic roots also in the Sanskrit *sarat*, meaning "thread". The best practical advice I received about how to contemplate and confront the task of writing the dissertation was provided by my Qualifying Exam Chair, the inimitable Louise Mozingo: *make it narrow, and deep*. Thus, the process in any work like this is to hopefully illuminate knowledge of something that is specific enough to be highly focused and constrained (and therefor achievable), and rigorously researched to the point that the Doctoral Candidate literally eliminates (to the extent possible) the likelihood of producing something erroneous – very often through the process of exhausting their materials, methods and selves along the way.

So how to position oneself in order to hopefully contribute to, complete – and perhaps even enjoy – walking *the path*? There, again, Louise had advice for me. "You're going to have to be poor for a while." Indeed, there is much about the life of a doctoral student that is unavoidably ascetic, even stoic. And, yes, perhaps there is also something of a roguish glamor to the community of wan, ink-stained wretches toiling away thanklessly in the wee hours of the ivory tower. One's work is balanced upon a strange fulcrum, from which they possess very little authority while often carrying considerable responsibilities. At some point, one realizes that the process has miraculously worked(!): they've developed deeper expertise (in that narrow place) than their advisers, mentors and teachers possess. And then, it is time to compose a document that constantly daunts and frequently taunts. A mentor named Andy Gunther helped me set expectations early in the process. "Don't try to make the dissertation perfect," he said wryly. "It will be perfect when it's done."

And yet. Filing a dissertation must feel something like dropping your child off for their first day of elementary school or perhaps college or the Army. To let go and let the thing become what it will be instead of trying to control what it is. In these final weeks leading up to filing this manuscript, I cannot stop thinking about whether anyone will read it. Not because of vanity, or at least not entirely. What I am actually curious about is the extent to which the information and work embodied here might actually be useful to someone, somewhere at some point hoping to approach and address some of the challenges of our era, society and world that this document describes, and with which it grapples.

Oh, the challenges. The entanglements of politics, markets and media in our modern world are profoundly resistant to actually allowing us to face and tackle the overriding and underpinning test for us all: the causes and impacts of global warming. What climate change threatens to do is fundamentally deform the actual context of our lives and communal existence; and to tear apart the fabric of life as we know it. In that sense, it governs all else. As an issue, it is unique in that its unfolding will worsen the vast majority of other issues we continue to scramble around fighting over. The competition for resources, safety and prosperity – and the sheer, elemental desperation that this strife will increasingly induce on a depleting planet – are poised to thrust us all into ever-worsening and ever-complicating sets of decisions intended to stem our losses and staunch the proverbial bleeding. As usual, the poor and disempowered will suffer first and worst.

While the works in this document are situated within academic and professional milieus (various engineering, ecology and environmental design and planning fields), the reason to ask and answer the questions at the heart of this dissertation is about intergenerational and interspecies environmental justice. There is simply no way to approach a rationale for rethinking technical and strategic aspects about how we must invest in better and more sustainable practices and futures – *adaptation* – without confronting profound ethical problems and their unsettling implications. I can't shoehorn too much on that front into this work, though it's evident to some extent via the concepts of the public realm and public goods and interest in Chapter One.

I hope that if anyone does read this (or even, literally, this foreword) they will glimpse my struggle with and commitment to this task: exploring how we (as individuals, cohorts, communities, regions, firms, nation states and as a species itself) might evolve, transform and expand our sensibilities of the public good that we are responsible for protecting and growing. Of all of the galling and needless losses, suffering and inefficiencies that our currently dominant paradigm perpetuates and cleaves to, the most damning and central tendency of this paradigm and era is, in-effect, the preposterously high discount rate we are willing to accept applying to our planetary future. It's maddening: to watch people (including myself) constantly going about their daily lives and careers ostensibly to ensure and invest in their futures (and those of their families, communities, enterprises, etc.) while completely ignoring the ways in which status quo modes of existence are undermining and depleting that future.

Grappling with this is exhausting, grinding, and frequently grim work. This is not a field for anyone to go into or be part of that is looking for an easy row to hoe, whether emotionally, intellectually or professionally. And for young people who choose to throw themselves in, I can only hope that your generation will be more bold, brave and intolerant of the greed, wastefulness and bigotry of your forebears. So Louise Mozingo is right: you will have to be poor for a while to submit to the academy; to get lettered; to become an expert. But this path can also lead you to a place of clear-eyed vision and leadership, things so badly needed now. Louise is also – and oddly – wrong in that respect: in my entire time walking *the path* and tracing the thread that was this dissertation, I felt positively rich. Yes, of course: rich in problems and frustrations; strife and confusion; rich in struggles and exhaustion. But no one commits themselves to a wealth of those things if they do not also believe – do not actually know – that this work is rich also in purpose, possibilities and, ultimately, hope.

Acknowledgements

How to even begin to recognize and celebrate all those without whom I cannot imagine how this would have actually gotten done? First, I wish to recognize those closest to the work, my exam and dissertation committee members. Notwithstanding the trials and tribulations of the PhD arc, I feel now on the eve of filing this work what I first sensed a decade ago when my life led me to the College of Environmental Design: that I was, for the first time in my life, where I was supposed to be; doing exactly what I should be doing. In short, *the path* has proved an abiding, unforeseen blessing for which I am sincerely grateful. This is made possible because of the people who coalesce around students and the original ideas they struggle and work to conjure. And it simply cannot happen without these people – the *teachers* – whose mission is service towards cultivating the next crop of knowledge, regardless of whether they ever reap or delight from it.

So thank you Kristina Hill, whose formidable intellect and no-nonsense demeanor is mirrored by a deep humanity and decency. I've valued and enjoyed working with you on many projects over many years – and you continue to teach me with each passing one. I know you wanted to be "The Lady of Beautiful Beaches", but our polluted estuaries are indescribably lucky to have you watching over them instead: our very own visionary *Tsagaglalal,* and One-Who-Teaches in addition to Watching. You've defined my path through life and Landscape(s) in profound ways. Because of you, I will wonder always what it means – and what it takes – to be human in our time. Ergo, I have reduced the use of italics and quotes herein for you.

Thanks to Arpad Horvath, whose curiosity, sardonic wit and love of teaching are captivating and infectious. I recall having a meltdown in Arpad's office because I could not believe the absolutely scandalous state of the information landscape I was encountering—the datasets (or lack thereof) I hoped to access and analyze. How was it possible that no one was tracking, recording and sharing this information? And how was I ever going to structure a doctoral degree around the topic, and in spite of these issues? Arpad took a deep breath. In his rather sober and sly way, he said simply, "Okay. So no one's done this before. What does that mean? It means someone has to take the first steps." An arched eyebrow indicated exactly who he might have in mind. Thank you Arpad, for helping me to understand that seeing the mountain clearly is the first step to climbing it well.

Thank you Nicholas de Monchaux, a true original. You've counseled and inspired me through countless decision points and moments of existential disorientation and occasional panic. From an unforgettable trip deep into Alaska (in February), to pinups gone awry that we wish we could forget, and everything in between. Your talents and magnetism draw good things and people toward you. Your iconoclastic perspective on power and space is a gift; and one you give away constantly to all in your orbit. Additionally, your reliably prompt attendance at Qualifying Exams will always further distinguish you in my eyes. This font is for you.

And to Louise Mozingo, thank you. Your dedication to intellectual and academic honesty and fidelity are timeless and true virtues that your students and colleagues cherish; and we all value your leadership and the sacrifices entailed that you've so consistently made for us. Your keen eye for an interesting problem and your equally keen nose for bullshit are lore, as are your copy editing skills. These last few years saddled me with a couple burdens I wasn't sure I was going to be able to carry while marching on down *the path.* Your efforts on behalf of myself and my family kept me from reaching that breaking point. Semper fiat lux. Aeternum.

Kristina once described a process for thinking about the members of a doctoral committee as a family of finger puppets: ones I could conjure and commune with at will – though in a fi(n)gurative sense, of course. It was a technique for testing how each of these finger-personalities would bring their own individual focus or perspective to a problem – and what critical questions and reactions they might offer. I could, in this sense, call them up and test propositions based on what I'd learned from them and how they think about and look at various issues. What I hadn't processed when initially employing this method in preparing for my Qualifying Exams was that it might become a kind of permanent and recursive mental construct and process. In other words, the people acknowledged in the paragraphs above are and will forever be with me in my intellectual endeavors: their values and approaches always close at hand, if you will.

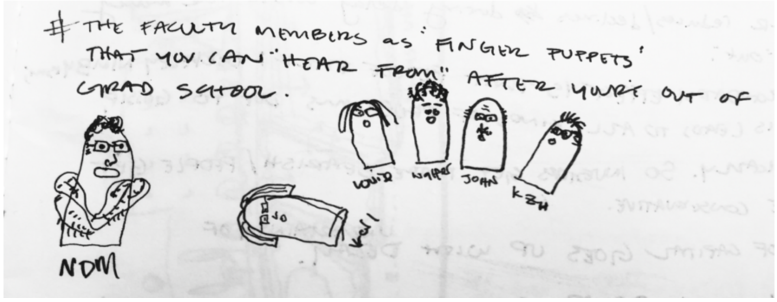


Exhibit A: The caption reads "The faculty members as 'finger puppets' that you can 'hear from' after you're out of grad school.", a (perhaps slightly unsettling) concept pioneered by Professor Kristina Hill. Though this illustration doesn't reflect my final dissertation committee (Arpad Horvath is missing), Nicholas de Monchaux can be seen at left channeling Elvis for unknown reasons.

My family helped me walk *the path* over these years. My mother Susan's patience and understanding made the whole shebang possible, and her husband Tony knew, perhaps before most others, that doing what I loved was the only way to (perhaps potentially) find success someday. Thanks to my sisters Molly and Mary and my brothers, Luke and Joe. A vast and varied cast of uncles and aunts and cousins remind me why any of this matters.

So thanks to the Buckleys: no one knows how to live better in and on the land than you; I'm honored to have known and loved Mike and to have you in my life. Thanks Beth and Jim for cultivating my pathologic love of landscapes, solitude and the sublime for decades. Chris and Kris, you've enchanted me with the elegant beauty of lives well-lived. Uncle Greg, whose character, humor and strength shine through so much loss. Darrell and Angela: you've built for me an entirely new and unexpected branch of the family tree, and you've always (and especially) had an open door for me when it looked dark and stormy on the horizon. Charlie Samson, your generosity and humor are boundless, bright, beautiful things.

I want to acknowledge my many, many students over these many years. You are a constant and enduring source of inspiration. Seeing you encounter and navigate difficult situations and complex problems is a richly rewarding experience, and seeing you enter the world as professionals looking to make the world better makes me deeply grateful for them and hopeful about our common plight. There are far too many mentors and guides to list here, and they have helped me grow and learn and lead in countless ways. You know who you are. But a few of them have significantly guided and shaped my capacity to undertake this whole mess of a process—*the path*—and I wish to acknowledge them especially. Shiva Berman: who's been a beacon and buttress above and beyond anything I ever might have asked or expected. Doug Wallace: you've helped lighten my load while sharing and caring endlessly for me and my wellbeing; and you've set a great example of how to mentally process existence. And last but not least, Andy Gunther, you stand as a model of the kind of man I hope to be in this life. And thanks to my close friends who've pushed me to push myself and occasionally remember to enjoy life and all its gorgeous, hilarious, tragic and incomprehensible richness.

Most of all, thank you Catherine Madeline McKnight, my partner through it all and more. You've been through a lot in your life, and you've never once failed to shine brightly as a remarkably compassionate and good person. You've been patient with a broke, wanderlusting grad student boyfriend and husband perhaps seemingly intent on never growing up. But you've also helped me grow into a better person at every step of the way along this wild ride. Your inner strength and drive have buoyed us profoundly. You're a great dog mom. You are hilarious and a total babe, and I still can't believe you married me.

Finally, I want to recognize my father, John Cornelius Kauffman. He was an architect, designer and builder, and I literally grew up working for and with him on construction sites scattered all over the Bay Area. He was a remarkable and tragically flawed human. It never once crossed my mind while my father was alive that I might gravitate towards the architectural and environmental design disciplines; nor that I might, in that respect, follow in his footsteps.

I go into the wilderness frequently and often with a handful of his ashes. I look at the landscape and think about nature and life and I scatter him to the winds and waters. I feel the ground and reaffirm a vow to Gaia, the earth-mother of us all, to fight until shedding the mortal coil against forces bent on debasing her. And I think about my own parents, and the gifts they gave me that I didn't know I possessed until they manifested in my very hands, before my very eyes. This dissertation is the documented record of some of those gifts; and it was written as a gift to those above, and those departed.

Thank you all.

Introduction: Human Beings As Geomorphic Agents

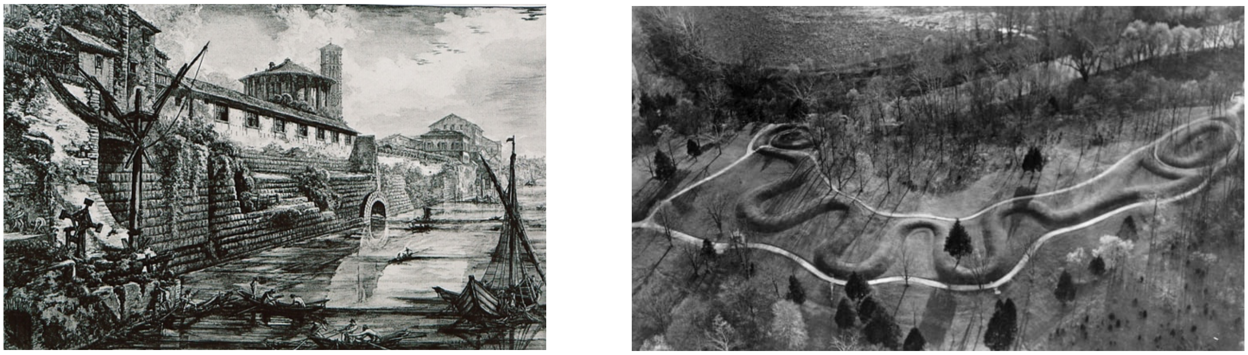
The impetus to intervene in the landscape by physically manipulating landform was historically most pressing in settlements adjacent to waterways and waterbodies for the purposes of preventing or controlling flooding and building commercially useful space. At the shoreline, shaping the landscape to establish desirable topographic relief offered a way of capitalizing resources and space in multiple ways: initially by removing soil from steep ground considered more difficult to develop (thereby improving it) and subsequently depositing it at the shore to create flat, low, valuable real estate (by "reclaiming" it from waters and wetlands). After industrialization, the disposal practices of urban and industrial wastes increasingly utilized excavated soils as a material for 'capping' wastes – at the shoreline and inland landfill sites alike.

This dissertation expands on a central thesis: the role of managed soil and sediment is poised to change dramatically in the 21st century. As human population rises, and people increasingly settle in ever-more dense (often coastal) cities, they will expand their built environment and excavate umpteen volumes of sediment doing so. Currently, dominant regimes defining the management of this resource view and treat it as a waste-product; and it is often ultimately and irretrievably interred in landfills. The relationship between these processes and resources may dramatically change in the climate change era. We consider themes and theories for contextualizing and situating this concept in relevant processes, patterns, places and problems related to earthworks, focusing on coastal urban development, design and planning.

Beginnings of Anthropogenic Earthworks

Humans have proved prodigious shapers of the face of the earth: manipulating landform to capture and control natural processes: in the Neolithic drive towards agrarian settlements; in the building of mounds and mounts for spiritual and civic purposes; in the urban society-building process; and in myriad other endeavors of environmental alteration since (Douglas, 2000; Hooke, 2012; Morrish, 2010; Pollock, 1999; Price, 2011; Sjoberg, 1960; Yoshida, 2018; McEvoy, 2004; Wilkinson, 2014). Often credited to Napoleon Bonaparte, the axiom "geography is destiny" implies an elegant and profound idea about humans and their place on earth. Yet it risks overlooking an important aspect of the human condition: where manipulation of the landscape could alter natural processes of the site, area, or region, manifold effects might result -- intentional and otherwise (and often both)

(Harrison, 1992; Reisner, 1993; Scott, 1998). In this way, humans have explored ways of engineering geography; and perhaps bending the arc of destiny to their will. Doing so inevitably seemed to entail the physical reworking of landform.



Form and Void: The 6th Century BC Cloaca Maxima of Rome's outfall at the Tiber River (Left) is still in existence and partially functional, thus sometimes referred to as the least expensive infrastructure ever built. While essentially invisible, its construction nonetheless involved extensive earthwork. (R): 3rd Century BC Adenaen Serpent Mound in Midwestern America: a notable earthwork of altogether different form and intent. University of San Francisco.

Manipulation of Landform in North American Cities: 1700-Present

Setting the Scene: Relevant Context and Trends: America in 1700-1850

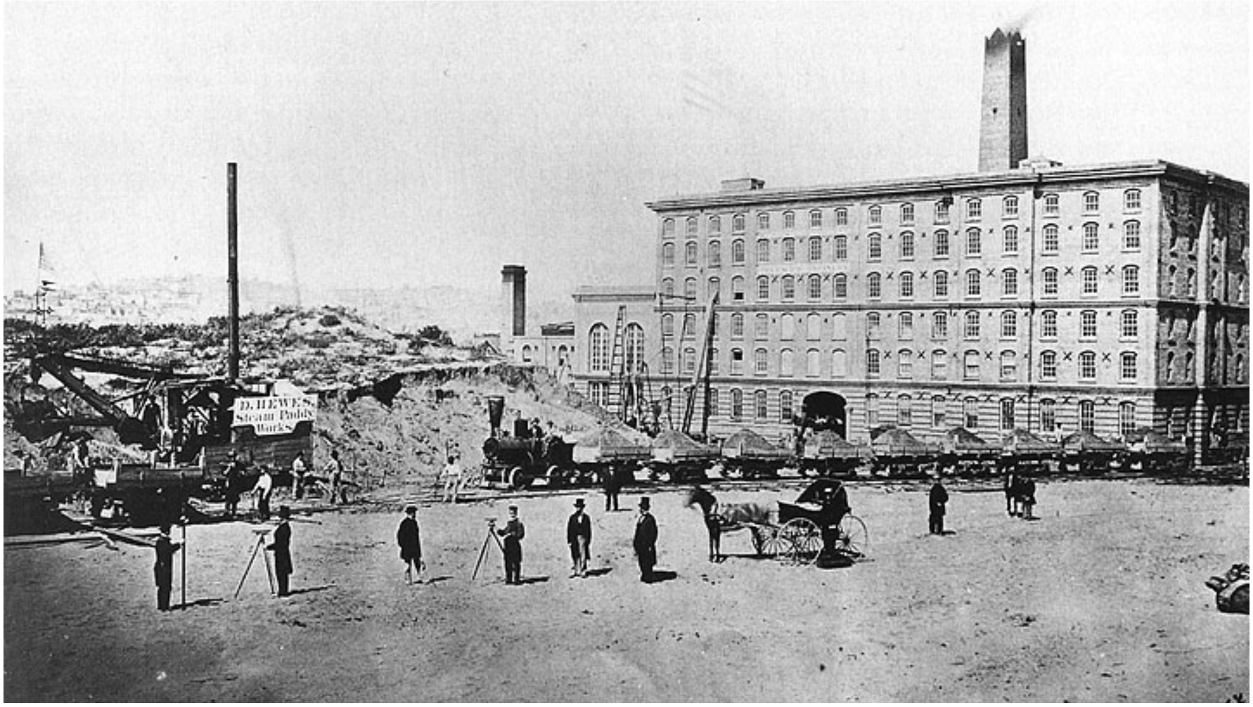
Understanding the patterns and processes of growth, industrialization and urbanization that led to the America of the mid-19th century requires consideration of several important trends and projects leading up to the era. Port cities were critical outposts in colonial times: access to natural resources, safe harbors and inland waterways made shallow bays and estuaries ideal loci of commerce, culture and the local urban development they engendered (ULI, 1983). Demand for waterfront access (wharves and docks) and flat, low ground to build urban space led to a common practice: land filling by deposition of all manner of material to establish vast swaths of constructed waterfront (Spirn, 1984). Urban development and functions found this the preferable condition for the logistical avoidance of schlepping goods uphill and the relative ease of siting and constructing buildings on flatlands and gradual grades. Laying low local hills relief yielded material for expanding land (by filling) while also producing lower, flatter ground in turn, thus improving it (Lockwood, 1978).

Extensive canals connected New England's port cities to points west. The Erie and Pennsylvania Mainline Canals were highly sophisticated, hundreds-of-miles-long constructions at the height of the "Canal Age" (Nye, 1994; Shaw, 1990). Enormous volumes of earthen material had to be dug and blasted out of their alignments, where horse carts and countless men did the digging (Haycraft, 2000). The Erie canal likely entailed the excavation of 11 million cubic yards of earth: side-casted to build a towpath levee (Clark, 1985; Shaw, 1990). Sanitation efforts in early American cities drove another suite of excavation processes that laced through cities and reached far into the hinterlands alike (Cronon, 1992; Granick, 1991; Nye, 1994). Outbreaks of typhoid, yellow fever, malaria, cholera and dysentery plagued early cities, and urban water was complicit in them all (Melosi, 2000). Inadequate drainage, tainted aquifers, and the need to convey drinking, wastewater and stormwater led to mass excavations to bury pipes and aqueducts beneath cities, in addition to the earthworks involved in trenching and tunneling through countryside, damming reservoirs and building levees (Gandy, 2002; Granick, 1991). Civil Engineering emerged as a formalized discipline to tackle these prominent and emergent challenges of the day (reclamation, transportation, sanitation), and America's first Engineering school was founded in 1820 (Melosi, 2000). Steam-powered plows began to revolutionize agriculture in North America, starting in the 1830s, and steam shovels and trains were used to reduce topography to cartloads of soil, sand and stone: very often to shunt the spoils to the shoreline (Lockwood, 1978; Spirn, 1984).

The Industrialized City: 1850-1950

Civil Systems: Infrastructure and its Earthworks

Enormous national growth and change characterized the decades leading up to the mid-19th Century, and the 1850 Gold Rush essentially began to reformat the political, population and economic dynamics of the nation (Caughey, 1975; Cronon, 1992). Millions of Europeans arrived, though the growth of cities was also due to migration from outlying rural areas -- partially a function from steam-powered agricultural machinery's rise, though increasingly it was put to use in other earthworks (Caughey, 1975; Haycraft, 2000; McKelvey, 1963; Miller, 1987; Mumford, 1961). If anything, the westward expansion and migration triggered by the Gold Rush made the imperative for large, dense, and prosperous cities on the East Coast and Great Lakes all the more important: driving towards an unprecedented level of interconnectedness, due in no small part to the 1869 transcontinental Railroad linkage, an enterprise entailing a network of innumerable earthworks to construct (Cronon, 1992; Nye, 1994; Schuyler, 1986; Tarr, 1996).

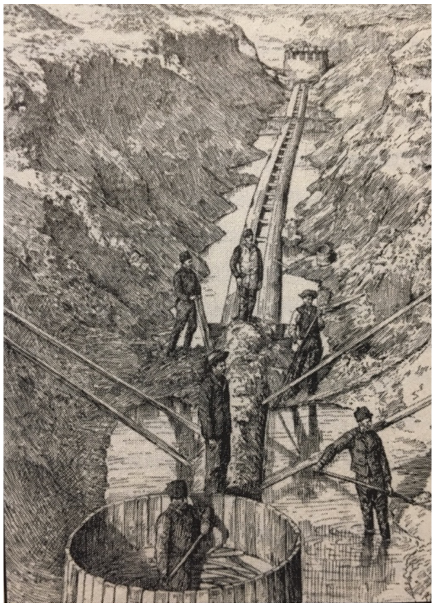


Above: San Francisco in the 1850s, as the region's extensive "wharfing out" period began in earnest. The sign reads, "D. Hewes Steam Paddy Works". Note the steam locomotive with carts full of soil surely headed to the shoreline; the flattened, barren expanse in the foreground; and the scrub-covered hill being reaped, center-left. Bancroft Library.

As the built environment spread, its infrastructural networks did too, and countless projects to underground pipelines and other provisional networks accompanied the landforms of development: graded hills and parcels; cuts through relief for roads and rails; dam-building; and excavating innumerable cellars, vaults, tunnels and basements. The trolley replaced the horse as electrification, emerging slowly in the 1880s, altered transport and energy regimes, adding layers to the underground in cities and suburbs (Granick, 1991; Kaika, 2005; Nye, 1994). Influential notions about how modernity might be physically constructed coalesced across the pond: Hausmann's 1850s "rationalization" of Parisian space established the souterrain as an urban "underground service layer" (Gandy, 2014). Bazalgette's massive 1860s sewerage and Thames River improvement project illustrated the potential balance between "cutting" and "filling" in a developed city, as trenches for sewers yielded spoils for remaking the Thames' newly bulkheaded banks and reinventing the basic hydrology of the city through the manipulation of land (Halliday, 1999).

Above: 1862 drawing of the St Martin canal (left) beneath Paris, being used for transport, which coincided with Hausmann's extensive renovation and the major sanitation infrastructure overhaul it sought to provide (middle). Photo of Thames River outfall into the River Lea (right), also in 1862. Royal College London

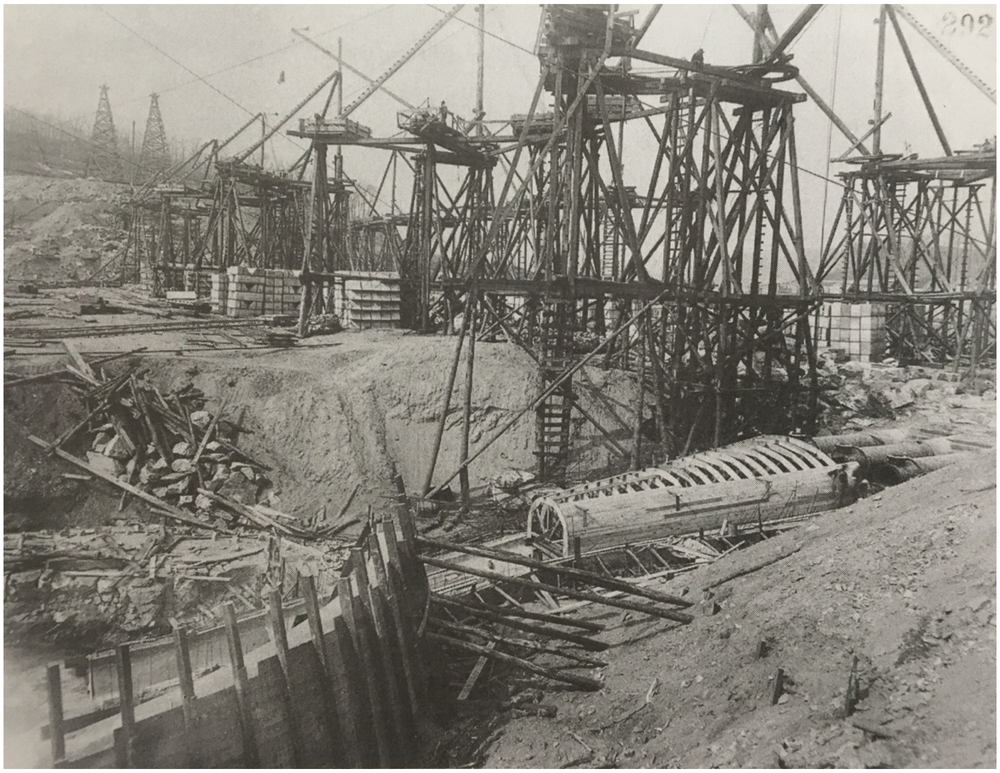
By the 1880s, centralized steam networks for municipal heat joined the urban underground, and engineers were gifted new powers with the 1890 invention of the Diesel internal combustion engine, widely deployed in endeavors ranging from agriculture (its raison d'être) to other earthmoving uses involved in mining, tunneling, and marine dredging (Granick, 1991; Haycraft, 2000; Melosi, 2000). Railroads extended suburbs, furthering their demand for civil infrastructure, much of it underground (Cronon, 1992; Miller, 1987; Spirn, 1998).



Above: A photograph (L) and drawing (R) of workers laying a 4'-diameter redwood water pipe in a ~1900 Denver, CO trench. 10,000 cubic yards of earth is displaced per-mile of pipe. In the 1880s and 1890s, the number of national waterworks increased faster than the population grew (Melosi, 2000). UCD; Engineering News.

Above: A 1910 cutaway drawing of a "city of flows", showing Paris' Place d'Opera metro and the urban underground. While intricate and impressive, the drawing actually omits numerous other layers of Hausmann's urban "service layer" that the souterrain provided to the City of Lights: including energy (hence the lights) and sanitary services. Mumford cited the "Underground City" as a natural outgrowth of urbanization. Popular Mechanics.

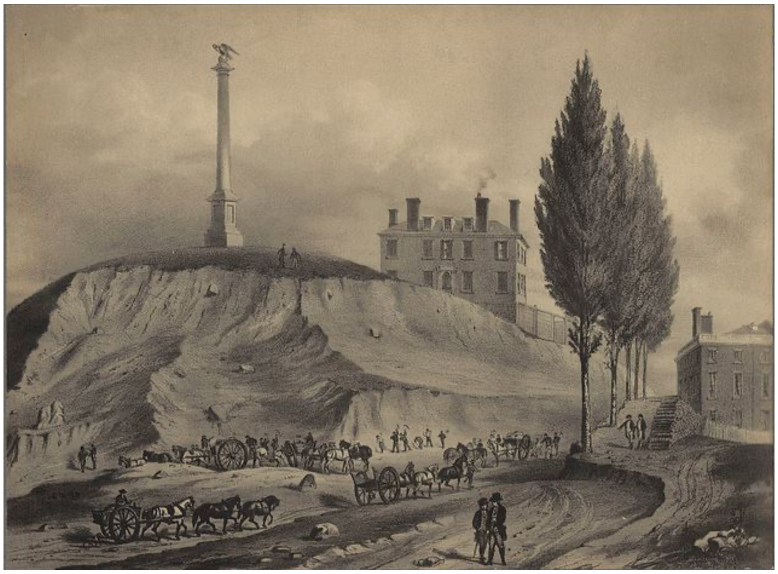
The rapid growth of the nation's cities continued to build a palimpsest of subterranean networks laced through increasingly tall, dense cities; networks inevitably requiring expansion, growth, repair and adaptation (Granick, 1991). This "city of flows" facilitated the movement of resources, goods, wastes, energy and people -- influenced by ever-expanding markets, technological mobility and a sense of control over commodities, resources, and perhaps nature itself (Cronon, 1992; Gandy, 2002; Kaika, 2005; Nye, 1994). Private automobilization redefined urban form everywhere in the 1920s and 30s, inevitably finding its way underground; and natural gas replaced coal in many cities by the 1940s, necessitating a novel underground distribution network of pipelines and storage wells (Mumford, 1961; Tarr, 1996).



Above: Croton Falls Dam, NY, 1909. Provisioning an urban enclave with various resources often entailed earthworks in the hinterlands (and connecting them, see previous picture) and many unintentional consequences for aquatic ecosystems and sediment flows to shorelines resulted. NY Historical Society.

The Making of Land near Water

Providing and ever-growing urban population with housing, services, and resources challenged growing port cities, which also contended constantly with the urban-industrial woes of the era (Melosi, 2000; Tarr, 1996). As ships grew, their drafts deepened. The sheer scale and tempo of commerce ticked up; extensive wharves, quays and proximal storage, processing and distribution facilities were built, very often on reclaimed land made from shallowing waters and wetlands (Whitehill & Kennedy, 2000).



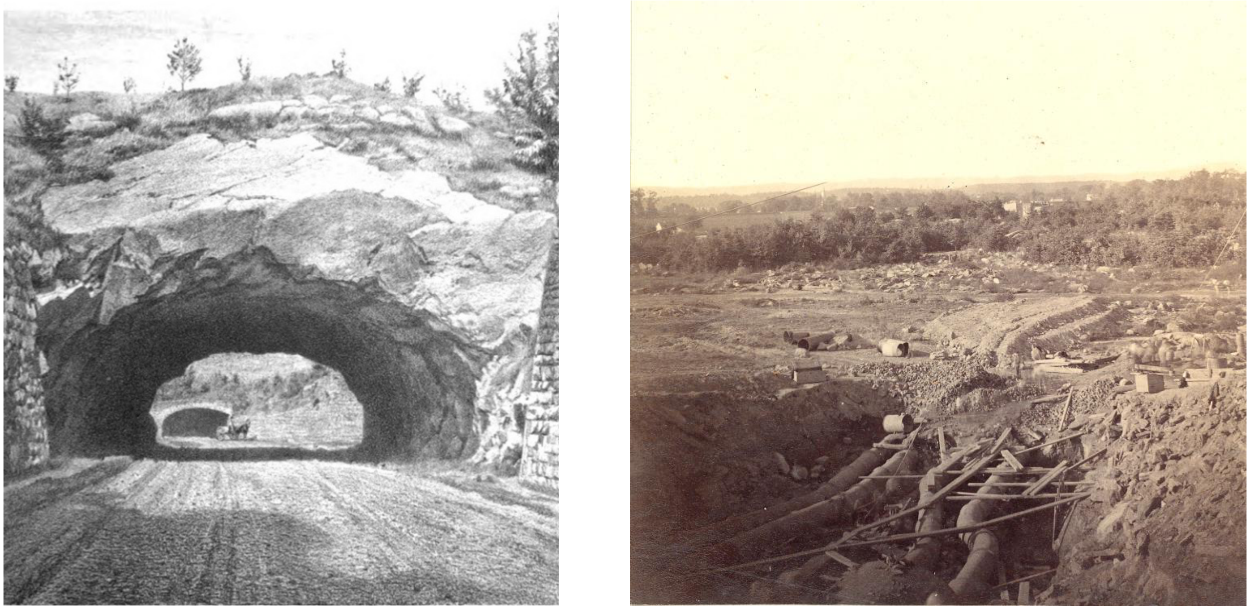
Above: Boston's Beacon Hill (~1890s) was not safe in the "wharfing-out" era, in which doing so was understood as a compound benefit: a more easily-traversed city was graded, while its waterfront expanded, and landowners were paid for the soil and sand reaped (Seasholes, 2003). Boston Historical Society.

To facilitate the near-constant rearticulation and growth of urban shorelines, waterfront cities employed all manner of technological means to source, transport and deposit materials. Commonly, earthen levees, or piles driven into the watery ground hemmed in reaches of shoreline -- in coastal estuaries, riverfronts and Great Lakes alike -- and Into these basins were deposited all manner of refuse and bulk material until a supratidal elevation was achieved: sand, soil, stone and gravel; dredged spoils; ship ballast; ashes, rubble and, increasingly, various solid wastes generated by urban and industrial life (Cronon, 1992; Melosi, 2000; Seasholes, 2003; Tarr, 1996).

Above: 1893's Columbian Exhibition on Lake Michigan's shore provided cutting-edge civil infrastructure in a reinvented swath of Chicago's waterfront as a Beaux-Arts dreamland (for a temporary event). Underpinning the plan were considerable land reclamations and earthworks overseen by Olmsted, and filling of Chicago's waterfront continued – for far-less civic-minded purposes – for decades thereafter (Larson, 2003; Taft, 2018). Chicago Public Library.

Regional Urbanism: Aesthetics and Ideals in Landform and Its Functions

Designers grappling with the emergent needs and challenges of the mid- and late-19th century embarked upon defining projects of the new American landscape. Frederick Law Olmsted's schemes for New York's Central Park was ambitious in several respects, not least of which was its sheer size and siting: a massive grading and earthwork-based "lungs" at the center of America's premier city (Schuyler, 1986). The Greensward Plan of 1858 audaciously foregrounded the simple preeminence of landscape in its own right: landforms blurred and obscured the park's boundaries, and it was the sole proposal to simply declare that surface-level roadways would be ruinous; requiring considerable tunneling and cut-and-cover operations to subordinate them (Schuyler, 1986). Landscape architecture, while not yet minted as a profession in America, had moved far beyond gardening to meet (and define) the scale of the city.

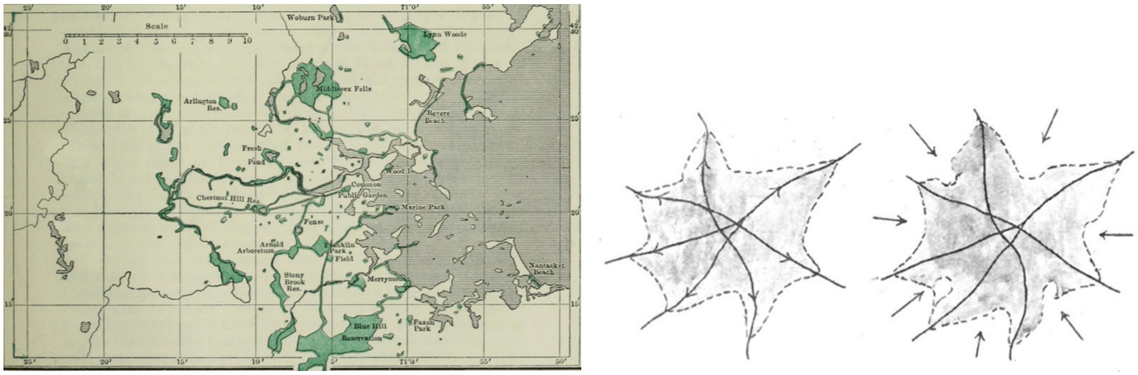


Above: While Olmsted and Vaux sought to showcase and play off the natural relief of Manhattan in their 1858 scheme for Central Park, the scale of earthwork involved is often overlooked. Shunting the transverse roads under the park (left) was unique to their Greensward Plan; construction of the new reservoir required extensive digging and grading. New York Public Library.

Concerns for the lack of quality of life in cities, echoing some of the romantic lamentations of Emmerson and Thoreau, gave voice to advocates of suburbanizing like Catharine Beecher and Andrew Jackson Downing (Marx, 2000). Waves of reimagining the relationship between nature and the city ensued, and notions about how the built environment might view, use or otherwise benefit from pastoralism, nature's aesthetics and ecological functionality evolved to herald the 20th century, and its ever-widening metropolitan regions that inevitably enveloped (and often degraded) the countryside surrounding the city (Hall, 2002; Miller, 1987). Nonetheless, leveraging advances in technology to overcome environmental inconveniences abounded, as cities in some instances took to undergrounding, and essentially denying, their fundamental hydrologic realities, often to their eventual, intergenerational detriment (Spirn, 1998). Yet this was of a pattern: while romantic notions about nature and wilderness were evolving in the American Psyche, the drive to "solve" urban problems through technocratic means was consuming (Gandy, 2014).

Above: The Undergrounding of Mill Creek in 1880s Western Philadelphia. Shunting stormwater into a massive culvert beneath the town caused extensive, multi-generational problems, and entailed an impressive earthmoving enterprise to accomplish in the first place. Note the sheer displacement of earth by the structure; and the volume required to eventually re-establish grade above it. Philadelphia Water Department

Ebenezer Howard's Garden City imagined a productive landscape adorned with agricultural self-sufficiency and modern modes of living; City Beautiful sought the injection of nature into the city, reclaiming its civic dignity and value; Progressive Era reformers promoted City Efficient to solve social and environmental problems, essentially ushering in the formalization of zoning as a central aspect of urban planning and governance (Hall, 2002; Marx, 2000; Miller, 1987; Schuyler, 1986, Taylor, 2009). The rise of metropoles perhaps demanded that regionalism and an understanding of the value of not developing land emerge, as luminaries like Charles Elliot Jr and Patrick Geddes challenged contemporary views about the role and value of ecological structures and systems -- inevitably linked to broader environmental and sociocultural wellbeing – that harmonized with a reformist Progressive era's discontented notions about urban-industrial growth and its impacts, becoming a focus of the cultural philosophies of Catherine Bauer, Lewis Mumford and others (Tyrwhitt, 1947; Hall, 2002; Ndubisi, 2002).



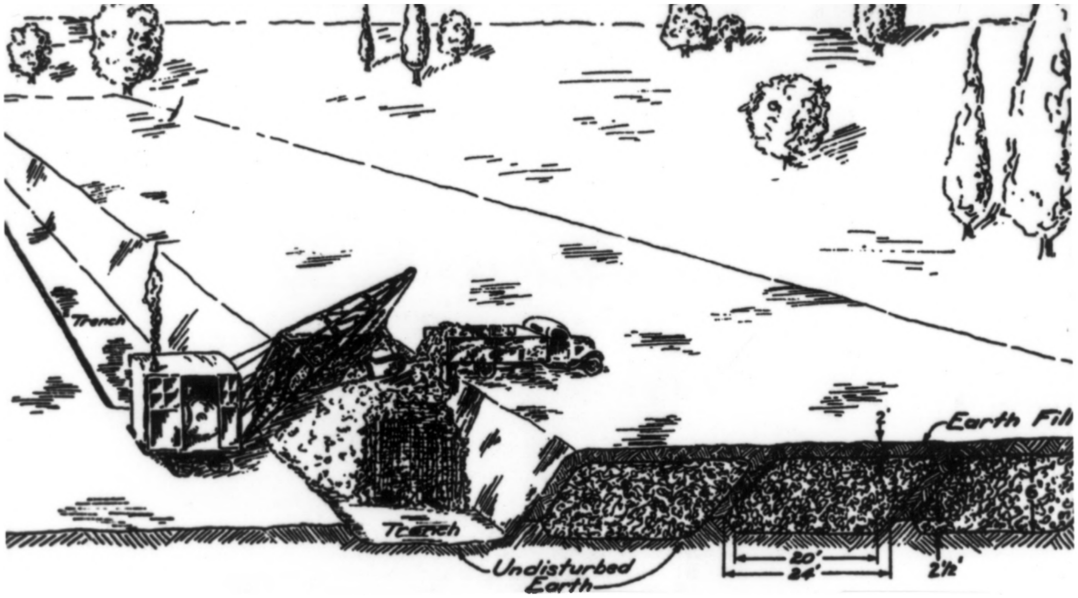
Above left: Charles Eliot Jr's networked open space sketch of the Neponset River basin (1902) and Patrick Geddes' (1915) sketch imagining the countryside constraining the sprawl of development spoke to increasing sociocultural concerns and interest in regional aspects of societal growth and development. University of Toronto.

Automobilization became a defining logic for urban form, rising hand-in-glove with technological leaps in the heavy machinery (and the scale of resultant earthworks) useful in city building projects (like linking interstate highway networks and shunting traffic below already built-out cities) including their rebuilding to address reformist concerns of the age, rural-urban migration and rising populations (Granick, 1991; Haycraft, 2000; McKelvey, 1963; Miller, 1987; Mumford, 1961). Civil engineering, ascendant in the early 21st century, sought to affect resource reallocation schemes on hitherto unknown scales, often imposing "top-down" notions of commanding and controlling nature for the benefit of humans: draining the Everglades; taming the Tennessee Valley; mastering the Mississippi and the monumental task of provisioning water out West all signified the public works projects of the New Deal (Holling, 1996; Grunwald, 2006; Hall, 2002; McPhee, 1989; Nye, 1994; Righter, 2005).

Above: Montana's 1938 Ft Peck Dam (partial) failure. The dam itself (lower left) is 250' tall at its crest with a 500-acre area. Inevitably, where control of water was concerned, manipulation of land was the medium for its realization, sometimes grandiosely. Army Corps of Engineers.

Landform Manipulation in the Modern Metropoles: 1950-Present

World War II introduced the military industrial complex to all aspects of American sociopolitical life, and processes of extraction, manufacturing and shipping exploded in their scope and scale. Strategic port cities found themselves injected anew with the imperative and impetus to grow and develop (Miller, 1987; Mumford, 1961). Rising populations in these regions engendered a bigger, denser built environment, which entailed all manner of excavation projects to construct and UUS expanded with these changes and advances in engineering's capacities and ambitions, (Jansson, 1978). A convenient, if not altogether original role for excavated soils to play in the dance of urban development emerged. "Sanitary landfills" spearheaded in Fresno and San Francisco CA in the 1930's provided a threefold solution: local municipal waste could be "capped" by earth (thus hiding its offensive aesthetics); done at the shoreline (some states had, by now, banned open ocean dumping), this formed a cornerstone of ongoing land reclamation projects; and it effectively "solved" the question of where and how to dispose of a constant and increasing flow of soils and spoils, which could be used to cap the (also increasing flow of) garbage (Melosi, 2000; Tarr, 1996).



Above: Fresno, CA's sanitary landfill, c. 1939. APWA

Numerous large-scale projects both real and imagined hinged upon this concept, which spoke to the scale of the bustling metropoles need for developable land and waste management in an expanding and ravenously hungry consumer culture (Melosi, 2000). Schemes aimed at engineering entire regional landscape dynamics and converting the world's largest landfill (Fresh Kills, NY) into valuable real estate stood as examples also of the oddly important role of soil and sediment as building material for projects of immense scale (Caro, 1974; Jackson, 1977; Trumpeter, 2012). And postwar frontiers across the country experimented with new ways of shaping, and conserving landscape in the rapid growth of the postwar period (Mozingo, 2011). Though environmental luminaries had been laying the groundwork for over a century, the troubling trends pertaining to growth, sprawl and environmental degradation coalesced in the postwar period as a "New Ecology" dawned and the environmental movement ultimately galvanized in the 1970s (Melosi, 2000; Ndubisi & ebrary Academic Complete, 2002). Insights of John Muir, Aldo Leopold and Rachel Carson were synthesized into a planning ethos by Ian McHarg and others sketching utopian merging of city and countryside into, and many environmentally-focused legislative acts were incepted into federal and state law, with implications for planning and development (De Monchaux, 2016) Fiorino, 2006).

Above: Eminent Landscape Architect Rich Haag's articulation of the elemental ethos of the landscape architect, "dig hole; build mound" at least half-evident in Seattle's Gas Works Park, opened in 1975. The "Great Mound" (right) is a cache of rubble, capped by soil and now standing as a novel landform simultaneously masking and referencing the site's past. University of Puget Sound.

A number of regulatory measures emerged; aimed at curtailing land filling and soil/sediment disposal in waterways and mostly for the protection of crucial habitat and species – regulations that persist today in many metropolitan shorelines (Platt, 1994). The Water Pollution Control and Coastal Zone Management Acts of 1972 restricted reclamation, land filling and shoreline development. The Endangered Species Act and Habitat Conservation Plans induced expanded stewardship of many national shoreline areas.

Future Directions

Physically altering the elevational profiles of shorelines is ancient, and evident in the rapid rise of America's port cities and their long legacies (Charlier, 2005; Hill 2013; Inman, 1974; Spirn, 1984). Excavated soil resources have played interesting roles in metropolitan shorelines: as a building material for physically constructing them; as byproducts of their development and growth; as components of waste management systems tied to changes in urbanization, infrastructure, technology and governance; and most recently in ecological restoration and adaptation projects. Extensive landforms are being considered for their role in coastal adaptation as multi-benefit flood barriers, and research is needed to connect an understanding of their material requirements with the soil management in urban shorelines: conceptually linking ongoing flows to an anticipated application, and exploring how their physical linkage might be accomplished.

The built environment is expected to grow at an astonishing rate in coming decades (de Monchaux, 2016). Urban development trending toward tight, dense, transit-oriented cores will concentrate excavation activities, very often in places much closer to under-nourished shorelines than landfills. The challenges of implementing (or simply planning) metropolitan shoreline adaptation schemes that might be required to meet several feet of SLR in the 21st century are immense; so complexified and contested are these geographies by actors of all stripes, operating at federal, state, regional, and local levels. Without research into the potential significance of sediment reuse in regional SLR strategies, coastal conurbations cannot compose an accurate picture of their fundamental options based on the material markets and ecology related to excavated sediment. And because of the existing regimes governing urban soils (and as a function of their nature), they are both nonrenewable and truly lost when landfilled. The drowning of coastal wetlands whose migration is impeded by the (also imperiled) built environment represents a major impetus for research into the material ecology of anthropogenically-managed urban soils and sediment.

Introduction References:

Admiraal, H., & Cornaro, A. (2016). Why underground space should be included in urban planning policy – And how this will enhance an urban underground future. Tunnelling and Underground Space Technology, 55, 214–220. https://doi.org/10.1016/j.tust.2015.11.013

Admiraal, H., & Cornaro, A. (2018). Underground spaces unveiled: Planning and creating the cities of the future. (Environmental Design NA2542.7 .A36 2018). London : ICE Publishing, [2018]; cat04202a.

Ascher, K., & Marech, W. (2007). The works: Anatomy of a city. (Environmental Design HT394.N4 A84 2007). New York : Penguin Press, 2007, c2005.; cat04202a.

Barnard, P. L., Schoellhamer, D. H., Jaffe, B. E., & McKee, L. J. (2013). Sediment transport in the San Francisco Bay Coastal System: An overview. Marine Geology, 345, 3–17. https://doi.org/10.1016/j.margeo.2013.04.005

Bartel, S., & Janssen, G. (2016). Underground spatial planning – Perspectives and current research in Germany. Tunnelling and Underground Space Technology, 55, 112–117. https://doi.org/10.1016/j.tust.2015.11.023

Besner, J. (2016). Underground space needs an interdisciplinary approach. Tunnelling and Underground Space Technology, 55, 224–228. https://doi.org/10.1016/j.tust.2015.10.025

Caro, R. A. (1974). The power broker: Robert Moses and the fall of New York. (Environmental Design NA9085.M68 C371 1974). New York, Knopf, 1974.; cat04202a.

Caughey, J. W. (1975). The California gold rush. (Asian American Studies F861.A1 C58). Berkeley : University of California Press, 1975, c1948.; cat04202a.

Charlier, R. H., Chaineux, M. C. P., & Morcos, S. (2005). Panorama of the History of Coastal Protection. Journal of Coastal Research, 211, 79–111. https://doi.org/10.2112/03561.1

Clark, R. (1985). Works of man. (Morrison T15 .C531 1985). New York : Viking, 1985.; cat04202a. \

Cronon, W. (1992). Nature's metropolis: Chicago and the Great West. (Earth Science/Map Collection F548.4 .C85 1992). New York : W. W. Norton, 1992, c1991.; cat04202a.

De Monchaux, N. (2016). Local code: 3,659 proposals about data, design & the nature of cities. (Environmental Design NA9053.E58 D4 2016). New York : Princeton Architectural Press, [2016]; cat04202a.

Delgado, J. P. (2009). Gold rush port: The maritime archaeology of San Francisco's waterfront. (Environmental Design F869.S347 D45 2009). Berkeley : University of California Press, c2009.; cat04202a.

Dixon, S. J., Viles, H. A., & Garrett, B. L. (2018). Ozymandias in the Anthropocene: The city as an emerging landform. Area, 50(1), 117–125. https://doi.org/10.1111/area.12358

Douglas, I., & Lawson, N. (2000). The Human Dimensions of Geomorphological Work in Britain. Journal of Industrial Ecology, 4(2), 9–33. https://doi.org/10.1162/108819800569771

Ferguson, L. E. (2018). A Gateway without a Port: Making and Contesting San Francisco's Early Waterfront. Journal of Urban History, 44(4), 603–624. https://doi.org/10.1177/0096144218759030

Gandy, M. (2002). Concrete and clay: Reworking nature in New York City. (Environmental Design HT243.U62 N74 2002). Cambridge, Mass. : MIT Press, c2002.; cat04202a.

Gandy, M. (2014). The fabric of space: Water, modernity, and the urban imagination. (Environmental Design TC405 .G36 2014). Cambridge, Massachusetts : The MIT Press, 2014.; cat04202a.

Geddes, P., Sir, & Tyrwhitt, J. (1947). Patrick Geddes in India; (Environmental Design NA9251 .G4). London, L. Humphries, 1947.; cat04202a.

Glacken, C. J. (1967). Traces on the Rhodian shore; nature and culture in Western thought from ancient times to the end of the eighteenth century. (Anthropology GF31 .G6). Berkeley, University of California Press, 1967.; cat04202a.

Granick, H. (1991). Underneath New York. (Environmental Design TD159.3 .G73 1991). New York : Fordham University Press, 1991.; cat04202a. h

Grunwald, M. (2006). The swamp: The Everglades, Florida, and the politics of paradise. (Main (Gardner) Stacks F317.E9 G78 2006). New York : Simon & Schuster, c2006.; cat04202a.

Haglund, K. (2003). Inventing the Charles River. (Environmental Design F72.C46 H33 2003). Cambridge, Mass. : MIT Press, c2003.; cat04202a.

Hall, P. (2002). Cities of tomorrow: An intellectual history of urban planning and design in the twentieth century. (Environmental Design HT166 .H349 2002). Oxford, UK ; Malden, MA : Blackwell Pub., 2002.; cat04202a.

Halliday, S. (1999). The great stink of London: Sir Joseph Bazalgette and the cleansing of the Victorian capital. (Main (Gardner) Stacks TD564.L6 H35 1999). Stroud : Sutton, 1999.; cat04202a.

Harrison, R. P. (1992). Forests. [Electronic resource]: The shadow of civilization. Chicago : University of Chicago Press, c1992.; cat04202a.

Hashimoto, S., Tanikawa, H., & Moriguchi, Y. (2007). Where will large amounts of materials accumulated within the economy go? – A material flow analysis of construction minerals for Japan. Waste Management, 27(12), 1725–1738. https://doi.org/10.1016/j.wasman.2006.10.009

Haycraft, W. R. (2000). Yellow steel: The story of the earthmoving equipment industry. (Institute for Research on Labor and Employment HD9715.25.U62 H39 2000). Urbana : University of Illinois Press, c2000.; cat04202a.

Hooke, R. LeB., Martín-Duque, J. F., & Pedraza, J. (2012). Land transformation by humans: A review. GSA Today, 22(12), 4–10. a9h.

Jackson, W. T., & Paterson, A. M. (1977). The Sacramento-San Joaquin Delta: The Evolution and Implementation of Water Policy: An Historical Perspective. edssch.

James, L. A. (2013). Legacy sediment: Definitions and processes of episodically produced anthropogenic sediment. Anthropocene, 2, 16–26. https://doi.org/10.1016/j.ancene.2013.04.001

Jansson, B. (n.d.). City Planning and the Urban Underground. 17.

Kaika, M. (2005). City of flows. [Electronic resource]: Modernity, nature, and the city. New York : Routledge, c2005.; cat04202a.

Katsumi, T. (2015). Soil excavation and reclamation in civil engineering: Environmental aspects. Soil Science and Plant Nutrition, 61(sup1), 22–29. https://doi.org/10.1080/00380768.2015.1020506

Larson, E. (2003). The devil in the white city: Murder, magic, and madness at the fair that changed America. (Environmental Design HV6248.M8 L37 2003). New York : Crown Publishers, ©2003.; cat04202a.

Lockwood, C. (1978). Suddenly San Francisco: The early years of an instant city. (Environmental Design F869.S3 L61 1978). San Francisco : Examiner Special Projects, c1978.; cat04202a. h

Marx, L. (2000). The machine in the garden: Technology and the pastoral ideal in America. (Environmental Design E169.1 .M35 2000). Oxford ; New York : Oxford University Press, c2000.; cat04202a.

McEvoy, D., Ravetz, J., & Handley, J. (2004). Managing the Flow of Construction Minerals in the North West Region of England.: A Mass Balance Approach. Journal of Industrial Ecology, 8(3), 121–140. https://doi.org/10.1162/1088198042442289

McKelvey, B. (1963). The urbanization of America, 1860-1915. (Environmental Design HT123 .M25). New Brunswick, N.J., Rutgers University Press [1963]; cat04202a.

McNichol, D., & Ryan, A. (2002). The Big Dig. (Environmental Design HE356.5.B6 M355 2002). New York, NY : Silver Lining Books, c2002, 2000.; cat04202a.

McPhee, J. (1989). The control of nature. (Anthropology TD170 .M361 1989). New York : Farrar, Straus, Giroux, 1989.; cat04202a.

Melosi, M. V. (2000). The sanitary city: Urban infrastructure in America from colonial times to the present. (Engineering TD223 .M45 2000). Baltimore : Johns Hopkins University Press, 2000.; cat04202a.

Miller, Z. L., & Mooney-Melvin, P. (1987). The urbanization of modern America: A brief history. (Environmental Design HT123 .M541 1987). San Diego : Harcourt Brace Jovanovich, c1987.; cat04202a.

Morrish, W. R. (2010). Civilizing terrains: Mountains, mounds and mesas. (Environmental Design SB472.7 .M67 2010). San Francisco, CA : William Stout Publishers, 2010.; cat04202a.

Mozingo, L. A. (2011). Pastoral capitalism: A history of suburban corporate landscapes. Cambridge, Massachusetts ; London, England : The MIT Press, 2011.; cat04202a.

Mumford, L. (1961). The city in history: Its origins, its transformations, and its prospects. (Environmental Design HT111 .M85). New York : Harcourt, Brace & World, ©1961.; cat04202a.

Ndubisi, F., [1955-] & ebrary Academic Complete. (2002). Ecological planning: A historical and comparative synthesis. awn.

Nye, D. E. (1994). American technological sublime. (Engineering T14.5 .N93 1994). Cambridge, Mass. : MIT Press, c1994.; cat04202a.

Platt, R. H., Rowntree, R. A., & Muick, P. C. (1994). The Ecological City: Preserving and Restoring Urban Biodiversity. University of Massachusetts Press; nlebk.

Pollock, S. (1999). Ancient Mesopotamia: The eden that never was. (Main (Gardner) Stacks DS71 .P65 1999). Cambridge : Cambridge University Press, 1999.; cat04202a.

Price, S. J., Ford, J. R., Cooper, A. H., & Neal, C. (2011). Humans as major geological and geomorphological agents in the Anthropocene: The significance of artificial ground in Great Britain. Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences, 369(1938), 1056–1084. https://doi.org/10.1098/rsta.2010.0296

Reisner, M. (1993). Cadillac desert: The American West and its disappearing water. (Bioscience & Natural Resources HD1739.A17 R45 1993). New York, N.Y., U.S.A. : Penguin Books, 1993.; cat04202a.

Righter, R. W. (2005). The battle over Hetch Hetchy: America's most controversial dam and the birth of modern environmentalism. (Bioscience & Natural Resources TD225.S25 R54 2005). New York : Oxford University Press, 2005.; cat04202a.

Schuyler, D. (1986). The new urban landscape: The redefinition of city form in nineteenth-century America. (Environmental Design HT167 .S2851 1986). Baltimore : Johns Hopkins University Press, c1986.; cat04202a.

Scott, J. C. (1998). Seeing like a state: How certain schemes to improve the human condition have failed. (Anthropology HD87.5 .S365 1998). New Haven [Conn.] : Yale University Press, c1998.; cat04202a.

Seasholes, N. S. (2003). Gaining ground: A history of landmaking in Boston. (Environmental Design F73.3 .S46 2003). Cambridge, Mass. : MIT Press, c2003.; cat04202a.

Shaw, R. E. (1990). Canals For A Nation. [Electronic resource]: The Canal Era in the United States, 1790-1860. Lexington, Ky. : University Press of Kentucky, c1990. (Baltimore, Md. : Project MUSE, 2015); cat04202a.

Sjoberg, G. (1960). The preindustrial city, past and present. (Anthropology HT113 .S46). Glencoe, Ill. : Free Press, c1960.; cat04202a.

Spirn, A. W. (1984). The granite garden: Urban nature and human design. (Environmental Design HT166 .S638 1984). New York : Basic Books, c1984.; cat04202a.

Spirn, A. W. (1998). The language of landscape. (Environmental Design SB472 .S685 1998). New Haven [Conn.] : Yale University Press, c1998.; cat04202a.

Strupp, C. (n.d.). Dealing with Disaster: The San Francisco Earthquake of 1906. 45.

Taft, C. E. (2018). Shifting shorelines: Land reclamation and economic blackmail in industrial South Chicago. Environment and Planning E: Nature and Space, 1(1–2), 186. edo.

Tanikawa, H., & Hashimoto, S. (2009). Urban stock over time: Spatial material stock analysis using 4d-GIS. Building Research & Information, 37(5–6), 483–502. https://doi.org/10.1080/09613210903169394

Tarr, J. A. (n.d.). THE METABOLISM OF THE INDUSTRIAL CITY. 35.

Tarr, J. A. (1996). The Search for the Ultimate Sink. [Electronic resource]: Urban Pollution in Historical Perspective. Akron, Ohio : University of Akron Press, 1996. (Baltimore, Md. : Project MUSE, 2015); cat04202a.

Trumpeter, K. (2012). Fresh Kills Landfill. Sage Publications, Inc; edsgvr.

Upton, D. (2008). Another city: Urban life and urban spaces in the new American republic. (Environmental Design HT123 .U68 2008). New Haven : Yale University Press, c2008.; cat04202a.

Walker, R. (2007). The Country in the City. [Electronic resource]: The Greening of the San Francisco Bay Area. Seattle : University of Washington Press, c2007. (Baltimore, Md. : Project MUSE, 2015); cat04202a.

Whitehill, W. M., & Kennedy, L. W. (2000). Boston: A topographical history. (Environmental Design F73.3 .W57 2000). Cambridge, Mass. : Belknap Press of Harvard University Press, 2000.; cat04202a.

Wilkinson, T. J., Philip, G., Bradbury, J., Dunford, R., Donoghue, D., Galiatsatos, N., Lawrence, D., Ricci, A., & Smith, S. L. (2014). Contextualizing Early Urbanization: Settlement Cores, Early States and Agro-pastoral Strategies in the Fertile Crescent During the Fourth and Third Millennia BC. Journal of World Prehistory, 27(1), 43–109. https://doi.org/10.1007/s10963-014-9072-2

Yoshida, K., Okuoka, K., & Tanikawa, H. (2018). Anthropogenic Disturbance by Domestic Extraction of Construction Minerals in Japan: Extraction of Construction Minerals in Japan. Journal of Industrial Ecology, 22(1), 145–154. https://doi.org/10.1111/jiec.12543

Chapter 1: Climate Change, Adaptation Planning and Institutional Integration: A Literature Review and Conceptual Framework

Abstract

The scale and scope of climate change has triggered widespread acknowledgement of the need to adapt to it. Out of recent work attempting to understand, define, and contribute to the family of concepts related to adaptation efforts, considerable contributions and research have emerged. Yet, the field of climate adaptation constantly grapples with complex ideas whose relational interplay is not always clear. Similarly, understanding how applied climate change adaptation efforts unfold through planning processes that are embedded in broader institutional settings can be difficult to apprehend. We present a review of important theory, themes, and terms evident in the literature of spatial planning and climate change adaptation to integrate them and synthesize a conceptual framework illustrating their dynamic interplay. This leads to consideration of how institutions, urban governance, and the practice of planning are involved, and evolving, in shaping climate adaptation efforts. While examining the practice of adaptation planning is useful in framing how core climate change concepts are related, the role of institutional processes in shaping and defining these concepts — and adaptation planning itself — remains complex. Our framework presents a useful tool for approaching and improving an understanding of the interactive relationships of central climate change adaptation concepts, with implications for future work focused on change within the domains of planning and institutions addressing challenges in the climate change era.

1. Introduction

The environmental severity and enormity of climate change is coming into sharper focus, as are considerations of crucial and complex impacts on society and daunting demands of the requisite efforts to adapt to it (Nordgren et al, 2016). Climate Change Adaptation (CCA) is understood as a challenge ensnaring numerous actors across multiple societal sectors, acting as a nexus of overlapping concerns and connections (Aylett, 2015). Significant increases in literature concerned with climate change adaptation is evident, with commensurate scholarship dedicated to exploring key concepts in the field (Einecker & Kirby, 2020; Gupta et al., 2010; Wang et al., 2018). Hurdles to effectively engaging with climate adaptation concepts run the gamut: from the inaccessibility of scientific "jargon" (Tribbia & Moser, 2008) to the need to synthesize research and identify areas lacking attention (Berrang-Ford et al., 2015; Ford & Pearce, 2010). Disentangling the roles and relationships between modes of preparing adaptive responses to climate change (planning) and the social patterns that govern these practices (institutions) reveal more areas of confusion and needed consideration; perhaps especially for examining how these practices and patterns may *themselves* adapt or be adapted (Giordano, 2012; Gupta et al., 2010; Patterson, 2021). While conceptual frameworks used to streamline and simplify complex ideas are common, frameworks constructed for the purpose of clarifying key concepts in the field of climate change adaptation planning are lacking.

Planning is a concept with wide and diverse meaning across numerous scales and disciplines (Lawrence, 2000). While climate impacts on the atmosphere and oceans of earth are increasingly severe (and entail their own planning considerations), we are concerned here with *spatial* planning, which frames the landscape as a crucial, dynamic medium—a geographic template—upon and within which effects of climate change will be experienced most acutely by humans (Ndubisi, 2002). Spatial planning uses diverse scientific methods and information to shape decisions about how features of the landscape are designed, constructed, and managed. Berkes and Folke (1998) sought to formalize the concept of *social-ecological systems* (SES) as linked human and natural systems that somehow "fit" together (Epstein et al., 2015); and a framework for "match[ing] the dynamics of *institutions* with the dynamics of *ecosystems* for mutual social-ecological *resilience* and improved performance." While earlier work on the concept was undertaken by Ratzlaff (1970) and later Cherkasskii (1988) reflects that the SES initialization is also used to denote '*socio-ecological*' or '*socioecological*' systems, Berkes and Folke sought to avoid a modifier (socio-) that would imply a subordinate role of the social features of SES (Colding, 2019). Nonetheless, they remain largely interchangeable in the literature.

The concept's presence in publications across numerous subject areas has exploded in the 21st century (Colding & Barthel, 2019), perhaps reflecting or coinciding with increasing interest in the climate crisis and the human role and responses to it. SESs are useful here as a way of examining human interactions with and within the geographic template, and determining how technical and scientific knowledge about SESs are used to inform action in order to shape it and its future states: the essence of spatial planning (Anderies et al., 2004; Gallopın, et al., 1989). Planning decisions about shaping SESs are implicitly ethical because they may generate opportunities and challenges for future generations (Leopold, 1949).

Because climate change is characterized by significant and potentially increasing uncertainty, decision-making processes are encountering complexity in planning adaptation efforts to address these "(super)wicked" problems (Albrechts, 2004; Giordano, 2012; Hallegatte, 2009; Levin et al., 2012; Toimil et al., 2020). This is especially true in urban regions complicated by the concentration, entanglement, exposure, and diversity of citizens, resources, assets, and the systems for their management evident there, as well as the numerous, multileveled and/or polycentric governance structures employed as administrative actors (Castán Broto, 2017; Pahl-Wostl, 2009). Urban areas are complex geographies, where deep and complicated histories, cultures, and institutions generate important questions about the social aspects of power, resources, and environmental health, safety, and justice (Bulkeley & Castán Broto, 2013; Rasmussen et al., 2020).

For these reasons, while we do not rigorously analyze or compare issues arising from various scales of consideration that spatial planning constantly confronts (local vs. national; site-based vs. regional), we examine central ideas and themes related to CCA that are especially evident in densely populated, developed areas. Extensive research on the role and function of multi-level governance (MLG) is evident in CCA circles, as are discussions of various traditions, processes, and planning cultures across nations and regions of the globe (including recent work by Ishtiaque (2021) and DiGreggorio (2019) useful for deeper examination of multilevel governance dynamics.) Most of the discussion within this article is derived from—and applies most directly to—developed nations and western planning traditions whose similarities and features lend toward the generalization and synthesis useful in the construction of the proposed framework.

Meadows' (1972) landmark 1972 study, *Limits to Growth*, was recently assessed to examine the "fit" between projections of troubling development trends modeled a half-century ago, and their potential implications for countless (and planetary) SESs. Specifically, the "Business as Usual" description of a scenario describing unsustainable development practices (in this instance, particularly as a function of pollution increases including atmospheric greenhouse gas concentrations) appears to be playing out today, potentially portending calamitous impacts for society by or before midcentury (Herrington, 2021). Given that countless planning endeavors have unfolded for decades within the context of a finite planet articulated in *Limits to Growth*, major questions emerge about what planning is fundamentally *for*, how it functions (or can fail), and how it is positioned to operate in the climate change era.

Moreover, insofar as planning is understood as a *practice* utilized for governing the use of resources and space, the *institutions*—rules, norms, customs, and conventions—that simultaneously overarch and undergird planning are crucial to consider, and perhaps the fundamental relationship between planning and institutions most of all (Gualini, 2001). This frames the basic question at the center of this review: how is climate change driving transformation of the human systems that must confront it? What prominent and salient concepts characterize this confrontation, and how are they related—to one another and to the planning and institutional domains grappling with climate change? This literature review draws upon important concepts and themes from these fields and areas of interest, as well as synthesizes and integrates prominent concepts into a broadly applicable framework to further research and consideration of the relationships between these fields and ideas. We demonstrate that core concerns stemming from climate change studies are commonplace and of increasing relevance in planning and institutional domains, and that logical links between them can be articulated to illustrate relationships framing notable conceptual and thematic intersections and interactions; these, in turn, work to clarify areas of emphasis, key linkages, and important "blind spots" that persist in CCA research.

This article is structured as follows: Section 2 describes the review approach, and briefly situates spatial planning within a historical and theoretical context that frames consideration of important concepts in the climate adaptation literature. Section 3 integrates these into a Climate Change Adaptation Planning (CCAP) schema, and we describe its key phases. Section 4 examines how, in turn, the practice of adaptation planning is related to theory about adaptation features of interest. Synthesis and integration of these features produces a conceptual framework that exhibits the 'nested' and covalent relationships and dynamics therein, which is followed by an examination of the role of institutions in these dynamics. We close with a brief discussion and conclusion examining insights and further questions framed by the work.

2. Climate Change Adaptation Planning: Prologue, Practice, Paradigm

Our research is focused around a literature review that examines prominent themes related across several domains of interest to CCA: spatial planning, climate change, and institutions. Comparing ideas and terminology of importance across diverse fields and phenomena involving various sociocultural dynamics is complex for a variety of reasons

(Ritchie, et al., 2014). This is especially true when theories of change in social patterns are involved because framing and contextualizing historical trends inevitably entails consideration of broad themes (Webster & Watson, 2021). Our review considered highly-cited literature in the domains of interest to assemble a network of conceptual and empirical articles and studies engaging concepts with broad prominence in CCA research. This formed the basis of an approach articulated by Paré, as geared towards "identifying, describing, and transforming [important] concepts, constructs and relationships…[to build a] higher order of theoretical structure" (Paré et al., 2015). In turn, this approach was used as a theoretical and narrative basis for constructing a *conceptual framework*. This is a common goal and outcome of research linking interdisciplinary bodies of knowledge to explore associated phenomena by articulating "key factors, constructs, or variables" to describe logical relationships among them that correspond to the main tenets of the research (Jabareen, 2009; Miles & Huberman, 1994.). Accompanying the narrative review, the framework is used to consider relevant issues in the institutional domain, as well as for framing a discussion about persistent challenges, emergent insights, and potential applications.

2.1. *A Very Brief History of Modern Spatial Planning*

Landscape architecture arose as a formal design discipline in the 19th century based partially on the increasing recognition of connections between environmental and social health, out of which the sub-discipline of *landscape planning* emerged (Hill, 2018). Landscape design and planning's interests in large-scale (watershed, regional) geographies and dynamic environmental and human (system, network) processes led to a broader rationale for incorporating ecological considerations into multi-scalar spatial planning (Ndubisi, 2002). In the postwar era, *ecological planning* entered common parlance, further shaped by the concerns of the modern environmental movement's discontent with harmful effects of unbridled development (McHarg, 1969; Swaffield, 2002). One of the overarching themes in ecological views of spatial planning is the concept of the *suitability* of landscapes: how their inherent and potential qualities predispose them to various uses by humans.

Modern perspectives focusing on Sustainable Development (SD) emerged in the late 20th century largely to address the obvious tensions between intensifying resource management practices and future prosperity (Meadows et al., 2004). Goals to achieve SD have become key concerns in the climate change era; especially in urban areas of high development intensity (Lélé, 1991; Sauvé et al., 2016). The means by which these goals are achieved—the "pathways" taken to reach them—inherently entail *strategic* planning approaches because limited resources force choices that entail tradeoffs (Albrechts, 2004; Carter et al., 2015; Rondinelli, 1976; Tyler & Moench, 2012). The scope and scale of climate change is coming into sharper focus in the 21st century, as are its implications for significant change and uncertainty over time (Chaffin et al., 2014; Fankhauser et al., 1999; Hallegatte, 2009; Toimil et al., 2020).

The failure of society to curb GHG emissions through climate mitigation has increased the need for climate adaptation, emerging as a central concern of spatial planners across the globe; with some anticipating a paradigm shift in the fields of spatial planning concerned with adaptation to more effectively address it (Birchall et al., 2021; Hill, 2016; Lawrence et al., 2018). Challenges especially evident for spatial planning in the climate era emerge when administrative units delineated in space (as municipal boundaries, borders, zones, etc.) do not adequately address or fit well with the climate phenomena that defy socio-politically conceived and articulated 'lines on the (proverbial) map' (Hannah, 2010; Wilder et al., 2010). Indeed, as the landscape itself is modified by climate change, increased flexibility will surely be required of the very planning processes meant to effectively manage it.

2.2. *Climate Change Adaptation: Central Concepts*

To situate the practice of spatial planning within CCA efforts and the diversity of interactions that SESs in the climate change era will confront, we summarize several core concepts important in climate adaptation work. These ideas serve to populate our conceptual framework in the next section, which, in turn, displays their relational and dynamic qualities within an integrated theoretical construct.

Sustainability

The harvesting, commodification, distribution, (re)uses, and disposal of resources is a ubiquitous human activity (Graedel & Allenby, 2010). This is especially true in (and for the provision of) urban areas, where intense turnover and concentration of stocks occurs, recognition of which has given rise to studies of urban ecology and metabolism (Restrepo & Morales-Pinzón, 2018; Ioppolo et al., 2013; Wu, 2014; Kennedy et al., 2011). These processes also entail significant energy footprints, and numerous environmental impacts, including pollution, result from them (Tarr, 1996). The concept of sustainability may be understood to mean the maintenance of some (economic, social, environmental) entity, process, and/or outcome over time, framed in the environmental context of SESs (Basiago, 1999; Berkes et al., 1998 & 2003). Thus, while resource management remains a central consideration of sustainability in general (and SD specifically), it is also understood as a concept with applications in broader social realms (Epstein et al., 2015).

Resource scarcity (and competition) resulting from unsustainable management practices carries equity implications – across both extant socioeconomic classes and for future generations who may be disadvantaged or disenfranchised by prior resource usage (Baccini & Brunner, 2012; Dipierri & Zikos, 2020; Stoddart, et al., 2011). Because planning is a core component of development, SD is frequently invoked as a concept to guide both the means and ends of planning-for-sustainability, a topic of increasing importance in an era of rising environmental concern, uncertainty, and flux (Gopalakrishnan & Bakshi, 2017; Lemons et al., 1998; Wheeler, 2004). Some authors argue that SES are the logical analytical unit for SD research, with others asserting that they contain inherently interrelated concepts with special relevance to adaptation, or the quality of adaptability (Anderies et al., 2004; Young et al., 2006).

Adaptation and Adaptive Capacity

Influential scholarship concerning fundamentals about adaptation is extensive. For the purposes of CCA, it entails altering or adjusting systems and behavior to "alleviate adverse impacts of change or take advantage of new opportunities" through anticipation or response to climate change impacts (Adger et al., 2005). Adaptation can be differentiated based on *who* is involved in adjustment, *what* prompts this adjustment, and *how* it is undertaken (Fischer, 2018a; Smit & Wandel, 2006). Together, they "manifest" *adaptive capacity*, through a variety of institutional and social mechanisms (Ibid.). While non-human (eco)systems may also be said to display CCA behavior (and possess adaptive capacity), we are concerned primarily with the active inception and application of human efforts to "influence the direction of change" in SESs affected by climate change (Fazey et al., 2016; Fischer, 2018b; Wilson, 2012). Pelling (2015) articulates transformation of SESs as a pathway along which adaptation may play out, arguing that adaptation may trigger fundamental changes that decouple systems from more linear modes of progression.

Efforts to manifest adaptive capacity may backfire: potentially increasing vulnerability (Eisenhauer, 2020). This is known as *maladaptation* (Oberlack, 2017; Scott et al., 2020). Maladaptive outcomes bear the double burden of generally worsening conditions (reducing resilience or increasing vulnerability) at the implied mutual exclusion of building adaptive capacity due to resource limits (Kondo & Lizarralde, 2021). While noting various viewpoints and definitions, Gallopín (2006) describes adaptive capacity in SES generally as the capability to cope with environmental change combined with the ability to improve in relation to it. Eakin (2014) argues that there are *generic* (development-focused) and *specific* (climate impact-focused) domains of adaptive capacity, and that pursuit of one may exclude, subordinate, or otherwise reduce the other. Whereas adaptation actions might be understood in intuitive ways as relating to adaptive capacity (a quality), these interact in the context of additional qualities — namely vulnerability and resilience — which define SESs in important ways.

Vulnerability and Risk

Vulnerability concerns adverse impacts that occur due to a state's "susceptibility to harm" resulting from potentially complex interplays of exposure and sensitivity to stresses; and it is amplified by a lack of adaptive capacity (Adger, 2006; Mccarthy et al., 2001; Smit & Wandel, 2006). When harmful, these stresses take the form of hazards representing threats to systems; events that "realize" hazards in significant ways by causing damage are *disasters*; and those stemming from or involving natural phenomena are natural disasters (Alexander, 1993; Oliver-Smith, 1996; Revi et al., 2014; Young et al., 2006). *Risk* essentially describes the condition and degree(s) of being vulnerable (based on exposure, sensitivity, and capacity) to hazards (Pescaroli & Alexander, 2018); and risks shape and define adaptive capacity itself (Dow, et al. 2013). Risks are generally thought to be, in some sense, quantifiable, i.e., capable of being rendered in terms of probabilities describing the likelihood of outcomes (Abbott, 2005; Haimes, 2004.; Mack, 1971.; Van Der Heijden, 1996). The concentration of people, resources, and systems in urban spaces implies increased exposure, and additional risk based on the location of urban assets (in coastal areas, for example) may arise (Carter et al., 2015; Rasmussen et al., 2020). Risk operates in and across various societal domains: it should be considered in social and economic terms in addition to physical ones, including their interactions (Martins et al., 2020).

Resilience and Robustness

Systems exposed to risk and experiencing vulnerability may cope with it by drawing upon internal resources, whose realization may reduce impacts. Since Holling's (1973) pioneering work in studying ecosystems' capacity to withstand and rebound from states of disturbance, — to "absorb" and "persist" — *resilience* has become something of a darling within adaptation circles; prompting some to caution that its over-invocation might dilute its meaning (Rose, 2007). Resilience is of particular importance in the context of climate change because it represents a desirable quality of interacting designed and natural systems, and their relationship to risk and vulnerability (Twigg, 2007); UNISDR, 2012).

Systems that are resilient possess features, including flexibility and diversity, redundancy and modularity, and safe failure characteristics (Tyler & Moench, 2012). These work to reduce risk from disasters, which manifests in various types that include interacting, interconnected, compound, and cascading risks (Pescaroli & Alexander, 2018). The UN's (2015) adoption of frameworks for identifying and evaluating these risks speaks to the centrality of disaster risk reduction (DRR) in adaptation and resilience concerns and approaches. If resilience is seen as flexibility in the face of disturbance, *robustness* might be understood as the capability to resist and withstand it (Anderies et al., 2004). According to this view, resilient and/or robust systems maintain their core structure despite disturbance, enough so as to avoid becoming vulnerable to the point of significant structural deformation or collapse (Holling & Meffe, 1996).

Uncertainty

Planning is a process of anticipating, preparing for, and influencing future states of affairs. *Uncertainty* is a critically important epistemic situation that is inherent to planning because these 'affairs' of future states are influenced by numerous processes that engender and shape events, eventualities, and exigencies (Levin et al., 2012; Lipshitz & Strauss, 1997). This is the meta-context of planning: the temporal dimension within which all socioecological systems inevitably must play out. Uncertainty intrinsically implies what is unknown and/or unknowable (Chow & Sarin, 2002). It is a matter of degree; hence, "levels" of uncertainty exist (van der Heijden, 2019). Uncertainty is generally understood to increase as more distant futures are considered; and uncertainty may reflect, or be considered as a function of, complexity (Abbott, 2005; Rauws, 2017).

As planning is intended to inform decision-making, it must ultimately confront uncertainty in that context; by influencing the selection of options for coping with or managing it in acceptable ways (Christensen, 1985; Emery & Trist. 1965; Fischhoff & Davis, 2014; van der Bles et al., 2019). In this sense, uncertainty actually produces the need to make decisions (Shackle 1969). These decisions theoretically address, but can also produce*,* uncertainty; environmental uncertainty (uncertainty *for* planning) and process uncertainty (uncertainty from planning) may also exist, emerge, and interact (Abbott, 2005; Gruber, 1994.). Christensen's (1985) elegant rendering of planning problems hinges on two related processes and their relationship with uncertainty: identifying what to do (a goal) and determining how to do it (through resources and technology), effectively invoking the "ends and means" dyad familiar across all disciplines of planning. The capacity to learn new information that changes how uncertainty is characterized (and, therefore, may change degrees of belief) is a fundamentally adaptive ability (Oppenheimer et al., 2008).

The sheer scale and scope of potential impacts that CCA seeks to address entail significant uncertainty about how and when they will play out, thus shaping the 'menu of options' for responding to them (McInerney et al., 2012; Rauws, 2017; Reeder & Ranger, 2010). Uncertainty might be epistemic (stemming from a lack of knowledge), aleatory (due to intrinsic stochasticity), or both – and it can produce delays in decision-making (van der Bles et al., 2019). A striking example of how the very conceptualization of uncertainty is evolving in the climate change era concerns the asserted "death" of stationarity (Milly et al., 2008). Stationarity refers to the statistical concept that environmental fluctuations are bounded inside a value range that is stable (or stationary) over meaningfully-long time scales, an assumption that undergirds countless modeling approaches in environmental science and engineering (Stedinger & Griffis, 2011; Stroup, 2011). Whether or not reports of stationarity's death have indeed been greatly exaggerated, uncertainty is certainly growing, in actuality and/or as a topic of interest and importance (Hallegatte, 2009).

2.3. Planning: Practice, Policy and Governance

Why Plan(ning)?

The practice of planning is the professionalized implementation of planning efforts, processes shaped by and based on the application of planning theories (Abbott, 2005; Cartwright, 1973). In exploring what the ultimate purpose of planning is, institutional perspectives have positioned it as operating, in effect, as a mode of *governing societal actions* through processes of "regulation, coordination and control" (Pierre, 1999), while others have extended this view to ideally incorporate progressive values linked to social justice and democracy more broadly (Alexander, 2009; Healey, 1998). Generally speaking, planning is practiced in order to use knowledge to shape and implement action by informing decision-making. While noting a multitude of theoretical approaches to spatial planning, Morphet (2011) acknowledges planning's inherent power as a redistributive social force, with implications for how power itself is mediated. For our purposes, planning occurs through governmentally-sanctioned processes that concern access to goods and services deemed socially beneficial, and which maintain or enhance public health, safety, and welfare within a particular place; these provisions are often simplified as public "good(s)" (Reyes Plata, 2020).

Planning's Mandate: Service to the Public Good(s) and Interest

Defining what, exactly, constitutes the public good — much less deciding how to go about achieving, maintaining, or enhancing it — is well-recognized as complex, contentious, and dynamic, involving many diverse stakeholders across multiple levels of society (Bolan, 1967; Faludi, 2000; Forester, 1980). Accordingly, Kunzmann (2000) identifies the planning process as one preferably led by the public sector. Numerous climate effects are expected to disproportionately impact (by definition) vulnerable communities, and greater concern for the wellbeing and livelihoods impacted by the products of the adaptation process are, thus, linked closely to planning (Rodima-Taylor et al., 2012). Erikson and Brown (2011) and Ribot (2010) articulate challenges for planning associated with sustainability, resilience, and vulnerability related to uncertainty and complexity in the climate era. Transformative adaptation resulting from effective planning ideally reinforces the legitimacy of the social contract underlying public consent that is granted to planning authorities, ostensibly in their efforts to protect and expand the public interest and good (Pelling, 2011).

Planning is understood on basic terms to be a collaborative process that must address what Myers and Kitsuse (2000) identified as one of planning's "twin hazards": disagreement (the other being uncertainty), which is confronted through a number of different techniques for conflict resolution in planning, including communication, collaboration, mediation, dialogue, discussion, deliberation, and debate (Leach & Sabatier (2003); Moore, 1987; Ostrom, 1990; Roberts, 1997 & 2002;; Ryan, 2001). Innes (Innes, 2004) offers an examination of consensus-building as a crucial process for approaching various planning and policy-based disagreements. These serve to discover and define that of which the public good(s) actually consist, and doing so is where the practice of planning partially derives its validity (Susskind et al., 1999). Owing to numerous factors emerging from climate impacts on the public sector, planning is being deeply reexamined in the context of climate change (Abbott, 2005; Carter et al., 2015; Macintosh, 2013).

So...What's the Plan?

A plan involves articulating and orienting towards a *vision* for the future—what some human geographers refer to as environmental or sociotechnical imaginaries. These frame discourses for structuring the relationship of human processes within places, based on societal imperatives and aspirations amounting to the "virtualities" of future states of affairs (Bulkeley & Betsill, 2013). This articulation, in the context of producing the "instrument" of a plan, might involve constructing a declarative set of goals, while orienting towards them identifies steps, stages, or strategies for their realization, though both should embody flexibility to changing circumstances, thus possibly entailing "menus" of scenarios that could be encountered (Faludi, 2000; Peterson et al., 2003). This serves to "situate" the future within an as-yet unrealized (imaginary) SES: one towards which the plan is intended to guide decision-making (Albrechts, 2006; Soden & Kauffman, 2019). Strategic plans are generally flexible, longer-term, and less fine-grained than more near-term and discrete project plans, owing partially to greater uncertainty existing in "further off" futures (Balducci et al., 2011).

Plan-making may be challenged as a function of numerous horizontal (sector and actor-related) and vertical (multi-level governance-related) connections and the legal, regulatory, and institutional standards at play (Daddi et al., 2020; Hughes, 2015; Nalau et al., 2021). Plans themselves must define and address the community they are intended to serve; and adopted plans represent, to some acceptable degree, the resolution of disputes and tensions that arise based on the interests of various stakeholders involved; as well as how they may have constructed their own visions for the future (Corfee-Morlot et al., 2011; Levin et al., 2012). From an adaptation standpoint, this principle also applies to plans that could impact broader communities, so that adaptation actions undertaken within or for one community do not unduly disadvantage another (Fankhauser et al., 1999). Resolving these overlaps, tensions, and tradeoffs is, therefore, part of mediating the planning process that shapes and, subsequently, manifests in the scope and strategy of a given adaptation plan (Turkelboom et al., 2018).

3. 'Sketching' Climate Change Adaptation Planning: Important Features of Interest

The considerations and theories outlined in the last section illustrate features of planning that are useful in apprehending the fast-emerging practices (and problems) involved in Climate Change Adaptation Planning (CCAP). In this section, we illustrate a conceptual schematic (schema), describing the interplay of notable, generalized features of CCAP (Figure 1). Walker (2001) describes a *thinking* (planning) and *implementation* (action) phase in adaptive theory applied to policy, to which we add a third phase related to the ongoing assessment of applied work: adaptive *management* (Allen & Garmestani, 2015).

These echo Peter Hall's (1993) trifurcated policy paradigm: overall goal-setting (planning), techniques or instruments (actions), and their "calibration" (management).

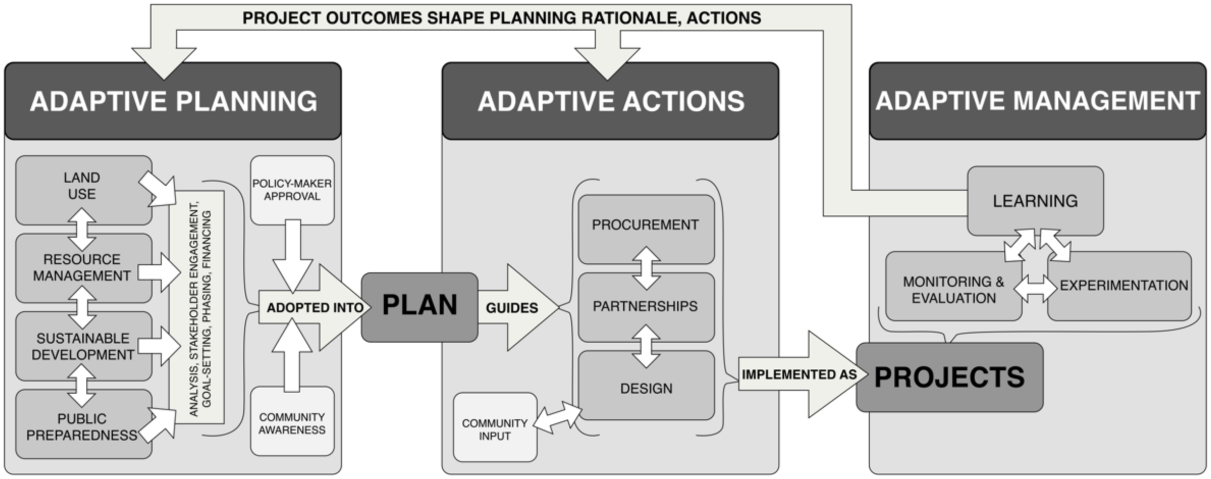


Figure 1. A Climate Change Adaptation Planning (CCAP) schema. In the *Adaptive Planning* phase, prominent planning concerns are addressed to produce a plan; Implementation based on guidance from plans yields *Adaptive Actions* in the forms of projects; these, in turn become subject to *Adaptive Management* practices for improving upstream and scaled-up efforts.

3.1. *Adaptive Planning*

Aspects of the planning process are inherently anticipatory in nature, wherein complex public policy decision-making occurs in the context of preparing for uncertain future states, thereby naturally engendering adaptive approaches (Birchall et al., 2021). As a feature of adaptive governance, adaptive planning naturally entails complexities owing to the diversity of actors and actions involved, especially in urban areas (Allen et al., 2011; Castán Broto, 2017; Folke et al., 2005). Anticipatory and planned adaptation within this phase prepare for (instead of react to) future states of affairs; in theory reducing vulnerability and costs (Burley et al., 2012; Klein & Tol, 1997; Tol et al., 2008). Adaptive planning entails stakeholder engagement that takes many forms, but the familiar top-down/bottom-up heuristic is useful in that planners operationalize the interactions of political decision makers in governance (top) and a broader public (bottom), though this group can be defined in various fashions, and based on criteria that, themselves, deserve scrutiny (Sabatier, 1986; Urwin & Jordan, 2008). Corfee-Morlot (2011), citing Mitchell (2006) and Cash (2003), identify requirements for science-policy assessments that inform and influence planning to be deemed publicly acceptable: namely that they be credible, legitimate, and salient.

Plans emerge as products of governance that identify steps for realizing goals in accordance with rules observed by the actor-networks involved, and they gain approval and adoption by passage through the "sluices of democratic and constitutional procedures" (Habermas 1998; Schroeder & Kobayashi, 2021). Adaptive planning ideally embraces learning processes concerned with the structure and effects of the overarching institutional contexts as a useful principle for improving outcomes (Huntjens et al., 2012; Schroeder & Kobayashi, 2021; Torabi et al., 2018). Adaptation plans may include financing components or supplementary plans for funding implementation (Barrett, 2013; Moser et al., 2019). "Evolutionary" processes in institutional and governance systems, in which processes of reframing and transformational learning occur, are understood as critical for adaptive and equitable systems, and are conceptually well-oriented toward adaptation (Geels 2002; Ostrom, 1990; Pahl-Wostl, 2009; van Assche et al., 2014). Limitations in validity assessment and/or forecasting methods may serve to constrain the adaptive planning applications to some extent, though climate change's overall uncertainty implies that flexible, adaptive approaches to planning for it are logical (Giordano, 2012; Goodwin & Wright, 2010; Kwakkel & van Der Pas, 2011; Hallegatte, 2009).

3.2. *Adaptive Actions*

We borrow from Aylett's (2015) description of adaptive governance as relying on distinct adaptation planning and action processes, thus echoing Ostrom's (2005) notion of the action situation. We use the term adaptive actions essentially to describe the inception of projects. Adaptation projects in urban areas might entail activities involving construction, such as urban greening to reduce heat island effects; improved shoreline defenses as approaches to coastal zone management; integration of "green" stormwater networks to mitigate upland flooding; and the regional management of "upstream" watersheds; and many municipal infrastructure systems represent adaptation imperatives and opportunities in some fashion (Chaffin et al., 2016; Erik Andersson et al., 2014; J. Lawrence et al., 2018; Storbjörk & Hedrén, 2011). Yet, adaptive actions might also include community initiatives involving outreach, education, and participation without resulting in changes to the physical environment (K. M. Allen, 2006). Thus, broad CCA interest categories in applied adaptation include land use planning (for reclamation, restoration, preservation, conservation aims, for example), natural resource management regimes (concerning water, for example), sustainable development projects (for housing, infrastructure, and public amenities), and community engagement initiatives (for educational or preparedness purposes) (Albrechts, 2010; Faludi, 2000; Fischer, 2018b; Leck, 2015; Main et al., 2021; Nalau et al., 2015; Pahl-Wostl, 2009; Satterthwaiteet al, 2009; Vogel & Henstra, 2015).

Large, complex, or costly adaptive actions that exceed the capacity of public policy and governance institutions often necessitate NGO and private sector involvement, in which planners operate at the "boundary" between the public and private entities (Bierbaum et al., 2013; Guston, 2001; Warsen, et al., 2018). Public-Private Partnerships (PPP) describe an arrangement in which collaborative, mutually-beneficial relationships are assembled; they are common in urban and municipal settings and a subject of interest in sustainable development circles, with noted promise for adaptation, despite their inherent complexities (Agrawal, 2010; Glasbergen, 2007; Leck & Simon; Harman et al., 2015; Rodima-Taylor et al., 2012). Procurement processes and partnerships are generally intended to alleviate capacity constraints of government. These arrangements can distribute risk and integrate diverse skills and resources into projects involving infrastructure, DRR, urban development, and, increasingly, adaptation projects (and which may entail some or all of the aforementioned project goals and concerns), though these arrangements in the context of CCA are still relatively novel (Bauer & Steurer, 2014; Harman et al., 2015).

3.3. *Adaptive Management*

CCA inherently acknowledges that traditional, linear project implementation "pipelines" for realizing plans may be of limited value in an era characterized by increasing uncertainty and complexity (Allen et al., 2011). While ancient in practice, recent interest in sustainable resource use, conservation, and ecosystem management have popularized the concept of adaptive management (Buck et al., 2001; Holling, 1973; Walters 1986; Williams, 2011). Other authors have stressed the ties of adaptive management to system resilience and flexibility (Gunderson, 1999). Drawing on work from Allen (2011) and his work with Garmestani (2015), Chaffin (2014) defines adaptive management as "implementation of management actions as *experiments*, followed by monitoring, evaluation and adjustment". Because of the prominence of nature-based solutions and green infrastructure in applied adaptation projects, numerous concerns of adaptive management are relevant to CCAP (Demuzere et al., 2014). Adaptive management applies flexible strategies that take into account emergent opportunities and are generally intended as modes of increasing learning and knowledge, thereby arguably building adaptive capacity and aiding adaptive governance (Hallegatte, 2009; Main et al., 2021).

Numerous approaches to understanding change in SESs exist, though central interest in investigating causal processes are especially relevant to planning, a notion termed by Dewey (1929) as "experimental knowing". Despite its experimental and flexible nature, adaptive management's potential to induce change (in broader practice and approaches) may be limited by institutional settings where change is itself problematized or opposed (Burley et al., 2012). The experimental underpinning of adaptive management may be useful for learning and information sharing across scales, theoretically aiding in expanding resourcefulness and responsiveness; and thereby increasing adaptive capacity (Bulkeley & Castán Broto, 2013; Tyler & Moench, 2012). The potential for specific adaptive actions (in the form of demonstration projects, for example) to broadly inform others might create synergies for syntheses of learning, testing, and adjustment across other sectors and policy realms (Burley et al., 2012). Experiments also may be efficient in the sense that small scales (and costs) may generate knowledge that is useful at broader scales of application, though experimentation itself — especially in large (landscape), complex (urban), and dynamic (climate-related) contexts — presents numerous challenges (Allen & Garmestani, 2015; Walters & Holling, 1990). While "scaling up" projects for broader regional application remains complex and daunting (Allan & Curtis, 2005; Garmestani et al., 2008; Lee, 2021), Hallegatte's (2009) identification of the desirable "low regret" quality of adaptation strategies and projects represents obvious conceptual correspondence with experimentation.

Adaptive management also presents opportunities to improve planning processes by incorporating enhanced social inclusiveness, including the dissemination and sharing of information (Buijs et al., 2016; Stringer et al., 2006). Monitoring that produces data useful for policy consideration is subject to a "reuptake mechanism", whereby conditions observed in adaptation actions may then inform improved planning practices of future or concurrent ones (Corfee-Morlot et al., 2011); while Fankhauser (1999) asserts that adaptation potential is predicated on having "room" (in the form of time) to change behavior. By providing the public, planners, and policymakers with real-time, real-world feedback that illustrates how selected adaptive actions are functioning, the "room" for adaptation may become better-parameterized through the reduction of uncertainty (especially relevant in the climate change era) provided by experimental observations. The "feedback loops" inherent to adaptive management suggest that CCAP is, thus, better conceived as looped processes, which are common in conceptualizations of SESs (Huntjens et al., 2012; Moser & Ekstrom, 2010; Ostrom, 1990).

4. Zooming Out: CCAP in Broader Context

Partially owing to the varied and multi-scale concerns and methods of practice, the literature exploring what CCAP is and how it operates contains no shortage of concepts and terminology for intellectualizing relevant ideas, themes, theories, and describing a diversity of applied work. While it is beyond the scope of this article and our study to exhaustively compare and square the myriad notions and constructs put forth to describe CCA, we offer a summary of important and interesting concepts, which we synthesize in this section. We then construct a conceptual, graphic framework (Figure 2) that strives to integrate these concepts into a holistic logic, offering a mode of rendering the important ideas and their relationships in a conceptual "space" that captures essential ideas of how important features and forces of CCA interact.

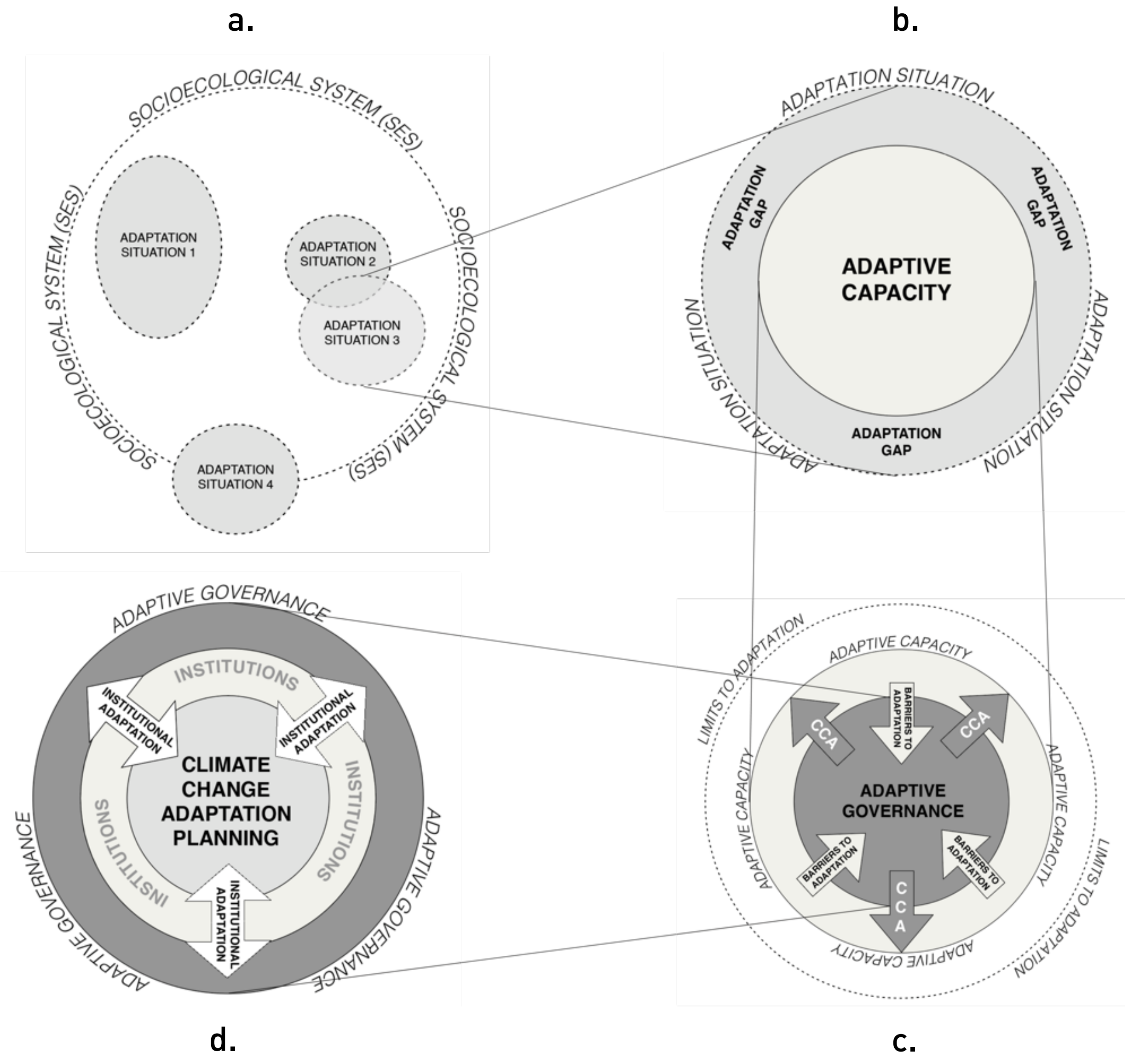


Figure 2. A framework displaying the 'nested' and 'coupled' nature of concepts and interactions of importance in climate change adaptation literature. Arrows denote force directionality; indicating how efforts or concepts "push or pull" towards and/or against other conceptual features or 'spaces'. Below is a glossary of key terms from the framework above; and a theoretical discussion follows.

'Glossary': (a) The *socioecological system* (SES) forms the basic conceptual unit of consideration for framing an adaptation situation. Numerous and interacting adaptation situations may exist within a given SES, or overlap, or "spill" into others. *Adaptation Situations* are characterized by features of the SES, including those in *sociotechnical* (human-based) and *biophysical* (natural setting and context-based) domains, which interact. Phenomena in the biophysical domain engender sociotechnical efforts to establish or expand ("realize") adaptative capacity. **(b)** *Adaptive capacity* is generated by sociotechnical efforts to adapt to biophysical features of the adaptation situation. In general, it is realized by building resilience/robustness and thus reducing vulnerability. An *adaptation gap* exists in the portion of the adaptation situation that lies beyond the adaptive capacity realized within it: it represents the amount of *unrealized* adaptive capacity. **(c) Adaptive governance** describes sociotechnical efforts in shaping the adaptation situation: when effective, adaptive governance increases adaptive capacity, thereby, ideally, shrinking the adaptation gap. Maladaptive (ineffective or counter-productive) efforts reduce adaptive capacity. ***Barriers to adaptation*** are produced, encountered, and addressed by the sociotechnical and biophysical domains, and in their interactions. Barriers constrain and shrink adaptive capacity, often by hindering adaptive governance or exceeding its reach; they exert restrictions and limits to the expansion of adaptive capacity that Climate Change Adaptation Planning (for example) seeks to realize. ***Limits to adaptation*** describe the extents of possible adaptation efforts, beyond which increasing adaptive capacity is (actually or considered) infeasible or impossible. Limits may be unknown. **(d)** Within the ***adaptive governance*** sphere, formal *organizational* practices *(planning)* are employed as modes of realizing efforts; and it is shaped by broader characteristic cultural features and processes called *institutions*. Its efficacy is the sum of institutional and organizational planning efforts performed in the interest of CCA. ***Integrated adaptation*** refers to the coordination and feedback between adaptation planning organization-based practices and institutional processes of adaptive change that coexist and combine.

4.1. Conceptualizing Climate Change Adaptation: Framework Features and Forces

4.1.1. Context: Defining Social-Ecological Systems

Pioneering work by Berkes and Folke (2003; 1998) to articulate the interactive dimensions and interplay between humans and their environments introduced the keystone concept of *social-ecological systems* (SES), based partly on work regarding the systematic nature of aspects of the human-nature interaction illustrated by concepts, including vulnerability, resilience, and sustainability (Füssel & Klein, 2006; Gallopín, et al., 1989; Young et al., 2006). These insights became key components of numerous interpretive framework approaches to understanding socioecological interdependencies. Of particular importance to planners is that SESs are inherently *spatially contextualized*. That is, because of the entanglement of particular and countless effects of some given environmental situation on sociotechnical (human) systems (and vice versa), they are understood as being in some way at play within a spatially distinct or discernible setting. However, this quality is also, by implication, malleable; and its definition or delimiting is based partially on the interest and perspective of those considering or using it as a construct for understanding, planning and managing actions to intentionally alter SESs—the basis of adaptation (Moser & Ekstrom, 2010).

4.1.2. Problem: Emergence of Adaptation Situations

Insofar as SESs contain or capture the dynamics between human drives to utilize natural resources and systems, dilemmas stemming from these drives and the capacity of the environment to accommodate them emerge constantly (Andereis, 2003; Hardin,1968). This produces phenomena in which the social and ecologic system aspects relate (or are situated with respect) to one another, generally impelling tensions regarding resources and governance, and thus engendering situations in which, according to Ostrom (2005), actions may be taken to address or resolve them — generating the concept of the *action situation* (Andersson et al., 2021; Marshall, 2013; Obeng-Odoom, 2016).

The magnitude of climate change on earth's biogeophysical systems has compelled some authors to refine Ostrom's original notion to define *adaptation situations* as a particular form of action situation (Reyes Plata, 2020). Citing previous work, Bisaro and Hinkel (2015) describe the adaptation situation as one involving "one or more actors interacting within a common biophysical and institutional environment in which outcomes are altered through climate change". This implies that social features of the situation may be interested in adapting *to* climate change, as well as that, regardless of their interest or efforts, outcomes will be shaped by biophysical effects *of* climate change; and this view resonates with other scholarship describing the centrality of human endeavors to shape the adaptation situation (Eakin, 2005; Roggero, 2015; Roggero et al., 2018).

4.1.3. Manifesting Adaptive Capacity: Adaptive Governance

The sociotechnical (human) features of SESs address the adaptation situation by making decisions about taking actions. These actions amount to Smit and Wandel's (2006) description of adaptation(s) as the "manifestation of adaptive capacity". The dominant means by which adaptive capacity is manifested by the sociotechnical entities of an SES is through adaptive governance, in large part because of the scale at which governmentally-organized action (and governmental organizations themselves) can operate, (Adger et al., 2003; Pahl-Wostl, 2009; Pelling & High, 2005). Chaffin (2014), in reviewing adaptive governance and synthesizing the perspectives of others, describes adaptive governance as emerging from the search for "modes of managing uncertainty and complexity in SESs". Adaptive governance might be understood as the exercised portion of adaptive capacity — the part that "people use" (Wamsler & Brink, 2014). Accordingly, depending on how and when adaptive capacity is used, it is dynamic over time; unfolding across scales in "coupled cycles of change" (Gunderson & Holling, 2002; Smit & Wandel, 2006). While we examine adaptive governance through the lens of climate change, concepts from theories of evolutionary governance may also be useful to consider and apply.

Though adaptive capacity is doubtless considered a desirable quality to possess, the particular and various ways in which adaptive governance is conceived and practiced may give rise to effects that tend to reduce or constrain adaptive capacity; or to outcomes that are maladaptive (Ekstrom & Moser, 2014; Juhola et al., 2016; Macintosh, 2013). Likewise, while adaptive capacity may reflect or express component qualities of the adaptation situation, including vulnerability, resilience, and sustainability, understanding how adaptive capacity is designed or generated (or not) remains complex (Anderies et al., 2004; Gunderson & Holling, 2002). Carter (Carter et al., 2015), drawing upon work by Rosenzweig (2011), after Mehrotra (2009), positions adaptive capacity in relation to vulnerability and hazards, the interactions of all three in essence serving to define risk. In this view, a system's adaptive capacity serves as a kind of counterweight against its vulnerability. While capacity intuitively refers to the *amount* of something (of which one might possess more or less), governance is not the only *source* of adaptive capacity, which can be possessed or provided by non-human features of an adaptation situation, or through non-governance-mediated human actions (Torabi et al., 2018; Tyler & Moench, 2012). We focus on adaptive governance because of its centrality to CCAP.

4.1.4. Aspirations: The Adaptation Gap

Lying between the optimal and actual adaptive capacity characterized within a given adaptation situation is a "*gap*", wherein the potential actions and outcomes of becoming optimally or fully adapted have not (yet) been realized. Moser and Eckstrom (2014), echoing Burton (2009), note this as a form of "adaptation deficit". In describing the analytical methodology of gap analysis for assessing climate hazards, Chen (2016) defines the adaptation gap as a "difference between existing adaptation efforts and adaptation need". The United Nations' recently published Adaptation Gap Report focuses on nature-based solutions in conceptualizing and further defining the adaptation gap, though previous volumes with different emphases all include the adaptation gap as a centralizing theme (UNEP, 2021). Numerous complications arise from attempts to quantify subjective, complex, and dynamic features of an adaptation situation that, in theory, define the adaptation gap; including the potential "unknowability" of what, precisely, the gap actually entails and includes (Chow, & Sarin, 2002; Davoudi, et al., 2011). Nonetheless, the concept of the adaptation gap is intuitive and useful in the same sense that adaptive capacity is: the former describing an amount of adaptation work *to* be done, and the latter describing the work that *has been* done (thereby establishing existing capacity) or *can be* done as a function of this work. If adaptive governance and other adaptation-oriented sociotechnical efforts are understood as seeking to build adaptive capacity, what forces and phenomena serve to constrain or diminish it?

4.1.5. Challenges: Barriers and Limits to Adaptation

A subject of broad interest is *barriers* to adaptation. Moser and Eckstrom (2010) define these as “impediments that can stop, delay, or divert the adaptation process”, specifying that they may be surmounted through “concerted effort, creative management, change of thinking, prioritization, and related shifts in resources, land uses, institutions, etc.”. Work from Anderies (2004), Ostrom (2007), and Adger (2009) helps situate this concept within the SES literature which, by extension, we project and integrate as features of adaptation situations (Hinkel & Bisaro, 2015). Some authors have invoked the notion of adaptation “obstacles”, which we consider essentially analogous to barriers (Corfee-Morlot et al., 2011). Barriers arise at different stages and levels of adaptation; and they may emerge because of features of governance itself — potentially influencing exactly how adaptive such governance can claim to be — and, by extension, defining its degree of adaptive capacity (Burley et al., 2012; Fischer, 2018b; Moser & Ekstrom, 2010). Importantly, Bisaro (2018), questioning the utility of the concept, points out that barriers that are easily identified might mask larger, structural, and *institutional* forces that produce the effect(s) of barriers without presenting obvious modes of addressing them.

A common phenomenon that arises from and promulgates barriers to adaptation (thus, in theory, reducing adaptive capacity) is *path dependency*, which occurs when institutions or organizations “fail to effectively adapt established practices to face changing circumstances”, a pattern of behavior observed across numerous sectors and organizational endeavors, though maladaptive outcomes are a common effect — with obvious and sector-specific implications for CCA, especially in urban settings (Aylett, 2015; Barnett et al., 2015; Healey, 2006). From an economic perspective, situations in which inferior practices perpetuated by path dependency may serve to “lock-in” inefficient (or maladaptive) behaviors and outcomes (Arthur, 1994). Citing Pierson (2000) and Wilson (2012), among others, Fischer (2018b) notes path dependency as a kind of *inertia* that results when future actions are shaped in profound or pernicious ways by previous ones. Path dependency, in this sense, is of particular importance for CCAP because of planning’s stepwise, cyclical, discursive, and constantly-unfolding nature; the ubiquity of decision-making points and processes therein; diverse sets of actors taking part in the process(es); and the variety of “embedded” cultural features and forces that steer and constrain them (Booth, 2011; Harman et al., 2015; Sanyal, 2005; Tilly,1984).

Whereas the notion of barriers (and obstacles) naturally conjures ideas about surmounting them, *limits* to adaptation refer to bounds that describe "level(s) of adaptive capacity…that cannot be surpassed", potentially defining the boundary between acceptable and intolerable risks, and those which might require transformative change to avoid (Dow et al., 2013; Klein et al., 2014). Barnett (2015) distinguishes between "hard" limits that are essentially defined by the environment and "soft" ones that are socially determined and, thus, theoretically malleable. Indeed, Eisenhauer (2020), in defining these limits as "factors that prevent adaptation from succeeding", points out that they have been articulated as both objectively identifiable (as in the case of certain biotic and economic examples) and, from a more constructivist perspective, presenting as difficult-to-define endogenous effects emerging from societies' "goals, values, risk perceptions and actions". Limits are perhaps also worth considering as "blended" between hard and soft characterizations because sociopolitical conceptualizations of limits emerge in response to environmental ones; which may then be redefined by human intervention. In general, limits define the extent to which adaptive capacity *could* be realized — apart from how effectively barriers *are* overcome in the practice of adaptive governance (to increase adaptive capacity). Again, this resonates with Adger's (2009a) view that limits are situational thresholds beyond which "adaptation actions fail to protect things stakeholders care about", which we take to include non-physical "things", such as social cohesion, morale, trust in institutions, etc.

4.2. CCAP: Integrating Institutional Adaptation

4.2.1. The Role of Institutions

Gupta (2010) elegantly renders institutions as "social patterns", while a more expansive view, according to Oberlack (2017), citing several others, describes institutions as "rules and procedures that structure action situations within which individual and collective decision-making [is affected to] constrain, enable and incentivize actions; link individual actions, events and outcomes; distribute authority and power; define reciprocal rights and duties; and shape beliefs, motivations and social learning" (Hagedorn, 2008; Ostrom, 2005; Paavola, 2007; Pahl-Wostl, 2009). Accordingly, institutions may be formal or informal (Schroeder & Kobayashi, 2021). Vatn (2005) describes the invisible or even unselfconsciously natural instantiation of institutions in behavior as conventions that are observed, referencing work by Crawford and Ostrom (1995), to compose a "grammar" of institutions and their functions. Institutions might be understood as self-reinforcing “regularities”: patterns of behavior evident in networks of social actors who “tacitly create [them] to solve a wide variety of recurrent problems” (Schotter, 2000). Yet, despite regularities and recurrences, institutions are not static; they “distribute obligations and entitlements to resources as well as the power to change such obligations and entitlements” (Basili et al., 2006). Though they may be nonmaterial (informal), institutions reify actual, tangible outcomes.

Institutional analyses focused on resources (components or products of the environment) and how the notion of property (which entails ownership, often of the landscape itself) factors into their management, is a well-established field of interest, and planning has been articulated as a mode of “bundling the rights” of ownership associated with property in this sense (Sorensen, 2018). From an economic perspective, the linkages between humans and their environment are mediated by countless rules that shape and reinforce beliefs and values, but these are dynamic and responsive (Knight & North, 1997). Where public policy is concerned, this dynamic quality of institutions has important implications because the question of how power and influence are distributed within society — including this critical capacity to alter existing situations and arrangements — is of enormous importance in the climate change era (Oberlack, 2017); insofar as planning efforts are understood as being shaped by larger cultural and institutional forces, and because these may fail to present obvious, accessible, and discrete decision-making processes themselves (Bisaro et al., 2018; Storbjörk & Hedrén, 2011).

4.2.2. Institutions and Change

In theorizing about the evolutionary nature of governance, Van Assche (2014) positions institutions as being designed for change; even postulating that the essence of democracy lies in the “rules of self-transformation; *rules to change the rules*”. As institutions occupy important features of SESs and spatial discourse generally, they are tightly linked with conceptions of the environmental imaginary (Milkoreit, 2017), entailing consideration of the distribution and access to power and influence involved in its realization, recalling Bromley’s (2006) obligations and entitlements (Ekers & Loftus, 2008). In other words, institutions structure *what is possible* based partially on how society *mediates the tensions arising from multitudes* (citizens, actors) shaping and *sharing something more unified*: the environment (Swyngedouw, 2009). Institutions influence aspirations (for a more healthy and just environment, for example), even while subject to inertia (perpetuating the status quo), and the outright resistance to change, termed the *precautionary principle*, which is important in situations involving uncertainty (Chhetri et al., 2010; Gollier & Treich, 2003; Lempert & Collins, 2007). Similar to the concept of path dependency in organizational endeavors, institutional inertia and "lock in" may occur when regimes and patterns of behavior become ossified due to various factors (Knight, & North 1997; Pierson, 2000). Institutions within or across SESs may constrain or delimit the actions of organizations by conformation and homogenization, producing institutional *isomorphism* (Scott, 2003), which may be induced by coercive, mimetic, or normative means (Daddi et al., 2020). Storbjörk and Hedrén (2011) describe clashing cultures, knowledge claims, and cross-sectoral integration problems as several notable barriers to institutional change.

While approaches to determining how institutions resist change are evident (in inertial, oppositional, and isomorphic ways), factors that instigate change within and across institutions are complex to identify, perhaps owing to requisite "concatenations" of underlying mechanisms (Smets et al., 2012; Tilly, 2001). Hodgson (2006) identified two dominant institutional modes: agent-*sensitive* and agent-*insensitive*, the latter describing an institution in which significant change affected by institution-shaping actors (agents) is unlikely or difficult. Individuals, organizations, and governance structures that cut across public and private sectors constantly respond to environmental change (thereby engendering change); thus, environmental change does not occur in an "institutional vacuum" (Agrawal, 2008; Smets et al., 2012). Influential individuals (leaders) (Mimura, et al., 2014), sociopolitical mobilization (Keskitalo, 2010), and/or catalytic or vivid events (Bazerman, 2005) that impose or focus urgency upon some situation may induce institutional change by creating or framing a state of urgency, though other factors have been identified as important "drivers" precipitating change dynamics (Biesbroek et al., 2009; Patterson, 2021; Smets et al., 2012). Aggregating these behavioral changes across scales and social structures — and mediating or coordinating them through planning mechanisms — in turn changes the institutional environment itself, in theory providing conditions for *institutional adaptation* (Morphet, 2011). Planning that attempts to engage these institutional change dynamics confronts a duality in that institutions are both behavior patterns "out in the world" (actions) and internal ones "in the head" (thoughts and feelings), which obviously presents complexities to planners attempting to derive institutional origins (Hodgson & Knudsen, 2006; MacKinnon et al., 2009). All of these qualities speak to the difficulty in clearly formalizing or mapping institutional dynamics, made especially complex when applied to situations in which the underlying environmental context is also in a state of flux.

4.2.3. Institutions, Climate Adaptation, Planning

Smit and Wandel (2006) note that adaptive capacity may be increased through improvements in technology and/or institutions, while Rodima-Taylor (2012) echoes Koppel's (1995) position that technological innovation is *induced* by institutional change. Christensen (1985) considers technology in the context of planning to be the "knowledge of how to do something"—literally, the *means*. Our CCAP schema illustrates that these means might be expanded by integrating adaptive principles into planning that make it more "nimble" (thus, resistant to path-dependence). Yet, how these qualities relate to an institutional adaptation discourse remains complex, in part owing to the need to disentangle the functions and mechanics of institutions themselves (Patterson, 2021; Petersen-Rockney et al., 2021; Voigt, 2013). In developing a framework for assessing institutional adaptive capacity, Gupta (2010) identifies two core characteristics: one essentially describing their inherent, extant qualities; and the second relating to the degree to which they "allow or encourage" their own (institutional) change, essentially describing adaptability itself. The *rate* of change, or timing, also matters: disparities between non-institutional changes that occur within SESs and that at which institutions are fundamentally *able to affect change* may lead to missed opportunities, including from a lack of timely collaboration and cooperation (Barnett et al., 2015; Ekstrom & Moser, 2014; Gupta et al., 2010).

Roggero (2015) explores how one aspect of institutional change is positioned with respect to CCA in his iteration of Hagedorn's (2008) notion of *integrative* institutions (that address climate-related *interdependencies*) versus *segregative* ones (that focus only on climate-impacted *resources* under their effective purview). Institutional complexity itself may work against institutional change or adaptation simply as a function of the increased "work" required to do so in complex networks, though structured learning processes may be useful (Lubell et al., 2014; Pahl-Wostl, 2009; Urwin & Jordan, 2008). Informal, 'behind-the-scenes' "shadow" processes may be important factors for inducing institutional change (Leck, 2015), in addition to the identification and inception of "additional or adjusted institutional design propositions" to address climate uncertainties and complexities (Huntjens et al., 2012).

A critical question for CCAP and its role in building adaptive capacity seems to concern the scope of its *influence* and *intentions*, particularly in relation to institutional forces that define, delimit, and direct them; as well as how these may differ from, or mesh with, planning practices and processes as traditionally understood. For example, failures to adapt may be due to issues of governance more so than the planned, technical implementation of applied adaptation efforts (projects), reflecting complexity inherent to multi-level governance (Armitage, 2015; Huitema et al., 2016; Pahl-Wostl, 2009). Patterson's (2021) work investigating dimensions and possible drivers of institutional adaptation in urban governance reveals that, in formal terms, "planning" is limited in its role: for example, it is not the job of planners to cultivate charismatic leaders, nor to foment community pressure (much less political disruptions), even though these may occur partially as a function of adaptation planning. The lack of real or perceived alignment of institutions with climate change adaptation risks the governance processes for achieving it being less adaptive and/or less strategic than optimal: a condition describing – or producing – institutional "voids" (Biesbroek et al., 2009).

5. Discussion

5.1. Central Insights

As explored and illustrated in this review, planning and institutional domains are being challenged or are changing because of the emergence, intensity, and importance of climate change within policy and governance spheres. The core goal of this review is to explore complicated topics across several domains and, based on thematic and conceptual linkages prominent in the literature, to construct an integrative perspective to increase clarity in comprehension of complex and related topics relevant to CCA. Several insights based on this work are notable. First, important concepts of climate change literature have been increasingly encountered and integrated into spatial planning practices, which have led to distinct *forms* of planning. Our CCAP schema demonstrates how, for example, uncertainty is being addressed not only as an increasing "fact of life" for planners to manage but one that can be understood and approached opportunistically and as a force driving innovation and learning processes that can increase adaptive capacity. In other words, the emphasis and engagement with climate change issues is leading to adaptation in the *practice* of planning itself.

Second, prominent and complex concepts of interest evident in climate change literature can be organized into a holistic construct that displays important tenets of the research; and displayed in such a fashion as to clarify their interplay, as through the proposed framework. These interplay may take the form of *positional* properties of features within a framework that group or separate concepts; nest or embed them in one another; or imply some connective linkage(s) or couplings. They can also be rendered in *mechanistic* terms: whereby dynamics of some feature of interest logically or implicitly affect others, thus illustrating *causal* relationships. These are of particular importance in adaptation work in a similar fashion to features of our CCAP schema, in that, fundamentally, *being adaptive* entails processes of feedbacks and responses in *systems*. Thus, in the same way that features of some given environmental context tend to exert pressures on the organizations and institutions within it, these, too, can exert forces that shape the environment itself. Because our framework's foundational feature (within and through which other features interact) are SESs, we can intuitively grasp this systematic structure and behavior. The framework, in this regard, is useful in two primary ways: it organizes and simplifies information; and it provides its own *logic* that is both emergent (arising from themes and ideas in the literature examined) and can be utilized, altered, adapted or critiqued by practitioners for case-specific or applied work; or as a basis for expansion or alteration through introducing additional or different theoretical components.

Finally, as a function of the deeply complex, subtle, and dynamic nature of institutions (including merely identifying or agreeing upon them), we display the limits of the framework; prompt consideration of how planning and institutions are, in theory and reality, bound together; and provide context for considering relevant connections or patterns as theses domains unfold and interact through CCA endeavors. For example, we discuss that organizational path dependency and institutional lock-in both serve to reduce adaptive capacity, while the modes of surmounting these barriers to adaptation are nonetheless domain-distinct, in terms of the means for assessing, addressing, or ameliorating them. Likewise, planning and institutions must be understood in a temporal context: planning because its legitimacy and efficacy depend on the results of its implementation and "follow through"; and institutions because their social utility, acceptance and adherence are derived, at least partially, by way of their durability. The examination of key features of the climate change era, namely uncertainty and change itself, present vexing questions and prompt provocative, perhaps even subversive, perspectives from which to consider the practice of planning and its institutional context. Insofar as the lack of change and innovation in so many organizational and institutional cultures has led to the unfolding climate catastrophe, which of them (or what components of them) should be challenged, adapted or even discarded for the sake of aiding the planning processes that must cope with the limits organizations and institutions impose upon them in the interest of supporting and expanding the public good(s)?

5.2. Adoption, Application, Adaptation of the Framework

This article seeks to articulate the ways in which important concepts relevant to climate adaptation might be more clearly differentiated and understood in their relational dynamics, partially through illustrating schema that can be adapted to various actual situations or case studies, and linking these with prominent themes and patterns from our literature review. An overarching challenge in CCA, planning, and institutional change (especially) is measuring or quantifying the magnitude or effects of concepts that, to some extent, resist or defy efforts to do so. Certain aspects of SESs are, after all, based on informal, constantly-changing, and nonmaterial qualities with which it is, nonetheless, important to grapple. Our "schematizing" of concepts in ways that can be visualized, to some extent, might provide interesting opportunities for researchers seeking to understand how individuals (within or across organizations, levels of government, and/or demographic groups) comprehend, or (literally) "picture", some of these concepts.

Future use of the framework along these lines might take the form of research employing templates that are used to gauge (for example) how different groups render adaptive capacity inside an adaptation situation, define magnitudes of effects for various barriers; order hierarchies of adaptation planning issues, "connect" causal influences or tensions between features and how they are situated relative to others, or articulate the "distance(s)" they imagine limits lie from adaptive capacity. Clearly, these exercises would yield abstractions: sketches or diagrams, that stand in for more nuanced work. Yet, these might reveal insights and/or patterns valuable to managers seeking to understand institutional or organizational dynamics, public sentiment, or differences across divisions, or even the age or career seniority of individuals. While not the focus of this article, social science methods applied to constructing impressions and understanding of how various groups apprehend the concepts explored here—and their relationships to each other—may be illuminating. A consistent theme of this research seems to be that what people believe is *possible* (and the institutional ramifications therein) is strongly linked with problem definition and framing, with obvious impacts on decision-making and commensurately dramatic implications for CCAP.

5.3. Critical Considerations and Questions

One of the appeals of institutions that are not only adaptive but well-integrated into CCAP is that their influence and capacity to "structure…political decision-making…[and] shape practices and behaviors" is understood as being vital for the success of large-scale, strategic efforts necessary in complex urban settings (Bulkeley & Betsill, 2013; Castán

Broto, 2017; Patterson, 2021). In this context, the utility of local knowledge and local institutions has been emphasized as a driver of adaptive capacity but also as *processes*, not merely information or rules (or *content*) (Berkes, 2009; Naess, 2013; Smit & Wandel, 2006). In one sense, planning is a practice of more than instrumentalizing content; it inherently represents engagement with ongoing processes. Yet, precisely because planning entities (individuals, agencies, departments, divisions, authorities) are empowered *by and within* overarching institutional milieus, questions emerge about planning as a force for transformational, fundamental change in the ongoing adaptation quest, which some see as amounting to the proposition of a paradigm shift for planning itself (Hill, 2016). In other words, can planning "unlock" institutions from nonadaptive tendencies, and, if so, how and to what degree?

We have examined the relationships between these concepts and their underlying theories to situate planning in a critical light, insofar as we question its agency and the scope of its traditionally-conceived responsibilities. Planning, in the face of massive environmental change and uncertainty, may itself obscure the clarity of future visions and complicate the steps for manifesting them, in no small part due to institutional inertia and dynamics. That is, uncertainties rooted in the institutional domain may amplify overall situational uncertainty and complicate planning processes attempting to address it. Dovers (2010) points out that even constructing an understanding of the limits to adaptation is fraught, in part, because of the institutional dimension; whose sheer complexity grows with the scale considered (Ostrom, 2012). With climate change altering resource regimes and shaping the public interest(s) and good(s) of citizens linked through institutional behavior and (ideally) aligned through adaptation planning practices, crucial questions about how common-pool resources and common-pool institutions can or should shape planning's role in allocating entitlements and obligations emerge (Armitage, 2015; Bromley, 1998; Dipierri & Zikos, 2020; van Klingeren & de Graaf, 2021; Wilson, 2012). This, in turn (and in ways beyond the scope of this chapter), ensnares any number of private sector considerations and the need to, among other things, understand how planning and institutions are positioned to address or adapt to markets relevant in adaptation (Hughes, 2015; Neil Adger et al., 2005).

6. Conclusions

Our review examined important concepts related to the CCA plight by exploring the theoretical and applied linkages between the practice of spatial planning and role of institutions in the governance of adaptation, with an emphasis on issues and dynamics broadly relevant in urban regions. Through this process, we sought to illustrate and situate prominent themes and concepts in climate adaptation work that connect to planning and institutional dynamics; as well as their effects on SESs, which Berkes and Folke originally termed the "linkages between ecosystems and institutions" (1998). Epstein expanded on this concept and considered the differentiation between social and ecological systems as reconciled by "fitting" them together through institutions themselves; and, in doing so, revealing strengths and limitations of the institutional *couplings* of these systems (2015). Planning, as we have discussed, represents a mode of instrumentalizing adaptive governance largely in the interest of increasing adaptive capacity; and, in the climate era, our schema demonstrates how planning employs various techniques to do so in the context of uncertainty and change, by embracing it and approaching it opportunistically. Likewise, our framework illustrates the nested and linked — or *coupled* — positionality and mechanics of planning to larger concepts and displaying how their interconnections might be understood. For their part, institutions, while playing important roles in shaping and constraining planning and defining various aspects of SESs, remain difficult to fully comprehend and describe when the same considerations of uncertainty and change characterize the (conceptual) landscape in which they exist and are realized.

In his treatise articulating the global, intergenerational ethical and moral implications of climate change, Stephen Gardiner (2006) identifies *institutional inadequacy* as a key characteristic; one that, for various reasons, cannot simply be overcome by better governance. This article situates adaptation planning as a critical link between governance and institutions: in the case of the former, as a "downstream" tool for facilitating policy through decision-making; in the latter, by triggering feedback from features of the SESs that have "upstream" implications for the "rules of the game" themselves, which define and constrain what futures are considered possible or desirable (Greif & Kingston, 2011). Planning, as a field seeking to integrate science and knowledge into decision-making, is surely constrained in its capacity to do so by various political and institutional arrangements and realities, though Roggero (2018) asserts that organizing knowledge in "*institutionally meaningful ways* can advance…understanding of the link between institutions and adaptation". What precisely constitutes institutional meaningfulness in the context of climate change remains complex, dynamic, and, surely, case-specific, to some degree.

Insofar as we consider institutions to be collectivized social patterns of behavior that are "rendered durable" over time by routine and habits, the task for planning to break from reinforced tendencies that reduce adaptive capacity seems pressing (Hodgson, 2006; MacKinnon et al., 2009). These reflections position planning in a crucial position that prompts consideration about the nature or characterization of planning entities themselves: are they primarily *agents* within Hodgson's (2006) reckoning (to whom institutions may be sensitive/responsive in terms of change), or merely a *means* by which those agents interact? If they fall into the former category (or if they are understood to be both), the question of intent emerges: is it the role and responsibility of planning to actively, aggressively attempt to alter — or even do away with — institutions in light of the knowledge planning inevitably encounters and frames? If so, which institutions? According to whose values, decisions or standards? In what circumstances, to what degree, why, and — critically — how? While this last question involves what Dover & Herzi (2010) term the *practicalities* of institutional change, the challenge for adaptation planning in the 21st century may be poised to be as much about principles as practicalities.

Ch. 1 References

Abbott, J. (2005). Understanding and Managing the Unknown: The Nature of Uncertainty in Planning. Journal of Planning Education and Research, 24(3), 237–251. https://doi.org/10.1177/0739456X04267710

Adger, W. N. (2006). Vulnerability. Global Environmental Change, 16(3), 268–281. https://doi.org/10.1016/j.gloenvcha.2006.02.006

Adger, W. N., Huq, S., Brown, K., Conway, D., & Hulme, M. (2003). Adaptation to climate change in the developing world. Progress in Development Studies, 3(3), 179–195. https://doi.org/10.1191/1464993403ps060oa

Adger, W. N., S. Dessai, M. Goulden, M. Hulme, I. Lorenzoni, D. R. Nelson, L. O. Naess, J. Wolf, and A. Wreford. 2009a. Are there social limits to adaptation to climate change? Climatic Change 93:335-354. (n.d.).

Agrawal, A. (2008). The Role of Local Institutions in Adaptation to Climate Change. World Bank. https://doi.org/10.1596/28274

Agrawal, A. (2010). Local institutions and adaptation to climate change. In R. Mearns, & A. Norton (Eds.), Social dimensions of climate change: Equity and vulnerability in the warming world (pp. 173e198).Washington, DC: TheWorld Bank. (n.d.).

Albrechts, L. (2004). Strategic (Spatial) Planning Reexamined. Environment and Planning B: Planning and Design, 31(5), 743–758. https://doi.org/10.1068/b3065

Albrechts, L. (2006). Bridge the Gap: From Spatial Planning to Strategic Projects. European Planning Studies, 14(10), 1487–1500. https://doi.org/10.1080/09654310600852464

Albrechts, L. (2010). More of the same is not enough! How could strategic spatial planning be instrumental in dealing with the challenges ahead? Environment and Planning B: Planning and Design, 37(6), 1115–1127. https://doi.org/10.1068/b36068

Alexander, D. E. (1993). Natural disasters. Boston, MA: Kluwer Academic Publishers. (n.d.).

Alexander, E. (2009). Dilemmas in Evaluating Planning, or Back to Basics: What is Planning For? Planning Theory & Practice, 10(2), 233–244. https://doi.org/10.1080/14649350902884177

Allan, C., & Curtis, A. (2005). Nipped in the Bud: Why Regional Scale Adaptive Management Is Not Blooming. Environmental Management, 36(3), 414–425. https://doi.org/10.1007/s00267-004-0244-1

Allen, C. R., Fontaine, J. J., Pope, K. L., & Garmestani, A. S. (2011). Adaptive management for a turbulent future. Journal of Environmental Management, 92(5), 1339–1345. https://doi.org/10.1016/j.jenvman.2010.11.019

Allen, C. R., & Garmestani, A. S. (Eds.). (2015). Adaptive Management of Social-Ecological Systems. Springer Netherlands. https://doi.org/10.1007/978-94-017-9682-8

Allen, K. M. (2006). Community-based disaster preparedness and climate adaptation: Local capacity-building in the Philippines: Community-Based Disaster Preparedness and Climate Adaptation. Disasters, 30(1), 81–101. https://doi.org/10.1111/j.1467-9523.2006.00308.x

Andereis, J. M. (2003). Economic development, demographics, and renewable resources: A dynamical systems approach. Environment and Development Economics, 8(2), 219–246. JSTOR. http://www.jstor.org.libproxy.berkeley.edu/stable/44379301

Anderies, J. M., Janssen, M. A., & Ostrom, E. (2004). A Framework to Analyze the Robustness of Social-ecological Systems from an Institutional Perspective. Ecology and Society, 9(1), art18. https://doi.org/10.5751/ES-00610-090118

Andersson, D., Bratsberg, S., Ringsmuth, A. K., & de Wijn, A. S. (2021). Dynamics of collective action to conserve a large common-pool resource. Scientific Reports, 11(1), 9208. https://doi.org/10.1038/s41598-021-87109-x

Armitage, D. (n.d.). Governance and the commons in a multi-level world. 26.

Arthur, W.B., 1994. Increasing Returns and Path Dependence in the Economy. University of Michigan Press, Ann Arbor. (n.d.).

Aylett, A. (2015). Institutionalizing the urban governance of climate change adaptation: Results of an international survey. Urban Climate, 14, 4–16. https://doi.org/10.1016/j.uclim.2015.06.005

Baccini, P., & Brunner, P. H. (2012). Metabolism of the anthroposphere: Analysis, evaluation, design. Cambridge, Mass. : MIT Press, ©2012; cat04202a.

Balducci, A., Boelens, L., Hillier, J., Nyseth, T., & Wilkinson, C. (2011). Introduction: Strategic spatial planning in uncertainty: theory and exploratory practice. Town Planning Review, 82(5), 481–501. https://doi.org/10.3828/tpr.2011.29

Barnett, J., Evans, L. S., Gross, C., Kiem, A. S., Kingsford, R. T., Palutikof, J. P., Pickering, C. M., & Smithers, S. G. (2015). From barriers to limits to climate change adaptation: Path dependency and the speed of change. Ecology and Society, 20(3), art5. https://doi.org/10.5751/ES-07698-200305

Barrett, S. (2013). Local level climate justice? Adaptation finance and vulnerability reduction. Global Environmental Change, 23(6), 1819–1829. https://doi.org/10.1016/j.gloenvcha.2013.07.015

Basiago, A. D. (1999). Economic, social, and environmental sustainability in development theory and urban plan- ning practice: The environmentalist. Boston: Kluwer Academic Publishers. (n.d.).

Basili, M., Franzini, M., & Vercelli, A. (2006). Environment, inequality and collective action. Routledge.

Bauer, A., & Steurer, R. (2014). Innovation in climate adaptation policy: Are regional partnerships catalysts or talking shops? Environmental Politics, 23(5), 818–838. https://doi.org/10.1080/09644016.2014.924196

Bazerman, M. (2005). Climate Change as a Predictable Surprise. Climatic Change, 77, 179–193. https://doi.org/10.1007/s10584-006-9058-x

Berkes, F. (2009). Indigenous ways of knowing and the study of environmental change. Journal of the Royal Society of New Zealand, 39(4), 151–156. https://doi.org/10.1080/03014220909510568

Berkes, F., Colding, J., Folke, C. (Eds.), 2003. Navigating Social- Ecological Systems: Building Resilience for Complexity and Change. Cambridge University Press, Cambridge. (n.d.).

Berkes, Fikret; Folke, Carl (1998). Linking Social and Ecological Systems: Management Practices and Social Mechanisms for Building Resilience. Cambridge University Press. (n.d.).

Berrang-Ford, L., Pearce, T., & Ford, J. D. (2015). Systematic review approaches for climate change adaptation research. Regional Environmental Change, 15(5), 755–769. https://doi.org/10.1007/s10113-014-0708-7

Bierbaum, R., Smith, J. B., Lee, A., Blair, M., Carter, L., Chapin, F. S., Fleming, P., Ruffo, S., Stults, M., McNeeley, S., Wasley, E., & Verduzco, L. (2013). A comprehensive review of climate adaptation in the United States: More than before, but less than needed. Mitigation and Adaptation Strategies for Global Change, 18(3), 361–406. https://doi.org/10.1007/s11027-012-9423-1

Biesbroek, G. R., Termeer, C. J. A. M., Kabat, P., & Klostermann, J. E. M. (2009). Institutional governance barriers for the development and implementation of climate adaptation strategies. https://edepot.wur.nl/108132

Birchall, S. J., MacDonald, S., & Slater, T. (2021). Anticipatory planning: Finding balance in climate change adaptation governance. Urban Climate, 37, 100859. https://doi.org/10.1016/j.uclim.2021.100859

Bisaro, A., Roggero, M., & Villamayor-Tomas, S. (2018). Analysis: Institutional Analysis in Climate Change Adaptation Research: A Systematic Literature Review. Ecological Economics, 151, 34–43. edselp.

Bolan, R. S. (1967). Emerging Views of Planning. Journal of the American Institute of Planners, 33(4), 233–245. https://doi.org/10.1080/01944366708977924

Booth, P. (2011). Culture, planning and path dependence: Some reflections on the problems of comparison. Town Planning Review, 82(1), 13–28. https://doi.org/10.3828/tpr.2011.4

Bromley, D. W. (1998). Searching for sustainability: The poverty of spontaneous order. Ecological Economics, 10.

Buck et al., 2001 L.E. Buck, C.C. Geisler, J. Schelhas, E. Wollenberg Biological diversity: Balancing interests through adaptive collaborative management CRC Press, Boca Raton, FL (2001). (n.d.).

Buijs, A. E., Mattijssen, T. J., Van der Jagt, A. P., Ambrose-Oji, B., Andersson, E., Elands, B. H., & Steen Møller, M. (2016). Active citizenship for urban green infrastructure: Fostering the diversity and dynamics of citizen contributions through mosaic governance. System Dynamics and Sustainability, 22, 1–6. https://doi.org/10.1016/j.cosust.2017.01.002

Bulkeley, H., & Betsill, M. M. (2013). Revisiting the urban politics of climate change. Environmental Politics, 22(1), 136–154. https://doi.org/10.1080/09644016.2013.755797

Bulkeley, H., & Castán Broto, V. (2013). Government by experiment? Global cities and the governing of climate change: Government by experiment? Transactions of the Institute of British Geographers, 38(3), 361–375. https://doi.org/10.1111/j.1475-5661.2012.00535.x

Burley, J. G., McAllister, R. R. J., Collins, K. A., & Lovelock, C. E. (2012). Integration, synthesis and climate change adaptation: A narrative based on coastal wetlands at the regional scale. Regional Environmental Change, 12(3), 581–593. https://doi.org/10.1007/s10113-011-0271-4

Burton I (2009) Climate change and the adaptation deficit. Earthscan Reader on Adaptation to Climate Change, eds Schipper ELF, Burton I (Earthscan, Sterling, VA), pp 89–95. (n.d.).

Carter, J. G., Cavan, G., Connelly, A., Guy, S., Handley, J., & Kazmierczak, A. (2015). Climate change and the city: Building capacity for urban adaptation. Progress in Planning, 95, 1–66. https://doi.org/10.1016/j.progress.2013.08.001

Cartwright, T. J. (1973). Problems, Solutions and Strategies: A Contribution to the Theory and Practice of Planning. Journal of the American Institute of Planners, 39(3), 179–187. https://doi.org/10.1080/01944367308977852

Cash DW, Clark WC, Alcock F, Dickson NM, Eckley N, Guston DH, Jaeger J, Mitchell RB (2003) Knowledge systems for sustainable development. PNAS 100(14):8086–8091. (n.d.).

Castán Broto, V. (2017). Urban Governance and the Politics of Climate change. World Development, 93, 1–15. https://doi.org/10.1016/j.worlddev.2016.12.031

Céspedes Restrepo, J. D., & Morales-Pinzón, T. (2018). Urban metabolism and sustainability: Precedents, genesis and research perspectives. Resources, Conservation and Recycling, 131, 216–224. https://doi.org/10.1016/j.resconrec.2017.12.023

Chaffin, B. C., Gosnell, H., & Cosens, B. A. (2014). A decade of adaptive governance scholarship: Synthesis and future directions. Ecology and Society, 19(3), art56. https://doi.org/10.5751/ES-06824-190356

Chaffin, B. C., Shuster, W. D., Garmestani, A. S., Furio, B., Albro, S. L., Gardiner, M., Spring, M., & Green, O. O. (2016). A tale of two rain gardens: Barriers and bridges to adaptive management of urban stormwater in Cleveland, Ohio. Journal of Environmental Management, 183, 431–441. https://doi.org/10.1016/j.jenvman.2016.06.025

Chen, C., Doherty, M., Coffee, J., Wong, T., & Hellmann, J. (2016). Measuring the adaptation gap: A framework for evaluating climate hazards and opportunities in urban areas. Environmental Science & Policy, 66, 403–419. https://doi.org/10.1016/j.envsci.2016.05.007

Chhetri, N., Easterling, W. E., Terando, A., & Mearns, L. (2010). Modeling path dependence in agricultural adaptation to climate variability and change. Annals of the Association of American Geographers, 100(4), 894e907. (n.d.).

Chow, C. C.; Sarin, R. K. (2002): Known, unknown, and unknowable uncertainties. Theory and Decision, 52, pp. 127–138. (n.d.).

Christensen, K. S. (1985). Coping with Uncertainty in Planning. Journal of the American Planning Association, 51(1), 63–73. https://doi.org/10.1080/01944368508976801

Colding, J., & Barthel, S. (2019). Exploring the social-ecological systems discourse 20 years later. Ecology and Society, 24(1). https://doi.org/10.5751/ES-10598-240102

Corfee-Morlot, J., Cochran, I., Hallegatte, S., & Teasdale, P.-J. (2011). Multilevel risk governance and urban adaptation policy. Climatic Change, 104(1), 169–197. https://doi.org/10.1007/s10584-010-9980-9

Crawford, S. E. S., & Ostrom, E. (1995). A Grammar of Institutions. American Political Science Review, 89(3), 582–600. https://doi.org/10.2307/2082975

Daddi, T., Bleischwitz, R., Todaro, N. M., Gusmerotti, N. M., & De Giacomo, M. R. (2020). The influence of institutional pressures on climate mitigation and adaptation strategies. Journal of Cleaner Production, 244, 118879. https://doi.org/10.1016/j.jclepro.2019.118879

Davoudi, S., Mehmood, A., Brooks, E., 2011. The London climate change adaptation strategy: Gap analysis. (n.d.).

Demuzere, M., Orru, K., Heidrich, O., Olazabal, E., Geneletti, D., Orru, H., Bhave, A. G., Mittal, N., Feliu, E., & Faehnle, M. (2014). Mitigating and adapting to climate change: Multi-functional and multi-scale assessment of green urban infrastructure. Journal of Environmental Management, 146, 107–115. https://doi.org/10.1016/j.jenvman.2014.07.025

Dewey, J. (1929) The Quest for Certainty: A Study of the Relation of Knowledge and Action. The Journal of Philosophy Volume 27, Issue 1, January 1930Pages 14-25. (n.d.).

Dipierri, A. A., & Zikos, D. (2020). The Role of Common-Pool Resources' Institutional Robustness in a Collective Action Dilemma under Environmental Variations. Sustainability, 12(24), 10526. https://doi.org/10.3390/su122410526

Dovers, S. R., & Hezri, A. A. (2010). Institutions and policy processes: The means to the ends of adaptation. WIREs Climate Change, 1(2), 212–231. https://doi.org/10.1002/wcc.29

Dow, K., Berkhout, F., Preston, B. et al. Limits to adaptation. Nature Clim Change 3, 305–307 (2013). Https://doi.org/10.1038/nclimate1847. (n.d.).

Eakin, H. (2005), 'Institutional change, climate risk, and rural vulnerability: Cases from central Mexico', World Development 33(11): 1923–38. (n.d.).

Eakin, H. C., Lemos, M. C., & Nelson, D. R. (2014). Differentiating capacities as a means to sustainable climate change adaptation. Global Environmental Change, 27, 1–8. https://doi.org/10.1016/j.gloenvcha.2014.04.013

Einecker, R., & Kirby, A. (2020). Climate Change: A Bibliometric Study of Adaptation, Mitigation and Resilience. Sustainability, 12(17), 6935. https://doi.org/10.3390/su12176935

Eisenhauer, D. C. (2020). Climate Change; Adaptation. In International Encyclopedia of Human Geography (pp. 281–291). Elsevier. https://doi.org/10.1016/B978-0-08-102295-5.10756-5

Ekers, M. and Loftus, A. (2008). The power of water: Developing dialogues between Foucault and Gramsci. Environment and Planning D: Society and Space 26 (4), pp. 698–718. (n.d.).

Ekstrom, J. A., & Moser, S. C. (2014). Identifying and overcoming barriers in urban climate adaptation: Case study findings from the San Francisco Bay Area, California, USA. Urban Climate, 9, 54–74. https://doi.org/10.1016/j.uclim.2014.06.002

Emery, Fred, and Eric Trist. 1965. The causal texture of organisational environments. Human Relations 18:21-32. (n.d.).

Epstein, G., Pittman, J., Alexander, S. M., Berdej, S., Dyck, T., Kreitmair, U., Rathwell, K. J., Villamayor-Tomas, S., Vogt, J., & Armitage, D. (2015). Institutional fit and the sustainability of social–ecological systems. Current Opinion in Environmental Sustainability, 14, 34–40. https://doi.org/10.1016/j.cosust.2015.03.005

Erik Andersson, Stephan Barthel, Sara Borgström, Johan Colding, Thomas Elmqvist, Carl Folke, & Åsa Gren. (2014). Reconnecting Cities to the Biosphere: Stewardship of Green Infrastructure and Urban Ecosystem Services. Ambio, 43(4), 445. edsjsr.

Eriksen, S., & Brown, K. (2011). Sustainable adaptation to climate change. Climate and Development, 3, 3e6. (n.d.).

Faludi, A. (2000). The Performance of Spatial Planning. Planning Practice and Research, 15(4), 299–318. https://doi.org/10.1080/713691907

Fankhauser, S., Smith, J. B., & Tol, R. S. J. (1999). Weathering climate change: Some simple rules to guide adaptation decisions. Ecological Economics, 30(1), 67–78. https://doi.org/10.1016/S0921-8009(98)00117-7

Fazey, I., Wise, R. M., Lyon, C., Câmpeanu, C., Moug, P., & Davies, T. E. (2016). Past and future adaptation pathways. Climate and Development, 8(1), 26–44. https://doi.org/10.1080/17565529.2014.989192

Fischer, A. P. (2018a). Pathways of adaptation to external stressors in coastal natural-resource-dependent communities: Implications for climate change. World Development, 108, 235–248. https://doi.org/10.1016/j.worlddev.2017.12.007

Fischer, A. P. (2018b). Pathways of adaptation to external stressors in coastal natural-resource-dependent communities: Implications for climate change. World Development, 108, 235–248. https://doi.org/10.1016/j.worlddev.2017.12.007

Fischhoff, B., & Davis, A. L. (2014). Communicating scientific uncertainty. Proceedings of the National Academy of Sciences, 111(Supplement_4), 13664–13671. https://doi.org/10.1073/pnas.1317504111

Folke, C., Hahn, T., Olsson, P., & Norberg, J. (2005). ADAPTIVE GOVERNANCE OF SOCIAL-ECOLOGICAL SYSTEMS. Annual Review of Environment and Resources, 30(1), 441–473. https://doi.org/10.1146/annurev.energy.30.050504.144511

Ford, J. D., & Pearce, T. (2010). What we know, do not know, and need to know about climate change vulnerability in the western Canadian Arctic: A systematic literature review. Environmental Research Letters, 5(1), 014008. https://doi.org/10.1088/1748-9326/5/1/014008

Forester, J. (1980). Critical Theory and Planning Practice. Journal of the American Planning Association, 46(3), 275–286. https://doi.org/10.1080/01944368008977043

Füssel, H.-M., & Klein, R. J. T. (2006). Climate Change Vulnerability Assessments: An Evolution of Conceptual Thinking. Climatic Change, 75(3), 301–329. https://doi.org/10.1007/s10584-006-0329-3

Gallopín, G. C. (2006). Linkages between vulnerability, resilience, and adaptive capacity. Global Environmental Change, 16(3), 293–303. https://doi.org/10.1016/j.gloenvcha.2006.02.004

Gallopı n, G.C., Gutman, P., Maletta, H., 1989. Global impoverishment, sustainable development and the environment: A conceptual approach. International Social Science Journal 121, 375–397. (n.d.).

Gardiner, S. M. (2006). A Perfect Moral Storm: Climate Change, Intergenerational Ethics and the Problem of Moral Corruption. Environmental Values, 15(3,), 397–413. http://www.jstor.org/stable/30302196

Garmestani, A. S., Allen, C. R., & Cabezas, H. (n.d.). Panarchy, Adaptive Management and Governance: Policy Options for Building Resilience. 20.

Geels, F.W., 2002. Technological transitions as evolutionary reconfiguration processes: A multi-level perspective and a case-study. Research Policy 31, 1257– 1274. (n.d.).

Giordano, T. (2012). Adaptive planning for climate resilient long-lived infrastructures. Utilities Policy, 23, 80–89. https://doi.org/10.1016/j.jup.2012.07.001

Giuseppe Ioppolo, Reinout Heijungs, Stefano Cucurachi, Roberta Salomone, & René Kleijn. (2013). Urban Metabolism: Many Open Questions for Future Answers. Pathways to Environmental Sustainability : Methodologies and Experiences, 23. edssjb. https://doi.org/10.1007/978-3-319-03826-1_3

Glasbergen P: Setting the scene: The partnership paradign in the making. In Partnerships, Governance and Sustainable Development: Reflections on Theory and Practice. Edited by Glasbergen P, Biermann F, Mol A. Edward Elgar Publishing; 2007: 314. (n.d.).

Gollier, C., Treich, N., 2003. Decision-making under scientific uncertainty: The economics of the precautionary principle. Journal of Risk and Uncertainty 27 (1), 77–103. (n.d.).

Goodwin, P.,Wright, G., 2010. The limits of forecasting methods in anticipating rare events. Technological Forecasting and Social Change 77, 355e368. (n.d.).

Gopalakrishnan, V., & Bakshi, B. R. (2017). Including Nature in Engineering Decisions for Sustainability. In Encyclopedia of Sustainable Technologies (pp. 107–116). Elsevier. https://doi.org/10.1016/B978-0-12-409548-9.10039-9

Graedel, T. E., & Allenby, B. R. (2010). Industrial ecology and sustainable engineering. (Engineering TS161 .G7425 2010). Upper Saddle River, NJ : Prentice Hall, c2010.; cat04202a.

Greif, A., & Kingston, C. (2011). Institutions: Rules or Equilibria? In N. Schofield & G. Caballero (Eds.), Political Economy of Institutions, Democracy and Voting (pp. 13–43). Springer Berlin Heidelberg. https://doi.org/10.1007/978-3-642-19519-8_2

Gruber, Judith. 1994. Coordinating growth management through consensus- building: Incentives and the generation of social, intellectual, and political capital. Berkeley: Institute of Urban and Regional Development (IURD), University of California, Berkeley. (n.d.).

Gualini, E. (2001). Planning and the Intelligence of Institutions: Interactive Approaches to Territorial Policy-Making Between Institutional Design and Institution-Building (1st ed.). Routledge. Https://doi.org/10.4324/9781315201726. (n.d.).

Gunderson, L & Holling, C.S. (eds), 2002. Panarchy: Understanding Transformations in Human and Natural Systems; Island Press. (n.d.).

Gunderson, L. 1999. Resilience, flexibility and adaptive management—- Antidotes for spurious certitude? Conservation Ecology 3(1): 7. (n.d.).

Gupta, J., Termeer, C., Klostermann, J., Meijerink, S., van den Brink, M., Jong, P., Nooteboom, S., & Bergsma, E. (2010). The Adaptive Capacity Wheel: A method to assess the inherent characteristics of institutions to enable the adaptive capacity of society. Environmental Science & Policy, 13(6), 459–471. https://doi.org/10.1016/j.envsci.2010.05.006

Guston DH. Boundary organizations in environmental policy and science: An introduction. Sci Technol Hum Values 2001, 26:339–408. (n.d.).

Habermas J (1998) Between facts and norms: Contributions to a discourse theory of law and democracy. MIT, Cambridge. (n.d.).

Hagedorn, K. (2008). Particular requirements for institutional analysis in nature-related sectors. European Review of Agricultural Economics, 35(3), 357–384. https://doi.org/10.1093/erae/jbn019

Haimes, Y.Y., 2004. Risk Modeling, Assessment, and Management. Wiley, Hoboken. (n.d.).

Hall, P.A., 1993. Policy paradigms, social learning, and the state: The case of economic policymaking in Britain. Comparative Politics 25, 275–296. (n.d.).

Hallegatte, S. (2009). Strategies to adapt to an uncertain climate change. Global Environmental Change, 19(2), 240–247. https://doi.org/10.1016/j.gloenvcha.2008.12.003

Hannah, L. (2010). A Global Conservation System for Climate-Change Adaptation. Conservation Biology, 24(1), 70–77. JSTOR. http://www.jstor.org.libproxy.berkeley.edu/stable/40419631

Hardin, G. (1968). The Tragedy of the Commons. Science, 162, 1243-1248. Http://dx.doi.org/10.1126/science.162.3859.1243. (n.d.).

Harman, B. P., Taylor, B. M., & Lane, M. B. (2015). Urban partnerships and climate adaptation: Challenges and opportunities. Current Opinion in Environmental Sustainability, 12, 74–79. https://doi.org/10.1016/j.cosust.2014.11.001

Healey, P. (1998) Planning: Shaping Places in Fragmented Societies (Bassingstoke, Macmillan). (n.d.).

Healey, P. (2006). Transforming governance: Challenges of institutional adaptation and a new politics of space. European Planning Studies, 14(3), 299–319. (n.d.).

Herrington, G. (2021). Update to limits to growth: Comparing the World3 model with empirical data. Journal of Industrial Ecology, 25(3), 614–626. https://doi.org/10.1111/jiec.13084

Hill, K. (2016). Climate Change: Implications for the Assumptions, Goals and Methods of Urban Environmental Planning. Urban Planning, 1(4), 103–113. https://doi.org/10.17645/up.v1i4.771

Hill, Kristina (2018). Oxford Bibliographies. DOI: 10.1093/obo/9780199363445-0099. (n.d.).

Hinkel, J., & Bisaro, A. (2015). A review and classification of analytical methods for climate change adaptation: Analytical methods for climate change adaptation. Wiley Interdisciplinary Reviews: Climate Change, 6(2), 171–188. https://doi.org/10.1002/wcc.322

Hodgson, G. M. (2006). What Are Institutions? Journal of Economic Issues, 40(1), 1–25. JSTOR. http://www.jstor.org.libproxy.berkeley.edu/stable/4228221

Hodgson, G. M., & Knudsen, T. (2006). Why we need a generalized Darwinism, and why generalized Darwinism is not enough. Journal of Economic Behavior & Organization, 61(1), 1–19. https://doi.org/10.1016/j.jebo.2005.01.004

Holling, C. S. (1973) Resilience and stability of ecological systems, Annual Review of Ecological Systems, 4, pp. 1–23. (n.d.).

Holling, C. S., & Meffe, G. K. (1996). Command and Control and the Pathology of Natural Resource Management. Conservation Biology, 10(2), 328–337. https://doi.org/10.1046/j.1523-1739.1996.10020328.x

Hughes, S. (2015). A meta-analysis of urban climate change adaptation planning in the U.S. Urban Climate, 14, 17–29. https://doi.org/10.1016/j.uclim.2015.06.003

Huitema, D., Adger, W. N., Berkhout, F., Massey, E., Mazmanian, D., Munaretto, S., Plummer, R., & Termeer, C. C. J. A. M. (2016). The governance of adaptation: Choices, reasons, and effects.

Introduction to the Special Feature. Ecology and Society, 21(3), art37. https://doi.org/10.5751/ES-08797-210337

Huntjens, P., Lebel, L., Pahl-Wostl, C., Camkin, J., Schulze, R., & Kranz, N. (2012). Institutional design propositions for the governance of adaptation to climate change in the water sector. Global Environmental Change, 22(1), 67–81. https://doi.org/10.1016/j.gloenvcha.2011.09.015

Innes, J. E. (2004). Consensus Building: Clarifications for the Critics. Planning Theory, 3(1), 5–20. https://doi.org/10.1177/1473095204042315

Jabareen, Y. (2009). Building a Conceptual Framework: Philosophy, Definitions, and Procedure. International Journal of Qualitative Methods, 8(4), 49–62. https://doi.org/10.1177/160940690900800406

Jianguo Wu. (2014). Urban ecology and sustainability: The state-of-the-science and future directions: Actionable urban ecology in China and the world: Integrating ecology and planning for sustainable cities. Landscape and Urban Planning, 209. edscal.

Juhola, S., Glaas, E., Linnér, B.-O., & Neset, T.-S. (2016). Redefining maladaptation. Environmental Science & Policy, 55, 135–140. https://doi.org/10.1016/j.envsci.2015.09.014

Kennedy, C., Pincetl, S., & Bunje, P. (2011). The study of urban metabolism and its applications to urban planning and design. Environmental Pollution, 159(8/9), 1965–1973. 8gh.

Keskitalo, E. C. H. (Ed.). (2010). Developing Adaptation Policy and Practice in Europe: Multi-level Governance of Climate Change. Springer Netherlands. https://doi.org/10.1007/978-90-481-9325-7

KLEIN, R.J.T. and TOL, R.S.J., 1997. Adaptation to Climate Change: Options and Technologies. An Overview Paper. Technical Paper FCCC/TP/1997/3. Bonn, Germany: United Nations Framework Convention on Climate Change Secretariat, 36p. (n.d.).

Klein RJT, Midgley GF, Preston BL, Alam M, Berkhout FGH, Dow K, Shaw MR (2014) Adaptation opportunities, constraints, and limits. In: Barros V et al (eds) Climate change 2014: Impacts, adaptation, and vulnerability. Part A: Global and sectoral aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, New York, pp 899–943. (n.d.).

Knight, J., & Douglass North [1997], "Explaining Economic Change: The Interplay Be- tween Cognition and Institutions," Legal Theory, 3, 211-226. (n.d.).

Kondo, T., & Lizarralde, G. (2021). Maladaptation, fragmentation, and other secondary effects of centralized post-disaster urban planning: The case of the 2011 "cascading" disaster in Japan. International Journal of Disaster Risk Reduction, 58, 102219. https://doi.org/10.1016/j.ijdrr.2021.102219

Koppel, B. M. (1995). Induced innovation theory, agricultural research, and Asia's green revolution: A reappraisal. In B. M. Koppel (Ed.), Induced innovation theory and international agricultural development: A reassessment (pp. 56e72). The John Hopkins University Press. (n.d.).

Kunzmann, K. (2000) Strategic spatial development through information and communication, in: W. Salet & A. Faludi (Eds) The Revival of Strategic Spatial Planning, pp. 259–265 (Amsterdam: Royal Netherlands Academy of Arts and Sciences). (n.d.).

Kwakkel, J., van der Pas, J.W.GH.M., 2011. Evaluation of infrastructure planning approaches: An analogy with medicine. Futures 43 (9), 934e946. (n.d.).

Lawrence, D. P. (2000). Planning theories and environmental impact assessment. Environmental Impact Assessment Review, 20(6), 607–625. https://doi.org/10.1016/S0195-9255(00)00036-6

Lawrence, J., Bell, R., Blackett, P., Stephens, S., & Allan, S. (2018). National guidance for adapting to coastal hazards and sea-level rise: Anticipating change, when and how to change pathway. Environmental Science & Policy, 82, 100–107. https://doi.org/10.1016/j.envsci.2018.01.012

Leach, W. and Sabatier, P. (2003) 'Facilitators, Coordinators, and Outcomes', in R. O'Leary and L.B. Bingham (eds) The Promise and Performance of Environmental Conflict Resolution, pp. 148–71. Washington, DC: Resources for the Future. (n.d.).

Leck, H. (2015). What lies beneath: Understanding the invisible aspects of municipal climate change governance. Current Opinion in Environmental Sustainability, 7.

Leck H, Simon D: Fostering multiscalar collaboration and co-operation for effective governance of climate change adaptation. Urban Stud 2013, 50:1221-1238. (n.d.).

Lee, K. N. (2021). Appraising Adaptive Management. 22.

Lemons, J., Westra, L., & Goodland, R. (Eds.). (1998). Ecological Sustainability and Integrity: Concepts and Approaches (Vol. 13). Springer Netherlands. https://doi.org/10.1007/978-94-017-1337-5

Lempert, R.J., Collins, M.T., 2007. Managing the risk of uncertain thresholds responses: Comparison of robust, optimum, and precautionary approaches. Risk Analysis 27, 1009–1026. (n.d.).

Leopold, Aldo, 1886-1948 and Charles Walsh, Schwartz. 1966. A Sand County Almanac: With Other Essays On Conservation From Round River.. New York: Oxford University Press. (n.d.).

Levin, K., Cashore, B., Bernstein, S., & Auld, G. (2012). Overcoming the tragedy of super wicked problems: Constraining our future selves to ameliorate global climate change. Policy Sciences, 45(2), 123–152. https://doi.org/10.1007/s11077-012-9151-0

Lipshitz, R., & Strauss, O. (1997). Coping with Uncertainty: A Naturalistic Decision-Making Analysis. Organizational Behavior and Human Decision Processes, 69(2), 149–163. https://doi.org/10.1006/obhd.1997.2679

LtLt, S. M. (n.d.). Sustainable Development" A Critical Review. WORLD DEVELOPMENT, 15.

Lubell, M., Robins, G., & Wang, P. (2014). Network structure and institutional complexity in an ecology of water management games. Ecology and Society, 19(4), art23. https://doi.org/10.5751/ES-06880-190423

Macintosh, A. (2013). Coastal climate hazards and urban planning: How planning responses can lead to maladaptation. Mitigation and Adaptation Strategies for Global Change, 18(7), 1035–1055. https://doi.org/10.1007/s11027-012-9406-2

Mack, Ruth. 1971. Planning on uncertainty: Decision making in business and government administration. New York: Wiley Interscience. (n.d.).

MacKinnon, D., Cumbers, A., Pike, A., Birch, K., & McMaster, R. (2009). Evolution in Economic Geography: Institutions, Political Economy, and Adaptation. Economic Geography, 85(2), 129–150. https://doi.org/10.1111/j.1944-8287.2009.01017.x

Main, K. L., Mazereeuw, M., Masoud, F., Lu, J., Barve, A., Ojha, M., & Krishna, C. (2021). Climate action zones: A clustering methodology for resilient spatial planning in climate uncertainty. In

Enhancing Disaster Preparedness (pp. 241–258). Elsevier. https://doi.org/10.1016/B978-0-12-819078-4.00013-7

Marshall, G. R. (2013). Transaction costs, collective action and adaptation in managing complex social–ecological systems. Ecological Economics, 88, 185–194. https://doi.org/10.1016/j.ecolecon.2012.12.030

Mccarthy, J., Canziani, O., Leary, N., Dokken, D., & White, K. (2001). Climate Change 2001: Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, 19.

McHarg, I. L. (1969). Design with nature. (Bioscience & Natural Resources HM206 .M18). Garden City, N.Y., Published for the American Museum of Natural History [by] the Natural History Press, 1969.; cat04202a.

McInerney, D., Lempert, R., & Keller, K. (2012). What are robust strategies in the face of uncertain climate threshold responses?: Robust climate strategies. Climatic Change, 112(3–4), 547–568. https://doi.org/10.1007/s10584-011-0377-1

Meadows, D. H. (1972). The Limits to growth: A report for the Club of Rome's project on the predicament of mankind. (Institute of Governmental Studies 90 01642). [S.l.] : Earth Island, 1972.; cat04202a.

Meadows, D. H., Randers, J., & Meadows, D. L. (2004). The limits to growth: The 30-year update. (Environmental Design HD75.6 .M437 2004). White River Junction, Vt : Chelsea Green Pub., c2004.; cat04202a.

Mehrotra, S., Natenzon, C., Omojola, A., Folorunsho, R., Gilbride, J., & Rosenzweig, C. (2009). Framework for city climate risk assess- ment. Fifth Urban Research Symposium. World Bank. Retrieved from. (n.d.).

Miles, M. B. , & Huberman, A. M. (1994). Qualitative data analysis: An expanded source book (2nd ed.). Newbury Park, CA: Sage. (n.d.).

Milkoreit, M. (2017). Imaginary politics: Climate change and making the future. Elementa: Science of the Anthropocene, 5, 62. https://doi.org/10.1525/elementa.249

Milly, P. C. D., Betancourt, J., Falkenmark, M., Hirsch, R. M., Kundzewicz, Z. W., Lettenmaier, D. P., & Stouffer, R. J. (2008). Stationarity Is Dead: Whither Water Management? Science, 319(5863), 573–574. https://doi.org/10.1126/science.1151915

Mimura, N., Pulwarty, R.S., Duc, D.M., Elshinnawy, I., Redsteer, M.H., Huang, H.Q., Nkem, J.N., Sanchez Rodriguez, R.A., 2014. Chapter 15: Adaptation planning and implementation, Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA. (n.d.).

Mitchell RB, Clark WC, Cash DW, Dickson N (eds) (2006) Global environmental assessments: Information, institutions, and influence. MIT, Cambridge. (n.d.).

Moore, C. W. (1987). The Mediation Process: Practical Strategies for Resolving Conflict. San Francisco: Jossey-Bass. (n.d.).

Morphet, J. (2011). Effective practice in spatial planning. Routledge.

Moser, S. C., & Ekstrom, J. A. (2010). A framework to diagnose barriers to climate change adaptation. Proceedings of the National Academy of Sciences, 107(51), 22026–22031. https://doi.org/10.1073/pnas.1007887107

Moser, S. C., Ekstrom, J. A., Kim, J., & Heitsch, S. (2019). Adaptation finance archetypes: Local governments’ persistent challenges of funding adaptation to climate change and ways to overcome them. Ecology and Society, 24(2), art28. https://doi.org/10.5751/ES-10980-240228

Myers, Dowell, and Alicia Kitsuse. 2000. Constructing the future in planning: A survey of theories and tools. Journal of Planning Education and Research 19:221-31. (n.d.).

Naess, L. O. (2013). The role of local knowledge in adaptation to climate change: Role of local knowledge in adaptation. Wiley Interdisciplinary Reviews: Climate Change, 4(2), 99–106. https://doi.org/10.1002/wcc.204

Nalau, J., Preston, B. L., & Maloney, M. C. (2015). Is adaptation a local responsibility? Environmental Science & Policy, 48, 89–98. https://doi.org/10.1016/j.envsci.2014.12.011

Nalau, J., Torabi, E., Edwards, N., Howes, M., & Morgan, E. (2021). A critical exploration of adaptation heuristics. Climate Risk Management, 32, 100292. https://doi.org/10.1016/j.crm.2021.100292

Ndubisi, F., [1955-] & ebrary Academic Complete. (2002). Ecological planning: A historical and comparative synthesis. awn. https://libproxy.berkeley.edu/login?qurl=http%3a%2f%2fsearch.ebscohost.com%2flogin.aspx%3fdirect%3dtrue%26db%3dawn%26AN%3dSO-1603-914281%26site%3deds-live

Neil Adger, W., Arnell, N. W., & Tompkins, E. L. (2005). Successful adaptation to climate change across scales. Global Environmental Change, 15(2), 77–86. https://doi.org/10.1016/j.gloenvcha.2004.12.005

Nordgren, J., Stults, M., Meerow, S., 2016. Supporting local climate change adaptation: Where we are and where we need to go. Environ. Sci. Pol. 66, 344–352. (n.d.).

Nuno Martins Mahmood Fayazi Faten Kikano Liliane Hobeica, (2020) Enhancing Disaster Preparedness From Humanitarian Architecture to Community Resilience, 1st Edition. Elsevier. (n.d.).

Obeng-Odoom, F. (2016). The Meaning, Prospects, and Future of the Commons: Revisiting the Legacies of Elinor Ostrom and Henry George: The Meaning, Prospects, and Future of the Commons. American Journal of Economics and Sociology, 75(2), 372–414. https://doi.org/10.1111/ajes.12144

Oberlack, C. (2017). Diagnosing institutional barriers and opportunities for adaptation to climate change. Mitigation and Adaptation Strategies for Global Change, 22(5), 805–838. https://doi.org/10.1007/s11027-015-9699-z

Oliver-Smith, A. (1996). ANTHROPOLOGICAL RESEARCH ON HAZARDS AND DISASTERS. Annual Review of Anthropology, 25(1), 303–328. https://doi.org/10.1146/annurev.anthro.25.1.303

Oppenheimer, M., O'Neill, B. C., & Webster, M. (2008). Negative learning. Climatic Change, 89(1–2), 155–172. https://doi.org/10.1007/s10584-008-9405-1

Ostrom, E. (2005). Doing Institutional Analysis Digging Deeper Than Markets and Hierarchies. In C. Menard & M. M. Shirley (Eds.), Handbook of New Institutional Economics (pp. 819–848). Springer US. https://doi.org/10.1007/0-387-25092-1_31

Ostrom, E. (2012). Nested externalities and polycentric institutions: Must we wait for global solutions to climate change before taking actions at other scales? Economic Theory, 49(2), 353–369. https://doi.org/10.1007/s00199-010-0558-6

Ostrom, E. (1990) Governing the Commons: The Evolution of Institutions for Collective Action. Cambridge, MA: Cambridge University Press. (n.d.).

Ostrom E (2007) A diagnostic approach for going beyond panaceas. Proc Natl Acad Sci USA 104:15181–15187. (n.d.).

Paavola, J. (2007). Institutions and environmental governance: A reconceptualization. Ecological Economics, 63(1), 93–103. https://doi.org/10.1016/j.ecolecon.2006.09.026

Pahl-Wostl, C. (2009). A conceptual framework for analysing adaptive capacity and multi-level learning processes in resource governance regimes. Global Environmental Change, 19(3), 354–365. https://doi.org/10.1016/j.gloenvcha.2009.06.001

Paré, G., Trudel, M.-C., Jaana, M., & Kitsiou, S. (2015). Synthesizing information systems knowledge: A typology of literature reviews. Information & Management, 52(2), 183–199. https://doi.org/10.1016/j.im.2014.08.008

Patterson, J. J. (2021). More than planning: Diversity and drivers of institutional adaptation under climate change in 96 major cities. Global Environmental Change, 68, 102279. https://doi.org/10.1016/j.gloenvcha.2021.102279

Pelling M (2011) Adaptation to climate change: From resilience to transformation. Routledge, London. (n.d.).

Pelling, M., & High, C. (2005). Understanding Adaptation: What Can Social Capital Offer Assessments of Adaptive Capacity? Global Environmental Change, 15, 308–319. https://doi.org/10.1016/j.gloenvcha.2005.02.001

Pelling, M., O'Brien, K., & Matyas, D. (2015). Adaptation and transformation. Climatic Change, 133(1), 113–127. https://doi.org/10.1007/s10584-014-1303-0

Pescaroli, G., & Alexander, D. (2018). Understanding Compound, Interconnected, Interacting, and Cascading Risks: A Holistic Framework: A Holistic Framework for Understanding Complex Risks. Risk Analysis, 38(11), 2245–2257. https://doi.org/10.1111/risa.13128

Petersen-Rockney, M., Baur, P., Guzman, A., Bender, S. F., Calo, A., Castillo, F., De Master, K., Dumont, A., Esquivel, K., Kremen, C., LaChance, J., Mooshammer, M., Ory, J., Price, M. J., Socolar, Y., Stanley, P., Iles, A., & Bowles, T. (2021). Narrow and Brittle or Broad and Nimble? Comparing Adaptive Capacity in Simplifying and Diversifying Farming Systems. Frontiers in Sustainable Food Systems, 5, 564900. https://doi.org/10.3389/fsufs.2021.564900

Peterson, G.D., Cumming, G.S., Carpenter, S.R., 2003b. Scenario planning: A tool for conservation in an uncertain world. Conservation Biology 17, 358–366. (n.d.).

Pierre, N.J. (1999) Models of urban governance: The institutional dimension of urban politics, Urban Affairs Review, 34(3), pp. 372–396. (n.d.).

Pierson, P. (2000). Increasing Returns, Path Dependence, and the Study of Politics. American Political Science Review, 94(2), 251–267. Cambridge Core. https://doi.org/10.2307/2586011

Rasmussen, D. J., Oppenheimer, M., Kopp, R. E., & Shwom, R. (2020). The political complexity of coastal flood risk reduction: Lessons for climate adaptation public works in the U.S. [Preprint]. Climatology (Global Change). https://doi.org/10.1002/essoar.10502705.3

Rauws, W. (2017). Embracing Uncertainty Without Abandoning Planning: Exploring an Adaptive Planning Approach for Guiding Urban Transformations. DisP - The Planning Review, 53(1), 32–45. https://doi.org/10.1080/02513625.2017.1316539

Reeder, T., & Ranger, N. (n.d.). How do you adapt in an uncertain world? Lessons from the Thames Estuary 2100 project. 16.

Revi, A., Satterthwaite, D., Aragón-Durand, F., Corfee-Morlot, J., Kiunsi, R. B. R., Pelling, M., Roberts, D., Solecki, W., Gajjar, S. P., & Sverdlik, A. (2014). Towards transformative adaptation in cities: The IPCC's Fifth Assessment. Environment and Urbanization, 26(1), 11–28. https://doi.org/10.1177/0956247814523539

Reyes Plata, J. A. (2020). Urban Planning, Urban Design, and the Creation of Public Goods. In W. Leal Filho, A. Marisa Azul, L. Brandli, P. Gökçin Özuyar, & T. Wall (Eds.), Sustainable Cities and Communities (pp. 899–905). Springer International Publishing. https://doi.org/10.1007/978-3-319-95717-3_82

Rianne Warsen, José Nederhand, Erik Hans Klijn, Sanne Grotenbreg & Joop Koppenjan (2018) What makes public-private partnerships work? Survey research into the outcomes and the quality of cooperation in PPPs, Public Management Review, 20:8, 1165-1185, DOI: 10.1080/14719037.2018.1428415. (n.d.).

Ribot, J. C. (2010). Vulnerability does not fall from the sky: Toward multi-scale propoor climate policy. In R. Mearns, & A. Norton (Eds.), Social dimensions of climate change: Equity and vulnerability in a warming world (pp. 47e74). Washington, DC: The World Bank. (n.d.).

Ritchie, J., Lewis, J., Nicholls, C.M. & Ormston, R., 2014, Qualitative research practice: A guide for social science students and researchers, 2nd edn., Sage, London. (n.d.).

Roberts, N. (1997) 'Public Deliberation: An Alternative Approach to Crafting Policy and Setting Direction', Public Administration Review 57(2): 124–32. (n.d.).

Roberts, N. (2002) 'Keeping Public Officials Accountable through Dialogue: Resolving the Accountability Paradox', Public Administration Review 62(6): 658–69. (n.d.).

Rodima-Taylor, D., Olwig, M. F., & Chhetri, N. (2012). Adaptation as innovation, innovation as adaptation: An institutional approach to climate change. Applied Geography, 33, 107–111. https://doi.org/10.1016/j.apgeog.2011.10.011

Roggero, M. (2015). Adapting institutions: Exploring climate adaptation through institutional economics and set relations. Ecological Economics, 118, 114–122. https://doi.org/10.1016/j.ecolecon.2015.07.022

Roggero, M., Bisaro, A., & Villamayor-Tomas, S. (2018). Institutions in the climate adaptation literature: A systematic literature review through the lens of the Institutional Analysis and

Development framework. Journal of Institutional Economics, 14(3), 423–448. https://doi.org/10.1017/S1744137417000376

Rondinelli, D. A. (1976). Public planning and political strategy. Long Range Planning, 9(2), 75–82. https://doi.org/10.1016/0024-6301(76)90080-7

Rose, A. (2007). Economic resilience to natural and man-made disasters: Multidisciplinary origins and contextual dimensions. Environmental Hazards, 7(4), 383–398. https://doi.org/10.1016/j.envhaz.2007.10.001

Rosenzweig, C., Solecki, W. D., Hammer, S. A., & Mehrohtra, S. (Eds.). (2011). Climate change and cities first assessment report of the urban climate change research network. Cambridge: Cam-bridge University Press. (n.d.).

Ryan, C.M. (2001) 'Leadership in Collaborative Policy Making: An Analysis of Agency Roles in Regulatory Negotiation', Policy Sciences 34(3): 221–45. (n.d.).

Sabatier, P.A., 1986. Top-down and bottom-up approaches to implementation research: A critical analysis and suggested synthesis. Journal of Public Policy 6, 21–48. (n.d.).

Sanyal, B. (2005). Planning as Anticipation of Resistance. Planning Theory, 4(3), 225–245. https://doi.org/10.1177/1473095205058495

Satterthwaite, D., Dodman, D., & Bicknell, J. (2009). Conclusions: Local development and adaptation. In J. Bicknell, D. Dodman, & D. Satterthwaite (Eds.), Adapting cities to climate change: Understanding and addressing the development challenges (pp. 359–383). London: Earthscan. (n.d.).

Sauvé, S., Bernard, S., & Sloan, P. (2016). Environmental sciences, sustainable development and circular economy: Alternative concepts for trans-disciplinary research. Environmental Development, 17, 48–56. edselp.

Schotter, A. (2000). The Economic Theory of Social Institutions. In Southern Economic Journal (Vol. 48). https://doi.org/10.2307/1058295

Schroeder, H., & Kobayashi, Y. (2021). Climate change governance: Responding to an existential crisis. In The Impacts of Climate Change (pp. 479–489). Elsevier. https://doi.org/10.1016/B978-0-12-822373-4.00006-9

Scott, C. A., Shrestha, P. P., & Lutz-Ley, A. N. (2020). The re-adaptation challenge: Limits and opportunities of existing infrastructure and institutions in adaptive water governance. Current Opinion in Environmental Sustainability, 44, 104–112. https://doi.org/10.1016/j.cosust.2020.09.012

Scott, W. (2003). Institutions and Organizations. Leadership & Organization Development Journal, 24, 469–470. https://doi.org/10.1108/01437730310505902

Shackle, G. L. S. 1969. Decision order and time in human affairs. Cambridge: Cambridge University Press. (n.d.).

Smets, M., Morris, T., & Greenwood, R. (2012). From Practice to Field: A Multilevel Model of Practice-Driven Institutional Change. Academy of Management Journal, 55(4), 877–904. https://doi.org/10.5465/amj.2010.0013

Smit, B., & Wandel, J. (2006). Adaptation, adaptive capacity and vulnerability. Global Environmental Change, 16(3), 282–292. https://doi.org/10.1016/j.gloenvcha.2006.03.008

Soden, R., & Kauffman, N. (2019). Infrastructuring the Imaginary: How Sea-Level Rise Comes to Matter in the San Francisco Bay Area. Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems, 1–11. https://doi.org/10.1145/3290605.3300516

Sorensen, A. (2018). Institutions and Urban Space: Land, Infrastructure, and Governance in the Production of Urban Property. Planning Theory & Practice, 19(1), 21–38. https://doi.org/10.1080/14649357.2017.1408136

Stedinger, J. R., & Griffis, V. W. (2011). Getting From Here to Where? Flood Frequency Analysis and Climate1: Getting From Here to Where? Flood Frequency Analysis and Climate. JAWRA Journal of the American Water Resources Association, 47(3), 506–513. https://doi.org/10.1111/j.1752-1688.2011.00545.x

Stoddart, H., Schneeberger, K., Dodds, F., Shaw, A., Bottero, M., Cornforth, J., & White, R. (2011). A pocket guide to sustainable development governance. Stakeholder Forum 2011. (n.d.).

Storbjörk, S., & Hedrén, J. (2011). Institutional capacity-building for targeting sea-level rise in the climate adaptation of Swedish coastal zone management. Lessons from Coastby. Ocean & Coastal Management, 54(3), 265–273. https://doi.org/10.1016/j.ocecoaman.2010.12.007

Stringer, L. C., Dougill, A. J., Fraser, E., Hubacek, K., Prell, C., & Reed, M. S. (2006). Unpacking “Participation” in the Adaptive Management of Social–ecological Systems: A Critical Review. Ecology and Society, 11(2), art39. https://doi.org/10.5751/ES-01896-110239

Stroup, L. J. (2011). Adaptation of U.S. Water Management to Climate and Environmental Change. The Professional Geographer, 63(4), 414–428. https://doi.org/10.1080/00330124.2011.604010

Susskind, L., McKearnan, S. and Thomas-Larmer, J. (eds) (1999) The Consensus Building Handbook: A Comprehensive Guide to Reaching Agreement. Thousand Oaks, CA: Sage. (n.d.).

Swaffield, S. R. (2002). Theory in landscape architecture: A reader. (Environmental Design SB472 .T44 2002). Philadelphia : University of Pennsylvania Press, c2002.; cat04202a.

Swyngedouw, E. (2009). The Antinomies of the Postpolitical City: In Search of a Democratic Politics of Environmental Production. International Journal of Urban and Regional Research, 33(3), 601–620. https://doi.org/10.1111/j.1468-2427.2009.00859.x

Tarr, J. A. (1996). The Search for the Ultimate Sink. [Electronic resource]: Urban Pollution in Historical Perspective. Akron, Ohio : University of Akron Press, 1996. (Baltimore, Md. : Project MUSE, 2015); cat04202a.

Tilly, C. (2001). Mechanisms in Political Processes. 22.

Tilly, C. (1984) Big Structures, Large Processes, Huge Comparisons. New York, NY. Russel Sage. (n.d.).

Toimil, A., Losada, I. J., Nicholls, R. J., Dalrymple, R. A., & Stive, M. J. F. (2020). Addressing the challenges of climate change risks and adaptation in coastal areas: A review. Coastal Engineering, 156, 103611. https://doi.org/10.1016/j.coastaleng.2019.103611

Tol, R. S. J., Klein, R. J. T., & Nicholls, R. J. (2008). Towards Successful Adaptation to Sea-Level Rise along Europe's Coasts. Journal of Coastal Research, 242, 432–442. https://doi.org/10.2112/07A-0016.1

Torabi, E., Dedekorkut-Howes, A., & Howes, M. (2018). Adapting or maladapting: Building resilience to climate-related disasters in coastal cities. Cities, 72, 295–309. https://doi.org/10.1016/j.cities.2017.09.008

Tribbia, J., & Moser, S. C. (2008). More than information: What coastal managers need to plan for climate change. Environmental Science & Policy, 11(4), 315–328. https://doi.org/10.1016/j.envsci.2008.01.003

Turkelboom, F., Leone, M., Jacobs, S., Kelemen, E., García-Llorente, M., Baró, F., Termansen, M., Barton, D. N., Berry, P., Stange, E., Thoonen, M., Kalóczkai, Á., Vadineanu, A., Castro, A. J., Czúcz, B., Röckmann, C., Wurbs, D., Odee, D., Preda, E., … Rusch, V. (2018). When we cannot have it all: Ecosystem services trade-offs in the context of spatial planning. Ecosystem Services, 29, 566–578. https://doi.org/10.1016/j.ecoser.2017.10.011

Twigg, J. (2007). Characteristics of a disaster-resilient community: A guidance note. London: DFID DRR Interagency Coordination Group. (n.d.).

Tyler, S., & Moench, M. (2012). A framework for urban climate resilience. Climate and Development, 4(4), 311–326. https://doi.org/10.1080/17565529.2012.745389

UNISDR. (2012). How to make cities more resilient: A handbook for local government leaders. Geneva: Author. (n.d.).

UNISDR. (2015). Sendai Framework for disaster risk reduction. Geneva: UNISDR. Retrieved from www.unisdr.org. UNISDR. (2017). National disaster risk assessment. Geneva: UNISDR. Retrieved from www.unisdr.org. (n.d.).

United Nations Environment Programme (2021). Adaptation Gap Report 2020. Nairobi. (n.d.).

Urwin, K., & Jordan, A. (2008). Does public policy support or undermine climate change adaptation? Exploring policy interplay across different scales of governance. Global Environmental Change, 18(1), 180–191. https://doi.org/10.1016/j.gloenvcha.2007.08.002

van Assche, K., Beunen, R., & Duineveld, M. (2014). Evolutionary Governance Theory. Springer International Publishing. https://doi.org/10.1007/978-3-319-00984-1

van der Bles, A. M., van der Linden, S., Freeman, A. L. J., Mitchell, J., Galvao, A. B., Zaval, L., & Spiegelhalter, D. J. (2019). Communicating uncertainty about facts, numbers and science. Royal Society Open Science, 6(5), 181870. https://doi.org/10.1098/rsos.181870

van der Heijden, J. (2019). Studying urban climate governance: Where to begin, what to look for, and how to make a meaningful contribution to scholarship and practice. Earth System Governance, 1, 100005. https://doi.org/10.1016/j.esg.2019.100005

Van der Heijden, Kees. 1996. Scenarios: The art of strategic conversation. Chichester, UK: John Wiley. (n.d.).

van Klingeren, F., & de Graaf, N. D. (2021). Heterogeneity, trust and common-pool resource management. Journal of Environmental Studies and Sciences, 11(1), 37–64. https://doi.org/10.1007/s13412-020-00640-7

Vatn, A. (2005). Institutions and the Environment / A. Vatn.

Vogel, B., & Henstra, D. (2015). Studying local climate adaptation: A heuristic research framework for comparative policy analysis. Global Environmental Change, 31, 110–120. https://doi.org/10.1016/j.gloenvcha.2015.01.001

Voigt, S. (2013). How (Not) to measure institutions. Journal of Institutional Economics, 9(1), 1–26. Cambridge Core. https://doi.org/10.1017/S1744137412000148

Walker, W. E., Rahman, S. A., & Cave, J. (2001). Adaptive policies, policy analysis, and policy-making. European Journal of Operational Research, 128(2), 282–289. https://doi.org/10.1016/S0377-2217(00)00071-0

Walters, C. J., & Holling, C. S. (1990). Large-scale experimentation and learning by doing. Ecology, 71, 2060–2068. (n.d.).

Walters, C. J. (1986). Adaptive management of renewable resources. New York: McGraw Hill. (n.d.).

Wamsler, C., & Brink, E. (2014). Interfacing citizens' and institutions' practice and responsibilities for climate change adaptation. Urban Climate, 7, 64–91. https://doi.org/10.1016/j.uclim.2013.10.009

Wang, Z., Zhao, Y., & Wang, B. (2018). A bibliometric analysis of climate change adaptation based on massive research literature data. Journal of Cleaner Production, 199, 1072–1082. https://doi.org/10.1016/j.jclepro.2018.06.183

Webster, J., & Watson, R. T. (2021). Analyzing the Past to Prepare for the Future: Writing a Literature Review. 12.

Wheeler, S. M. (n.d.). Planning for Sustainability: Creating Livable, Equitable, and Ecological Communities. 289.

Wilder, M., Scott, C. A., Pablos, N. P., Varady, R. G., Garfin, G. M., & McEvoy, J. (2010). Adapting Across Boundaries: Climate Change, Social Learning, and Resilience in the U.S.–Mexico Border Region. Annals of the Association of American Geographers, 100(4), 917–928. JSTOR. http://www.jstor.org.libproxy.berkeley.edu/stable/40863611

Williams, B.K., 2011. Adaptive management of natural resourcesеframework and issues. Journal of Environmental Management 92 (5), 1346e1353. (n.d.).

Wilson, G. A. (2012). Community resilience, globalization, and transitional pathways of decision-making. Geoforum, 43(6), 1218–1231. (n.d.).

Wilson, J. (n.d.). Scientific Uncertainty, Complex Systems, and the Design of Common-Pool Institutions. 24.

Young, O. R., Berkhout, F., Gallopin, G. C., Janssen, M. A., Ostrom, E., & van der Leeuw, S. (2006). The globalization of socio-ecological systems: An agenda for scientific research. Global Environmental Change, 16(3), 304–316. https://doi.org/10.1016/j.gloenvcha.2006.03.004

Chapter 2: Urban Sediment Systems in Coastal Adaptation Planning
A Concept and Case Study

Abstract

Systems and strategies for improving Urban Metabolism (UM) are being challenged by climate change. While most considerations of industrial ecology (IE) as applied to climate issues focus on mitigation, there are significant ways in which climate adaptation outcomes may be improved utilizing IE approaches. In developed shorelines, a fundamental tension is emerging between the drive to develop dense, compact city cores designed to improve efficiency and reduce wastes; and the threat of sea level rise (SLR) in reducing the availability land. This spatial aspect of adapting to rising waters, and its planning and policy considerations offer significant challenges and emerging opportunities for prominent IE concepts, tools and techniques to aid in the challenge of adapting populous, dense coastal cities. We describe the relationship between space as a basic resource in planning, and increasing flows of excavated soils in urban shorelines, which may be useful as a building material for SLR barriers. We consider the San Francisco Bay Area of California as an example of a metropolitan region experiencing rapid urban development as new coastal flooding imposes spatial constraints on it. The region's planning agencies lack a mass balance framework allowing efficient use of excavated material flows for adaptation to flooding. We examine the human-driven processes affecting soils and sediment management in a developed shore and consider their relevance to climate adaptation planning. We discuss the conceptual potential of the circular economy (CE), urban metabolism (UM), and material flow analysis (MFA) to inform and improve adaptation outcomes for urban shorelines.

Introduction

Global SLR is forcing developed shorelines everywhere to plan strategies for adapting to it, and cities are facing numerous, pressing sustainability challenges in the 21st century (Reese and Wackernagel 1994; Moffatt 2000; Kennedy et al. 2014). As global population rises, so too does the proportion of people settling in cities and most the planet's largest cities are located on or near coastlines, where physiographic and sociopolitical factors often constrain the growth boundaries of cities (Bianchi and Allison 2009). A focus on centralized, dense urban cores has been widely adopted by many of the world's major metropolitan areas, (Rees 1999) even as SLR threatens to inundate them and devastate coastal ecosystems delivering major flood protection to adjacent urban areas (Valiela et al. 2018). Expansion of urban underground space (UUS) is rapidly expanding in many population centers (Admiraal and Cornaro 2016). The construction of UUS yields geomaterials, including soils and sediment, which are important resources in ecologically-based adaptation strategies. Certain themes and approaches evident in IE may be useful in adaptation planning that incorporates these resources to achieve sustainable development (SD) goals.

Within city boundaries, resource extraction is usually considered null or residual (Niza, Rosado, and Ferrão 2009), as the hinterlands have historically served as the sources of raw materials provided to cities (Hodson et al. 2012) . Though cities generally consume a narrow range of most raw materials, certain mineral resources like sand and gravel (which are elemental material inputs of the modern built environment) still represent major inflows (Douglas and Lawson 2000). Indeed, cities currently consume the majority of extracted material resources by volume for building housing stock and infrastructure (Fischer-Kowalski et al. 2011; Hu, Van Der Voet, and Huppes 2010) : a trend likely to increase with the construction of higher density urban spaces. Recent decades have seen greater focus emerge on the efficiency of the Circular Economy (CE), and where local waste reduction and increased reuse and recycling of material is possible, urban sustainability may be improved (Acselrad 1999; Céspedes Restrepo and Morales-Pinzón 2018). Urban symbiosis has served as a conceptual link for CE applied to the urban context, where one sector's waste stream becomes another's resource (Chertow 2008). This reasoning may extend past goods and products to regional resource management and municipal public works, the subject of this paper.

White's (1994) description of IE as "the study of the flows of materials and energy…of the effects of these flows on the environment, and of the influences of economic, political, regulatory, and social factors on the flow, use, and transformation of resources" serves to frame its broad, institution-spanning relevance. Specifically, in recognizing the spatiotemporal dynamics, complexity, and geographic context-dependency of resource management, the importance of "strategic resource optimization" is evident and of major interest here (Cerceau, Mat, and Junqua 2018). We consider the promise of IE to improve the technical and strategic capacity of cities to optimize a particular resource flow intimately connected to development and UM, and frame a discussion about the complexities and challenges evident in applying IE to problems paradigmatic of the climate change era. As such, we focus on the systematic aspects of spatial planning components of UM as it relates to regional/territorial resource flows.

Our discussion of IE draws on the aforementioned disciplinary definition offered by White while integrating perspectives from several fields to offer interpretations of IE concepts and embracing a view of IE that frames its proven utility while pointing to its expanded potential in environmental planning processes. To do so, Ramaswamy's (2003) articulation that, "an Industrial Ecology based system-level perspective is essential to identify the major flows of materials in a region for planning resource optimization and for solving environmental problems" is considered salient and relevant herein. Moreover, adaptation planning's clear harmonization with these themes presents possibilities for IE to advance efforts in schematizing a resource-optimization system, address relevant data challenges, and recognizing its utility as a planning tool for improving adaptation outcomes.

Sustainable Development in the era of Rising Seas: Key Challenges

Because of IE's disciplinary concern with systems, urban infrastructure's importance in effectively integrating planning and adaptation has been noted as an opportunity for planners to "overcome fragmentation through integration" (Neuman 2009; Hodson et al. 2012; Ness and Xing 2017). The construction of novel adaptation infrastructure may represent a convergent opportunity of this type, and one reliant upon the systems perspective implicit in IE. Though focused on climate mitigation, Seto and colleagues (2014) recognize that spatial planning advances are possible where interlinked efforts can essentially yield a "whole" outcome greater than the sum of its parts. As Wíjkman and Skånberg (2015) emphasize, "climate change mitigation strategies need to become more holistic and consider resource efficiency as a key instrument" (Ness and Xing 2017), potentially through climate adaptation efforts, which are often less evident (Reckien et al. 2018). The impetus to seek and develop creative solutions to pressing problems effecting and effected by UM is evident in the impacts on the built and natural environments in developed shorelines, and linked through the possible innovations in resource management practices and adaptation planning.

SLR Impacts on the Built Environment

SLR in the 21st century will worsen flooding globally, in more frequent and sustained nuisance flooding and during extreme weather events (Ruggiero 2008; Moftakhari et al. 2017). In addition to surface flooding of private property and major transportation infrastructure, subsurface changes induced by rising groundwater in coastal zones may threaten subterranean infrastructure and prompt its retrofitting and repair (Fletcher 2012; Hoover et al. 2017). In many coastal zones, urban development built on filled wetlands is also physically sinking: subsiding as soils compress (Hoover et al. 2017). In many coastal conurbations, the majority of coastal protective infrastructure was designed assuming a static sea surface elevation, and without SLR in mind.

SLR Impacts on Ecosystems

Alterations in landscape composition, changes in surface cover and impacts on ecosystems as a function of the built environment are recognized as effects of urbanization (MEA 2005). Pereira et al. (2010) identified habitat destruction and species distribution shifts as two major spatially-linked drivers of biodiversity loss likely to affect countless ecosystems in the 21st century. Habitat destruction, biodiversity loss, and fragmentation of ecosystems as effects of urbanization are well-recognized, and the effect of these trends are compounded by the richness and variation evident in shorelines, where biodiversity is high, ecosystem services are rich, complex and linked to broader, global systems (Spencer et al. 2016; Singh and Kennedy 2018). Coastal wetlands are also sensitive to land use change and important landscape complexes for muting upland flooding (Bilskie et al. 2014; Ding 2017; Bigalbal et al. 2018).

The Coastal Wetland "Squeeze"

As sea levels change, tidal wetlands naturally migrate and reestablish their biogeophysical processes accordingly, demarcating novel shorelines in the process (Crosby et al. 2016). A major ecological concern for developed (and developing) coastal cities is that the built environment is often situated in close proximity to the shoreline. Rising seas that trigger the inland and upward migration of wetlands on developed shorelines will drive them toward physical barriers like highways, urban centers and other developed spaces whose current configurations and design do not support wetlands. Tidal wetlands that cannot successfully migrate with rising waters will destabilize and drown, and their capacity to adapt to rising waters is of global concern (Sánchez-Arcilla et al. 2016; Phillips 2018; Reed et al. 2018).

Coastal Sediment Deficits: a "Mass Imbalance"

Douglas and Lawson (2000) estimated that human beings actively transport more than three times as much earthen material than the natural geomorphic processes of the planet, and most extracted material is bound for cities, where It is capitalized into building stock, infrastructure and other materials in the evolution of "urban morphology". At the same time, numerous human endeavors aimed at industrial processes and "command and control" of natural systems have substantially reduced the "throughput" of sediment that reaches coastal waters and nourish shorelines, whose profiles play major roles in governing the severity of coastal flooding, and where sediment loss has been linked to coastal erosion, more severe storm impacts, and damage to coastal ecosystems (Holling and Meffe 1996; Schoellhamer, Wright, and Drexler 2013; Florsheim et al. 2013; Voss, Christian, and Morris 2013). The impacts described above are based on the projected inability of developed shorelines to "keep pace" with SLR as a function of a shortage of sediment flowing to the shore – creating a localized "mass imbalance".

To make coastal ecosystems and cities more resilient to climate impacts, there is interest in increasing sediment flows to shorelines. In addition to nourishing existing shorelines, establishment of multi-benefit flood protection barriers will require considerable volumes of soils and sediment to construct. Urban development constantly yields geomaterial resources (through excavation), which can both bolster the viability of the built environment (through construction of SLR barriers) and improve the resilience of ecological systems (through wetland restoration and construction). The spatial proximity of the processes of excavation to the sites of material reuse is significant. Kenway et al (2011) acknowledge the need for cities to "source from within" resources where possible, echoed in the "urban harvest" approach (Agudelo-Vera et al. 2012). Indeed, the concept of reclaiming and reusing material resources gleaned in urban metabolic process for adapting the urban fabric to climate change is a critical challenge that IE is well-suited to address.

2. Case Study Area

The San Francisco Bay Area and Estuary (SF Bay) is a large, fast-growing metropolitan "megaregion" of Northern California, which encircles its namesake waterway (Florida et al. 2008). Development patterns of the modern era focused development near the Bay's shoreline, and destroyed the majority of its tidal marshes, which are now a major focus of ecological restoration. The SF Bay is experiencing a severe housing crises, and pressure to build homes and implement land use controls to meet demand in a region projected to host 2 million more residents by 2040 is widely recognized (Mackenzie et al. 2017). Planning efforts aimed at preventing sprawl and developing dense, transit-oriented urban centers have identified Priority Development Areas (PDAs), to serve as the urban cores to accommodate population increase and an intensification of the built environment's use and demands [Figures I and II]. Much of the region's major civil infrastructure is built near the shoreline, and faces increased strains from age and use, in addition to major threats posed by SLR (Biging, Radke and Lee 2012).

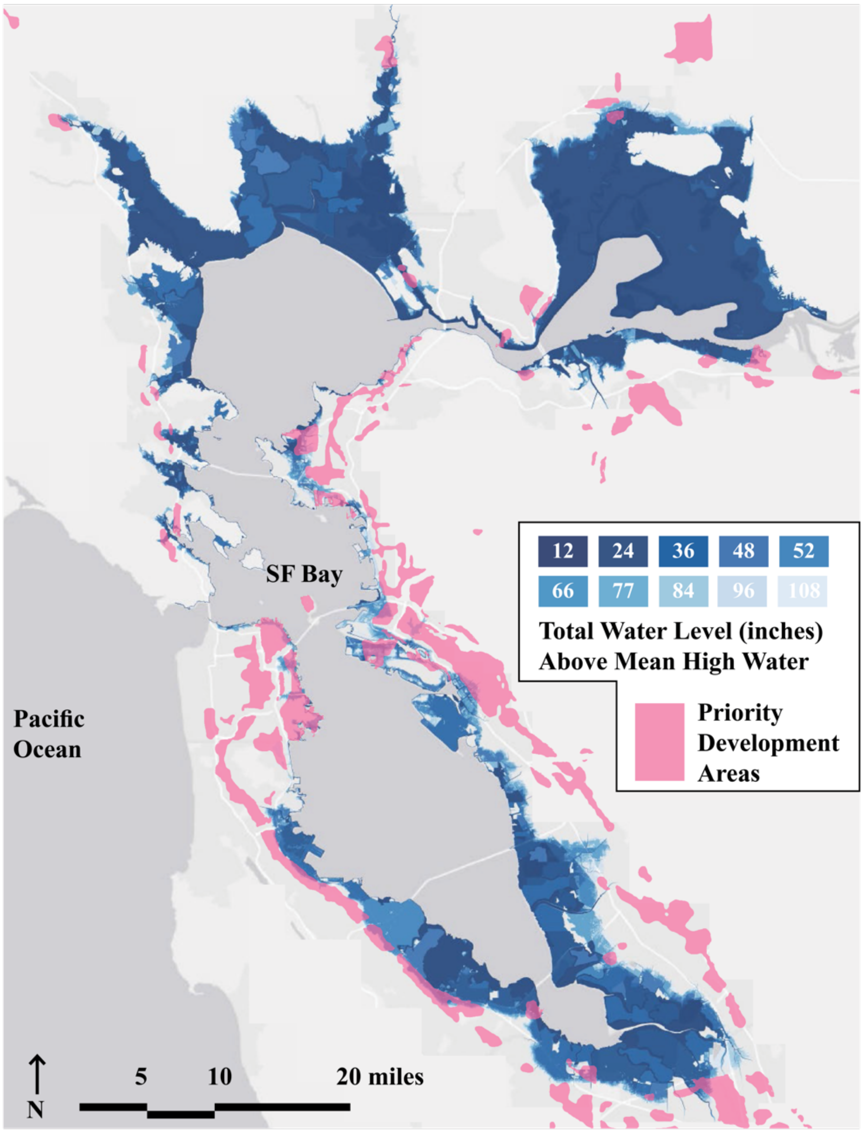


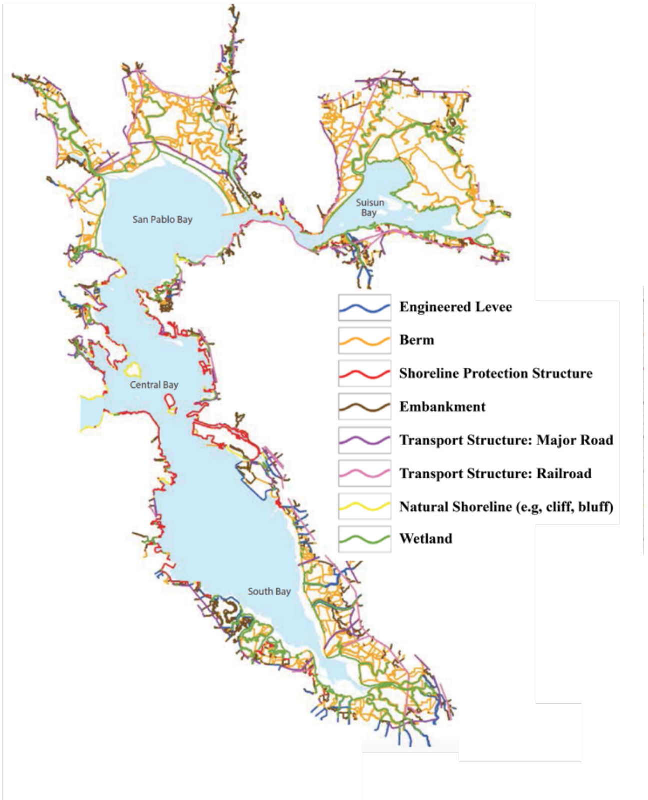
Figure 1 : A map showing the placement and proximity of regional Priority Development Areas (PDAs) in pink within 10 miles of the existing shoreline; and their proximity and position relative to potential flooding extents, displayed in blue, which includes a wide range of possible SLR-induced inundation. Sources : Sea Level Rise Data: BCDC, MTC, AECOM, Adapting to Rising Tides Bay Area Sea Level Rise Analysis and Mapping Project 2017, SF Greenbelt Alliance.

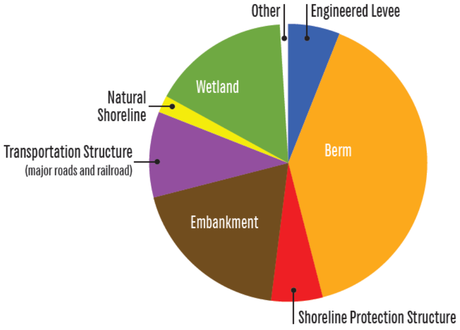
	2010	2015	2040	Change 2010-40	Change 2015-40	2010-2040 (%)	2015-2040 (%)
Population[1]	7,150.7	7,609.0	9,522.3	2,371.6	1,913.3	33.2%	25.1%
Households[2]	2,606.3	2,699.3	3,388.6	782.8	689.8	30.0%	25.6%

[1] 2015 Is July 2015 estimate from the California Department of Finance. [2] 2015 is Association of Bay Area Governments estimate for mid-year, based on 2015 January data and growth estimates.

Table 1: Table showing projected regional population and households. Source : Association of Bay Area Governments, Plan Bay Area 2040 Report. If excavation processes and their commensurate yield of excavated soils are indeed a proxy for building and infrastructure construction projects, a rising population driving demand for housing should correlate to increased volumes of excavated soils.

Developed shorelines inevitably feature coastal infrastructure to prevent flooding. SF Bay's development necessitated an extensive network of earthen berms and levees (built from indigenous soils and sediment), and hardened protection structures. The impact of a rising Bay on the region's shore is already evident in places, and projected to become widespread and severe by midcentury (Heberger et al. 2012.). Regional interest in the need to improve the shoreline was ratified in a 2016 ballot measure that will direct $500 million dollars to its improvement in coming decades. Using this financing to establish ecological structures and systems that deliver flood protection benefits under anticipated SLR conditions is understood as a regional priority.





Class	Percent	Miles
Engineered Levee	6%	170
Berm	40%	1,215
Shoreline Protection Structure	6%	175
Embankment	19%	558
Transportation Structure (major roads, railroad)	10%	313
Natural Shoreline	2%	66
Wetland	16%	486
Other	1%	29
TOTAL	**100%**	**3,012**

Figures 2 and 3: Extent and type of shoreline reaches in the SF Bay, displaying the abundance of earthen berms and shoreline protection structures (Note: The San Pablo, South, Central and Suisun Embayments comprise the SF Bay Estuary). Source: San Francisco Estuary Institute, Bay Shore Inventory, 2016.

2.1 Landforms as Flood Barriers : The Ecotone Slope and its Material Demands

Armoring and "hard" treatments for shoreline protection may telegraph floodwaters to adjacent reaches of the shore, potentially worsening flooding in neighboring areas, whereas ecological structures like wetlands tend to dissipate and absorb erosive energy (Neil Adger, Arnell, and Tompkins 2005; Foster-Martinez et al. 2018). While restoring tidal marsh plains remains a regional priority, a novel strategy for doing so is the construction of landforms as SLR barriers, which is currently being piloted. An "ecotone slope" (also regionally referred to as a "horizontal levee") is a landform featuring a bay-facing, gradually-sloped face (at a 1:30 to 1:50 slope ratio) that provides several regional benefits (Lowe et al. 2013). Ecotones' biogeophysical processes allow them to trap sediment and build incrementally upwards in the process of accretion. The ecotone's wetland edge attenuate waves, may reduce overtopping potential of storm surge, and can be more economical to construct than a traditional levee (Lowe 2013; Hirschfeld and Hill 2017;

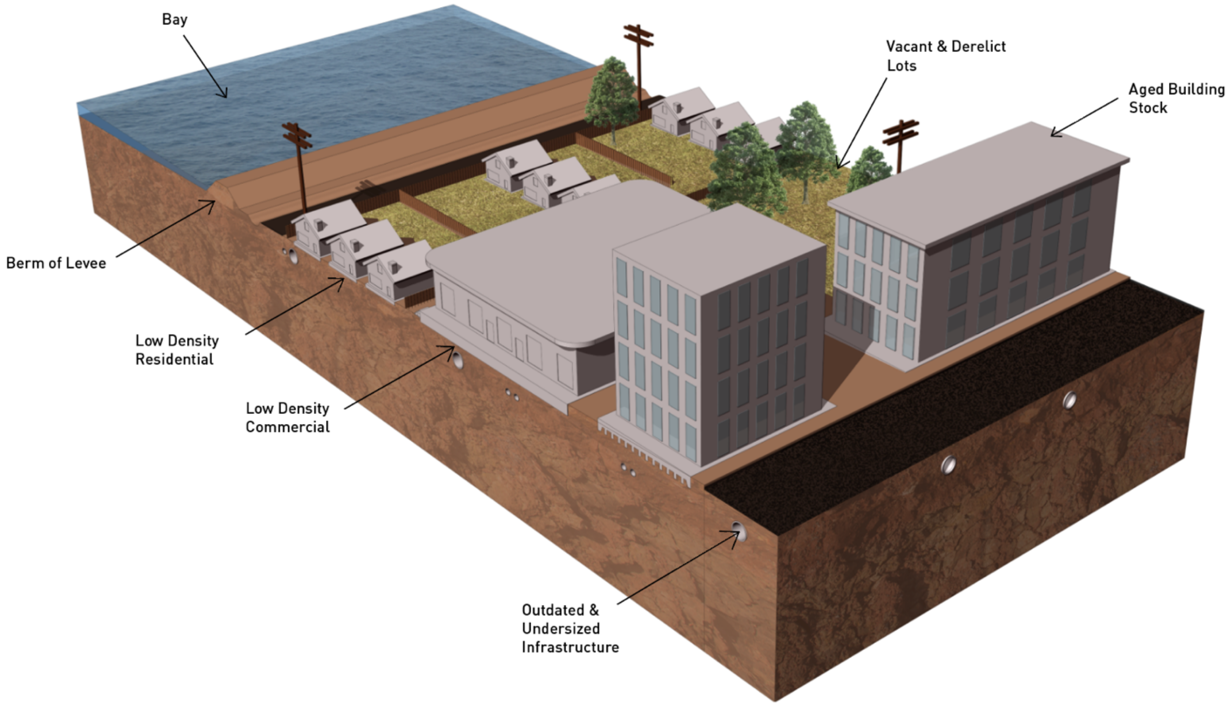
Foster-Martinez et al. 2018). The volume of material required to construct ecotones on a regional scale depends on many factors, and the topic remains under-researched, in part because of unclear adaptation planning goals. A widely-circulated white paper estimates the gross volume of sediment required to build the barriers in question encircling the Bay, and considering a range of SLR rates and subsequent ecotone heights. It estimates a range between three hundred million and two billion cubic yards of material will be required (Gunther 2014). How and where the material for this massive construction operation would be sourced remains unclear.

2.2 Excavation Processes in Urban Shorelines: Regional Material Supplies

Effects of modern anthropogenic actions affecting the mass balance of sediment in various regions is well-known (Happ et al. 1945; Knox 1972; Douglas and Lawson 2000), but the implication of these understandings as relevant for climate change adaptation is unclear. James (2013) proposes a broad definition of the activities and processes that produce or interact with "legacy sediment" (material impacted or activated by human activities) to encompass urbanization, and we consider urban morphology's relationship to a particular type of legacy sediment: excavated urban soils. Excavated urban soils are often yielded as locally-produced construction wastes, while many UM material flows are directed towards cities to meet the need of people within them (Hodson, 2012; Tukker et al. 2014; Gorgolewski 2018). Few raw material resources emerge from within cities and travel for use to the hinterlands. Excavated urban soils are rather idiosyncratic in this respect. Trends driving excavation processes to establish an increasingly dense built environment will continue to produce these materials: a resource stock whose potential has not been evaluated in the context of SLR adaptation planning.

2.2.1 Urban Underground Space

The relationship between urban underground space (UUS) and the possible reuse of geomaterials evident there have not been deeply considered in urban planning, though dense cities are increasingly considering these resources (Parriaux et al. 2004; Li et al. 2016), and UUS has been extensively developed and studied in a variety of geographic settings over many decades (Jansson 1978). Drivers of large-scale excavation processes include public works projects in addition to expansion of building stock, and these processes will increase with the need of cities to house more people. Likewise, extensive infrastructure projects are important to consider, as cities adapt their civil systems to meet greater demands and stress from population increases (Heller 2001; Kaliampakos et al. 2016). UUS is established for diverse purposes [Figure 5], but the re-use of the resources extracted in their construction varies widely by region, geology and potential re-use strategies and needs. While UUS has been built in numerous geographic settings with varied underlying geologic conditions (Bartel and Janssen 2016), consideration of the suitability of the physical subsurface strata is critical to understand in attempting to estimate or articulate a likely or maximal intensity and extent UUS, and its commensurate yield of excavated material. Nonetheless, surveying, tunneling, and other technologies involved in establishing UUS continue to advance, as do building techniques and processes that may increase the feasibility and sustainability of UUS construction (Makana et al. 2016; Nelson 2016).



Urban Shoreline 'Fabric':
Pre-2025

Figure 4: Block diagram illustration of an urban shoreline parcel, showing an arrangement of typical elements of recent (pre-2025) development patterns. Low-slung, low-density development associated with suburban "sprawl" may feature limited exploitation of subsurface space and the soil and sediment resources present therein.

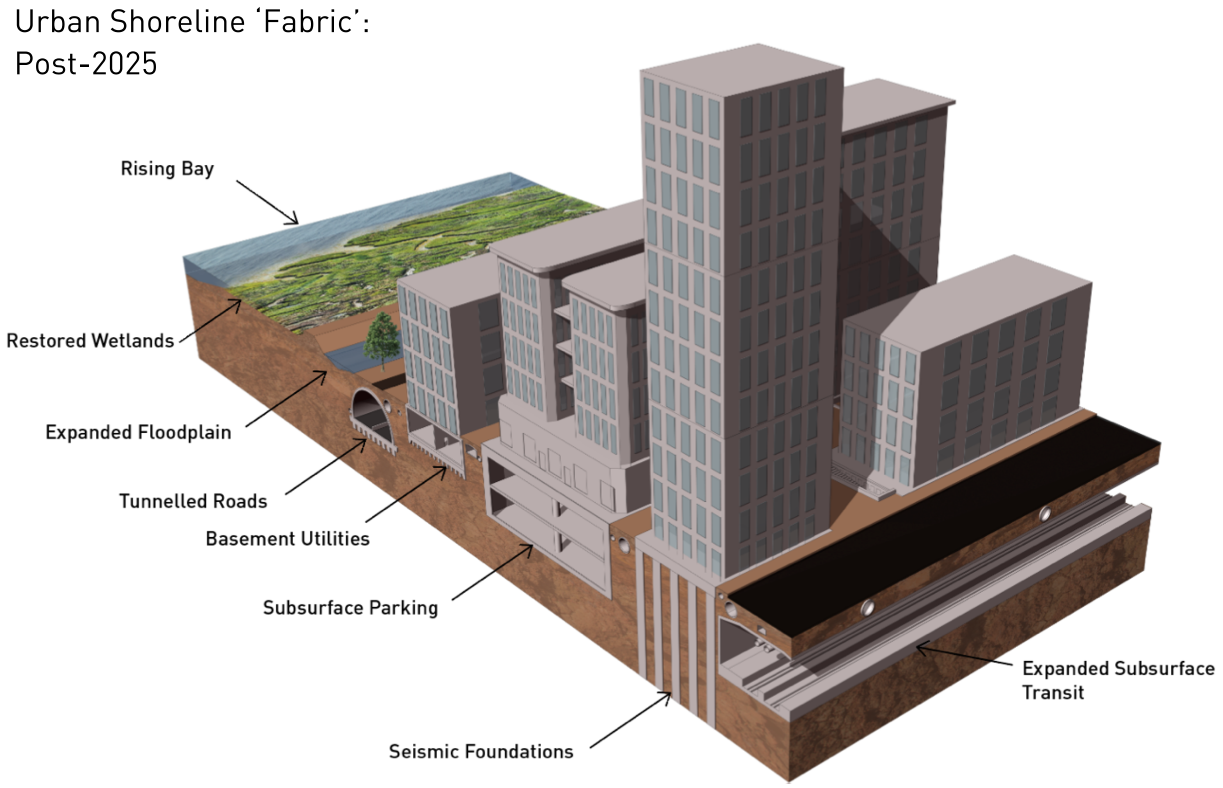


Figure 5 : Block diagram showing features of urban development in more dense and vertical arrangements of building and infrastructure stock. These are elements typical in the SF Bay's Priority Development Areas (PDAs) and their orientation towards both sustainable development practices and orientation towards public/mass transit.

Schiller et al. (2017) observes that knowledge gaps persist regarding the "construction technologies and qualitative and procedural aspects that govern the recovery of recycled materials", while inefficiencies in urban development and waste reduction in development booms have been noted (Ness and Xing 2017). Van Timmeren's (2008) contemplates the (often) overlooked resources in "interrelated networks" for insights into creative ways of viewing materials and spatially-extensive infrastructure systems, as advances in UUS construction is facilitating more extensive projects and the need for connections between them (Broere 2016; Zhao and Künzli 2016; Labbé 2016). Some major cities are advanced in their subterranean planning and development processes. Helsinki, hosts some 10 million cubic meters of UUS, including public attractions and major public infrastructure, with plans for further expansion (Vähäaho 2016). Singapore expects to double its municipal rail service length by 2030, the majority of which will be underground (Zhou and Zhao 2016). Hong Kong has conducted a territory-wide study to assess the utility of UUS in its planning implications, a spatial resource that it has already heavily utilized (Wallace and Ng 2016). These cities face major inundation by rising seas, and UUS may play a role in maximizing SD goals as their density increases (Hunt et al. 2016).

Process scale	Process example
micro	Residential construction earthwork (seismic retrofits, home expansions); local utility repairs and retrofits; geologic hazard management (bank control, slump removal); local flood control work (dredging, clearing channels)
meso	Large building stock replacement, expansion, improvement (undergrounding parking structures, utilities, seismic work); municipal works (undergrounding public utilities and local transport infrastructure); large-scale flood control work (dredging dam-impounded sediment; removing flood control structures for broadened floodplains).
macro	Regional dredge regimes; extensive infrastructure undergrounding (electric power lines or long-distance tunneling and boring for passenger or public transportation systems)

Table 2 : Table listing known UM processes involving excavated urban soils and sediment, as interpreted through CE scales emphasized by Yuan et al. (2006), Su et al. (2013) and synthesized by Ghiselini (2016). Note: "Process scale" refers to operational size for individual project type. A total volume of the soils and sediment governed by these processes remains publicly unknown for the SF Bay's regional UM, as a function of proprietary data protection and the nonintegrated nature of relevant information.

Landfill or Landform?

In dense cities, demand for spatial resources due to surface scarcity will tend to discourage or limit local re-use or recycling possibilities of excavated materials. Accordingly, excavated urban soils are often transported to landfills and applied as "daily cover" for dust and odor suppression, and preventing windblown trash and scavenging. Comparing the functional utility of landfilling soils against possible alternative uses is complex, especially where this alternative might deliver widespread, diverse regional benefits if effectively used to construct SLR adaptation landforms.

To adequately establish a rationale for comparing the possible end-of-life (EOL) impacts or utility of excavated soils requires regional, cross-disciplinary examination of the potential of excavated soils to benefit society in some way. Currently, though the sediment shortfall of the Bay Area (and many developed shorelines around the globe) is well-recognized, strategic planning efforts remain nascent, and thus a rigorous understanding of the comparative economic, social and ecological impacts of different EOL scenarios for excavated soils remains a topic in need of greater consideration. Nonetheless, the simple, axiomatic relationship between resource proximity and system efficiency evident in IE provides a basic premise for further exploring this concept (Metson, Aggarwal, and Childers 2012), specifically for marrying excavated soils proximal to sediment-starved shorelines. Also, the possibility that wastes gleaned in the establishment of some civil infrastructures might represent the foundation of a material ecology for constructing another in the form of an landform-based coastal flood protection system is compelling from a resource-efficiency perspective.

Methods and Data Modeling

To understand the potential significance of excavated soil resources, and their utility and scale as a landform-building material, we collected and analyzed data on a known "sink" for this material: regional landfills (for the purposes of this paper, "landfill" refers to a "dump" for solid waste disposal, not sites or applications using earthen material as "fill" in reclamation or construction). California's Department of Resources Recycling and Recovery (CalRecycle) provided data recoding the tonnage of soils, received quarterly, at seven of the nine Bay Area counties' landfills. San Francisco county contains no active landfills (and disposes of their soils in adjacent counties), and Sonoma County's data was rejected because of low confidence in fidelity due to anomalies and inconsistencies (thus our total volume estimates may be lower than the actual volumes received by regional landfills). We analyzed the overall trend in soil volumes received by regional landfills for years 2007 – 2017, and compared these volumes across counties, and over this timeframe. We then compared these volumes to average annual sediment-inputs (to the estuary) estimates to contextualize our results in a regional earthen material flow and expanded sediment budget.

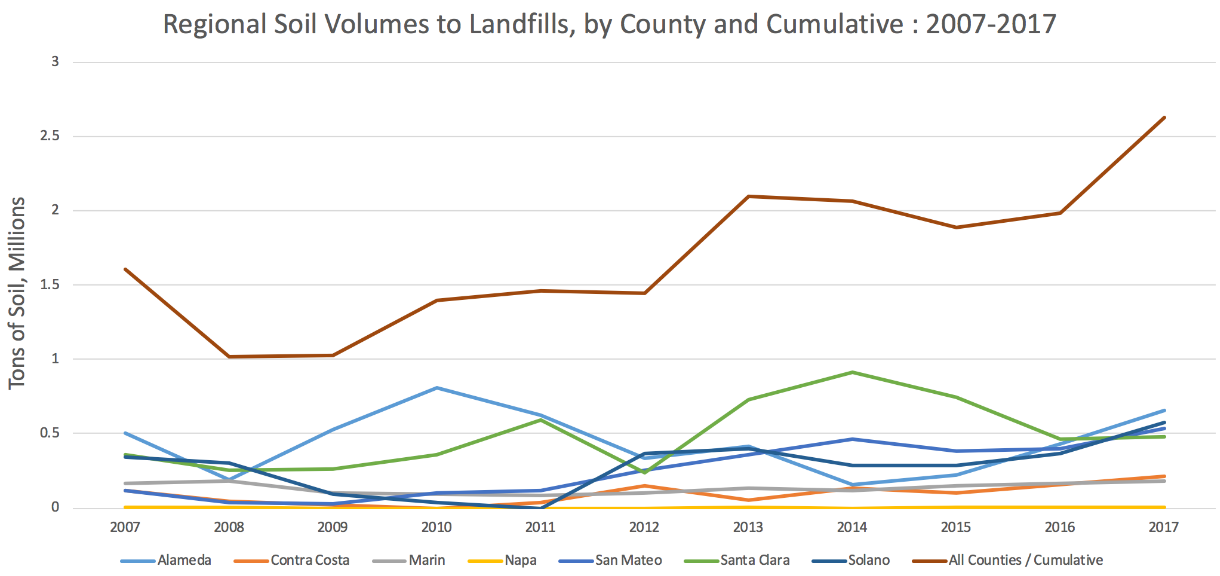


Figure 6 : Comparison chart of the seven Bay Area counties surveyed for their disposal of soils at regional landfills. The top (red) line indicates a net volume of this material.

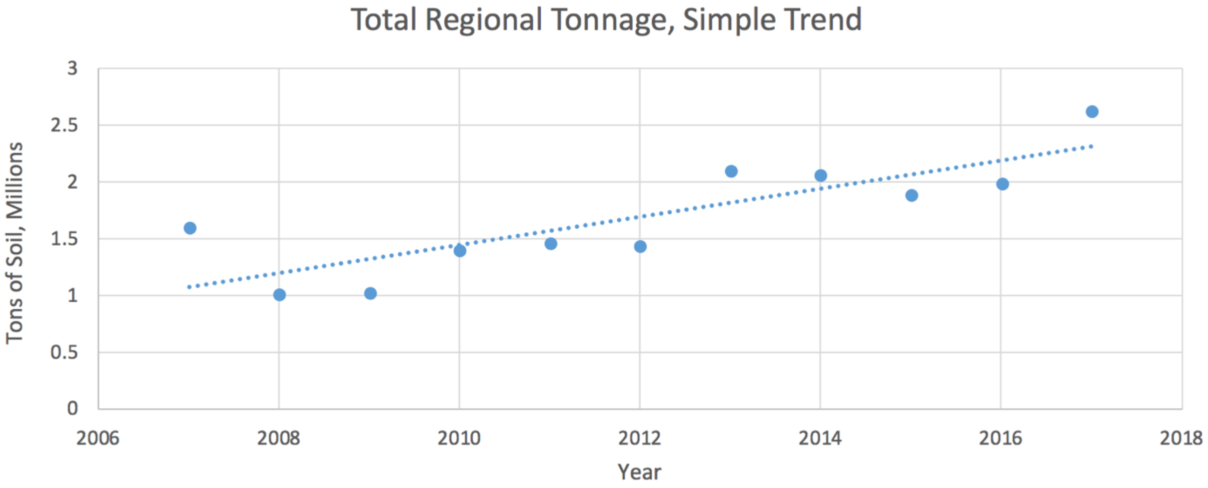


Figure 7 : A simple trend line displaying the total volume of landfilled soils from the counties surveyed (see Figure 4, above) over a recent ten year period. Note the drop in the 2008-09 range, correlating to the economic downturn, and the upward trend, potentially illustrating the relationship between economic activity and construction processes, and their commensurate soil yields by proxy.

Discussion

Interpretation and Limits of Data Analysis, and Next Steps for Ongoing Research

To thoroughly assess the potential utility and scale of excavated soils being reused as the building material for flood-protection landforms in an adaptation scheme, numerous aspects of the planning rationale and approach of a given study region must be identified and assumed, which is not the focus of this paper. Similarly, because of this nascence in the development of building ecotones beyond pilot projects (i.e. on a large scale deployed along some portion of the SF Bay's 500-mile shoreline, and over an extended time period), there does not exist a firm set of parameters for their optimal (or average) size, nor the exact geotechnically-acceptable characteristics of suitable soils for their construction. Additionally, soils and sediment reused in ecological restoration projects must pass stringent testing and permitting processes that prevent a wide range of contaminants being introduced to critical habitat areas, a major concern in reusing earthen materials in an historically industrialized port region. Neither the geotechnical composition nor contaminant presence or type is tracked by CalRecycle for the purposes of receiving soils for daily cover at regional landfills.

As such, our analysis is intended to provide a general sense of the volumes of these materials, and to contextualize this volume in the other known or estimated flows that govern the "sediment budget" for the estuary and its effects in nourishing the region's shoreline. Research has demonstrated that the average annual volume of waterborne sediment flowing into the Bay from local tributaries and the San Joaquin Delta complex (~2M tons/year) is comparable to the volume of soils annually interred in regional landfills, though landfilled soil volume is both greater and rising (Barnard et al. 2013; McKee et al. 2013; Schoellhamer, Wright, and Drexler 2013; Schoellhamer et al., 2018). This suggests that, in the context of a material flow examination of soil and sediment transport by human and natural processes, excavated soil volumes can be viewed as a significant component of the regional sediment budget. Since the regional yield volume of these soils is increasing on average, intensifying demands for construction (in increased building stock for a growing population) and the need to protect these assets from flooding (as a function of SLR) presents a compelling reason to further study and consider the flows, fate transport and resource reuse potential of these soils as possible building materials unto themselves.

IE Tools and Frameworks : Utility and Challenges in SLR Adaptation Planning

Though some aspects of the material flow of sediment can be observed in instances where volumes are tracked and recorded (as discussed the previous section), these publicly available data provide an incomplete picture of the total material ecology of excavated soils in a developed shoreline. SF Bay and coastal cities everywhere contemplating adaptation planning strategies involving landforms as SLR barriers face difficulties in surveying, sourcing and supplying soil and sediment for their construction. Though the focus of this paper is excavated soils due to the regional geomorphology and geologic composition of the estuary, other extracted geomaterials including sand, gravel and stone abundant in other coastal cities may be assessed using similar approaches and tools. Methods and models for advancing this endeavor, and modes of revealing the underlying costs, benefits and efficiencies possible on several fronts are evident in prominent IE scholarship and applications. We discuss CE, UM and MFA as concepts and tools that may aid planners, revealing climate adaptation opportunities.

The Circular Economy and Urban/Industrial Symbioses

CE's inclusion of multi-scale actors and processes is well-suited to informing optimized urban soils management, where a system's efficiency of scale and scope will need to recognize flows of various magnitudes, frequencies and rates of change (Ghisellini, Cialani, and Ulgiati 2016). While many IE tools and approaches have focused on stocks and flow processes, interest in more nuanced and potentially efficient systems has also emerged (Van Berkel et al. 2009; Jiao and Boons 2014). Soils gleaned in processes of coastal urban development being re-used or recycled locally to improve sustainability and adaptation outcomes aligns well with foundational concepts of a CE (with roots in environmental and ecological economics), and may be especially relevant in real estate and construction industries (Boulding 1966; Pearce and Turner 1989; Yang and Feng 2008; EMF 2015; Ghiselini et al. 2016). Supporting CE are the implementation tools offered by industrial and urban symbioses for improving material recycling, and useful when applied to larger scales than typical corporate or consumer operations (Ghiselini et al. 2016; Ness and Xing 2017) and Chertow and Lombardi's (2005) definition of industrial symbiosis as a concept useful in working across individual boundaries to maximize "efficient use of material, energy and facility resources at a broader systems level" serves as a useful perspective for positioning industrial symbiosis in the broader IE field.

Urban Metabolism

Wolman's (1965) popular thesis of UM as a mode of understanding the web of relationships between cities and their wider environment remains a powerful and important thematic framework for studying cities, whose rich, complex, interconnected spaces, defined by their many and varied flows may be seen as the "milieu defining the urban ecosystem"

(Rudolf 2008; Cerceau, Mat, and Junqua 2018) and wherein Wu (2014) identifies the adaptive processes required to promote human well-being and ecosystem services in response to urban land use change as one key aspect of the relationship between sustainable development and the ecologic health of surrounding regions. Singh and Kennedy (2018) also recognize the impact of UM processes on complex natural systems, and note metrics like biodiversity as indicators of ecosystem health that are complex, dynamic and perhaps an underdeveloped aspects of UM. The optimized reuse of urban soils illustrates an relationship between an urban waste product (or byproduct of development) and its potential to bolster the threatened ecosystems on the urban fringe.

Modeling resource flows and UM, and gathering, sharing, accessing, and integrating of data remains a challenge in efforts to accurately model UM at an urban scale (Niza, Rosado, and Ferrão 2009). Recent and emerging technological improvements are clearly tools for improving the resolution and fidelity of data and models -- or for calculating their uncertainties (Patrício et al. 2015) -- but cooperation between actors and across sectors and institutional divides is also necessary not only for an accurate understanding of UM, but a basic consensus on how (or why) to shape it: a fundamental concern of environmental planning in this context. The Stockholm Royal Seaport's use of a framework of "smart" UM approach aims to capture and utilize vast amounts of data at high resolution and in real-time, to improve the sustainability of urban development outcomes and incorporating a variety of stakeholder concerns and goals (Shahrokni et al. 2015).

Material Flow Analysis (MFA)

Brunner and Rechberger (2004) describe MFA's system elements as the "components of material flow systems" which include "flows, processes, stocks, and materials." Assessment or design of a systems-level approach to optimizing the reuse potential of urban soils for adaptation landform building depends on evaluating the quantity of material involved and its quality (Schiller, Gruhler, and Ortlepp 2017). Quantifying the total material volume is a data-dependent task complicated by numerous factors, and the quality of soils excavated in urban development processes across a region are likely variable in their geologic origin and composition, geotechnical fitness and potential contaminants. Though Sibley (2009) suggests that a comprehensive MFA should "take into account in-ground stocks" of extracted resources, the responsibility for doing so in the case of "hibernating" urban soil stocks is unclear, as is an understanding of the future market for these and other buried resources (Niza, Rosado, and Ferrão 2009). How in-ground urban soils should be assessed and evaluated in the context of current or future markets – as wastes or byproducts of construction, or as a foundational material resource for a future landform-based flood protection system – should employ MFA to reveal possible planning opportunities as a function of spatial relationships and their significance in various use scenarios.

Hurdles to Applying MFA for Adaptation Planning

While CE and UM themes generally align well with adaptation planning goals, successful application of MFA in the case of urban soils presents certain technical challenges. They include:

Unbounded, Complex System

Where a resource or its flows are not limited or contained within stark physical or political boundaries, its modelling becomes complicated. Cerceau (2018), citing numerous authors, asserts that "For most of the IE scientific community, geographic issues are reduced to the question of system boundaries." A major challenge for MFA at a regional or urban scale is the unclear boundaries of cities, where numerous physical, regulatory, and political borders – some of which change over time – are at play, and do not necessarily correspond to one another (Niza et al 2009; Rosado et al. 2014). Insights into "bounding" a system whose dynamics are defined by urban land use (and sea level) change, and the materials flowing in it may depend on novel ways of defining spatial components of systems as a function of their resource availability and needs.

The proper spatial scale of a system to optimize urban soils for adaptation planning is variable based on technological, political and geographic factors. Where regional modeling is possible, the task of policy implementation may fall to political "sub systems" composing the region. Sharifi and Murayama (2014) argue that city districts are the "suitable geopolitical entities" most fit to incorporate or introduce sustainable urban development practices. Improvements in a broader system for optimizing excavated soils use in adaptation landforms will almost certainly depend on the innovation of the "sub systems" (through local action and implementation), to achieve "system innovation" (Ness and Xing 2017) through regional adoption.

Where modelling across urban boundaries is possible, other problems may arise, including the potential to ignore certain UM processes like storage or local material distribution (Kennedy et al. 2007; Keirstead and Sivakumar 2012). Effectively capturing both the static components and active flows of the system is complex in the case of urban soils because of the variety of processes, regulations and actors involved. Rosado et al. (2014) cites the dynamic nature of resource flows often rendered as static for the purposes of information interpretation and which may exclude or obviate insights into a material's possible end-of-life. This may be especially important in thinking about the transport networks of urban soils and their relationship to possible sites of need. Urban soil management reuse options are limited by logistics, market forces, regulations and regional planning uncertainties, and scenario analyses demonstrate that accurate MFAs depend on numerous sociotechnical and underlying economic dynamics (Hu et al. 2010).

Inadequate Information Infrastructure

MFA are based on the interpretation of information to improve operations and applications. The UN's Millenium Development Goals report recognizes that data is crucial for decision making to achieve sustainable development goals. Indeed, to this end, the report recognizes the need for "(A) data revolution to improve the availability, quality, timeliness and disaggregation of data" (UN 2015; Malik et al. 2018). The accurate assessment of the potential for urban soils to aid adaptation planning is complicated by numerous factors. Rebitzer et al. (2004) describe some of many challenges in simply collecting data, and the complex interactions of people, media, technology and sociopolitical structures involved. And while some operations, regions or even nations may track their extracted and reused soils (Katsumi 2015), assessment of their comparative utility or usefulness in reuse roles is under-researched, a reality which may change in the era of rising seas and worsening storms.

Other challenges include the sheer availability of data; its quality and reliability; scale and resolution; and various degrees and sources of uncertainty. In instances where a system is well-defined, the quality and uncertainty of data may be mostly a function of limited knowledge (Laner et al. 2016). "Defects of information" arising from these knowledge limitations are recognized as a distinct type of uncertainty, not one arising from natural variability (Dubois and Prade 2010; Schwab and Rechberger 2018). In their study of the New York/New Jersey Harbor and its sediment loads, Boehme et al. (2009) describe the importance of evaluating data "richness" for surveying key contaminants in a complex, dynamic geographic setting. Laner (2016) lays out a method for data quality assessment and characterization of uncertainty for effective MFA. Rebitzer (2004) identifies a number of difficulties and hurdles in data processing necessary to assess a functional unit's life cycle.

Problems may arise from data confidentiality issues when few firms manage a given resource (Hammer et al. 2003). Where possible, a centralized databank tracking relevant resources is a desirable feature for "harmonizing" MFA concepts and methods (Patrício et al. 2015). In the United States the USGS might serve as a logical institution to track information on in-ground resource reserves that are "economical to recover", yet it does not directly measure reserves nor do governments directly report to them (Sibley 2009). Likewise, in the Environmental Protection Agency's Resource Conservation and Recovery Act, urban soils occupy an apparent "blind spot". It appears that without a broader awareness of the potential utility of these materials, the need to accurately survey them on a large scale is lacking. Malik et al. (2018) observe that the recent surge in computational capacity has theoretically increased the efficacy of tools and techniques for large-scale input-output modeling, but that integration with "small data" is nonetheless necessary at local and regional scales : a clear priority for cities managing local resources while facing regional impacts.

While small-scale data gathering may be logistically easier, Patrício et al. (2015) note the increasing difficulty in data availability and uncertainty as smaller spatial and systems scales are considered, though Pincetl et al. (2014) demonstrate a method for statistically inferring larger trends from small data sets. Keirstead and Sivakumar (2012) identify some of the advantages and efficiencies possible in using specialized land use and transportation techniques to glean data of high spatiotemporal resolution. Aspects of all of these challenges are evident in constructing a clear picture of the urban soils flows in the SF Bay, and these and other examples of applied IE methods should be considered in formulating how best to assess a region's excavated soil resources.

Translating IE Insights into Policy and Planning

Though sediment deficits are a recognized and increasingly problematic reality in developed global shorelines, efforts to understand excavated urban soil's significance as an adaptation resource remain underdeveloped. Binder (2009) posits that the ultimate function of MFA should be to influence policy or practices that increase sustainability and generally improve the relationship between natural and human-made environments, specifically through the wise use of materials evident in cities. For the purposes of translating IE insights into improvements in SLR adaptation planning using urban soils, developed shorelines might consider:

Novel System Definition and Demarcation

Borrowing notions from Inddigo (2012) and Cerceau et al. (2018), a SLR adaptation-oriented system may be spatially understood as a specialized "territorial resource basin" established to optimize and manage material flows over time and across political jurisdictions, and in which spatial constraints on the basin naturally impose restriction of the volumes of material and possible flows therein (Eckelman and Chertow 2009). A "basin" implies that certain resources flow in but not out– they remain and are used therein. Various institutions may cooperate to define a territorial basin that contains the resources required to achieve the particular goal of constructing SLR barriers. Factors including spatial proximities, logistical factors, planning phase and financial mechanisms including incentives or subsidies to capture, gather and redirect soils may shape the basin. In this way, applying IE might serve as a mode of enacting governance and adaptation actions based on the "territoriality" of SLR impacts, and a societal response: localized urban soils reuse for regional benefit (Beaurain and Brullot, 2011; Brullot et al. 2017).

Adaptation-Based Information Infrastructure

IE tools and techniques for understanding resource flows in human systems is advancing technically by harnessing computing power and "big" data, theoretically improving public access and planning insights (Baynes 2009; Fischer-Kowalski, 2011). Establishing adaptation planning as a regional priority with access to databases maintained by private firms (developers, transportation contractors) and integration with relevant public databases (waste management, flood control agencies, the dredging industry) is a necessary step toward framing the realistic "menu of options" based on the soil and sediment flows in a territorial basin. Updating and reconfiguring data and its collection methods to respond to changes in development, SLR projections, or institutional reconfiguration will be important for modeling achievable outcomes given uncertain future environmental conditions.

IE as Adaptation Planning Decision-Support Toolkit

IE can be viewed as a component of local planning strategy that fosters interactions among various actors, by providing a “shared understanding” of how an infrastructure transition might look, and its relationship to local resources involved in its inception (Beaurain and Brullot 2011; Buclet 2011; Hodson 2012; Cerceau 2018). Cross-disciplinary embrace of visions of novel, multi benefit, resource-wise, infrastructure and its spatial effects might redefine sociecological relationships thereby “resignifying” the urban environment (Broto, Allen, and Rapoport 2012; Ranhagen and Groth 2012) or revealing emergent power dynamics shaping the sociopolitical relationships of a new kinds of territories or “terrains” (Elden 2010): ones that will inevitably involve collaboration to the community level (Cheng et al. 2003). These novel territories, and their resource flows, infrastructures and sociopolitical relationships will require common tools and platforms for evaluating and enacting policy. In the same way that IE may schematize systems or the information infrastructure of SLR adaptation planning, so too might its role expand to underpin this “common ground” for decision-making.

Discussion

Relevant aspects of urban soil and sediment management, and tools for their assessment, were not examined here but bear mention to frame future discussions. For an IE-based approach to urban soils as an adaptation resource, Life Cycle Assessment (LCA) may reveal broader economic, energy, and environmental impacts with major policy and planning implications (Curran 1996; European Commission 2003; Ardente et al. 2007). In the SF Bay, the impact of passenger vehicles on the region’s waste, energy and environmental quality have been assessed and considered (Chester, Horvath, and Madanat 2010), and long-distance highway transport of heavy material (soils) obviously contributes to these impacts. The ability to render a “menu of options” by modeling various possible uses of a resource (or system) can significantly improve efficiencies and may reveal “win wins” for the SD goals of coastal cities (Wilson et al. 1998). In imagining the effect of redirecting soils from landfills, the material ecology of alternative daily cover materials must be considered.

Extensive research and IE tools have been applied to the dredge regimes and cycles of coastal cities. These should be examined for their systems components and cyclical nature, in addition to the beneficial re-use of dredged sediment. Resource extraction processes in general are receiving greater scrutiny in the climate change era (Hatfield-

Dodds et al. 2017; Krausmann et al. 2018), and though Calvo (2018) offers an example of mineral resource modelling can account for scarcity and energy profiles, these materials' utility to society is generally mediated through their commoditization, not as components of public-benefit infrastructure. Notably, commercial sand mining in SF Bay and other coastal zones has been contested as a resource flow "blurring the line" between an extraction process and depletion of a natural resource that may lie in the public trust, for its regional role in mitigating coastal erosion.

Conclusion

As some of the planet's most vibrant, populous places, sociopolitical resources for innovation are clearly evident in coastal cities (Major, Lehmann, and Fitton 2018). At the same time, inefficient, even counterproductive management of space and resources engendered by historic, bureaucratic and technocratic complexities present opportunities for policy improvement, which may come in part through de-emphasizing the focus on individual components of a given system (O'Brien et al. 2011; Admiraal and Cornaro 2016; Ness and Xing 2017). Coastal cities are intense process landscapes (Hägerstrand 1993; Anderberg 1998) whose sustainability and adaptation goals are constantly evolving, and where the sovereignty of a current generation or regimes' values and goals is fleeting (Norton, Costanza, and Bishop 1998).

Linking spatial patterns of development to UM, and operationalizing systems that present future generations with more options towards prosperity, not fewer, should inform near-term adaptation goals. Similarly, bolstering the resilience of coastal wetland ecosystems for the benefit of future generations is a pressing and important task (Crosby et al. 2016; Gopalakrishnan and Bakshi 2017; Liu et al. 2017; Leonardi et al. 2018). As traditional notions of cost and value are challenged by climate change, novel methods for "situating" the economy in the (changing) physical world to organize its complexities are sorely needed (Forrester 1969; Baynes 2009; Rochat et al. 2013). IE appears clearly disposed technically and in its core ethos to increasingly inform, improve, and influence climate adaptation planning.

Ch. 2 References:

Acselrad, H., 1999. Sustentabilidad y Ciudad. EURE 25, 36–46. http://dx.doi.org/10.4067/S0250-71611999007400003.

Admiraal, Han, and Antonia Cornaro. 2016. "Engaging Decision Makers for an Urban Underground Future." Tunnelling and Underground Space Technology 55 (May): 221–23. https://doi.org/10.1016/j.tust.2015.08.009.

Agudelo-Vera, Claudia Marcela, Adriaan Mels, Karel Keesman, and Huub Rijnaarts. 2012. "The Urban Harvest Approach as an Aid for Sustainable Urban Resource Planning: Urban Harvest Approach." Journal of Industrial Ecology 16 (6): 839–50. https://doi.org/10.1111/j.1530-9290.2012.00561.x.

Anderberg, Stefan. 1998. "Industrial Metabolism and the Linkages between Economics, Ethics and the Environment." Ecological Economics 24 (2–3): 311–20. https://doi.org/10.1016/S0921-8009(97)00151-1.

Ardente, Fulvio, Maurizio Cellura, Valerio Lo Brano, and Marina Mistretta. 2007. "Multidiscipline LCA Application to an Experience of Industrial Symbiosis in South of Italy." Integrated Environmental Assessment and Management preprint (2009): 1. https://doi.org/10.1897/IEAM_2008-065.1.

Barnard, Patrick L., David H. Schoellhamer, Bruce E. Jaffe, and Lester J. McKee. 2013. "Sediment Transport in the San Francisco Bay Coastal System: An Overview." Marine Geology 345 (November): 3–17. https://doi.org/10.1016/j.margeo.2013.04.005.

Bartel, Sebastian, and Gerold Janssen. 2016. "Underground Spatial Planning – Perspectives and Current Research in Germany." Tunnelling and Underground Space Technology 55 (May): 112–17. https://doi.org/10.1016/j.tust.2015.11.023.

Baynes, Timothy M. 2009. "Complexity in Urban Development and Management." Journal of Industrial Ecology 13 (2): 214–27. https://doi.org/10.1111/j.1530-9290.2009.00123.x.

Bianchi, T. S., and M. A. Allison. 2009. "Large-River Delta-Front Estuaries as Natural 'Recorders' of Global Environmental Change." Proceedings of the National Academy of Sciences 106 (20): 8085–92. https://doi.org/10.1073/pnas.0812878106.

Binder, Claudia R., Ester van der Voet, and Kirsten Sinclair Rosselot. 2009. "Implementing the Results of Material Flow Analysis." Journal of Industrial Ecology 13 (5): 643–49. https://doi.org/10.1111/j.1530-9290.2009.00182.x.

Boehme, Susan E., Marta A. Panero, Gabriela R. MuÃ±oz, Charles W. Powers, and Sandra N. Valle. 2009. "Collaborative Problem Solving Using an Industrial Ecology Approach." Journal of Industrial Ecology 13 (5): 811–29. https://doi.org/10.1111/j.1530-9290.2009.00166_2.x.

Broere, Wout. 2016. "Urban Underground Space: Solving the Problems of Today's Cities." Tunnelling and Underground Space Technology 55 (May): 245–48. https://doi.org/10.1016/j.tust.2015.11.012.

Broto, Vanesa Castán, Adriana Allen, and Elizabeth Rapoport. 2012. "Interdisciplinary Perspectives on Urban Metabolism: Interdisciplinary Perspectives on Urban Metabolism." Journal of Industrial Ecology 16 (6): 851–61. https://doi.org/10.1111/j.1530-9290.2012.00556.x.

Brullot, Sabrina, Guillaume Junqua, and Bertrand Zuindeau. 2017. "Écologie industrielle et territoriale à l'heure de la transition écologique et sociale de l'économie." Revue d'Économie Régionale & Urbaine Décmbr (5): 771. https://doi.org/10.3917/reru.175.0771.

Brunner, Paul H., and Helmut Rechberger. 2004. Practical Handbook of Material Flow Analysis. Advanced Methods in Resource and Waste Management 1. Boca Raton, Fla.: Lewis.

Calvo, Guiomar, Alicia Valero, and Antonio Valero. 2018. "Thermodynamic Approach to Evaluate the Criticality of Raw Materials and Its Application through a Material Flow Analysis in Europe: Evaluation of Critical Raw Materials Using Rarity." Journal of Industrial Ecology 22 (4): 839–52. https://doi.org/10.1111/jiec.12624.

Cerceau, Juliette, Nicolas Mat, and Guillaume Junqua. 2018. "Territorial Embeddedness of Natural Resource Management: A Perspective through the Implementation of Industrial Ecology." Geoforum 89 (February): 29–42. https://doi.org/10.1016/j.geoforum.2018.01.001.

Céspedes Restrepo, Juan D., and Tito Morales-Pinzón. 2018. "Urban Metabolism and Sustainability: Precedents, Genesis and Research Perspectives." Resources, Conservation and Recycling 131 (April): 216–24. https://doi.org/10.1016/j.resconrec.2017.12.023.

CHENG, ANTONY S., LINDA E. KRUGER, and STEVEN E. DANIELS. 2003. "'Place' as an Integrating Concept in Natural Resource Politics: Propositions for a Social Science Research Agenda." Society & Natural Resources 16 (2): 87–104. https://doi.org/10.1080/08941920309199.

Chertow, Marian R. 2008. "'Uncovering' Industrial Symbiosis." Journal of Industrial Ecology 11 (1): 11–30. https://doi.org/10.1162/jiec.2007.1110.

Chertow, Marian R. n.d. "Quantifying Economic and Environmental Benefits of Co-Located Firms," 7.

Chester, Mikhail V., Arpad Horvath, and Samer Madanat. 2010. "Comparison of Life-Cycle Energy and Emissions Footprints of Passenger Transportation in Metropolitan Regions." Atmospheric Environment 44 (8): 1071–79. https://doi.org/10.1016/j.atmosenv.2009.12.012.

Crosby, Sarah C., Dov F. Sax, Megan E. Palmer, Harriet S. Booth, Linda A. Deegan, Mark D. Bertness, and Heather M. Leslie. 2016. "Salt Marsh Persistence Is Threatened by Predicted Sea-Level Rise." Estuarine, Coastal and Shelf Science 181 (November): 93–99. https://doi.org/10.1016/j.ecss.2016.08.018.

Daniella Hirschfeld, and Kristina Hill. 2017. "Choosing a Future Shoreline for the San Francisco Bay: Strategic Coastal Adaptation Insights from Cost Estimation." Journal of Marine Science and Engineering 5 (3): 42. https://doi.org/10.3390/jmse5030042.

Ding, Yan. n.d. "Sea-Level Rise and Hazardous Storms: Impact Assessment on Coasts and Estuaries," 45.

Douglas, Ian, and Nigel Lawson. 2000. "The Human Dimensions of Geomorphological Work in Britain." Journal of Industrial Ecology 4 (2): 9–33. https://doi.org/10.1162/108819800569771.

Eckelman, Matthew J., and Marian R. Chertow. 2009. "Using Material Flow Analysis to Illuminate Long-Term Waste Management Solutions in Oahu, Hawaii." Journal of Industrial Ecology 13 (5): 758–74. https://doi.org/10.1111/j.1530-9290.2009.00159.x.

Elden, Stuart. 2010. "Land, Terrain, Territory." Progress in Human Geography 34 (6): 799–817. https://doi.org/10.1177/0309132510362603.

Fischer-Kowalski, M., F. Krausmann, S. Giljum, S. Lutter, A. Mayer, S. Bringezu, Y. Moriguchi, H. Schütz, H. Schandl, and H. Weisz. 2011. "Methodology and Indicators of Economy-Wide Material Flow Accounting: State of the Art and Reliability Across Sources." Journal of Industrial Ecology 15 (6): 855–76. https://doi.org/10.1111/j.1530-9290.2011.00366.x.

Florsheim, Joan L., Anne Chin, Karen Gaffney, and Dennis Slota. 2013. "Thresholds of Stability in Incised 'Anthropocene' Landscapes." Anthropocene 2 (October): 27–41. https://doi.org/10.1016/j.ancene.2013.10.006.

Foster-Martinez, M.R., J.R. Lacy, M.C. Ferner, and E.A. Variano. 2018. "Wave Attenuation across a Tidal Marsh in San Francisco Bay." Coastal Engineering 136 (June): 26–40. https://doi.org/10.1016/j.coastaleng.2018.02.001.

Ghisellini, Patrizia, Catia Cialani, and Sergio Ulgiati. 2016. "A Review on Circular Economy: The Expected Transition to a Balanced Interplay of Environmental and Economic Systems." Journal of Cleaner Production 114 (February): 11–32. https://doi.org/10.1016/j.jclepro.2015.09.007.

Gopalakrishnan, Varsha, and Bhavik R. Bakshi. 2017. "Including Nature in Engineering Decisions for Sustainability." In Encyclopedia of Sustainable Technologies, 107–16. Elsevier. https://doi.org/10.1016/B978-0-12-409548-9.10039-9.

Gorgolewski, Mark. 2018. Resource Salvation: The Architecture of Reuse. http://www.myilibrary.com?id=1044761.

Hatfield-Dodds, Steve, Heinz Schandl, David Newth, Michael Obersteiner, Yiyong Cai, Tim Baynes, James West, and Petr Havlik. 2017. "Assessing Global Resource Use and Greenhouse Emissions to 2050, with Ambitious Resource Efficiency and Climate Mitigation Policies." Journal of Cleaner Production 144 (February): 403–14. https://doi.org/10.1016/j.jclepro.2016.12.170.

Heberger, Matthew, Heather Cooley, Eli Moore, and Pablo Herrera. n.d. "THE IMPACTS OF SEA LEVEL RISE ON THE SAN FRANCISCO BAY," 32.

Hinterberger, Friedrich, Stefan Giljum, and Mark Hammer. n.d. "Material Flow Accounting and Analysis (MFA)," 21.

Hodson, Mike, Simon Marvin, Blake Robinson, and Mark Swilling. 2012. "Reshaping Urban Infrastructure: Material Flow Analysis and Transitions Analysis in an Urban Context." Journal of Industrial Ecology 16 (6): 789–800. https://doi.org/10.1111/j.1530-9290.2012.00559.x.

Holling, C.S., and Gary K. Meffe. 1996. "Command and Control and the Pathology of Natural Resource Management." Conservation Biology 10 (2): 328–37. https://doi.org/10.1046/j.1523-1739.1996.10020328.x.

Hoover, Daniel J., Kingsley O. Odigie, Peter W. Swarzenski, and Patrick Barnard. 2017. "Sea-Level Rise and Coastal Groundwater Inundation and Shoaling at Select Sites in California, USA." Journal of Hydrology: Regional Studies 11 (June): 234–49. https://doi.org/10.1016/j.ejrh.2015.12.055.

Hu, Mingming, Ester Van Der Voet, and Gjalt Huppes. 2010. "Dynamic Material Flow Analysis for Strategic Construction and Demolition Waste Management in Beijing." Journal of Industrial Ecology 14 (3): 440–56. https://doi.org/10.1111/j.1530-9290.2010.00245.x.

Hunt, D.V.L., L.O. Makana, I. Jefferson, and C.D.F. Rogers. 2016. "Liveable Cities and Urban Underground Space." Tunnelling and Underground Space Technology 55 (May): 8–20. https://doi.org/10.1016/j.tust.2015.11.015.

"IMPACTS OF PREDICTED SEA-LEVEL RISE AND EXTREME STORM EVENTS ON THE TRANSPORTATION INFRASTRUCTURE IN THE SAN FRANCISCO BAY REGION." n.d., 80.

"Intergovernmental Panel on Climate Change - 2014 - Climate Change 2014 Mitigation of Climate Change .Pdf." n.d.

James, L. Allan. 2013. "Legacy Sediment: Definitions and Processes of Episodically Produced Anthropogenic Sediment." Anthropocene 2 (October): 16–26. https://doi.org/10.1016/j.ancene.2013.04.001.

Jansson, Birger. n.d. "City Planning and the Urban Underground," 17.

Kaliampakos, D., A. Benardos, A. Mavrikos, and G. Panagiotopoulos. 2016. "The Underground Atlas Project." Tunnelling and Underground Space Technology 55 (May): 229–35. https://doi.org/10.1016/j.tust.2015.03.009.

Katsumi, Takeshi. 2015. "Soil Excavation and Reclamation in Civil Engineering: Environmental Aspects." Soil Science and Plant Nutrition 61 (sup1): 22–29. https://doi.org/10.1080/00380768.2015.1020506.

Keirstead, James, and Aruna Sivakumar. 2012. "Using Activity-Based Modeling to Simulate Urban Resource Demands at High Spatial and Temporal Resolutions: Activity-Based Modeling of Urban Resource Demands." Journal of Industrial Ecology 16 (6): 889–900. https://doi.org/10.1111/j.1530-9290.2012.00486.x.

Kennedy, Chris, Iain D. Stewart, Nadine Ibrahim, Angelo Facchini, and Renata Mele. 2014. "Developing a Multi-Layered Indicator Set for Urban Metabolism Studies in Megacities." Ecological Indicators 47 (December): 7–15. https://doi.org/10.1016/j.ecolind.2014.07.039.

Kennedy, Christopher, John Cuddihy, and Joshua Engel-Yan. 2007. "The Changing Metabolism of Cities." Journal of Industrial Ecology 11 (2): 43–59. https://doi.org/10.1162/jie.2007.1107.

Kenway, Steven, Alan Gregory, and Joseph McMahon. 2011. "Urban Water Mass Balance Analysis." Journal of Industrial Ecology 15 (5): 693–706. https://doi.org/10.1111/j.1530-9290.2011.00357.x.

Krausmann, Fridolin, Christian Lauk, Willi Haas, and Dominik Wiedenhofer. 2018. "From Resource Extraction to Outflows of Wastes and Emissions: The Socioeconomic Metabolism of the Global Economy, 1900–2015." Global Environmental Change 52 (September): 131–40. https://doi.org/10.1016/j.gloenvcha.2018.07.003.

Labbé, Monique. 2016. "Architecture of Underground Spaces: From Isolated Innovations to Connected Urbanism." Tunnelling and Underground Space Technology 55 (May): 153–75. https://doi.org/10.1016/j.tust.2016.01.004.

Laner, David, Julia Feketitsch, Helmut Rechberger, and Johann Fellner. 2016. "A Novel Approach to Characterize Data Uncertainty in Material Flow Analysis and Its Application to Plastics Flows in Austria: Characterization of Uncertainty of MFA Input Data." Journal of Industrial Ecology 20 (5): 1050–63. https://doi.org/10.1111/jiec.12326.

Leonardi, Nicoletta, Iacopo Carnacina, Carmine Donatelli, Neil Kamal Ganju, Andrew James Plater, Mark Schuerch, and Stijn Temmerman. 2018. "Dynamic Interactions between Coastal Storms and Salt Marshes: A Review." Geomorphology 301 (January): 92–107. https://doi.org/10.1016/j.geomorph.2017.11.001.

Li, XiaoZhao, Congcong Li, Aurèle Parriaux, Wenbo Wu, HuanQing Li, Liping Sun, and Chao Liu. 2016. "Multiple Resources and Their Sustainable Development in Urban Underground Space." Tunnelling and Underground Space Technology 55 (May): 59–66. https://doi.org/10.1016/j.tust.2016.02.003.

Liu, Wen, Andrew C. Chang, Weiping Chen, Weiqi Zhou, and Qi Feng. 2017. "A Framework for the Urban Eco-Metabolism Model - Linking Metabolic Processes to Spatial Patterns." Journal of Cleaner Production 165 (November): 168–76. https://doi.org/10.1016/j.jclepro.2017.07.055.

Mackenzie, Jake, Scott Haggerty, Alicia C Aguirre, Tom Azumbrado, Jeannie Bruins, Damon Connolly, Dave Cortese, Carol Dutra-Vernaci, and Dorene M Giacopini. n.d. "Metropolitan Transportation Commission," 96.

Major, David C., Martin Lehmann, and James Fitton. 2018. "Linking the Management of Climate Change Adaptation in Small Coastal Towns and Cities to the Sustainable Development Goals." Ocean & Coastal Management 163 (September): 205–8. https://doi.org/10.1016/j.ocecoaman.2018.06.010.

Makana, L.O., I. Jefferson, D.V.L. Hunt, and C.D.F. Rogers. 2016. "Assessment of the Future Resilience of Sustainable Urban Sub-Surface Environments." Tunnelling and Underground Space Technology 55 (May): 21–31. https://doi.org/10.1016/j.tust.2015.11.016.

McKee, L.J., M. Lewicki, D.H. Schoellhamer, and N.K. Ganju. 2013. "Comparison of Sediment Supply to San Francisco Bay from Watersheds Draining the Bay Area and the Central Valley of California." Marine Geology 345 (November): 47–62. https://doi.org/10.1016/j.margeo.2013.03.003.

Metson, Geneviève, Rimjhim Aggarwal, and Daniel L. Childers. 2012. "Efficiency Through Proximity: Changes in Phosphorus Cycling at the Urban-Agricultural Interface of a Rapidly Urbanizing Desert Region." Journal of Industrial Ecology 16 (6): 914–27. https://doi.org/10.1111/j.1530-9290.2012.00554.x.

Moffatt, Ian. 2000. "Ecological Footprints and Sustainable Development." Ecological Economics, 4.

Moftakhari, Hamed R., Amir AghaKouchak, Brett F. Sanders, and Richard A. Matthew. 2017. "Cumulative Hazard: The Case of Nuisance Flooding: CUMULATIVE HAZARD: NUISANCE FLOODING." Earth's Future 5 (2): 214–23. https://doi.org/10.1002/2016EF000494.

Neil Adger, W., Nigel W. Arnell, and Emma L. Tompkins. 2005. "Successful Adaptation to Climate Change across Scales." Global Environmental Change 15 (2): 77–86. https://doi.org/10.1016/j.gloenvcha.2004.12.005.

Nelson, Priscilla P. 2016. "A Framework for the Future of Urban Underground Engineering." Tunnelling and Underground Space Technology 55 (May): 32–39. https://doi.org/10.1016/j.tust.2015.10.023.

Ness, David A., and Ke Xing. 2017. "Toward a Resource-Efficient Built Environment: A Literature Review and Conceptual Model: Towards a Resource Efficient Built Environment." Journal of Industrial Ecology 21 (3): 572–92. https://doi.org/10.1111/jiec.12586.

Neuman, Michael. 2009. "Spatial Planning Leadership by Infrastructure: An American View." International Planning Studies 14 (2): 201–17. https://doi.org/10.1080/13563470903021241.

Niza, Samuel, Leonardo Rosado, and Paulo Ferrão. 2009. "Urban Metabolism: Methodological Advances in Urban Material Flow Accounting Based on the Lisbon Case Study." Journal of Industrial Ecology 13 (3): 384–405. https://doi.org/10.1111/j.1530-9290.2009.00130.x.

Norton, Bryan, Robert Costanza, and Richard C Bishop. 1998. "The Evolution of Preferences Why 'Sovereign' Preferences May Not Lead to Sustainable Policies and What to Do about It." Ecological Economics, 19.

Patrício, João, Yuliya Kalmykova, Leonardo Rosado, and Vera Lisovskaja. 2015. "Uncertainty in Material Flow Analysis Indicators at Different Spatial Levels: Uncertainty in Material Flow Analysis Indicators at Different Spatial Levels." Journal of Industrial Ecology 19 (5): 837–52. https://doi.org/10.1111/jiec.12336.

Pereira, H. M., P. W. Leadley, V. Proenca, R. Alkemade, J. P. W. Scharlemann, J. F. Fernandez-Manjarres, M. B. Araujo, et al. 2010. "Scenarios for Global Biodiversity in the 21st Century." Science 330 (6010): 1496–1501. https://doi.org/10.1126/science.1196624.

Ramaswamy, Ramesh. n.d. "Industrial Ecology – A New Platform for Planning Sustainable Societies," 11.

Reckien, Diana, Monica Salvia, Oliver Heidrich, Jon Marco Church, Filomena Pietrapertosa, Sonia De Gregorio-Hurtado, Valentina D'Alonzo, et al. 2018. "How Are Cities Planning to Respond to Climate Change? Assessment of Local Climate Plans from 885 Cities in the EU-28." Journal of Cleaner Production 191 (August): 207–19. https://doi.org/10.1016/j.jclepro.2018.03.220.

Reed, Denise, Bregje van Wesenbeeck, Peter M.J. Herman, and Ehab Meselhe. 2018. "Tidal Flat-Wetland Systems as Flood Defenses: Understanding Biogeomorphic Controls." Estuarine, Coastal and Shelf Science, August. https://doi.org/10.1016/j.ecss.2018.08.017.

Rees, William E. 1999. "FORUM: Consuming the Earth: The Biophysics of Sustainability." Ecological Economics 29 (1): 23–27. https://doi.org/10.1016/S0921-8009(98)00074-3.

Rochat, David, Claudia R. Binder, Jaime Diaz, and Olivier Jolliet. 2013. "Combining Material Flow Analysis, Life Cycle Assessment, and Multiattribute Utility Theory: Assessment of End-of-Life Scenarios for Polyethylene Terephthalate in Tunja, Colombia." Journal of Industrial Ecology, May, n/a-n/a. https://doi.org/10.1111/jiec.12025.

Rosado, Leonardo, Samuel Niza, and Paulo Ferrão. 2014. "A Material Flow Accounting Case Study of the Lisbon Metropolitan Area Using the Urban Metabolism Analyst Model: The Urban Metabolism Analyst Model." Journal of Industrial Ecology 18 (1): 84–101. https://doi.org/10.1111/jiec.12083.

Sánchez-Arcilla, Agustín, Manuel García-León, Vicente Gracia, Robert Devoy, Adrian Stanica, and Jeremy Gault. 2016. "Managing Coastal Environments under Climate Change: Pathways to Adaptation." Science of The Total Environment 572 (December): 1336–52. https://doi.org/10.1016/j.scitotenv.2016.01.124.

Schiller, Georg, Karin Gruhler, and Regine Ortlepp. 2017. "Continuous Material Flow Analysis Approach for Bulk Nonmetallic Mineral Building Materials Applied to the German Building Sector: Continuous MFA for Nonmetallic Mineral Materials." Journal of Industrial Ecology 21 (3): 673–88. https://doi.org/10.1111/jiec.12595.

Schoellhamer, David H., Scott A. Wright, and Judith Z. Drexler. 2013. "Adjustment of the San Francisco Estuary and Watershed to Decreasing Sediment Supply in the 20th Century." Marine Geology 345 (November): 63–71. https://doi.org/10.1016/j.margeo.2013.04.007.

Schoellhamer, David, Mathieu Marineau, Lester McKee, Sarah Pearce, Pete Kauhanen, Micha Salomon, Scott Dusterhoff, Letitia Grenier, and Philip Trowbridge. n.d. "Sediment Supply to San Francisco Bay, Water Years 1995 through 2016: Data, Trends, and Monitoring Recommendations to Support Decisions about Water Quality, Tidal Wetlands, and Resilience to Sea Level Rise," 91.

Schwab, Oliver, and Helmut Rechberger. 2018. "Information Content, Complexity, and Uncertainty in Material Flow Analysis: Uncertainty and Complexity in MFA." Journal of Industrial Ecology 22 (2): 263–74. https://doi.org/10.1111/jiec.12572.

Shahrokni, Hossein, Louise Årman, David Lazarevic, Anders Nilsson, and Nils Brandt. 2015. "Implementing Smart Urban Metabolism in the Stockholm Royal Seaport: Smart City SRS: Implementing SUM in the Smart City SRS." Journal of Industrial Ecology 19 (5): 917–29. https://doi.org/10.1111/jiec.12308.

Sharifi, Ayyoob, and Akito Murayama. 2014. "Neighborhood Sustainability Assessment in Action: Cross-Evaluation of Three Assessment Systems and Their Cases from the US, the UK, and Japan." Building and Environment 72 (February): 243–58. https://doi.org/10.1016/j.buildenv.2013.11.006.

Shirzaei, Manoochehr, and Roland Bürgmann. 2018. "Global Climate Change and Local Land Subsidence Exacerbate Inundation Risk to the San Francisco Bay Area." Science Advances 4 (3): eaap9234. https://doi.org/10.1126/sciadv.aap9234.

Sibley, Scott F. 2009. "Using U.S. Geological Survey Data in Material Flow Analysis." Journal of Industrial Ecology 13 (5): 670–73. https://doi.org/10.1111/j.1530-9290.2009.00160.x.

Singh, Shweta, and Christopher Kennedy. 2018. "The Nexus of Carbon, Nitrogen, and Biodiversity Impacts from Urban Metabolism: Nexus of Carbon, Nitrogen, and Biodiversity Impacts from Urban Metabolism." Journal of Industrial Ecology 22 (4): 853–67. https://doi.org/10.1111/jiec.12611.

Spencer, Thomas, Mark Schuerch, Robert J. Nicholls, Jochen Hinkel, Daniel Lincke, A.T. Vafeidis, Ruth Reef, Loraine McFadden, and Sally Brown. 2016. "Global Coastal Wetland Change under Sea-Level Rise and Related Stresses: The DIVA Wetland Change Model." Global and Planetary Change 139 (April): 15–30. https://doi.org/10.1016/j.gloplacha.2015.12.018.

Vähäaho, Ilkka. 2016. "An Introduction to the Development for Urban Underground Space in Helsinki." Tunnelling and Underground Space Technology 55 (May): 324–28. https://doi.org/10.1016/j.tust.2015.10.001.

Valiela, Ivan, Javier Lloret, Tynan Bowyer, Simon Miner, David Remsen, Elizabeth Elmstrom, Charlotte Cogswell, and E. Robert Thieler. 2018. "Transient Coastal Landscapes: Rising Sea

Level Threatens Salt Marshes." Science of The Total Environment 640–641 (November): 1148–56. https://doi.org/10.1016/j.scitotenv.2018.05.235.

Voss, Christine M., Robert R. Christian, and James T. Morris. 2013. "Marsh Macrophyte Responses to Inundation Anticipate Impacts of Sea-Level Rise and Indicate Ongoing Drowning of North Carolina Marshes." Marine Biology 160 (1): 181–94. https://doi.org/10.1007/s00227-012-2076-5.

Wallace, M.I., and K.C. Ng. 2016. "Development and Application of Underground Space Use in Hong Kong." Tunnelling and Underground Space Technology 55 (May): 257–79. https://doi.org/10.1016/j.tust.2015.11.024.

Wolman, A. 1965. The Metabolism of Cities. https://books.google.com/books?id=XNuqNwAACAAJ.

Yang, Shanlin, and Nanping Feng. 2008. "A Case Study of Industrial Symbiosis: Nanning Sugar Co., Ltd. in China." Resources, Conservation and Recycling 52 (5): 813–20. https://doi.org/10.1016/j.resconrec.2007.11.008.

Zhao, Jian, and Olivia Künzli. 2016. "An Introduction to Connectivity Concept and an Example of Physical Connectivity Evaluation for Underground Space." Tunnelling and Underground Space Technology 55 (May): 205–13. https://doi.org/10.1016/j.tust.2015.12.017.

Zhou, Yingxin, and Jian Zhao. 2016. "Assessment and Planning of Underground Space Use in Singapore." Tunnelling and Underground Space Technology 55 (May): 249–56. https://doi.org/10.1016/j.tust.2015.12.018.

.

Landfill or Landform? The Management of Excavated Sediment in a Developed Shoreline: Case Study Insights for Climate Adaptation Planners

Abstract: Dominant management regimens of excavated soil and sediment are unsustainable and potentially incompatible with coastal adaptation demands. Excavated sediment is generally treated as a waste product; thus constantly received in significant volumes by municipal waste landfills. In the context of emerging and expected climate change impacts, this is an especially wasteful and regressive material management model. Sea level rise is forcing developed coastal regions to reconsider landforms that may be constructed and augmented as shoreline adaptation strategies: by raising barriers, restoring subsided wetlands and nourishing existing ones including tidal marsh plains. Actions intended to construct and maintain these structures and ecological complexes require the sourcing, transport and application of enormous amounts of geomaterials – namely various sediment resources. Our analysis demonstrates that long-term SLR adaptation goals in a study region require strategically planning the future management of excavated sediment; and we demonstrate that various applications and timeframes for successful adaptation plans will require significant shifts in the current management practices of these resources. By considering the likely amounts of reusable excavated sediment currently being received at landfills and modeling alternative uses as adaptation applications, our case study makes clear that the industrial and material ecologies of these resources must change to meet adaptation goals – as will the environmental governance involved in the urban and landscape planning related to these resources. While the study area entails specific geophysical and developmental conditions, the implications of the broad trends and underlying rationales are of global importance and applicability for adaptation planners to consider.

1. Introduction

Global sea surface elevations will rise significantly in the 21st century, an issue of increasing concern and importance for coastal developments (Hallegatte et al., 2013). Approximately half of the global population and the majority of the world's most populous cities are sited in and around the coastal zone, with important implications for the exposure and risk of large populations and the substantial infrastructure assets concentrated in coastal conurbations (Barragán & de Andrés, 2015; McGranahan et al., 2007; Seto et al., 2011). Rising seas and their associated biogeophysical processes and impacts will lead to dramatic changes in the built and natural environments of coastlines everywhere on earth. Adaptation to these changes is an increasingly pressing imperative in the planning of both urban and ecological landscapes (Brown et al., 2013; Tessler et al., 2018; Wilby, 2007). In the United States alone, costs associated with sea level rise (SLR) adaptation will constitute the majority of national adaptation costs by 2100 (Neumann et al., 2014).

Developed shorelines, where hydrologic, geomorphic and ecological processes interact with structures and processes of the built environment, exemplify coupled human and natural systems that entail complex environmental governance approaches. They often encompass landscapes with rich and contested cultural histories and display significant evolution and flux as a function of development pressures and patterns (Bianchi & Allison, 2009; Liu et al., 2007). Moreover, many are directly vulnerable not only to SLR and other climate change-induced phenomena (including urban heat islands, wildfire and drought), but environmental risks like earthquakes and tsunamis, in addition to other mass movement events such as mudslides and erosion which may be exacerbated by climate impacts (Lawrence et al., 2018, 2020). The concentration of infrastructure, capital, resources, and the populations they serve and sustain, complicates and intensifies coastal climate hazard mitigation and risk management practices applied to developed shorelines (Macintosh, 2013).

Rising seas pose flood risks not only to shoreline settlements, but also threaten coastal landscapes, ecosystems, biodiversity and habitat that have frequently been degraded, depleted and fragmented by prior industrial processes and urban development, often in ways that now predispose shoreline communities to significant flood exposure and impacts (Foster-Martinez et al., 2018; Valiela et al., 2018). Historically, typical means of flood protection included the construction of static barriers including levees and sea walls (Hill, 2015). More recently, major tensions have emerged in considering options for protecting a given site, community, or shoreline reach using engineered defenses because constructed barriers may prevent flooding in one location while worsening it in others by "telegraphing" floodwaters, thus complicating matters regarding jurisdictional mandates, collective action in planning processes, and how environmental justice is assessed and addressed as a function of interplays between these considerations and proposals (Hummel et al., 2021; Lubell et al., 2021).

Tidal wetlands act to reduce wave energy by creating frictional drag, which saps destructive energy from surging waterbodies, in turn reducing wave heights (eg. mitigating the overtopping of landward barriers) and/or by reducing erosion and preventing coastal land loss, delivering two crucial ecosystem services highly valued by coastal settlements (Barbier, 2013; Möller,et al., 2014). In light of widespread research indicating the relative cost-effectiveness and multiple-benefit qualities of nature-based shoreline "green infrastructure" systems in the form of preserved, restored or constructed wetlands, much attention has focused on the feasibility of maintaining or fundamentally creating these ecological complexes and landscapes in an era of rising seas (Bayraktarov, et al., 2016; Taillardat et al., 2020; Zhao et al., 2016). However, this focus has also served to further illuminate several troubling realities: tidal wetlands are increasingly vulnerable to destabilization and drowning via SLR; their restoration is often in tension with urban developments; and these developments themselves are generally, and increasingly, made more vulnerable to costly impacts of rising seas in the absence of wetlands to buffer them (Kirwan & Megonigal, 2013; Narayan et al., 2017; Nicholls, 2004).

Attempts to address these tensions often encounter an underlying and problematic planning paradigm rooted in the tradeoffs between allowing wetlands to "migrate" upland as rising sea surface elevations force their spatial realignments towards inland areas (creating land use conflicts with development) and/or the proclivity to armor urban shorelines with barriers which may further degrade wetlands that *cannot* migrate. This attenuation of the spatial "band" in which wetlands can endure is a situation colloquially known as coastal or wetland "squeeze" (Spencer et al., 2016; Torio et al., 2013). Management approaches that allow tidal wetlands to accrete (build up) matter and establish and maintain critical elevations relative to rising seas is a cornerstone of the restoration ecology and engineering involved in sustaining these landscapes, approaches that hinge on the provision and availability of *sediment, loose earthen material* (Fagherazzi et al., 2012; Stagg & Mendelssoh. 2011). Indeed, sediment represents a material backbone of countless coastal restoration and, increasingly, adaptation projects (Aarninkhof et al., 2010; Brand et al., 2012).

Because of the diversity of shoreline landscapes (and their associated topographic forms, and ecologic, urban and biogeophysical processes) that will inevitably experience increased SLR pressures, coastal landscape and urban planners across the globe, are modeling, planning, and testing a variety of strategies are being modeled, planned and tested by (Diaz, 2016. Kleint et al., 2022; Spencer et al., 2016). And while the physical realignment of urban shorelines based on managed retreat scenarios may become broadly necessitated by SLR, the use of landforms as adaptation applications represent a common and widely evident suite of strategies for addressing SLR in the near-term (van Slobbe et al., 2013). Construction of large-scale landform-based networks functioning as multi-benefit shoreline infrastructure systems require considerable material demands for sediment that can be gathered, transported and placed by ecological and/or human processes.

Troublingly, the supply of naturally occurring sediment is dwindling or insufficient to meet SLR demands in many urban shoreline regions, prompting consideration of other sources and supplies, including the strategic management of excavated (upland) sediment (Milligan & Holmes, 2017). Yet to date, the emerging role of this material in SLR adaptation has been considerably overlooked and/or underestimated in the literature. This represents a significant blind spot and knowledge gap for planners that imposes limitations both in forecasting future conditions based on sediment budgets, and the adaptation objectives and options linked to them. We explore the ways in which sediment materials that are ubiquitous byproducts of urban development might be reconsidered as physical resources that will surely grow in global importance as SLR adaptation projects unfold in the 21st century and beyond. Our study examines how supplies and demand for this increasingly important resource presents challenges, and shapes the adaptation planning paradigm, in a case study of interest.

The paper's five sections present our findings. The introduction section summarizes and situates the research problem and prominent trends and issues in the urban and landscape adaptation planning of developed shorelines, including the importance of sediment dynamics for constructed coastal landforms in these regions; and we describe a case study region and site. Our methods section explores a research approach applied to data related to our socio-ecological phenomena of interest, in addition to a description of an alternative resource management regime. The next section interprets and considers our analytical results, and frame them in the context of a forecasted decade in the case study and its resource dynamics. A section discusses the implications of these results and future research areas of importance to adaptation planning illuminated by the study. A brief conclusion summarizes key takeaways and recommendations from the work.

1.1 Historical Patterns and Processes of Shoreline Development and their Effects

Patterns of urban development sited in proximity to floodplains have consistently depended upon the use or creation of higher ground (areas situated above flood stages or supratidal elevations) as basic flood prevention strategies. At the same time, proximity to waterways and waterbodies is universally understood as a condition conferring multiple beneficial socioeconomic qualities, including the facility of accessing navigable channels (in the siting of industrial ports, for example) in addition to the desirability of proximity to water for aesthetic and cultural reasons (as with commercial urban waterfront districts). This tension is present in many of the world's largest and most dense cities, where shoreline development and the concentration of assets is a prominent, perhaps even consistent, urban situation, often characterizing extensive metropolitan regions surrounding core cities (Biging et al., 2012; Chhetri, et al., 2015; Hallegatte, et al., 2011). Accordingly, in the world's largest and most rapidly-developing coastal cities, considerable socio-environmental impacts are emerging as function of climate change (Glasow, et al., 2013).

The planning, development and protection processes of myriad coastal areas around the world required the intentional, physical movement of enormous volumes of sediment resources (Charlier et al., 2005). Historically, raising the elevations of local shorelines has been accomplished by the accumulation and deposition of various materials to "reclaim" land from water by the placement of soil, sand, rock, ballast, various forms of refuse, and any number of other material masses at the shoreline (Ferguson, 2018; Han et al., 2013; Martín-Antón et al., 2016). Seaward land reclamation was often accomplished by using fill material to bury and obliterate wetlands whose ecologic and environmental functions were generally and profoundly under-valued or altogether unrecognized (Vileisis, 1999). Soil resources generated by grading, digging and land-clearing projects in upland areas were very often directed to shorelines and used to "cap" solid waste and debris for the establishment of novel real estate near the shore, property of increasing, multifunctional utility and value for urban development schemes (Seasholes, 2003).

Taken together, these development patterns and practices in urban shoreline regions have resulted in several prominent challenges for SLR adaptation planners to consider. These include: land subsidence due to settlement of fill material and subsurface compaction (Shirzaei & Bürgmann, 2018; Sun, 1999); the rise and emergence of groundwater due to SLR, and its potential to mobilize subsurface contaminants (Hoover et al., 2017; Plane et al., 2019); and the deprivation of sediment throughput from upper watersheds into receiving waterbodies including estuaries, as a function of historic and ongoing upstream flood control, development and water management schemes (Barnard et al., 2013).

1.2 Future Shoreline Adaptation Strategies Using Constructed Landforms

Examples of linking anthropogenically managed sediment to large-scale coastal restoration, maintenance, and flood control projects and systems are evident in the beneficial reuse of dredged benthic sediment and thin-layer placement on wetlands to help them accrete matter and maintain critical elevations (Ford et al., 1999; Mchergui et al., 2014); beach nourishment projects to mitigate coastal erosion (Staudt et al., 2021); the construction of barriers including dikes and levees to prevent inundation of landward areas (Temmerman & Kirwan, 2015); and use of breakwaters to protect vital infrastructure from waves and surges (Becker et al., 2016). In regional networks of constructed and augmented landform-based strategies to build "elevation capital", enormous physical material supplies are required due to the spatiotemporal scales involved (Cahoon et al., 2019).

Examination of *anthropogenic sediment budgets,* those based primarily on human management processes and practices, is a critical aspect to strategically plan how (and where and when) these extensive construction endeavors may be undertaken even though work to assess sediment budgets that function based on natural processes are also useful to consider (Cappucci et al., 2020; Shellenbarger et al., 2013). The considerable scale of the resources involved in these projects is a function not only of their spatial extents, but the long-term, often cyclical nature of adaptively managed sediment placement. SLR means that the magnitude of material, frequency of application and physical size of landforms are expected to increase dramatically this century, driving commensurate cost increases (Hirschfeld & Hill, 2017; Perry et al., 2020). A future characterized by higher sea surface elevations, densifying coastal development, and intensifying storm regimes will inevitably entail a reworking of the physical form and elevational profile of shorelines where protection of development is intended (Du et al., 2020; Hill, 2015). While certain climatic, physiographic and socio-environmental characteristics of developed shorelines will vary widely by region, coastal planner will need to consider several broad categories of adaptation strategies related to landforms. These categories may be useful to consider as typological classifications that apply to certain spatial, temporal and planning conditions.

A number of prominent strategies for shoreline restoration and adaptation may be helpful to consider to illustrate the interplay of sediment resources and landforms that are constructed or augmented. In the case study region (See section 1.4), recent work to understand the impacts of SLR on the watershed and its shoreline processes and form have considered the filling of subsided ponds, called polders, and other diked wetlands that are starved of sediment delivered by natural processes, as well as the nourishment of existing wetlands (Dusterhoff et al., 2021; Williams & Orr, 2002). Ongoing work in the case study area to raise existing flood-protection levees by raising their elevations is also evident, as are planning processes considering the construction of novel landforms including ecotone and horizontal levees (discussed in section 1.3).

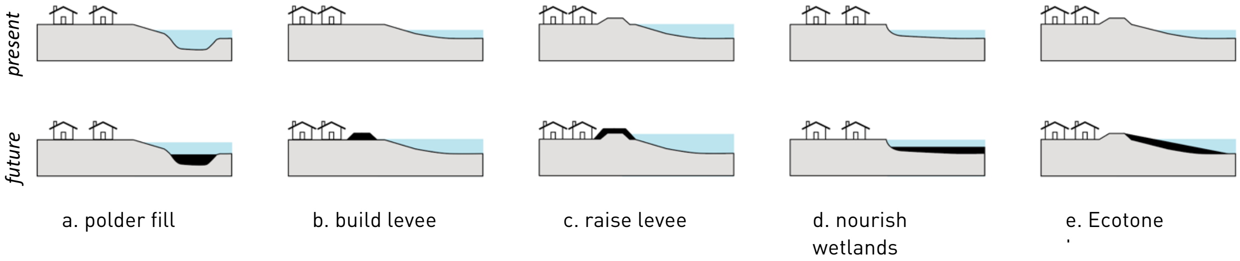


Figure 1: Several common and contemplated landform-based SLR adaptation strategies for coastal and shoreline development. The top row shows typical conditions of the present day; the bottom row illustrates where material applied as fill (in black) might be placed to accomplish various goals including flood protection and habitat restoration. Because of the extensive spatial nature of many SLR strategies, these approaches entail significant volumes of material deployed as landscape-based infrastructural networks. And because many approaches may entail repeated treatments (raising, nourishing) on a long temporal scale, the need to adequately source and procure the physical material for landform constructions along these lines is an increasingly important task for planners. Illustration by Nate Kauffman.

While landscape designers and planners are accustomed to engaging with landscapes as topologic structures representable as surficial fields (through site plans and analytical "layers") and profiles (cross-sections) like those above, the central spatial dimension of interest at the intersection of land and water is, of course, three-dimensional. This intersection is defined by *volumes* that water bodies represent and which meet and resolve at shorelines with certain topographic forms, themselves volumes of land. And insofar as environmental planners and designers embrace their role in proposing *novel* landforms as adaptation strategies, understanding the systematic and logistical realities related to sourcing and manipulating volumes of land reveals numerous avenues for planners to explore. These include: practicalities related to sourcing, procurement, stockpiling and delivery; resource management practices related to long-term forecasting and conservation; considerations tied to the market and political economies involved; and the public policies that shape all of these aspects. Our study explores how some of these considerations are at play in the strategic landscape and urban planning involved in SLR adaptation and how the industrial and material ecologies of excavated sediment present environmental planners with an emergent realm of critical consideration and innovation.

1.3 Sediment Dynamics in Developed Coastal Watersheds

An extensive literature has studied natural processes related to sediment supply within and through watersheds. Fluvial and marine transport of sediment has been extensively examined for its multiplicity of roles in sustaining ecological biodiversity and habitat composition in various waterways (Milhous, 1998; Pitlick & Wilcock, 2001; Soulsby, 2001). In addition, investigation of wetland restoration and survival link adequate sediment resources to receiving bodies and landscapes in the lower watershed (Allison et al., 2012; Haltiner et al., 1996). The biogeochemistry and contaminant profiles of sediment used in restoration projects has also been noted as an important issue in urbanized shorelines (Berkowitz et al., 2016; Morris et al., 2014). The effects of flood control processes on sediment transport, and vice versa, have also been studied as problematic issues in the context of conveyance and containment structures associated with urban development including dams, lined canals, engineered channels and subsurface stormwater structures (Griggs & Paris 1982; Meade & Moody, 2010; Taylor et al., 2009; Smith, 2001).

The prevalence of socioenvironmental issues involving sediment lead to interventions devised to physically gather, remove, stockpile, remediate, sort, guide, distribute, apply and otherwise manage various types of sediment resources to balance development and infrastructural operations with environmental concerns (Kondolf et al., 2014). As the tidal prism rises to higher elevations via SLR, coastal resource managers and planners are increasingly recognizing that more active, ambitious, creative, and long-term coordinated efforts may be required to ensure that critical elevations of important landscapes and ecosystems are established and persist in managed shorelines, and that excavated sediment will have a role to play in this endeavor (Dusterhoff et al., 2021). Indeed, excavated sediment resources represent a useful and versatile building material for constructing ecologically-based landform structures with the potential to aid the adaptation and sustainability efforts of urban regions.

1.3.1 Excavated Sediment Dynamics in Developed Shorelines

Supply: Characteristics of Excavated Sediment

Soil and sediment resources extracted through excavation are ubiquitous and increasingly common byproducts of the growth and *urban metabolism* of cities. They constitute the vast majority, by mass, of construction and demolition "wastes" generated by urban development processes and projects (Hu et al., 2010; Kennedy et al., 2011). In shoreline developments, these resources are often the in situ products of depositional geomorphological processes that have accumulated and weathered alluvial and colluvial material that can be relatively easily withdrawn from the ground, in contrast to consolidated bedrock, for example. The sector of environmental contracting and its global fleet of earthmoving machinery has largely developed as a direct result of the ubiquitous and constant need for settlements and societies to physically shape the landscape (Haycraft, 2000).

Surficial soils and sediment that is excavated in urban areas may contain legacy contaminants as a function of prior industrial uses of the landscape--an important material feature to consider where environmental applications may be the ultimate goal of reuse (Katsumi, 2015; McClintock, 2015). This is especially true for reuse projects at the shoreline because various contaminant may be mobilized by the effects of exposure to waterbodies, and stringent regulations are therefore common in these zones and projects (Bolan et al., 2014). Nonetheless, excavated sediment is a useful building material, and one whose geotechnical and geochemical qualities predisposes it for certain applications that other sediment managed and encountered in urban watersheds may not (Craul, 1992; Hale et al., 2021). In fact, precisely because this material is generally classified as a waste product, certain permitting and record-keeping processes are employed in places where environmental concerns drive regulations. Excavated sediment can be seen as a resource whose dynamics are shaped by the interplay of stocks and flows useful to consider (Myers et al., 2019).

Stocks - Sediment and its Excavation as a Function of Urban & Sustainable Development

As cities develop and densify, the removal of earthen material from in-ground stocks is a ubiquitous and increasing phenomena. This removal serves the construction of myriad subsurface constructions collectively known as Urban Underground Space (UUS) (Admiraal, 2006; Admiraal & Cornaro, 2018). Sediment is excavated from the ground to accommodate the placement of foundations, parking garages, stormwater and wastewater systems, various utility infrastructure utilities including multimodal transportation tunnels and entire multifunctional municipal districts in some cases (Vähäaho, 2016). Compact, dense urban design and construction practices inevitably increase the proportion of UUS, which aligns with various sustainability goals but entails complex planning issues, including the need to manage massive amounts of excavated sediment, typically the greatest proportion, by far, of construction and demolition waste-generating projects (Bobylev, 2009; Llatas, 2011; Magnusson et al., 2019; Villoria Sáez & Osmani, 2019).

Flows - Resource Ownership, Stewardship and Markets

Subsurface sediment is generally considered a substance that is owned by the purchaser of property in the same sense as the surficial area of the site itself (Sprankling, 2008). Upon being withdrawn from the in-ground stocks via excavation, sediment in urban environments is almost invariably managed by environmental contractors who take stewardship of the payload to transport it out of dense and developed districts due to a lack of nearby sites for reuse or stockpiling. This sediment stewardship model creates various economic opportunities for private-sector environmental contractors, who seek to pay less to dispose of sediment than they were paid to haul it, effectively their profit margin. Or, potentially, to be paid twice once to remove it as "cut" (material withdrawn) from a site, and again to provide it as "fill" (material deposited) needed at another site (Cox & Ireland, 2006). This, in turn, creates a situation in which the fleets of trucks used to transport sediment have obvious incentives to dispose of their payload as quickly and inexpensively as possible while being limited to doing so only at sites that able to receive it, most often at solid waste landfills outside of cities and far from the source of excavation (McDonald & Smithers 1998; Hao at al., 2007).

Flux – Interplay of Stocks and Flows

Our data demonstrate that while overall trends in the amounts of sediment documented by grading permits may imply net production of cut or fill, (cut representing an influx into the overall material flow of the study region; fill representing net imports to construction sites) two aspects of their interplays are important to consider. First construction sites that are proximate to each other may trade excavated sediment between them. Material is excavated, documented in the site's cut grading permit) and then directly redeposited at another site, documented as fill in that site's permits. In this way, these flows between sites do not contribute to the accumulated end-of-life phase (or sink) of excavated sediment, discussed below. Secondly, this means that balanced cut and fill or net-negative cut does not imply a lack of excavation but, rather, that whatever the magnitude of that material extraction, it can "cancel out" when balanced by commensurate demand for fill in other construction processes unrelated to municipal landfill facilities. In this sense, when similar rates of supply and demand for cut/fill on projects exist within a given study area (i.e. when the states of flux are comparable) flows may be difficult to plot as individual vectors, their dynamics creating a kind of internal homeostatic balance.

Sinks - The Sustainability and Adaptation Problem for Planners: Landfill or Landform?

While construction sites in need of fill do represent locations of final destination for excavated sediment, solid waste landfills have traditionally been highly receptive of soils and sediment resources, which are distributed as a layer of material called "daily cover" to mitigate odors, windblown trash, and scavenging (Christensen et al., 1989). These facilities, many privately owned, charge a "tipping fee" for their receipt of sediment, Aspects of landfill economics may engender resistance to resource recovery and recycling programs that might divert uncontaminated soils from being permanently interred in landfills, what some scholars have termed the "ultimate sink" (Ready & Ready, 1995; Tarr, 1996). And while dramatic improvements in recycling and diversion of various consumer goods, products, and wastes have occured in recent decades, various characteristics of sediment resources (including their aforementioned utility in landfill operations) dramatically shape and constrain their flows through the urban metabolism of developed regions (Peng, et al., 1997; Magnusson et al., 2015; Rosado et al., 2014).

Taken together, these material, urban, and economic dynamics sketch the contours of a chaotic marketplace whose varied, complex, and inconsistent policy features define the current standard of excavated sediment management: one in which characteristics of the resource's industrial ecology heavily incline towards the constant and ongoing landfilling of excavated sediment in massive quantities. Environmental concerns triggered by rising seas, and associated implications for sustainable development and adaptation efforts, are presenting imperatives and opportunities for innovative resource management approaches, illustrated by increasing demand for coastal protection landforms that will form a central strategy of SLR adaptation work around the globe in the decades to come.

As such, more coherent and consistent policies regarding if and how sediment resources can, should or must be reused for various socioenvironmental benefits–ones that have not been traditionally foregrounded as societal imperatives–may illuminate areas of potential innovation and improvement for various efforts tied to sediment resources.

Emergent Demand of Adaptation Landforms: Ecotone & Horizontal Levees

Our study assesses the potential of excavated sediment to be used as a building material for the construction of "ecotone" levees: landforms that employ a gradually sloping seaward face that acts as a flood mitigating complex. The underlying principle of ecotone levees is the mimicry of natural wetlands, whose extensive lateral dimension saps wave and surge energy through attrition (Costanza et al., 2008). In engineered applications, these landforms can also restore wetland habitat, recycle and scrub treated effluent as an irrigation supply, and create a subtle ramp up which wetlands may migrate in futures characterized by higher waters (Cecchetti et al., 2020). In that sense, this constructed landform represents a bridge between the upland and wetland biomes, an ecological principle from which its name (ecotone) is derived. While still the subject of experimentation, Ecotones have been incorporated into flood and climate adaptation planning schemes (Holmes et al., 2022). The feasibility or rollout of these projects will depend on the sourcing of sediment material to physically construct them.

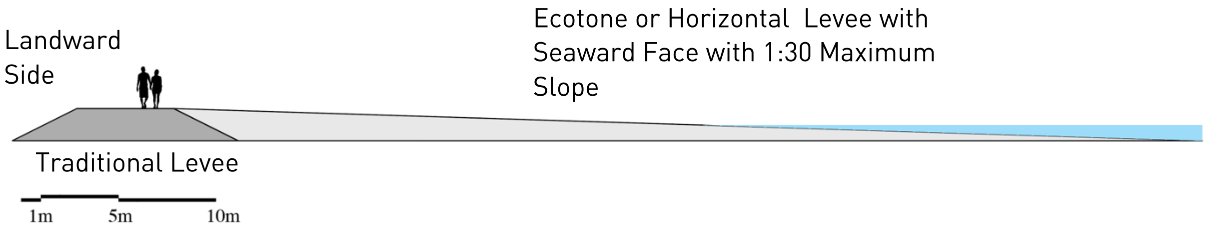


Figure 2. The notable feature of the ecotone levee (light grey wedge, above) is its extensive seaward face, which is prominently horizontally extended (relative to the steep face of traditional levees, shown in dark grey) and which creates its flood-protection benefits, but also delineates a considerable three-dimensional volume when extruded in space along a shoreline reach: illustrating the material demands involved in construction of Ecotone Levees at scale. It should be noted that ecotone levees may be constructed with more subtle slopes – and, therefore, possess larger cross-sectional areas – that would translate into larger volume demands. Illustration by Nate Kauffman.

A particular type of ecotone levee being pioneered in the case study region (described in the following section) is called a *horizontal levee*. Its basic landform is identical to the ecotone (illustrated in Figure 2, above) but which incorporates a wastewater-treatment seepage slope that involves irrigating vegetation on its seaward (horizontal) face (Cecchetti, 2022). This vegetation sequesters compounds and metabolizes nutrients that are problematic when discharged directly into the receiving waters of the adjacent estuary, as typically occurs currently. Wastewater treatment plants are municipal infrastructural assets that face major impacts as a function of SLR, as they are often being sited at extremely low elevations to take advantage of gravity-aided collection of storm- and wastewaters (Heberger et al., 2011; Hummel, 2018). As such, major interest in relieving or avoiding costs involved in replacing or retrofitting the traditional infrastructure used for treatment, pumping and discharging has come into focus as a regional priority, one potentially possible using the green infrastructure of horizontal levees.

In the context of planning adaptation measures that employ large-scale restoration and adaptation strategies that utilize landforms like ecotone and horizontal levees, shortfalls in coastal sediment supply are problematic. The sheer size of these levees as constructed earthworks is considerable and, as they work as an adaptation network in the landscape along extensive reaches of shoreline, the understanding of sourcing, allocating, transporting and applying sediment material is crucial. How are planners working at the intersection of flood protection and restoration ecology approaching the systematic study of anthropogenic sediment dynamics that are linked to landform construction? What tools and insights might aid their work and potentially open new avenues for innovation and improvements in efficiency and sustainability?

Our study examines a region grappling with these questions and issues, and the implications of a natural sediment supply shortfall, even as it plans extensive restoration work. We examine the system of excavated sediment flows within a case study on a systematic level and demonstrate a set of methods for estimating the quantities of sediment in various states within that system. Underpinning the work are central questions about the nature of excavated sediment in a developed shoreline region that may increasingly rely on it as a resource. What is the magnitude of the material involved, and how does it move through, or operate within, urban and industrial systems? By examining these questions and employing methods for surveying, modeling, and forecasting material *flows*, we illustrate the potential of excavated sediment that typically has been landfilled, for reuse in coastal adaptation to sea level rise.

1.4 Case Study Geographic Context

SF Bay Metropolitan Region

Assessing the potential of excavated sediment as a resource which might be optimized for landform construction as a component of a regional SLR adaptation strategy is grounded in estimating the *yield* of this material over time: an amount generated as a function of development projects that entail excavation processes. To explore this potential, we present a case study framing the management of this material, and investigate whether an alternative reuse strategy could be feasible or meaningful in accomplishing local benefits and regional goals. Accordingly, this study involves examining trends in known data related to recent excavated sediment yields and a plausible, causal relationship to known patterns and processes of urban development, namely population.

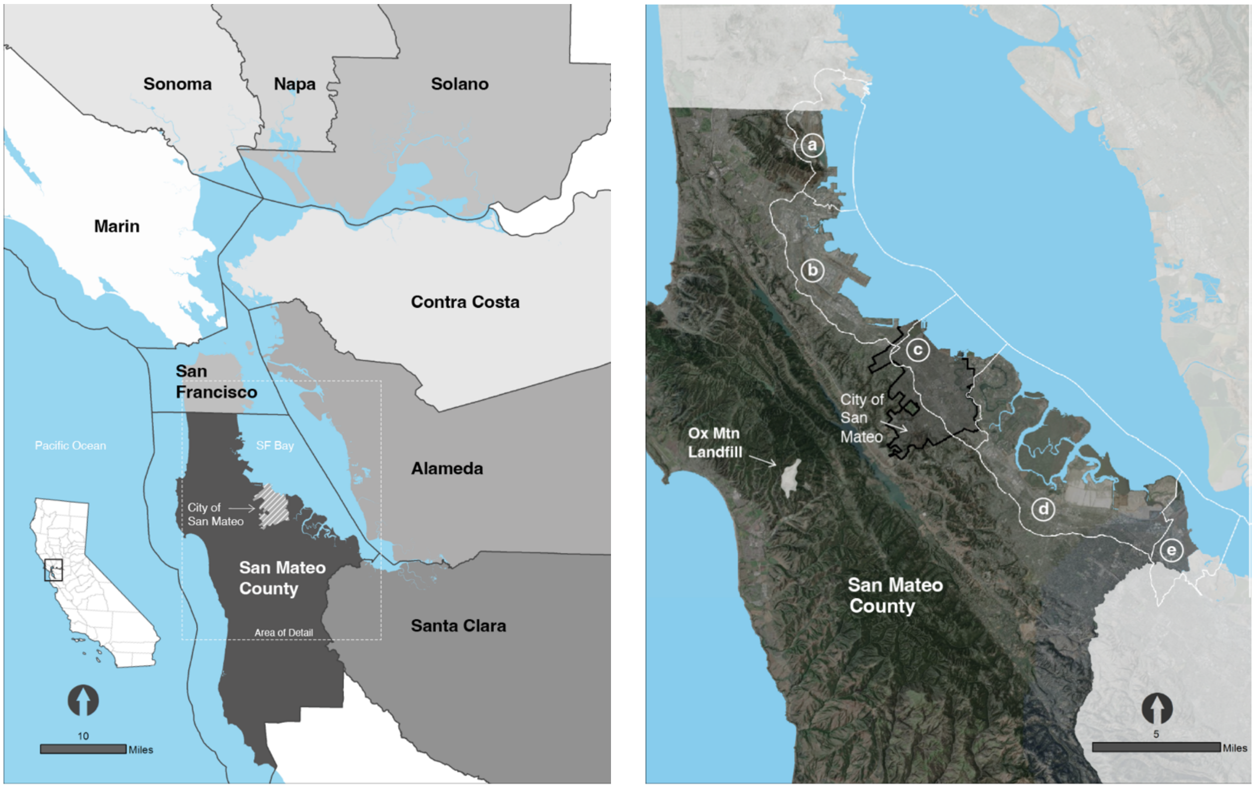
The San Francisco Bay Area of Northern California encompasses the largest deltaic estuary complex in the Americas, whose extensive watershed encompasses an enormous diversity of land uses, settlements, and physiographic regions straddling the state. The broader metropolitan agglomeration of the most-developed heart of the watershed is centered around San Francisco's namesake Bay (Bay Area), formally composed of 9 counties. Development of the Bay Area in the 19th and 20th century substantially depleted many of the region's ecological complexes, none more important to expected SLR impacts than the region's tidal wetlands and their associated ecological complexes including seaward mudflats and shoreward uplands, a landscape band regionally known as the Baylands (Goals Report, 2015). As a function of upstream development projects and dwindling natural sediment supplies flowing to the Bay, large-scale wetland restoration based on connecting Baylands to sediment supplies has come into focus as a regional adaptation priority (Brew &, Williams, 2010; Schoellhamer et al., 2013).

In recent years, the Bay Area has experienced impacts from wildfires spurred by a megadrought, upland flooding associated with atmospheric river events, exacerbation of urban heat island effects, biodiversity declines and increases in coastal erosion, tidal flooding and the rise of groundwater associated with SLR (Moser & Eckstrom, 2012; Swain, 2021; Cloern et al., 2011). These dynamics clearly illustrate the Bay Area finds itself grappling with numerous climate change-related challenges expected to intensify in the 21st century, even as its population and urban environment is expected to grow considerably. The siting of urban development in low-lying areas formerly occupied by the Baylands is a common condition of the Bay Area's urbanized tracts and their various infrastructural assets–and one with troubling implications in the climate change era.

Recent work to evaluate the capacity of the broader SF Bay watershed to link adaptation and restoration work has seized on the concept of Operational Landscape Units (OLUs) as an approach to identify landscape types of paired hydrologic and ecologic features as spatially-distinct units in places where development patterns have significantly altered biogeophysical processes (Verhoeven et al., 2008). OLUs may be understood as spatial components helpful in analyzing and planning resource management and development of SF Bay's shoreline and have been broadly adopted as a useful framework by the restoration and adaptation circles for this purpose (SFEI & SPUR, 2019).

A shoreline inventory of OLUs identified within San Mateo County forms the basis of our assessment of one county's ability to construct horizontal levees (SFEI, 2021). The assessment of the use five OLUs entirely or mostly within the county bounds the determine the potential of various possibilities linked to landform and landscape processes near the shoreline, and their interactions with the built environment. Of particular interest for our study are the linear miles of horizontal levee building opportunities. These reaches of the shoreline are essentially those in which ecotones might be constructed within approximately 2 miles of wastewater treatment plants, thus making possible the incorporation of the horizontal levee's seepage slope features and function.

Significantly, OLUs are not delineated based on municipal boundaries except when they relate to geographic features that the OLU employs in its classification logic. How might the SLR challenges faced by the region and the opportunities for horizontal levee construction play out on a local level with respect to sediment resources? We examine this question on the scale of a county grappling with significant SLR exposure, and examine aspects of its growth and development that may offer insights into its adaptative capacity (Adger et al., 2009).



Figures 2 & 3: A context map (above, left) showing the counties of the SF Bay Area and including their offshore extents. The Area of Detail is expanded (above, right) to show the County of San Mateo in greater detail, and the positions of its Ox Mtn Landfill facility and the City of San Mateo (outlined in black). The white lines correspond to Operational Landscape Units of San Mateo County, and the horizontal levee building opportunities identified within them: a) Yosemite-Visitacion, 0 miles; b) Colma-San Bruno; 2.2 miles; c) San Mateo, 0.7 miles; d) Belmont-Redwood, 3.3 miles; and e) San Francisquito, 4.2 miles. There are 10.4 miles of horizontal levee opportunity identified within OLUs that exist entirely or partially within San Mateo County's bounds. Note that OLUs incorporate offshore tracts as part of their geographic logic, as they are applied for study of Bayshore areas and processes. Images by Nate Kauffman.

1.4.1 Case Study Area:

San Mateo County

San Mateo County (SMC) straddles a large peninsula that includes both coastal exposure to the Pacific Ocean and a considerable stretch of shoreline frontage on the Bay itself, where the majority of SMC's population in centered. SMC is home to twenty incorporated cities and includes prominent regional assets including the multibillion-dollar San Francisco International Airport (SFO) and two highway bridge landings. SMC's population as of the 2020 Census was listed as 764,442; making it the 15th most populous of California's fifty-eight counties. It is part of the region's globally renown technology hub, a considerable concentration of jobs and private-sector investment. Partially a function of necessity given its extensive shoreline, SMC is recognized as a regional leader in environmental restoration and adaptation efforts aimed at addressing expected climate change impacts. SMC is notable also for its recent efforts to restore degraded and subsided wetlands by raising their elevational profiles to inter-tidal levels through the active placement of enormous quantities of sediment. The 1,400-acre restoration of Inner Bair Island, a project initiated by the US Department of Fish and Game and San Francisco Bay's Wildlife Society, involved the importation and placement of hundreds of thousands of cubic yards of fill including large volumes of excavated upland sediment to raise marsh elevations into the intertidal zone (Duke et al., 2004). Plans for protecting SFO and ongoing levee improvement and construction projects also involve the placement of fill sediments to build flood-mitigating landforms.

2. Methods

Our central hypothesis is that population growth and increasing density drive development processes that yield sediment resources as a byproduct. To test this hypothesis, we first investigate the relationship between an example city's population and the number of building permits issued in development projects. Then we examine the share of these permits that are related to known excavation processes and permitting. Next, to assess the potential for excavated sediment flows to be used for the development of landform-based adaptation strategies including the construction of horizontal levees in the San Mateo County region, we present a characterization and analysis of sediment material flows of interest within our case study.

We use permits and records of the stocks and flows of excavated sediment, and describe how the recorded sources, sinks and flows of sediment and the hidden, unrecorded flows are represented in the overall material ecology. We employ methods of analyzing material flows to test these known flows against our central hypothesis that increasing population drives sediment excavation in an urban region. The City of San Mateo is used as a proxy for other smaller cities and towns in the case study area. Using this proxy and extrapolating based on population change leads to an estimate of sediment yields associated with the County as a whole. Subtracting known flows from the volume of the primary sink allows us to estimate hidden flows in the County. Finally, we consider the potential of only the modeled flows, which we have estimated based on the recorded flows, to aid in the construction of horizontal levees. Hidden flows are not used for this comparison of urban sediment supply and the coastal adaptation demand.

2.1 System Description

Material Flow Schema: System Description and Components of Importance

Developing an understanding of the socioenvironmental system governing the uses of excavated sediment involves several methodological approaches. Material Flow Analyses (MFA) are a suite of mixed-method approaches for illustrating how movements and interactions of matter, energy and wastes are related, often for considering development patterns and processes for provisioning goods and services to society. As is typical of many MFA, our study employed literature review of similar studies and material management processes; including the reuse of excavated soil and its relationship to development projects (For example, see Hale et al., 2021; Hu et al., 2010; Magnusson et al., 2015) in combination with a process of logically testing and iteratively developing the components (stocks and flows) of the study and how they are articulated inside the system (Baccini & Brunner, 2012). Consultation with municipal offices, whose furnished data was used directly and indirectly in our quantitative analysis phase, and interviews with industry experts was also conducted to ensure the theoretical logic, and descriptive plausibility of the constructed MFA schema, and certain estimations that informed modeling (section 2.3).

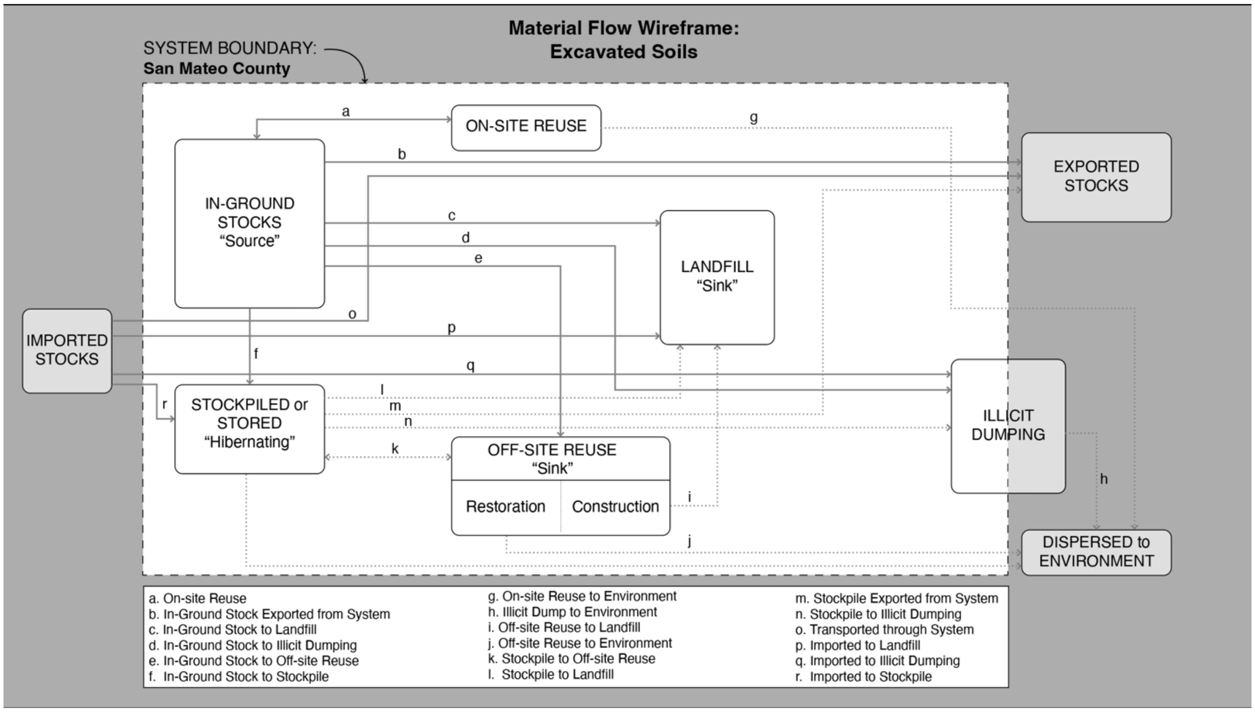


Figure 4: Material Flow Analysis Schema: The figure above represents an analytical tool common in studying the industrial ecology of various resources, substances and products: a conceptual Material Flow Analysis schematic 'wireframe'. The dashed line around the inner white rectangle represents an idealized system boundary corresponding

to San Mateo County; and the boxes within it therefor correspond to features contained therein. Dotted lines show flows that are secondary, and imply that material being moved has already been moved at least once before. The key at the bottom of the image describes flows connecting stocks. Image by Nate Kauffman.

System Features & Analysis: Stocks, Flows, Sources, Sinks and their Characterizations

MFAs necessarily simplify complex sets of elements and dynamics to convey approaches to illustrate central features of a system and the relationships between them, as is typical of conceptual frameworks applied in many fields (Paré et al., 2015). Especially when attempting to describe complex socioecological systems, MFA confront limitations prominently including the notion of system boundaries, which are simultaneously needed to scope a process of interest, and are generally also imperfect (Bartrola et al., 2001). Insofar as we rely upon data that is gathered by municipal and regional actors (as opposed to directly observing and measuring excavation in a study area), we have idealized San Mateo County as our system of interest, essentially as a spatially-discrete administrative unit charged with certain data collection practices within its bounds, while recognizing that boundaries are complex, porous and "fuzzy" with respect to the actual movement of material. These are illustrated as various *flows* that excavated sediment may take in and through the study area. Flows originate at a *source* from which they emanate, movements that can be idealized and pictured as general system behaviors or specific events or known trends during a given window of time.

Material at rest at some given location for some period exist as *stocks*. Stocks may represent a resource pool that is untapped (previously undisturbed in-ground sediment); sediment that has been relocated as a component of another project or process (as in the case of the Bair Island project, fill material used at a construction site, or as daily cover in landfills); and/or material that has been temporarily stockpiled for future reuse or movement. Because of their systematic nature, MFA often employ secondary analytical techniques to examine and emphasize particular material stocks, flows and/or system components in greater detail. Our study aims to do so by considering the interplay between two system components–certain *flows* and an end-of life stock called a *sink*–related to known data tracking processes that describe some aspects of the metabolism of excavated soils and the flows of excavated sediment and stocks of landfilled sediment occurring and existing within San Mateo County over a decade.

Hidden Flows

Stocks and flows of non-valuable, waste material on a large scale and in complex socioecological systems are often difficult to observe directly and, thus, rigorously track. Some authors have described flows as "hidden" in cases where they do not effectively "enter" the economy as commodified products or are understood as having little economic value, notably including excavated soils (Aoki-Suzuki et al., 2012; Matthews, 2000). While disagreement might exist over whether or not excavated sediment effectively do, in fact, enter the economy, the underlying notion is that hidden flows exist, especially regarding certain classes of materials. The conceptual and practical implication of hidden flows is that studies attempting to grapple with these materials will likely encounter incomplete and otherwise problematic records and data-tracking procedures for analysis. In that respect, hidden flows might be characterized as *unknown* from an analytical standpoint, but only insofar as they may not be directly measured. That is, the existence and systematic behavior or articulation of hidden flows might be known while their magnitude is not. We use the term hidden for this reason: our MFA recognizes them as being at play, while our methods attempt to quantify their gross magnitude, in part by tallying those that are not hidden.

Assessing these known and unknown sources and sinks–and the known, estimated, and inferred flows that connect them systematically–is useful for developing insights about the status of materials; specifically where they are positioned or concentrated in a system, or how various activities in the urban and industrial processes at play relate to materials of interest (Rosado et al., 2014). In our case study, examination of available data is necessary to develop an estimate of material quantities that could influence future policies and regulations that would support excavated sediment reuse in constructed adaptation landforms. This would require the re-routing of existing flows to novel sinks in a future shoreline with ecotone levees that reduce the impacts of sea level rise.

2.2 Data Collection & Analysis

Overview, Timeframe, Uncertainty

Our study gathered data related to the 10-year period between 2010 and 2019 to capture recent trends, while avoiding significantly poorer-quality datasets prior to this period. It omits the unique events of the 2008-09 recession and COVID-19 outbreak. Quantifying the amount of sediment excavated in our case study area within this time period is complicated by several issues. Fist, excavation is not directly observed and recorded by any office. Rather, norms and regulations based on self-reporting expectations and official receipt of documentation and permits defines the culture of practice associated with excavated sediment management. This documentation, in the form of permits and records, is not centrally documented and must be gathered from a variety of county, municipal and private offices. Then the data can be examined and compared to other data, such as population, to assemble an indirect impression of the material flows of interest. Second, not all excavation projects require permitting, as is the case with projects occurring in the public right of way and/or those performed by municipal service providers (for infrastructure, utilities, transport, etc.). In fact, in general, the excavation of earthen material is recorded if and when it exceeds some given amount on a given project. A minimum threshold is used to trigger certain permitting requirements. In San Mateo County, this amount is often designated as 50 cubic yards of "soil disturbance." Excavation projects below this threshold or those that do not comply with reporting procedures (see flow vectors *d, n,* and *q* in Figure 5) effectively escape cataloging altogether and therefor represent a hidden flow of unknown magnitude within the system, producing an underestimate when assessments are based on documented records.

A third set of complications arises as a function of variations in tracking, permitting and reporting procedures, including the heterogeneity of data types; the related variations in standards (procedures for data generation, collection, and archiving followed or enforced by local government entities), adherence (the degree to which said standards or requirements are observed by private sector actors), and the management and accessibility of data (if and how records are constructed, curated and shared). Incomplete, heterogenous, varied, fragmented and inaccessible information is a constant and common challenge for studying material flows in complex socioenvironmental contexts (Schwab et al., 2017), particularly when the flow represents a material considered a waste rather than a resource.

Accordingly, our study represents a coarse-resolution estimate of the material flows of interest, serving as both an initial evaluation of material yields and dynamics and as a starting point for future research. Since the ultimate aim of this study is to advance knowledge for planners and resource managers about how existing material flows and the regimes that track data related to these processes may change to advance adaptation outcomes, we apply the methods developed in this section to a forecasting approach that attempts to recognize uncertainty and sensitivity related to the supply of sediment. To examine these sensitivities, we close with a study of how the amount of sediment that would be of sufficient quality within these urban flows may vary, using estimates from previous studies. We also consider the sensitivity of the demand for sediment, using the potential height of ecotone levees to represent a range of different goals for adaptation. These considerations are presented in the results and discussion sections.

2.2.1 Acquisition, Processing & Composition of Data

Acquisition: Sources and Collection of Datasets

Available data were gathered from permitting processes and records tracked and collected by public offices. In all cases, the data used in our study was obtained through research to determine which offices held what data records (sourcing) establishing lines of communication with the offices to describe and parameterize our experimental design and data request (collection). This data was then screened to standardize and streamline datasets by eliminating duplicates and any other evident recording errors. In all instances, data were provided electronically as spreadsheets and accompanying documents related to permitting processes, etc. and consultation with office representatives provided insight and context for interpretation of data. The information we used in our modeling involved comparing and combining data provided by offices operating at various levels of government.

	SYSTEM FEATURE		
DATA FEATURE	**Flows**	**Flows**	**Stocks** (end-of-life)
Data Scale & *Agent*	County-wide *San Mateo County* unincorporated areas (**SMC**)	*City-wide* *City of San Mateo* (**CSM**)	State-Wide *Ox Mountain Landfill* (**Ox Mtn**)
Data Source(s)	San Mateo County ("SMC") Department of Building and Planning	City of San Mateo ("CSM") Dept. Public Works	Department of Resources, Recycling & Recovery "CalRecycle"; California Environmental Protection Agency
Data Element	Grading Permits (as component of Building Permits issued)	Waste Recycling Permits (REC); Stormwater Permits (STOPPP); Building Permits	Daily Cover Records
Data Attribute(s) Used	Permit #, Date Issued; Number of permits; *Volume* of "cut" produced from sitework (Cubic yards)	Permit #, Date Issued; Number of permits; Mass (Waste recycling -- direct) and volume (STOPPP -- estimated)	Quarterly Reports of mass received (tonnage)

Table 1. Data collected from various sources within the Case Study Area were analyzed and combined to estimate flows of excavated sediment from known sources within the County to the Ox Mountain landfill facility (tracked by the state of California) during the study period.

Data from nested jurisdictions

City-Level Data: City of San Mateo ("CSM")

Construction and Demolition Waste (CDW) Recycling Plans are (officially) required for new residential construction and demolition projects in the City of San Mateo, which is overseen by the Recycling division of the Public Works department (RecycleWorks). Waste Recycling Permits (RECs) track, among other things, the mass (in tons) and percentage (of total waste masses) of CDW identified and tracked as "Inert" materials consisting of soil and rubblized concrete. Stormwater Pollution Prevention Permits (STOPPPs) are also collected by CSM. These records reflect the incidence of projects that trigger permitting based on water quality regulations, and in which a "soil disturbance" exceeding 20 cubic yards occurs.

County-Level Data: Unincorporated San Mateo County ("SMC")

The County of San Mateo's Planning and Building department issues grading permits for construction projects related to private property development in unincorporated areas of the county in which 50 cubic yards or more soil is "disturbed". These permits record the cut/fill quantities of soil in cubic yards, thus reflecting which projects export sediment off-site, and in what quantities.. We examined only the "cut" component of these projects – those that become a known source contributing to material flows. Thus our SMC fill numbers are not incorporated into the model, though we do consider the implications of this logic in the Discussion section.

State-Level Data: CalRecycle & Ox Mountain Landfill ("Ox Mtn")

The Corinda Los Trancos Landfill, referred to as Ox Mountain, is SMCs only operational solid waste landfill. While privately owned and operated, a division within California's Environmental Protection Agency (CalRecycle) requires reporting on all landfills in the state, specifically related to their receipt of waste masses (recorded in tons). One of the material classifications tracked is the amount of soil received; this material is used by landfills as daily cover (see section 1.3.1).

2.3 Analyses and Modeling

Assumptions, Integration, and Use of the City of San Mateo as a Proxy

The underlying hypothesis of our study, that increases in population are an important driver of increases in the quantity of excavated urban sediment, is rooted in the observation that while development and construction projects are shaped by zoning and other land use regulations, they are driven by housing and commercial projects constructed by the private sector within the fixed boundaries of a given county. These private sector-led developments in the San Francisco Bay region are associated with the region's increasing population density, particularly in cities and counties on the Bay. Regional public sector initiatives within the study area guide local planning processes. These planning processes incentivize private-sector development projects in dense urban cores clustered around key transportation corridors, so-called Transit Oriented Development (TOD). New construction that increases urban residential, retail and commercial density requires excavation of foundations and underground spaces that produce sediment as a byproduct. We tested this hypothesis for San Mateo County by comparing population changes with sediment yields for the City of San Mateo during our study period.

Our model adds the sum of three known and estimated *sources* of sediment (yields in tons) and compares this number to a known *sink* (tons received at the Ox Mtn Landfill). First, we represented known and estimated yields of excavated sediment from the City of San Mateo (CSM) using the recorded number of building permits that involve sediment excavation. Building permits are associated with a secondary permit triggered in certain situations where earthwork, the hauling of soils/sediment, and/or impacts on stormwater as a function of grading occurs. The proportion of these secondary permits as a percentage of total building permits remained remarkably stable over the study period (12, 12, 12, 11, 13, 12, 12, 13, 11, and 6%, respectively).

Then, we used these numbers from the City of San Mateo as a proxy for calculating other unknown yields from the other incorporated cities in San Mateo County (CsSM). We used a per capita scaling number based on records in the City of San Mateo to estimate total building and secondary permit numbers using the population of incorporated cities in CsSM as our base, in all years of the study. The rationale for using CSM as a useful proxy for comparison to CsSM is based on several observations. CSM represents 14% of the county's overall population (a proportion that has remained stable over the decade of our study) making it a useful sample in and of itself. It is ranked 6th in the county in terms of its density with respect to other 19 incorporated cities and 9th in comparison with all 33 cities including those that are unincorporated. Therefore, we assume that the percentage of building permits that involve sediment excavation in all San Mateo cities (CsSM) will be comparable to that percentage of building permits in the City of San Mateo (CSM). Having an estimate of the number of permits that include sediment excavation allows us to estimate total sediment yield for all the incorporated cities of San Mateo County.

There are important differences in the data recorded at each nested jurisdictional scale. County-level data included information about cut and fill operations explicitly referring to earthwork–in other words, these permits track only excavated sediment. By contrast, the City of San Mateo includes rubblized concrete in its sediment export records. Based on their analyst's best estimate, we accepted a 4:1 ratio of sediment to rubblized concrete for the City of San Mateo's permit records. This number corresponded closely with landfill managers' estimates of 75-80% sediment and 20% rubblized concrete as a proportion of their daily cover. For our estimates of sediment yield from cities in San Mateo County and our estimates of sediment included in daily cover at the landfill, we used an 80% proportion to estimate the mass of sediment (minus concrete rubble) flowing out of the City of San Mateo and into the Ox Mountain Landfill.

Data Modeling

We built a simple material flow model to represent these data and the various assumption we applied. Our assumptions are listed below, along with a description of the data used estimate the volume of each model component:

I. <u>Population and building permits</u>

a. *As population rises over the study period, so do the number of building permits that track development and construction.*

The data on population and building permits reveal a positive correlation between building permits and population in our city-scale case study, the City of San Mateo (CSM). We calculated the annual rate of change in population and in the number of building permits year-over-year. We also calculated the average rate of growth for each variable.

b. *Within a known sample (CSM) and over the study period, a relatively stable proportion of building permits include secondary permits associated with excavation.*

   i. One set of these, waste recycling permits (RECs) directly measures excavated sediment tons as a flow.

RECs track Construction and Demolition Waste (CDW) mass totals in tons; and we apply an assumption that 80% of this is soil/sediment as opposed to rubblized concrete.

$$\text{CSM REC tonnage, year } a = (\text{Total known mass in year } a) \times (0.8)$$

   ii. The second set of these, stormwater pollution prevention permits (STOPPPs) do not directly track tonnage, but an average (per permit) is estimated.

Based on our interviews with experts from the City and County of San Mateo surveyed for this project, we assume that STOPPP permits yield an average of 50 tons of sediment per permit. Multiplying the number of STOPPP permits by this amount yields an estimate of the total mass of excavated sediment tracked by STOPPPs.

$$\text{CSM STOPPP total tonnage, year } a = (n\,\text{STOPPP in year } a) \times (50)$$

c. *We used the number of RECs and STOPPPs in the City of San Mateo to estimate their respective percentages as a share of building permits in each year of the study period and as averages.*

Using City of San Mateo data, we divided the total number of STOPPPs by the number of building permits in a given year, and divided the total number of RECs by the number of building permits in a given year.

$$\text{Percentage secondary permits of total building permits year a} = \left(\frac{n \text{ secondary permits in year } a}{n \text{ building permits in year } a}\right)(100)$$

d. *The City of San Mateo is a reasonable proxy for the other cities of San Mateo County because it likely has similar distributions of building permits per capita.*

The City of San Mateo represents 14% of the county's overall population, and as its population has grown that percentage has remained stable over the decade of our study. It is ranked 6th in the county in density with respect to 19 other incorporated cities; and 9th in comparison with all 33 cities including those that are unincorporated. The same regional and county-level planning processes and incentives that encourage dense transit-oriented development are in place across all of these communities.

II. Extrapolation of building permit numbers based on population

e. Since population is correlated with the total number of building permits, as we have observed in section I.a. above, then the number of total building permits in the cities of San Mateo County can be estimated using our previous estimates of sediment yield per permit, number of building permits per capita (both from the City of San Mateo), and the population of these other small cities.

Population totals for the other cities of San Mateo County (CsSM) are calculated by subtracting the sum of the populations of unincorporated San Mateo County and the City of San Mateo from the total County population for each year of the study. By dividing the number of building permits in the City of San Mateo by its population in a given year, we produce a coefficient that we then multiply by the population of the other small cities of the County (CsSM) for that same year. The process is repeated for all years.

$$n \text{ population Total County in year } a - ((n \text{ population SMC in year } a) + (n \text{ population CSM in year } a))$$

$$= n \text{ population CsSM in year } a$$

and

$$\frac{(n \text{ building permits CSM in year } a)}{(n \text{ population CSM in year } a)} = k^a$$

therefore

$$(k^a) \times (n \text{ population CsSM in year } a) = n \text{ building permits CsSM in year } a$$

f. The total number of secondary – STOPPP and REC – permits can be estimated for CsSM using their typical percentages of total building permits for a given area *(as observed in CSM). An average volume for these permits (on a volume per-permit basis) based on CSM permit volumes can be applied and converted to tonnages. These can be tallied on an annual basis.*

Multiplying CsSM's estimated building permit totals in a given year by the percentages calculated in the proxy case yields an estimate of the number of secondary permits (STOPPPs and RECs, respectively). Multiplying these respective totals by the proxy tonnage-per-permit values produces a tonnage estimate. The process is repeated for all years.

For RECs:

$$\left[(n\text{ building permits CsSM in year } a) \times \left(\frac{n\text{ RECs CSM in year } a}{n\text{ building permits CSM in year } a}\right)(100)\right] \times 41 = \text{RECs total tons CsSM in year } a$$

and

For STOPPPs:

$$\left[(n\text{ building permits CsSM in year } a) \times \left(\frac{n\text{ STOPPPs CSM in year } a}{n\text{ building permits CSM in year } a}\right)(100)\right] \times 50 = \text{STOPPPs total tons CsSM in year } a$$

therefore

$$\text{Total CsSM flows in year } a = (\text{RECs total tons CsSM in year } a) + (\text{STOPPPs total tons CsSM in year } a)$$

g. The sum of these annual sediment yields from the City of San Mateo and the other cities of San Mateo County (CSM and CsSM) can be added to known flows from unincorporated San Mateo County (SMC) to represent total annual flows estimated from recorded sources (not including hidden flows).

We combined the tons of sediment yield per year that we estimated for the City of San Mateo (CSM) and the other cities of San Mateo County (CsSM), and added them to the recorded tons of sediment yield from unincorporated San Mateo County (SMC). Conveniently, soil and sediment volumes recorded as cubic yards are analogous to mass tonnage (both in terms of the recording standards in our case study and as an industry standard broadly): whereby one cubic yard is assumed to be equivalent to one (US or "short") ton: 2,000 lbs. Total flows may be estimated as tons for any given year, span or range within the study period.

$$\text{Total modeled flows in year } a =$$

$$(\text{total CsSM flows in year } a + \text{total CSM flows in year } a + \text{total SMC Flows in year } a)$$

III. Comparison of our modeled sediment flows to actual tons of sediment arriving at the landfill (sink)

h. Subtracting our total modeled sediment flows from the recorded sink totals at the Ox Mountain landfill estimates the magnitude of total hidden flows into the landfill for a given year, which we can use to estimate the volume of those hidden flows produced within our study period.

The tons of material received by the Ox Mountain landfill were recorded in each year of our study period. We applied an 80% filter because expert estimates noted that about 20% of the total sediment inflow is concrete composition by mass. This percentage, estimated by Ox Mountain staff, is the same as the percentage estimated by staff in the City of San Mateo with regard to REC permits. We subtracted the sum of all known and estimated sediment flows sums (from SMC, CMS and CsSM) from 80% of the total material received by the landfill.

$$\textbf{Total hidden flows year } a = \textbf{Ox Mtn total sediment sink in year } a - \textbf{ total modeled flows in year } a$$

IV. Estimation of the demand for sediment required for adaptation landforms on the San Mateo shoreline

i. The total magnitude and annual yield of these excavated urban sediment flows can be compared to the need for excavated sediment required in the construction horizontal levees that have been proposed in the region. This will allow an assessment of whether excavated sediment flows can make a meaningful contribution to coastal adaptation using horizontal levee, a strategy which is currently limited by the lack of sediment availability.

To assess the comparative magnitudes of modeled flows and the emergent demand for sediment that would support horizontal levee construction, we take the length of shoreline that is suitable for horizontal levees from existing literature (SFEI & SPUR, 2019), and calculate the volume of ecotones that have three different cross-sectional areas as a function of their crest heights: 1m, 1.5m, and 2m respectively. All incorporate a 1:30

seaward slope. Using the cross-sectional areas of these profiles, we calculated volumetric extrusions for mile-long reaches; and used these volumes to estimate sediment demand in tons. Our findings are discussed in the following section.

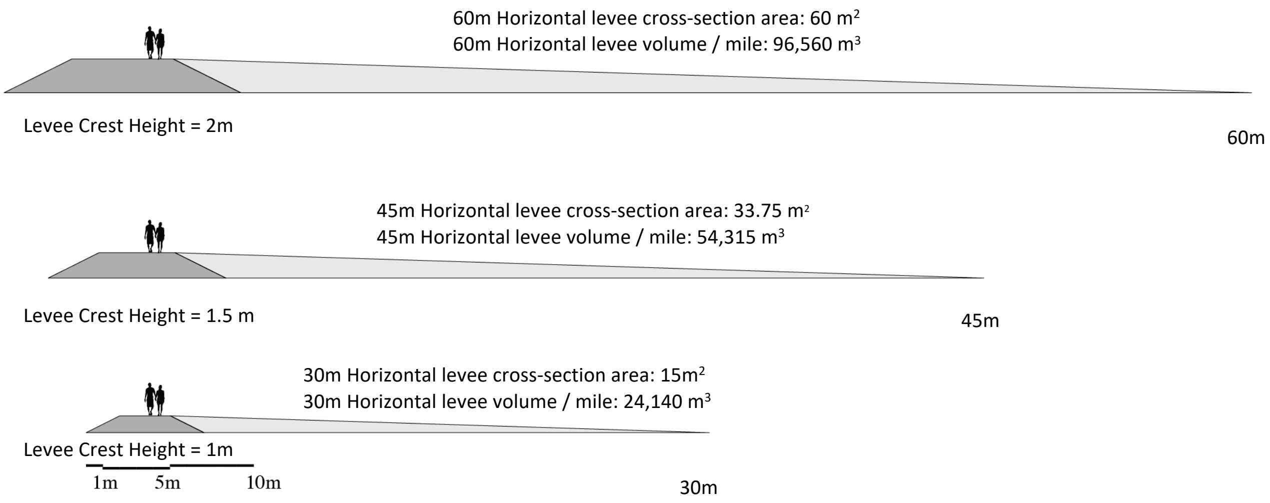


Figure 5: The sketches above represent the cross-sectional areas (in light grey) of three ecotone profiles with slopes of 30:1 that are constructed on the seaward face of traditional levees (dark grey) that have face slopes of 2:1. The ecotone width is measured from the toe of the existing levee.

3. Results

Our analytical findings demonstrate several relevant trends and relationships in the data, material and system of interest. In this section, we discuss the results of the modeling efforts and frame several important outcomes and prominent insights from the work.

a. *As population rises over the study period, so does the number of building permits that track development and construction:*

Year	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	Correlation Coefficient
Population CSM (*n*)	97,207	95,957	97,322	98,601	100,114	101,335	102,224	103,500	104,035	104,333	**0.90**
Building permits CSM (*n*)	1,696	1,816	1,936	2,218	2,310	2,834	2,788	2,700	2,590	2,729	

Table 2. A strong positive correlation (0.0900) exists between the growth rates of population and building permits issued in the City of San Mateo.

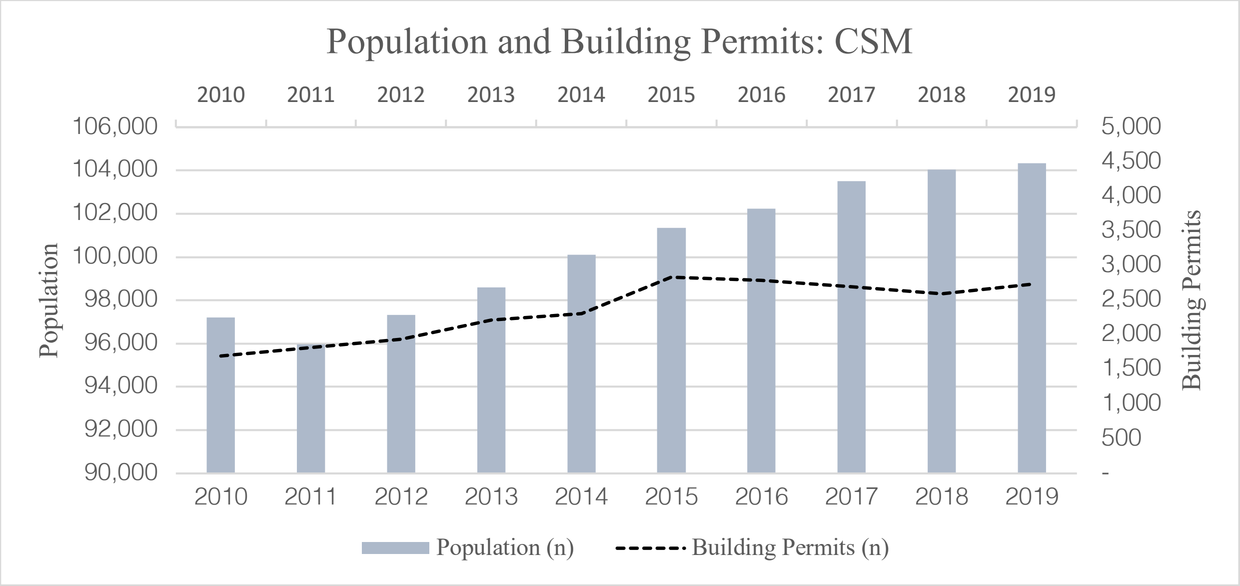


Figure 6: The overall trends in growth of population and number of building permits. Over the study period, the average annual growth rate increase was 1%. The average number of building permits issued grew by 6% per year.

b. Within a known sample (City of San Mateo), a relatively stable proportion of building permits over the study period include secondary permits associated with sediment excavation.

	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	**Average**
Building permits total (n)	1,696	1,816	1,936	2,218	2,310	2,834	2,788	2,700	2,590	2,729	**2,362**
REC permits total (n)	49	58	49	45	48	48	56	61	65	47	**53**
Percentage REC of building permits	3%	3%	3%	2%	2%	2%	2%	2%	3%	2%	**2.29%**
STOPPP permits total (n)	161	164	191	188	257	283	289	297	232	106	**217**
Percentage STOPPP of building permits	9%	9%	10%	8%	11%	10%	10%	11%	9%	4%	**9.22%**
Total percentage REC + STOPPP	**12%**	**12%**	**12%**	**11%**	**13%**	**12%**	**12%**	**13%**	**11%**	**6%**	**11.51%**

Table 3. Percentages of REC and STOPPP permits as a proportion of total building permits, by year and total averages, in the City of San Mateo.

c. *Using RECs and STOPPPs permits, we estimated an average sediment yield per permit within the City of San Mateo during our study period.*

	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	Average
REC permits total (n)	49	58	49	45	48	48	56	61	65	47	53
REC total tonnage*	1,178	6,040	2,009	3,476	1,127	3,784	771	1,396	604	715	2,110
STOPPP permits total (n)	161	164	191	188	257	283	289	297	232	106	217
STOPPP total tonnage†	8,050	8,200	9,550	9,400	12,850	14,150	14,450	14,850	11600	5,300	**10,840**
Average total tonnage (REC+STOPPP)	9228	14240	11559	12876	13977	17934	15221	16246	12204	6015	9,228

Table 4. Using known secondary permit totals for City of San Mateo, tonnages are calculated as averages, annual and overall totals. RECs are waste recycling permits. STOPPPs are stormwater pollution prevention permits.
*REC totals are calculated as 80% proportion of totals recorded to eliminate concrete constituency.
† STOPPP totals are estimated based on an average 50ton/permit assumption.

d. *The City of San Mateo (CSM) is logical for use as a proxy for the other cities of SMC because it resembles the typical urban form of the conglomeration of cities forming the county's population center.*

City	**Population 2010**	**Population 2020**	**% Growth**
San Mateo	97,207	105,806	9%
Daly City	101,123	105,024	4%
Redwood City	76,815	84,476	10%
South San Francisco	63,632	66,184	4%
San Bruno	41,114	43,947	7%
Pacifica	37,234	38,674	4%
Foster City	30,567	33,841	11%
Menlo Park	32,026	33,830	6%
Burlingame	28,806	31,416	9%
San Carlos	28,406	30,748	8%
East Palo Alto	28,155	30,139	7%
Belmont	25,835	28,361	10%

Millbrae	21,532	23,227	8%
Half Moon Bay	11,324	11,814	4%
Hillsborough	10,825	11,393	5%
Atherton	6,914	7,194	4%
Woodside	5,287	5,313	0%
Brisbane	4,282	4,858	13%
Portola Valley	4,353	4,457	2%
Colma	1,792	1,510	-16%

Table 5. Populations of San Mateo County's incorporated cities in 2010 and 2020 and their growth rates. Source: US Census

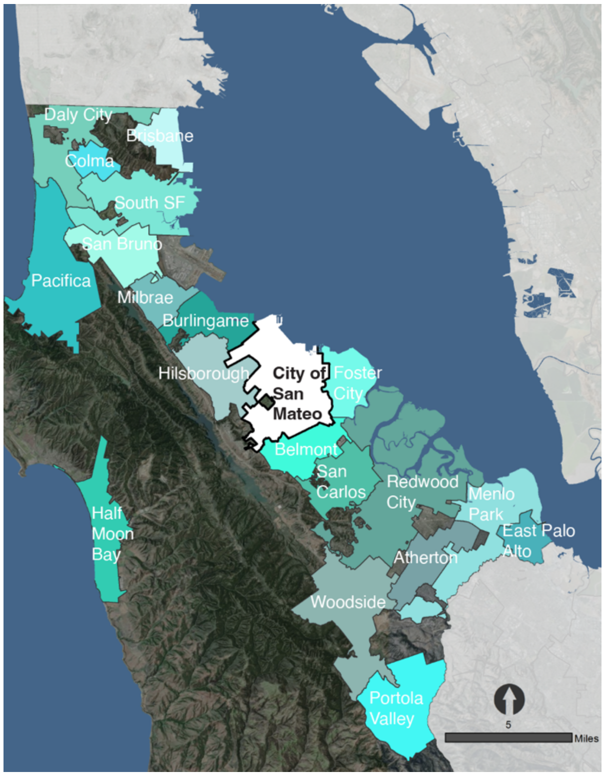


Figure 7 . The location of San Mateo County's incorporated cities. Notice their clustering along the eastern side of the peninsula and Bayshore.

e. Since we have observed a correlation in population and the number of building permits, we estimated the number of total building permits over the same period in CsSM (not including CSM) based on their population.

	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	Average
CsSM Population*	565145	574672	583202	590600	596927	602906	604270	603665	602902	593310	**591,760**
Estimated building permits total (n)	9860	10,876	11,601	13285	13773	16861	16481	15748	15010	15519	**13,901**

Table 6. Estimated building permits, tallied annually and as totals, in the other cities of San Mateo County using the City of San Mateo as a proxy case.
* CsSM is calculated by subtracting the populations of unincorporated SMC and CSM from total county population.

f. *The total number of REC and STOPPP permits are estimated for the other cities of San Mateo County (CsSM) using the typical number of building permits per person (as observed in the records of the City of San Mateo). An average volume for these permits (estimated on a volume per-permit basis based on City of San Mateo permit volumes) is applied and converted to tons. These are tallied on an annual basis:*

	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	Average
Estimated REC permits total (n)	226	249	266	304	315	386	377	361	344	355	**318**
REC total tonnage*	9258	10211	10893	12474	12932	15831	15474	14786	14092	14571	**13,052**
Estimated STOPPP permits total (n)	909	1003	1070	1225	1270	1555	1520	1452	1384	1431	**1,282**
STOPPP total tonnage	45456	50137	53483	61246	63495	77730	75975	72597	69194	71543	**64,086**
Average total estimated tonnage (REC+STOPPP)	54,714	60348	64375	73719	76427	93561	91449	87,383	83,286	86,113	77,138

Table 7: Estimated totals of secondary building permits in the other Cities of San Mateo, tallied annually and as totals, using recorded numbers from CSM as proxy.
* REC tonnage assumes 41tons/permit (previously calculated).
† STOPPP tonnage assumes 50ton/permit (estimation).

g. *The sum of excavated sediment flows from the City of San Mateo (CSM) and the other cities of San Mateo County (CsSM), added to recorded flows from unincorporated San Mateo County:*

	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
Total SMC Tonnage	2,978	2,990	2,902	4,075	4,853	9,223	17,128	30,447	10,021	25,486
Total CSM Tonnage*	9,228	14,240	11,559	12,876	13,977	17,934	15,221	16,246	12,204	6,015
Total CsSM Tonnage†	54,714	60,348	64,375	73,719	76,427	93,561	91,449	87,383	83,286	86,113
Total Modeled Flow Tonnage	**66,919**	**77,578**	**78,836**	**90,670**	**95,257**	**120,719**	**123,798**	**134,076**	**105,512**	**117,614**

Table 8: Sums of modeled and recorded flows from unincorporated San Mateo County, the City of San Mateo and other cities in San Mateo County, tallied annually and as totals for the study period.
* Includes recorded and estimated flows.
†Based on estimated flows.

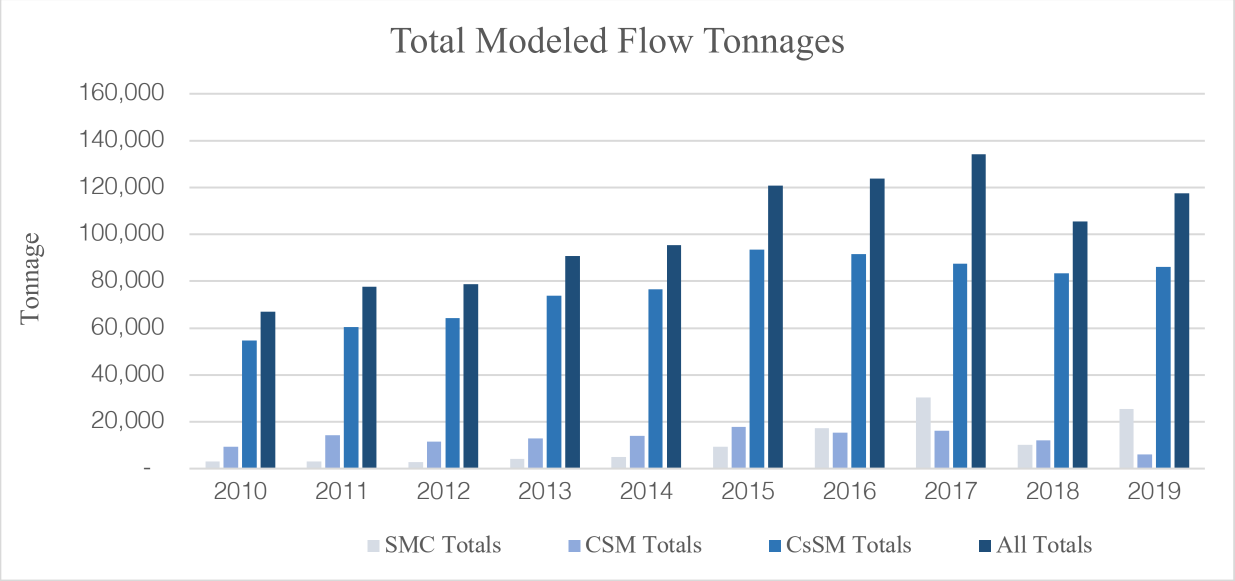


Figure 8: Bar chart showing recorded and estimated sediment yields from unincorporated San Mateo County, the City of San Mateo, and other incorporated Cites in the County of San Mateo by year.

h. Subtraction of these modeled flows from the recorded sink totals at the Ox Mountain landfill provides an estimate of the magnitude of total hidden sediment flows entering the landfill as daily cover.

	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
Total modeled Flow tonnage	66,919	77,578	78,836	90,670	95,257	120,719	123,798	134,076	105,512	117,614
Total sink tonnage*	82,055	94,032	204,711	286,532	370,038	304,947	321,242	425,879	469,364	500,194
% Total sink sodeled as flows	**82%**	**83%**	**39%**	**32%**	**26%**	**40%**	**39%**	**31%**	**22%**	**24%**
Total hidden flow tonnage	15,136	16,454	125,875	195,862	274,781	184,228	197,444	291,803	363,852	382,580

Table 9: Percentages of total modeled flows (dark grey band) as proportions of the total tons of landfilled soils, by year. The total unmodeled flow tonnage (hidden flows) is calculated as the difference between total modeled flow and total recorded sink tonnages, by year (lowermost row).

* Sink tonnage of sediment is estimated by using the assumption that 80% of the material received for daily cover is actual sediment, while 20% is rubblized concrete that is also classed as "soils" in landfill records.

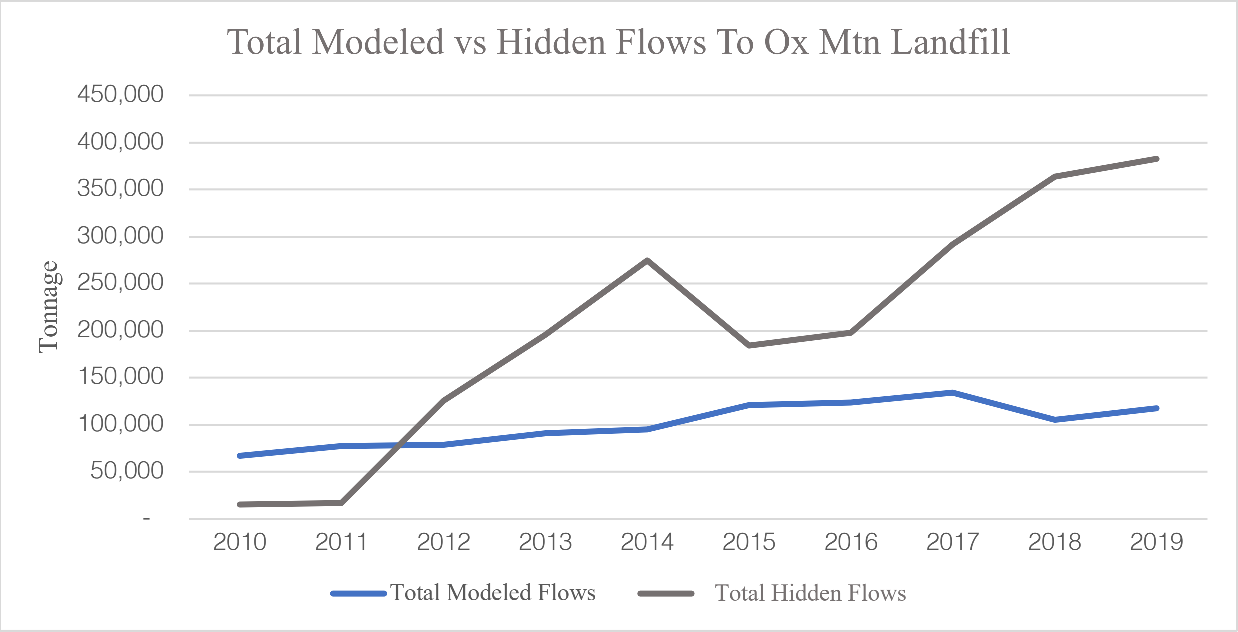


Figure 9: Graph of the trends in total modeled flows (blue line) to Ox Mountain Landfill compared to the inferred hidden flows (grey line) over the study period. According to our estimate, the proportion of hidden flows that are not recorded at the source has increased by a large amount over the past decade.

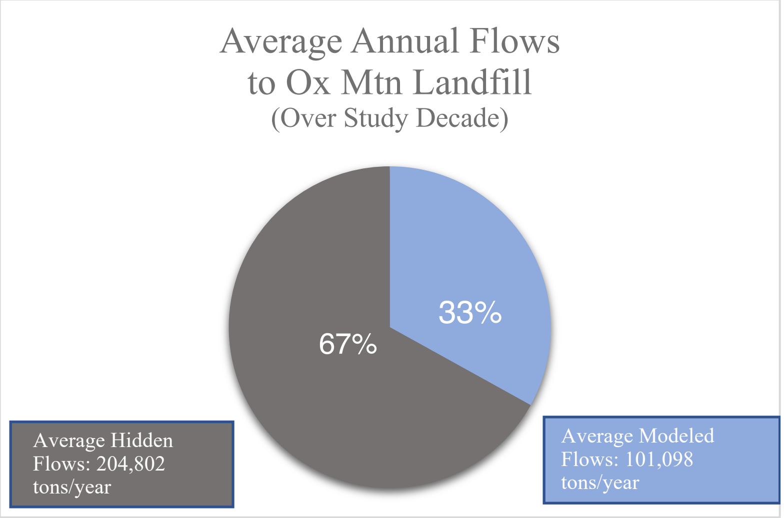


Figure 10: An average of 305,900 tons of excavated sediment flowed to the Ox Mountain Landfill, per year, over the study period. One third of these are the modeled flows from our material flow analysis, which averaged 101,098 tons/year.

i. *The magnitude of these urban sediment flows is comparable to the need for excavated sediment required in the construction of horizontal levees that have been proposed in the region; facilitating an assessment of whether excavated sediment flows can make a meaningful contribution to coastal adaptation using horizontal levees, a strategy which is currently limited on the regional scale by a lack of sediment availability.*

Horizontal Levee Height (meters)	**Horizontal Levee Sediment Demand** (tons per mile)	**SMC Total: 10.4 Miles Horizontal Levee Demand** (tons)	**Average *Annual* Modeled Flows as Percentage of SMC Total Horizontal Levee Demand**
1m	24,140	251,056	40%
1.5m	54,315	564,876	18%
2m	96,560	1,004,224	10%

Table 10: Comparing the supply of annual modeled flows in San Mateo County to demand for horizontal levees on the San Mateo County shoreline. Columns show (from left) three levee height cases; the per-mile tonnage demand for sediment under those height assumptions; total demand from all of SMCs currently identified miles of horizontal levee opportunity; and the percentage of modeled excavated sediment flows as a proportion of the total estimated demand for SMC's horizontal levees. At 1 m of levee height, the modeled sediment yield from the County's building permits makes a significant contribution. For the highest levees, more of the hidden flows would need to be harnessed in order to provide a significant input.

4. Discussion

Our modeling reveals several trends of interest in the study area that directly reflect and link population, permits and excavated sediment yields. Given our assumptions, excavated sediment in urbanizing San Mateo County could be a significant source of material for coastal adaptation projects.

The results also raise a set of obvious and fundamental questions: where do the hidden flows originate that comprise the majority of flows into the Ox Mtn landfill? What factors and forces effectively work to "hide" them in terms of the processes of excavation or sediment hauling at work, and the procedures for tracking these practices in the form of data records that might be further analyzed? Why are such wide variations evident in the tonnage of total modeled flows as a percentage of total sink tonnage, ranging from 83% in 2011 to 22% in 2018? Does this gap indicate that the percentage of hidden flows has increased significantly over the study period, or do other factors generate this apparent gap? In this section, we reflect on these questions and consider the potential contribution of modeled flows that might be redirected for use in horizontal levee construction (Table 10, above), considering future population dynamics and questioning the likely proportion of these flows that might be suitable for sensitive environmental applications like shoreline restoration. Our Conclusion section then frames our key takeaways and the central insights and challenges of this analysis as a whole.

4.1 Comparing Known Sources and Sinks: Hidden Flows and Leaky Systems

Mass Balances

A central concept in industrial ecology and its related methods concerns the notion of "mass balance," which describes the constancy of matter despite its movement and/or transformation within a system of study (Brunner & Rechberger, 2004). A mass balance principle is especially important to consider for studies in which the known input and output from a given process differ. This would lead to a so-called mass *im*balance, indicating that some portion of the material has been "lost" from an informational perspective (i.e. material whose state, position or situation is unclear). Our work has illustrated that estimating excavated urban sediment flows in a case study region using recorded data and estimates based on per capita sediment yields can only account for the minority of flows arriving at a prominent sink. Several features of the study and system may explain the difference in these recorded and estimated (modeled) flows and the records of landfill receipts. An overall picture emerges of a system that is very "leaky," one in which, for a variety of reasons, a lack of rigorous understanding persists regarding various features.

The first relates to the scope of the study. Specifically, because the sink at the heart of our analysis – the Ox Mountain landfill facility – is located in San Mateo County, it is reasonable to assume that a considerable proportion of its daily cover resources are the result of flows of sediment excavated within the County. However, this does not prevent other counties from disposing of sediment at Ox Mountain. In fact, the adjacent and relatively population-dense county of San Francisco (SF) has no landfill. So, it is logical to assume that they export their excavated sediment to other counties. San Mateo County's proximity and ease of access (not requiring trucks to travel across congested bridges, for example) may predispose it to receive a large amount of SFs excavated sediment resources. The other two adjacent counties, Santa Clara and Santa Cruz, are also not modeled or assessed here in terms of their potential contribution to overall flows of sediment to Ox Mtn. Records that track both the county-of-origin and material mass categorized by type (municipal wastes, green waste, shredded tires, daily cover, construction and demolition wastes, etc.) would be needed in order to make a meaningful estimate of actual inter-county flows. The boundaries of the system we defined for this material flow analysis would need to be expanded to include all three counties, at least, in order to represent the area that contributes to the major sink at Ox Mountain.

Similarly, SMC is surely also a source of hidden flows. That is, not all projects producing excavated soil and sediment that occur within the County will find their way to Ox Mtn as flows. Some are exported out of the County to landfill facilities or construction sites, depending on the economics of the contracting for doing so. A potentially complex calculus linked to and based on aspects of the project portfolios of numerous private sector actors and firms of various sizes, ranging from independent contractors who are essentially drivers that own or rent a dump truck to companies that own a fleet of trucks and may employ many drivers as staff in addition to contracting with independent drivers. There are also hidden *intra-county flows:* those that originate from sources within SMC but are routed to sinks or stocks within the county other than Ox Mtn. These may be illegal dump sites, stockpiles of material, and construction or environmental projects in need of fill material. Both the inter-county and intra-county flows are effectively hidden from our data survey and modeling efforts. Additional consideration should be given to any record keeping and permitting requirements that may not apply, may not be clear to permit staff, or may not be adequately observed or enforced.

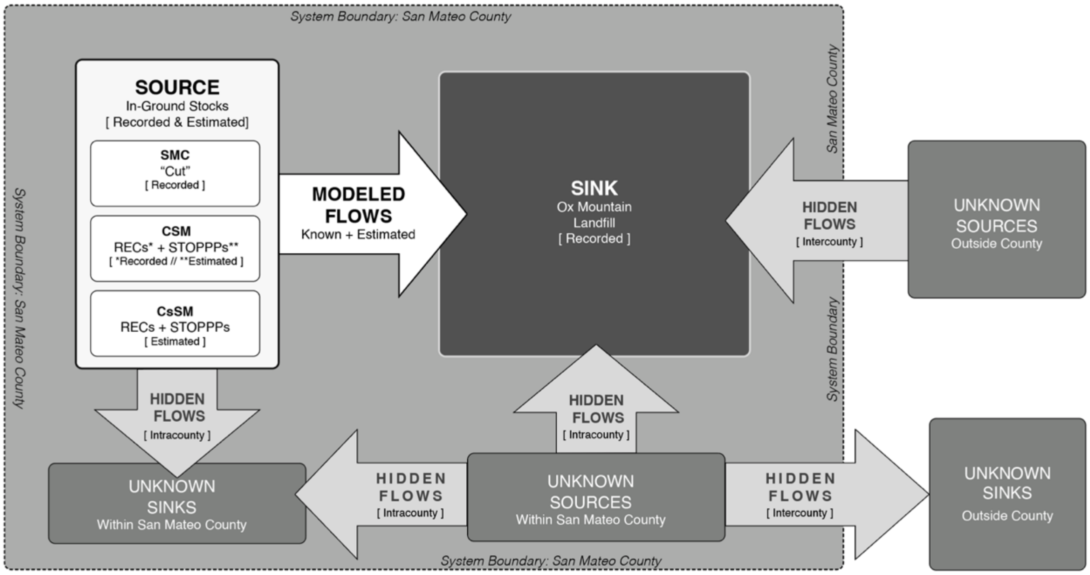


Figure 11: A portion of the overall MFA showing the sources, sinks and flows of interest and importance. In particular, our study examined the sources of in-ground stocks of excavated sediment that could be quantified or estimated as Modeled Flows (white arrow). The figure above also displays a secondary set of stock and flow features that are at play; and, in fact, constitute the majority of material that eventually makes its way to Ox Mtn, on average, during our study period. The system is "leaky": unknown sources, flows and sinks all affect the overall mass balance of excavated sediment in the study region, though as a function of numerous issues related to data that correspond to these material dynamics, it is difficult to rigorously appraise more fine-grained features of hidden flows and unknown sources and sinks, including their respective magnitudes.

An entire category of hidden flows might be collectively termed *unpermitted flows*, reflecting the primary challenge in estimating their magnitude: a lack of records and information associated with their potential share of total flows arriving at the Ox Mtn sink. Unpermitted flows occur for several reasons. One is that certain permitting requirements and their application to various types and locations of projects are initiated only when a minimum threshold of soil/sediment is disturbed. For example, unincorporated SMC's grading permits (usually issued as a secondary permit associated with building permits) include a 50 cubic yard threshold that triggers the permitting process, and projects under these thresholds effectively escape voluntary reporting and cataloguing. If a large proportion of excavation projects are smaller than this volume threshold, that could account for significant hidden flows.

Projects of various sizes routinely fail to follow proper permitting procedures, according to the consulting analysts we spoke with from the County and City of San Mateo. In fact, it was observed by more than one of these experts that unpermitted projects likely outnumber those properly permitted. In some instances, this may be due to a simple oversight or lack of clarity as to whose responsibility the permitting is (especially in cases of secondary permit procedures, notably including the RECs of SMC, for example). In other instances, failure of landowners and contractors to file for permits may simply reflect a lack of incentives for doing so (or, more to the point, a lack of disincentives for not doing so). Some permitting procedures rely on voluntary self-reporting practices and warnings are usually issued as first steps to correct lack of permits. Permitting procedures also cost money and time, and even in instances where a fine might be assessed, paying the fine for not following permitting procedures (including consideration of the odds of getting cited, and the time involved in following the rules) might be simply understood as worth the associated risk and costs. Across the experts surveyed about this phenomenon, the lack of enforcement resources was cited as a perpetual challenge that surely leads to under permitting.

A third and important category of unpermitted flows relates to the projects that involve excavation in the public Right-Of-Way (ROW), which is a publicly-owned section of land generally defined as the total width of streets, sidewalks and the utilities clustered within them. These are interesting to consider in several respects, not least of which is that in the case study area (and in other cities and counties in the case study region), projects in the ROW are not required to follow many of the permitting processes associated with private development projects. Underground utilities are concentrated in ROWs, including various water conveyance structures (drinking water pipes, sewers, storm drains) and other lines and conduits (gas lines, electrical cables, etc.). These networks are subject to upgrading, repair and replacement procedures that often entail significant excavation projects unfolding across considerable linear distances in urban settings.

Roadwork in the ROW and projects associated with low-impact-development and urban greening are also projects that produce excavated materials. Partially as a function of the lack of external revenue generation (municipalities would not assess fees against their own municipal service providers), these projects are not diligently recorded for their contribution to flows of excavated sediment. Notably, precisely because of the close working relationship of municipal offices to those that do routinely track construction permits (in fact, in many cases these are both integrated into municipal Public Works divisions), major improvement in resource tracking might be possible to implement.

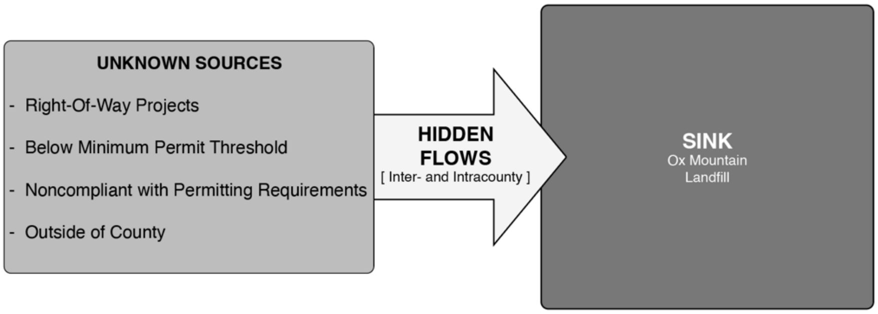


Figure 12: A portion of the overall MFA schema displaying a major contributor to the Ox Mtn soil and sediment receipt totals in a given year (and often representing the majority of the resources): Hidden Flows. Hidden flows emanate from sources within and outside of San Mateo County, and are generated from a variety of processes that are, for various reasons, not rigorously tracked and recorded by public-sector offices.

4.2 Scenario Forecasting: Future Supply and Demand of Excavated Sediment

One of the central sustainability issues that this work illustrates relates to the linear nature of the *excavation-to-landfill* paradigm of sediment management. This paradigm leads to a terminal point of permanent, irretrievable internment of resources in waste facilities like Ox Mtn. In short, there is no "going back and getting" the soil and sediment resources that have been consigned as daily cover in landfills: that material is forever lost in terms of its reuse in an alternative application and more circular economic reckoning of its life cycle. In this respect, and to better understand the potential contribution of modeled flows of excavated urban sediment to the construction of horizontal levees in SMC, requires forecasting their yields over a future timeframe and assessing the overall portion of likely yields in that timeframe that might realistically be captured for adaptation purposes.

SMC Population Projections and Future Yields: Will we have more or less?

Our study decade (2010-2019) saw an average rise in SMCs total county-wide population of about 1% per year. Since the study period, the population in SMC experienced a net negative growth period probably due to the COVID-19 pandemic. We used population projections from the 2018 Association of Bay Area Government's Plan Bay Area 2040 report to establish a plausible time series of total population in SMC over the next decade (Mackenzie et al., 2018). Because this study was published before COVID-19, we used a linear interpolation technique to plot populations for all years between 2020 (using US Census data from that year) and the ABAG projections, and adjusted the annual estimates by reducing them by 3% (the proportion of population overestimation in the ABAG report for 2020), thus attempting to correct the baseline for their projection estimation method while still assuming overall growth rates of ~ +0.7% per year in accordance with our prior data set and ABAGs projections.

To estimate the number of likely building permits that will be issued in the coming decade, we applied a forecasting method based on known population numbers for the case study decade and our estimates of total building permits issued in the County of San Mateo. On average, the number of building permits in the county is rising 6% per year. This makes sense because of the dense development pressures and incentives previously described. Using the case study timeframe to establish an average increase of this coefficient per-year, we extended coefficient values into the forecasting window, in-effect providing a number by which out population estimates can be multiplied to produce a likely number of building permits. Applying the method previously described for calculating the tonnage associated with secondary permits that can be derived as a percentage of total building permits, we estimated yields for the coming decade.

	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032
SMC* Population Projections	774,672	780,373	786,074	791,776	797,477	803,179	808,880	814,582	820,283	825,984	831,686
Estimated Building Permits Total (n)	23624	25041	26543	28136	29824	31614	33510	35521	37652	39911	42306
Forecasted Yield (tons)	**131085**	**138950**	**147287**	**156124**	**165491**	**175421**	**185946**	**197103**	**208929**	**221465**	**234753**

Table 11: Projections of potential yields (bottom row) by year in the coming decade, estimated using population trends and the previously-described methods for assessing the likely share of secondary building permits associated with grading as a share of total building permits issued.
* SMC in this table denotes the entire county and its populace, as opposed to only the unincorporated areas.

4.3 Effects of Quality Standards on Estimated Yields

While we have discussed landfill facilities as *sinks* for the receipt of material including large amounts of sediment resources, these sediment materials act as “substance sinks” themselves, defined as physical media that receive and effectively store numerous compounds (Fellenberg 1994; Sauerwein, 2011). These compounds may include arsenic and other hazardous metals, petroleum products, and herbicides, among other potential chemicals. In our case study region, strict screening protocols are applied to the use of imported fill material in areas where water quality may be impacted, including fill that would be placed in the Bay itself. A number of different environmental agencies and organizations track and enforce the standards by which material used in sensitive areas, including the Baylands, is assessed for various pollutants, including legacy contaminants from industrial activities and naturally occurring compounds including certain heavy metals (Katsumi, 2015; McClintock, 2015; Schoellhamer, et al., 2007). Water quality concerns regarding SF Bay, which serves as a receiving body of a vast watershed, have demonstrated the long-term effects of pollution in the estuary (Connor et al., 2007; Steding et al., 2000). In the region's active restoration projects, the concentration of various contaminants associated with legacy impacts (including those from manufacturing, industrial dumping, land development, local waste disposal, and excessive pesticide or fertilizer use) have been studied to inform ongoing testing and screening procedures; and overall concern about concentrating contaminants in the food webs that wetlands support persists (Davis et al., 2007; Grenier & Davis 2010; Miles & Ricca, 2010).

Based on the environmental concerns in the region and the nature of urban soils pollution, upland excavated sediment volumes – especially those withdrawn from urban environments – are likely to contain some portion in which contaminants are present that may exceed standards for reuse in restoration applications including ecotone levees (McClintock, 2015). For example, significant lead concentrations stemming from leaded gasoline use is widely evident in surficial soils of urban areas (Wong & Li, 2004). Mapping surficial sediment in developed regions, and the complexities associated with historical impacts on these resources has led to work attempting to characterize "urban soils" in a variety of settings (Bullock & Gregory 1991; Craul, 1992; Effland & Pouyat, 1997). Unfortunately, generalizing about the likely portion of excavated urban sediment that contains contamination in a broad and varied geographic region (as in the case of our sources of interest) is difficult. A number of considerations illustrate why this is so.

For one thing, many different *kinds* of contaminants are present in the urban pedosphere, and these vary both *spatially* in terms of their distributions across the urban landscape, and in their concentrations within a given *volume* of sediment based on the *depth* of their presence through infiltration into soils from biogeochemical processes or as a function of being previously buried by human activity, etc. In this sense, a small volume of surficial sediment might be quite contaminated, while more volumes extracted from deeper layers of the same dig site might be significantly less so, both as a function of "skimming" the most-problematic surficial layer, and because contaminant thresholds are often assessed based on concentrations, that is, compounds-per-volume/amount of overall material. In other words, larger excavation projects might effectively dilute contaminants as a function of their sheer volume, and/or the depths from which they are extracted.

However, in areas with high water tables, including our study region, certain labile compounds can be motivated and transported into previously uncontaminated areas and their underlying sediment volumes by groundwater–a problem made significantly worse by SLR's effect in elevating groundwater tables and especially in areas with previously buried contaminants that may be inundated by evolving groundwater dynamics (Plane et al., 2019). Because of these trends and dynamics, it is logical to assume that contaminant spread in subsurface sediment is yet another impact of climate change that may intensify in coming decades, and potentially reduce the supply of sediment useful in restoration and adaptation applications.

Clearly, multiple complications exist as a function of the physical nature and processes of urban excavated sediment, not least of which is the set of challenges associated with analyzing which sediment sources might be contaminated, since the permitting requirements for some projects simply do not take account of contaminant issues. Indeed, as we have repeatedly discussed, overall tracking and records in the context of many, if not most, construction sites and excavation processes is an afterthought, in no small part because excavated soils are broadly understood as waste products bound for landfills, a categorization that surely generally serves to reduce the likelihood of screening for contaminants. Common analytical approaches that directly address these problematic compounds found in soils are frequently based on large-scale site mapping of contamination based on past land use and surficial presence of hazardous compounds or on site-scale remediation efforts in which soil volumes are tested, treated, sequestered or removed (Dermont, et al., 2008; Lin 2002; Van Meirvenne & Goovaerts, 2001).

Given the wide variety of excavated sediment sources (in terms of their geographic, geophysical and geochemical profile) present in our modeled flows of the study region, and owing to the lack of information regarding contamination prevalence and concentrations that can be definitely correlated to these sources, we assess a range of the potential proportions of contaminants that might be present in the modeled flows. This would likely disqualify these portions of overall yields from reuse in ecotone and horizontal levees. While certain sites encountering urban fill material in excavation may yield volumes that are all, to some extent, contaminated, we would expect these to only comprise a portion of overall yields in the study area over a given year (Boudreault et al., 2010). Review of literature concerning contaminant concentrations in projects associated with soil excavation range widely, and considerable uncertainty must be managed on any given project (Goovaerts, 2001).

We reviewed literature discussing instances of urban, brownfield redevelopment and post-heavy industrial projects involving management of polluted sediment volumes. The cases ranged widely in their percentages of contaminated sediment as proportions of total volumes excavated or otherwise managed. For example, in post-industrial projects, established contaminated volumes were equivalent to 16% of total project volume; to upper estimate proportions ranging from 34% to 44% of site volumes that were likely contaminated past an acceptable threshold (Boudreault et al., 2010; D'Or et al., 2009; Hendriks et al., n.d.). Urban sites that have experienced fewer or less severe impacts from industry but still reflect anthropogenic contaminants in surficial sediment have commonly shown the top layer (10-30cm) to contain significant amounts of toxins including lead, thus constituting, by volume, 10% - 30% of a cubic yard excavated at the surface (Chen et al., 1997; Meuser, 2010). However, because of the likelihood that deeper and potentially less-contaminated volumes are a constituent of excavated sediment, and due to the fact that greenfield development processes also contribute to overall yields and flows, the overall share of contaminated sediment is likely somewhat reduced from the higher (30%) bound of this range.

4.4 Sensitivity Analyses

Effects of Sediment Quality Screens and Levee Heights on Future Ecotone Construction

For the purposes of planning how forecasted supply yields, quality standards and material demands (based on horizontal levee heights) will impact the potential to build these structures for adaptation to rising seas over the next decade, we assessed the duration of construction project cycles that will likely be associated with these variables. This effectively demonstrates the sensitivity of a dependent variable (construction timeframe) to the independent variables (quality screening and levee heights) associated with the respective supply and demand variation included in our model. Doing so involved several assumptions and methods to incorporate key variables into the modeling process.

Given the particularity of cases from the literature wherein the concentration of highly-polluted post-industrial soils was a large proportion of *overall* excavated volumes, we deemed the highest percentage (44%) encountered in the literature to be an unlikely proportion to apply to total forecasted flows in our case study area. On the other hand, given the broad ubiquity of contaminants evident in urban surficial soils, we adopted the 10% lower limit for our screening and sensitivity methodology. As an upper limit, we adopted a 30% screening level and calculated yields based on 5% increments to estimate total yields that might be disqualified from reuse in ecotone construction, which we subtracted from annual tonnage yields.

Maximum Construction Duration in Years (beginning various years)

Year	Horizontal levee height (m)	Contamination screen (%)				
		10%	15%	20%	25%	30%
2022	1m	2.1	2.3	2.4	2.6	2.7
	1.5m	4.8	5.1	5.4	5.7	6.2
	2m	8.5	9.0	9.6	10.2	10.9
2023	1m	2.0	2.1	2.3	2.4	2.6
	1.5m	4.5	4.8	5.1	5.4	5.8
	2m	8.0	8.5	9.0	9.6	10.3
2024	1m	1.9	2.0	2.1	2.3	2.4
	1.5m	4.3	4.5	4.8	5.1	5.5
	2m	7.6	8.0	8.5	9.1	9.7
2025	1m	1.8	1.9	2.0	2.1	2.3
	1.5m	4.0	4.3	4.5	4.8	5.2
	2m	7.1	7.6	8.0	8.6	9.2
2026	1m	1.7	1.8	1.9	2.0	2.2
	1.5m	3.8	4.0	4.3	4.6	4.9
	2m	6.7	7.1	7.6	8.1	8.7
2027	1m	1.6	1.7	1.8	1.9	2.0
	1.5m	3.6	3.8	4.0	4.3	4.6
	2m	6.4	6.7	7.2	7.6	8.2
2028	1m	1.5	1.6	1.7	1.8	1.9
	1.5m	3.4	3.6	3.8	4.1	4.3
	2m	6.0	6.4	6.8	7.2	7.7
2029	1m	1.4	1.5	1.6	1.7	1.8
	1.5m	3.2	3.4	3.6	3.8	4.1
	2m	5.7	6.0	6.4	6.8	7.3
2030	1m	1.3	1.4	1.5	1.6	1.7
	1.5m	3.0	3.2	3.4	3.6	3.9
	2m	5.3	5.7	6.0	6.4	6.9
2031	1m	1.3	1.3	1.4	1.5	1.6
	1.5m	2.8	3.0	3.2	3.4	3.6
	2m	5.0	5.3	5.7	6.0	6.5
2032	1m	1.2	1.3	1.3	1.4	1.5
	1.5m	2.7	2.8	3.0	3.2	3.4
	2m	4.8	5.0	5.3	5.7	6.1

Table 12: Using the overall forecasted yields for the coming decade, various levee height scenarios will entail different years-long construction processes based on the percentage of sediment screened for quality standards. The light grey cells in the main body of the chart show the overlapping middle estimates of important variables: those of a 1.5m levee height and 20% screening proportion, respectively. This chart shows the maximum construction durations (in years) because it does not factor in increasing supplies that might become available as construction projects proceed.

We then calculated the volumes associated with our three levee design heights under the various screening levels to establish the maximum number of years that construction, initiated in any given year, would take to build the 10.4 miles of horizontal levees at various heights based on the availability of sediment. These calculations are based on the forecasted flow yields for the coming decade (see Table 10). This method stipulates a *maximum* number of years because it does not factor in the anticipated annual increases in sediment over successive years (which would, in theory, reduce build times). A second set of methods to incorporate the effects of increasing supply year-over-year was also applied, and is discussed below.

Finally, and using the same variables described above (levee heights, screening percentages, forecasted flow yields), we modeled the effects of incorporating *increases in sediment supply* as a function of overall yield increases year-over-year, assuming that levee construction began in 2022. This approach essentially subtracts total demand from previous forecasted yield years for each successive year; and, in this sense, reflects a situation in which increasing supply effectively shortens levee construction timeframes. However, and as we have seen, while sediment flows do indeed trend upwards with population increases, their increases are not linear. It should therefore be noted that whereas in the previous approach (see Table 12) was hindered by a lack of an updating annual supply function, it also tested for the potential for levee building projects initiated in a *future* year.

This difference reflects the theoretical assumptions at play. For instance, whereas the former approach estimated that, starting in 2022, it would take over a decade (10.9 years) to construct the full (10.4) miles of 2m levees when the screening was most stringent (30%), the latter approach estimated that initiating the process in the same year (under the same assumptions) would take 8.7 years. The difference is due to the former process stipulating a *maximum* construction duration that assumes supply yields do not fall in future years, but also does not assume that they rise. The subtlety here is meaningful because sediment supply does not actually occur in a step-wise process (whereby on the first day of the year all sediment resources that will be yielded that year suddenly are available for levee construction) but also is not predictably linear (whereby a new and greater total becomes available on a rolling basis). Thus, while it would be possible to use a linear interpolation technique to build more fine-grained timeframes into the model, the results from doing so would be of limited value because of the non-linear nature of sediment flows which do, indeed, ebb also. Both processes can be used to frame realities related to the years-long nature of projects based on the tranche of forecasted sediment supplies considered available for reuse in this study, and as a coarse-grained estimation logic.

	Construction duration starting in 2022 based on estimated sediment yields (years)		
	Height of horizontal levee (meters)		
Contamination screen (%)	**1 m**	**1.5 m**	**2 m**
10%	2.1	4.3	7.1
15%	2.2	4.6	7.4
20%	2.3	4.8	7.8
25%	2.4	5.1	8.2
30%	2.6	5.4	8.7

Table 13: Estimation of construction duration to construct 10.4 miles of horizontal levees in the Case Study Region, using a method that incorporates an annual increase in forecasted supply yields. The light grey cell in the middle of the main body of the chart shows the middle ranges for the screening (20%) and horizontal levee height (1.5) variables used.

5. Conclusion

Our study frames an important set of material flows occurring in the study region and illustrates that numerous factors effectively conceal a large magnitude of these flows, indeed the *majority* of them, according to our survey and modeling entering or emerging from the county whose end-of-life phase is reached at the Ox Mountain landfill facility. Our work outlines a material flow analysis that is populated by a complex set of actors and agents whose work is involved both in the physical management of sediment resources and the informational "landscape" that can be examined to describe and assess the system overall. As previously discussed, MFA that concern low-value resources are relatively rare for a variety of reasons. Though we also present a contextual logic for supporting the expectation that excavated sediment may, in fact, be or become seen as a more valuable resource in coming decades.

Notwithstanding the prominence of unknown sources and stocks and the nature of hidden flows in the overall MFA (and, perhaps more to the point, the lack of data to sufficiently identify and substantiate them), we present a method for using available data from public offices to build an estimation of excavated sediment flows that can be modeled and compared to known overall flows. Population and development trends linked to certain urban density initiatives in the region, and increasingly common in many others, can be understood as a driving force of flows that might be broadly publicly valuable in their optimization as SLR protection, adaptation and restoration applications. One of the interesting insights of the work is that, while excavated sediment flows exhibit flux–changes in the *rate* at which they are produced–scrutiny of secondary permits that track excavation suggest that they also exhibited very low variation across the study period in relation to total building permits issued in our proxy example.

Use of the illustrated methods also serve as a forecasting tool, and the work suggests that San Mateo County is well-positioned to construct the majority or full extent of horizontal levees (10.4) identified as opportunities in the case study context area in the coming decade if sediment yields continue to rise and if adequate time for construction durations are factored in given the central variables used as assumptions that will reflect sediment supply (quality assurance screening) and demand (levee heights). Interestingly, using the mid ranges of those variables (20% and 1.5m, respectively), we've estimated that a project to construct all horizontal levee miles that is initiated in 2022 would take 4.8 years to complete, while one begun halfway through the forecast window (2026) would take 4.3 years, a rather close correspondence, ceteris paribus. As previously discussed, both approaches entail uncertainty as a function of the non-linear flux of supply yields.

How resources are marshalled to accomplish or satisfy goals is a fundamental aspect of strategic planning, broadly speaking. The study and features of interest here illustrate this in specific ways as it relates to a physical material resource and regional adaptation and restoration goals and initiatives linked to it. Moreover, their interplay should be considered in the context of the considerable uncertainty and change that global warming represents. For example, catastrophic warming in coming decades might simultaneously drive SLR to greater elevations necessitating higher levees (and thus resource *demands*), while at the same time potentially leading to increased in-migration to the relatively stable micro-climate of the SF Bay region (with commensurate impacts on development and thus resource *supplies*). While our study focused on a more narrow or conservative set of scenarios (with respect to population trends and likely levee heights), planning as a professionalized practice is increasingly confronting previously unforeseen pressures and complications in the public realm.

As such, a number of interesting policy and planning considerations might stem from this work. While, to-date, rigorous understanding of the material and industrial ecologies that functionally comprise the life cycles of excavated soils is still lacking, increased coordination across municipal offices and departments could advance knowledge concerning the classification of resources that are, and will be, directly implicated in large spatiotemporal schemes for regional resilience and public benefit. Seeking collaborative opportunities that might be of interest to private sector contractors might also reveal opportunities for building more robust data tracking and records practices. For example, by incentivizing (or potentially requiring) disclosure of certain records and coordinating operations by pointing contractors towards active or planned restoration projects. By helping illuminate the connections between the logistical realities and resource and information management considerations that involve sediment resources, this work may aid in advancing future plans, policies and research to more deeply consider and understand this increasingly important subject and area of study.

Ch 3. References:

Aarninkhof, S. G. J., van Dalfsen, J. A., Mulder, J. P. M., & Rijks, D. (2010). Innovations in project design and realisation. 12.

Adger, W. N., S. Dessai, M. Goulden, M. Hulme, I. Lorenzoni, D. R. Nelson, L. O. Naess, J. Wolf, and A. Wreford. 2009a. Are there social limits to adaptation to climate change? Climatic Change 93:335-354. (n.d.).

Admiraal, H., & Cornaro, A. (2018). Underground spaces unveiled: Planning and creating the cities of the future. (Environmental Design NA2542.7 .A36 2018). London : ICE Publishing, [2018]; cat04202a. https://libproxy.berkeley.edu/login?qurl=http%3a%2f%2fsearch.ebscohost.com%2flogin.aspx%3fdirect%3dtrue%26db%3dcat04202a%26AN%3ducb.b24425606%26site%3deds-live

Admiraal, J. B. M. (2006). A bottom-up approach to the planning of underground space. Safety in the Underground Space - Proceedings of the ITA-AITES 2006 World Tunnel Congress and 32nd ITA General Assembly, 21(3), 464–465. https://doi.org/10.1016/j.tust.2005.12.102

Allen, F. W., Halloran, P. A., Leith, A. H., & Lindsay, M. C. (2009). Using Material Flow Analysis for Sustainable Materials Management. Journal of Industrial Ecology, 13(5), 662–665. https://doi.org/10.1111/j.1530-9290.2009.00168.x

Allison, M. A., Demas, C. R., Ebersole, B. A., Kleiss, B. A., Little, C. D., Meselhe, E. A., Powell, N. J., Pratt, T. C., & Vosburg, B. M. (2012). A water and sediment budget for the lower Mississippi–Atchafalaya River in flood years 2008–2010: Implications for sediment discharge to the oceans and coastal restoration in Louisiana. Journal of Hydrology, 432–433, 84–97. https://doi.org/10.1016/j.jhydrol.2012.02.020

Aoki-Suzuki, C., Bengtsson, M., & Hotta, Y. (2012). International Comparison and Suggestions for Capacity Development in Industrializing Countries: Policy Application of Economy-Wide Material Flow Accounting. Journal of Industrial Ecology, 16(4), 467–480. https://doi.org/10.1111/j.1530-9290.2012.00480.x

Baccini, P., & Brunner, P. H. (2012). Metabolism of the anthroposphere: Analysis, evaluation, design. Cambridge, Mass. : MIT Press, ©2012; cat04202a. https://libproxy.berkeley.edu/login?qurl=http%3a%2f%2fsearch.ebscohost.com%2flogin.aspx%3fdirect%3dtrue%26db%3dcat04202a%26AN%3ducb.b20558662%26site%3deds-live

Barbier, E. (2013). Valuing Ecosystem Services for Coastal Wetland Protection and Restoration: Progress and Challenges. Resources, 2(3), 213–230. https://doi.org/10.3390/resources2030213

Barnard, P. L., Schoellhamer, D. H., Jaffe, B. E., & McKee, L. J. (2013). Sediment transport in the San Francisco Bay Coastal System: An overview. Marine Geology, 345, 3–17. https://doi.org/10.1016/j.margeo.2013.04.005

Barragán, J. M., & de Andrés, M. (2015). Analysis and trends of the world's coastal cities and agglomerations. Ocean & Coastal Management, 114, 11–20. https://doi.org/10.1016/j.ocecoaman.2015.06.004

Bartrola, J., Martin, M. J., & Rigola, M. (2001). Issues in System Boundary Definition for Substance Flow Analysis: The Case of Nitrogen Cycle Management in Catalonia. The Scientific World JOURNAL, 1, 892–897. https://doi.org/10.1100/tsw.2001.260

Bayraktarov, E., Saunders, M.I., Abdullah, S., Mills, M., Beher, J., Possingham, H.P., Mumby, P.J. and Lovelock, C.E. (2016), The cost and feasibility of marine coastal restoration. Ecol Appl, 26: 1055-1074. Https://doi.org/10.1890/15-1077. (n.d.).

Becker, A., Chase, N. T. L., Fischer, M., Schwegler, B., & Mosher, K. (2016). A method to estimate climate-critical construction materials applied to seaport protection. Global Environmental Change, 40, 125–136. https://doi.org/10.1016/j.gloenvcha.2016.07.008

Berkowitz, J. F., Green, L., VanZomeren, C. M., & White, J. R. (2016). Evaluating soil properties and potential nitrate removal in wetlands created using an Engineering With Nature based dredged material placement technique. Ecological Engineering, 97, 381–388. https://doi.org/10.1016/j.ecoleng.2016.10.022

Bianchi, T. S., & Allison, M. A. (2009). Large-river delta-front estuaries as natural "recorders" of global environmental change. Proceedings of the National Academy of Sciences, 106(20), 8085–8092. https://doi.org/10.1073/pnas.0812878106

Biging, G. S., Radke, J. D., & Lee, J. H. (n.d.). IMPACTS OF PREDICTED SEA-LEVEL RISE AND EXTREME STORM EVENTS ON THE TRANSPORTATION INFRASTRUCTURE IN THE SAN FRANCISCO BAY REGION. 83.

Bobylev, N. (2009). Mainstreaming sustainable development into a city's Master plan: A case of Urban Underground Space use. Land Use Policy, 26(4), 1128–1137. https://doi.org/10.1016/j.landusepol.2009.02.003

Bolan, N., Kunhikrishnan, A., Thangarajan, R., Kumpiene, J., Park, J., Makino, T., Kirkham, M. B., & Scheckel, K. (2014). Remediation of heavy metal(loid)s contaminated soils – To mobilize or to immobilize? Journal of Hazardous Materials, 266, 141–166. https://doi.org/10.1016/j.jhazmat.2013.12.018

Boudreault, J.-P., Dubé, J.-S., Chouteau, M., Winiarski, T., & Hardy, É. (2010). Geophysical characterization of contaminated urban fills. Engineering Geology, 116(3), 196–206. https://doi.org/10.1016/j.enggeo.2010.09.002

Brand, L. A., Smith, L. M., Takekawa, J. Y., Athearn, N. D., Taylor, K., Shellenbarger, G. G., Schoellhamer, D. H., & Spenst, R. (2012). Trajectory of early tidal marsh restoration: Elevation, sedimentation and colonization of breached salt ponds in the northern San Francisco Bay. Ecological Engineering, 42, 19–29. https://doi.org/10.1016/j.ecoleng.2012.01.012

Brew DS, Williams PB. 2010. Predicting the impact of large-scale tidal wetland restoration on morphodynamics and habitat evolution in South San Francisco Bay, California. Journal of Coastal Research 26:912–924. (n.d.).

Bruce Mcdonald & Mark Smithers (1998) Implementing a waste management plan during the construction phase of a project: A case study, Construction Management and Economics, 16:1, 71-78, DOI: 10.1080/014461998372600. (n.d.).

Brunner, P. H., & Rechberger, H. (2004). Practical handbook of material flow analysis. Lewis.

Bullock, P. and Gregory, P. J. (1991) Soils: A neglected resource in urban areas. In Soils in the urban environment (P. Bullock and P. J. Gregory, eds.), pp. 1–5. Blackwell Scientific Publications, Oxford, Great Britain. (n.d.).

Cahoon, D.R., Lynch, J.C., Roman, C.T. et al. Evaluating the Relationship Among Wetland Vertical Development, Elevation Capital, Sea-Level Rise, and Tidal Marsh Sustainability. Estuaries and Coasts 42, 1–15 (2019). Https://doi-org.libproxy.berkeley.edu/10.1007/s12237-018-0448-x. (n.d.).

Cappucci, S., Bertoni, D., Cipriani, L. E., Boninsegni, G., & Sarti, G. (2020). Assessment of the Anthropogenic Sediment Budget of a Littoral Cell System (Northern Tuscany, Italy). Water, 12(11). https://doi.org/10.3390/w12113240

Cecchetti, A. R., Stiegler, A. N., Gonthier, E. A., Bandaru, S. R., Fakra, S. C., Alvarez-Cohen, L., & Sedlak, D. L. (2022). Fate of Dissolved Nitrogen in a Horizontal Levee: Seasonal Fluctuations in Nitrate Removal Processes. Environmental Science & Technology, 56(4), 2770-2782. (n.d.).

Cecchetti, A. R., Stiegler, A. N., Graham, K. E., & Sedlak, D. L. (2020). The horizontal levee: A multi-benefit nature-based treatment system that improves water quality and protects coastal levees from the effects of sea level rise. Water Research X, 7, 100052. https://doi.org/10.1016/j.wroa.2020.100052

Charlier, R. H., Chaineux, M. C. P., & Morcos, S. (2005). Panorama of the History of Coastal Protection. Journal of Coastal Research, 211, 79–111. https://doi.org/10.2112/03561.1

Chen, T. B., et al. "Assessment of trace metal distribution and contamination in surface soils of Hong Kong." Environmental pollution 96.1 (1997): 61-68. (n.d.).

Christensen, T. H., Cossu, R., & Stegmann, R. (1989). Sanitary landfilling: Process, technology and environmental impact. (Engineering TD795.7 .S266 1989). London ; San Diego : Academic Press, c1989.; cat04202a. https://libproxy.berkeley.edu/login?qurl=http%3a%2f%2fsearch.ebscohost.com%2flogin.aspx%3fdirect%3dtrue%26db%3dcat04202a%26AN%3ducb.b14571703%26site%3deds-live

Chun-Li Peng, Domenic E. Scorpio & Charles J. Kibert (1997) Strategies for successful construction and demolition waste recycling operations, Construction Management and Economics, 15:1, 49-58, DOI: 10.1080/014461997373105. (n.d.).

CLIMATE CHANGE IMPACTS, VULNERABILITIES, AND ADAPTATION IN THE SAN FRANCISCO BAY AREA. (n.d.). 67.

Cloern, J. E., Knowles, N., Brown, L. R., Cayan, D., Dettinger, M. D., Morgan, T. L., Schoellhamer, D. H., Stacey, M. T., van der Wegen, M., Wagner, R. W., & Jassby, A. D. (2011). Projected Evolution of California's San Francisco Bay-Delta-River System in a Century of Climate Change. PLOS ONE, 6(9), e24465. https://doi.org/10.1371/journal.pone.0024465

Connor, M. S., Davis, J. A., Leatherbarrow, J., Greenfield, B. K., Gunther, A., Hardin, D., Mumley, T., Oram, J. J., & Werme, C. (2007). The slow recovery of San Francisco Bay from the legacy of organochlorine pesticides. Environmental Research, 105(1), 87–100. https://doi.org/10.1016/j.envres.2006.07.001

Costanza, R., Pérez-Maqueo, O., Martinez, M. L., Sutton, P., Anderson, S. J., & Mulder, K. (2008). The Value of Coastal Wetlands for Hurricane Protection. Ambio, 37(4), 241–248. Http://www.jstor.org/stable/25547893. (n.d.).

Cox A.; Ireland P.; and Townsend M., 2006. Managing in Construction Supply Chains and Markets. Report, Thomas Telford. (n.d.).

Craul, P. J. (1992). Urban soil in landscape design. (Bioscience & Natural Resources S592.17.U73 C73 1992). New York : Wiley, c1992.; cat04202a. https://libproxy.berkeley.edu/login?qurl=http%3a%2f%2fsearch.ebscohost.com%2flogin.aspx%3fdirect%3dtrue%26db%3dcat04202a%26AN%3ducb.b15533967%26site%3deds-live

Daniella Hirschfeld & Kristina Hill. (2017). Choosing a Future Shoreline for the San Francisco Bay: Strategic Coastal Adaptation Insights from Cost Estimation. Journal of Marine Science and Engineering, 5(3), 42. https://doi.org/10.3390/jmse5030042

Davis JA, Hetzel F, Oram JJ, McKee LJ. Polychlorinated biphenyls (PCBs) in San Francisco Bay. Environ Res. 2007 Sep;105(1):67-86. Doi: 10.1016/j.envres.2007.01.013. Epub 2007 Apr 23. PMID: 17451673. (n.d.).

Dermont, G., Bergeron, M., Mercier, G., & Richer-Laflèche, M. (2008). Metal-contaminated soils: Remediation practices and treatment technologies. Practice periodical of hazardous, toxic, and radioactive waste management, 12(3), 188-209. (n.d.).

Diaz, D.B., 2016. Estimating global damages from sea level rise with the Coastal Impact and Adaptation Model (CIAM). Climatic Change, 137(1), pp.143-156. (n.d.).

D'Or, D., Demougeot-Renard, H., & Garcia, M. (2009). An Integrated Geostatistical Approach for Contaminated Site and Soil Characterisation. Mathematical Geosciences, 41(3), 307–322. https://doi.org/10.1007/s11004-009-9213-9

Du, S., Scussolini, P., Ward, P. J., Zhang, M., Wen, J., Wang, L., Koks, E., Diaz-Loaiza, A., Gao, J., Ke, Q., & Aerts, J. C. J. H. (2020). Hard or soft flood adaptation? Advantages of a hybrid strategy for Shanghai. Global Environmental Change, 61, 102037. https://doi.org/10.1016/j.gloenvcha.2020.102037

Duke, R. R., Stephens, P. D., Terrill, S., Shellhammer, H., Webb, E., Henkel, L., & Thomson, D. (2004). BAIR ISLAND RESTORATION PROJECT MONITORING PLAN. (n.d.).

Dusterhoff, S., McKnight, K., Grenier, L., and Kauffman, N. 2021. Sediment for Survival: A Strategy for the Resilience of Bay Wetlands in the Lower San Francisco Estuary. A SFEI Resilient Landscape Program. A product of the Healthy Watersheds, Resilient Baylands project, funded by the San Francisco Bay Water Quality Improvement Fund, EPA Region IX. Publication #1015, San Francisco Estuary Institute, Richmond, CA. (n.d.).

Effland, W. R., & Pouyat, R. V. (1997). The genesis, classification, and mapping of soils in urban areas. Urban Ecosystems, 1(4), 217–228. https://doi.org/10.1023/A:1018535813797

Fagherazzi, S., et al. (2012), Numerical models of salt marsh evolution: Ecological, geomorphic, and climatic factors, Rev. Geophys., 50, RG1002, doi:10.1029/2011RG000359. (n.d.).

Ferguson, L. E. (2018). A Gateway without a Port: Making and Contesting San Francisco's Early Waterfront. Journal of Urban History, 44(4), 603–624. https://doi.org/10.1177/0096144218759030

Ford, M. A., Cahoon, D. R., & Lynch, J. C. (1999). Restoring marsh elevation in a rapidly subsiding salt marsh by thin-layer deposition of dredged material. Ecological Engineering, 12(3–4), 189–205. https://doi.org/10.1016/S0925-8574(98)00061-5

Foster-Martinez, M. R., Lacy, J. R., Ferner, M. C., & Variano, E. A. (2018). Wave attenuation across a tidal marsh in San Francisco Bay. Coastal Engineering, 136, 26–40. https://doi.org/10.1016/j.coastaleng.2018.02.001

Goals Project. 2015. The Baylands and Climate Change: What We Can Do. Baylands Ecosystem Habitat Goals Science Update 2015 prepared by the San Francisco Bay Area Wetlands Ecosystem Goals Project. California State Coastal Conservancy, Oakland, CA . (n.d.).

Goovaerts, P. (2001). Geostatistical modelling of uncertainty in soil science. Estimating Uncertainty in Soil Models, 103(1), 3–26. https://doi.org/10.1016/S0016-7061(01)00067-2

Grenier, J. L., & Davis, J. A. (2010). Water quality in South San Francisco Bay, California: Current condition and potential issues for the South Bay Salt Pond Restoration Project. Reviews of environmental contamination and toxicology, 206, 115–147. Https://doi.org/10.1007/978-1-4419-6260-7_6. (n.d.).

Hale, S. E., Roque, A. J., Okkenhaug, G., Sørmo, E., Lenoir, T., Carlsson, C., Kupryianchyk, D., Flyhammar, P., & Žlender, B. (2021). The Reuse of Excavated Soils from Construction and Demolition Projects: Limitations and Possibilities. Sustainability, 13(11), 6083. https://doi.org/10.3390/su13116083

Hallegatte, S., Green, C., Nicholls, R. et al. Future flood losses in major coastal cities. Nature Clim Change 3, 802–806 (2013). Https://doi.org/10.1038/nclimate1979. (n.d.).

Hallegatte, S., Ranger, N., Mestre, O. et al. Assessing climate change impacts, sea level rise and storm surge risk in port cities: A case study on Copenhagen. Climatic Change 104, 113–137 (2011). Https://doi-org.libproxy.berkeley.edu/10.1007/s10584-010-9978-3. (n.d.).

Haltiner, J., Zedler, J. B., Boyer, K. E., Williams, G. D., & Callaway, J. C. (1996). Influence of physical processes on the design, functioning and evolution of restored tidal wetlands in California (USA). Wetlands Ecology and Management, 4(2), 73–91. https://doi.org/10.1007/BF01876230

Han, Q., Schaefer, W., & Barry, N. (2013). Land Reclamation Using Waste as Fill Material: A Case Study in Jakarta. 7(6), 10.

Hao, J. L., Hills, M. J., & Huang, T. (2007). A simulation model using system dynamic method for construction and demolition waste management in hong kong. Construction Innovation, 7(1), 7-21. Doi:https://doi.org/10.1108/14714170710721269. (n.d.).

Haycraft, W. R. (2000). Yellow steel: The story of the earthmoving equipment industry. (Institute for Research on Labor and Employment HD9715.25.U62 H39 2000). Urbana : University of Illinois Press, c2000.; cat04202a. https://libproxy.berkeley.edu/login?qurl=http%3a%2f%2fsearch.ebscohost.com%2flogin.aspx%3fdirect%3dtrue%26db%3dcat04202a%26AN%3ducb.b15816880%26site%3deds-live

Heberger, M., Cooley, H., Herrera, P., Gleick, P. H., & Moore, E. (2011). Potential impacts of increased coastal flooding in California due to sea-level rise. Climatic Change, 109(1), 229-249. (n.d.).

Hendriks, L. A. M., Leummens, H., Stein, A., & Bruijn, P. J. D. (n.d.). Use of Soft Data in a GIS to Improve Estimation of the Volume of Contaminated Soil. 18.

Hill, K. (2015). Coastal infrastructure: A typology for the next century of adaptation to sea-level rise. Frontiers in Ecology and the Environment, 13(9), 468–476. https://doi.org/10.1890/150088

Holmes, R., Burkholder, S., Holzman, J., King, J., & Suedel, B. (2022). Integrating Engineering With Nature® strategies and landscape architecture techniques into the Sabine-to-Galveston Coastal Storm Risk Management Project. Integrated Environmental Assessment and Management, 18(1), 63–73. https://doi.org/10.1002/ieam.4434

Hoover, D. J., Odigie, K. O., Swarzenski, P. W., & Barnard, P. (2017). Sea-level rise and coastal groundwater inundation and shoaling at select sites in California, USA. Journal of Hydrology: Regional Studies, 11, 234–249. https://doi.org/10.1016/j.ejrh.2015.12.055

Hu, M., Van Der Voet, E., & Huppes, G. (2010). Dynamic Material Flow Analysis for Strategic Construction and Demolition Waste Management in Beijing. Journal of Industrial Ecology, 14(3), 440–456. https://doi.org/10.1111/j.1530-9290.2010.00245.x

Hummel, M. A., Berry, M. S., & Stacey, M. T. (2018). Sea level rise impacts on wastewater treatment systems along the US coasts. Earth's Future, 6(4), 622-633. (n.d.).

Hummel Michelle A., Griffin Robert, Arkema Katie, & Guerry Anne D. (2021). Economic evaluation of sea-level rise adaptation strongly influenced by hydrodynamic feedbacks. Proceedings of the National Academy of Sciences, 118(29), e2025961118. https://doi.org/10.1073/pnas.2025961118

J. E. Neumann et al., Joint effects of storm surge and sea-level rise on US coasts: Neweconomic estimates of impacts, adaptation, and benefits of mitigation policy.ClimaticChange129, 337–349 (2014). (n.d.).

Katsumi, T. (2015). Soil excavation and reclamation in civil engineering: Environmental aspects. Soil Science and Plant Nutrition, 61(sup1), 22–29. https://doi.org/10.1080/00380768.2015.1020506

Kennedy, C., Pincetl, S., & Bunje, P. (2011). The study of urban metabolism and its applications to urban planning and design. Environmental Pollution, 159(8/9), 1965–1973. 8gh. https://libproxy.berkeley.edu/login?qurl=http%3a%2f%2fsearch.ebscohost.com%2flogin.aspx%3fdirect%3dtrue%26db%3d8gh%26AN%3d61258043%26site%3deds-live

Kirwan, M. L., & Megonigal, J. P. (2013). Tidal wetland stability in the face of human impacts and sea-level rise. Nature, 504(7478), 53–60. https://doi.org/10.1038/nature12856

Kleint, R. J. T., Nichollst, R. J., Ragoonaden, S., Capobianco, M., Astontt, J., & Buckley, E. N. (2022). Technological Options for Adaptation to Climate Change in Coastal Zones. 14.

Kondolf, G. M., Gao, Y., Annandale, G. W., Morris, G. L., Jiang, E., Zhang, J., ... & Yang, C. T. (2014). Sustainable sediment management in reservoirs and regulated rivers: Experiences from five continents. Earth's Future, 2(5), 256-280. (n.d.).

Kulp, S. A. & Strauss, B. H. New elevation data triple estimates of global vulnerability to sea-level rise and coastal flooding. Nat. Commun. 10, 4844 (2019). (n.d.).

Lawrence, J., Bell, R., Blackett, P., Stephens, S., & Allan, S. (2018). National guidance for adapting to coastal hazards and sea-level rise: Anticipating change, when and how to change pathway. Environmental Science & Policy, 82, 100–107. https://doi.org/10.1016/j.envsci.2018.01.012

Lawrence, J., Blackett, P., & Cradock-Henry, N. A. (2020). Cascading climate change impacts and implications. Climate Risk Management, 29, 100234. https://doi.org/10.1016/j.crm.2020.100234

Lin, CW. Mapping Soil Lead and Remediation Needs in Contaminated Soils. Environmental Geochemistry and Health 24, 23–33 (2002). Https://doi-org.libproxy.berkeley.edu/10.1023/A:1013949917278. (n.d.).

Liu, J., Dietz, T., Carpenter, S., Alberti, M., Folke, C., Moran, E., Pell, A., Deadman, P., Kratz, T., Lubchenco, J., Ostrom, E., Ouyang, Z., Provencher, W., Redman, C., Schneider, S., & Taylor, W. (2007). Complexity of Coupled Human and Natural Systems. Science (New York, N.Y.), 317, 1513–1516. https://doi.org/10.1126/science.1144004

Llatas, C. (2011). A model for quantifying construction waste in projects according to the European waste list. Waste Management, 31(6), 1261–1276. https://doi.org/10.1016/j.wasman.2011.01.023

Lubell, ., Stacey, M. & Hummel, M.A. Collective action problems and governance barriers to sea-level rise adaptation in San Francisco Bay. Climatic Change 167, 46 (2021). Https://doi-org.libproxy.berkeley.edu/10.1007/s10584-021-03162-5. (n.d.).

Macintosh, A. (2013). Coastal climate hazards and urban planning: How planning responses can lead to maladaptation. Mitigation and Adaptation Strategies for Global Change, 18(7), 1035–1055. https://doi.org/10.1007/s11027-012-9406-2

Mackenzie, J., Haggerty, S., Aguirre, A. C., Azumbrado, T., Bruins, J., Connolly, D., Cortese, D., Dutra-Vernaci, C., & Giacopini, D. M. (n.d.). Metropolitan Transportation Commission. 180.

Magnusson, S., Johansson, M., Frosth, S., & Lundberg, K. (2019). Coordinating soil and rock material in urban construction – Scenario analysis of material flows and greenhouse gas emissions. Journal of Cleaner Production, 241, 118236. https://doi.org/10.1016/j.jclepro.2019.118236

Magnusson, S., Lundberg, K., Svedberg, B., & Knutsson, S. (2015). Sustainable management of excavated soil and rock in urban areas – A literature review. Journal of Cleaner Production, 93, 18–25. https://doi.org/10.1016/j.jclepro.2015.01.010

Martín-Antón, M., Negro, V., del Campo, J. M., López-Gutiérrez, J. S., & Esteban, M. D. (2016). Review of coastal Land Reclamation situation in the World. Journal of Coastal Research, 75 (10075), 667–671. https://doi.org/10.2112/SI75-133.1

Matthews, E. (Ed.). (2000). The weight of nations: Material outflows from industrial economies. World Resources Institute.

McClintock, N. (2015). A critical physical geography of urban soil contamination. Geoforum, 65, 69–85. https://doi.org/10.1016/j.geoforum.2015.07.010

McGranahan, G., Balk, D., & Anderson, B. (2007). The rising tide: Assessing the risks of climate change and human settlements in low elevation coastal zones. Environment and Urbanization, 19(1), 17–37. https://doi.org/10.1177/0956247807076960

Mchergui, C., Aubert, M., Buatois, B., Akpa-Vinceslas, M., Langlois, E., Bertolone, C., Lafite, R., Samson, S., & Bureau, F. (2014). Use of dredged sediments for soil creation in the Seine estuary (France): Importance of a soil functioning survey to assess the success of wetland restoration in floodplains. Ecological Engineering, 71, 628–638. https://doi.org/10.1016/j.ecoleng.2014.07.064

Meuser, H. (2010). Contaminated Urban Soils (Vol. 18). Springer Netherlands. https://doi.org/10.1007/978-90-481-9328-8

Miles, A. K., & Ricca, M. A. (2010). Temporal and spatial distributions of sediment mercury at salt pond wetland restoration sites, San Francisco Bay, CA, USA. The Science of the total environment, 408(5), 1154–1165. Https://doi.org/10.1016/j.scitotenv.2009.10.04. (n.d.).

Milhous, R.T. (1998), Modelling of instream flow needs: The link between sediment and aquatic habitat. Regul. Rivers: Res. Mgmt., 14: 79-94. Https://doi-org.libproxy.berkeley.edu/10.1002/(SICI)1099-1646(199801/02)14:1<79::AID-RRR478>3.0.CO;2-9. (n.d.).

Milligan, B., & Holmes, R. (2017). Sediment is critical infrastructure for the future of California's Bay-Delta. 85(2), 13.

Möller, I., Kudella, M., Rupprecht, F., Spencer, T., Paul, M., Van Wesenbeeck, B.K., Wolters, G., Jensen, K., Bouma, T.J., Miranda-Lange, M. and Schimmels, S., 2014. Wave attenuation over coastal salt marshes under storm surge conditions. Nature Geoscience, 7(10), pp.727-731. (n.d.).

Morris, M. A., Spencer, K. L., Belyea, L. R., & Branfireun, B. A. (2014). Temporal and spatial distributions of sediment mercury in restored coastal saltmarshes. Estuarine Biogeochemistry, 167, 150–159. https://doi.org/10.1016/j.marchem.2014.09.010

Myers, R. J., Fishman, T., Reck, B. K., & Graedel, T. E. (2019). Unified Materials Information System (UMIS): An Integrated Material Stocks and Flows Data Structure: Unified Materials Information System. Journal of Industrial Ecology, 23(1), 222–240. https://doi.org/10.1111/jiec.12730

Narayan, S., Beck, M. W., Wilson, P., Thomas, C. J., Guerrero, A., Shepard, C. C., Reguero, B. G., Franco, G., Ingram, J. C., & Trespalacios, D. (2017). The Value of Coastal Wetlands for Flood Damage Reduction in the Northeastern USA. Scientific Reports, 7(1), 9463. https://doi.org/10.1038/s41598-017-09269-z

Nicholls, R. J. (2004). Coastal flooding and wetland loss in the 21st century: Changes under the SRES climate and socio-economic scenarios. Climate Change, 14(1), 69–86. https://doi.org/10.1016/j.gloenvcha.2003.10.007

Perry, D. C., Chaffee, C., Wigand, C., & Thornber, C. (2020). Implementing adaptive management into a climate change adaptation strategy for a drowning New England salt marsh. Journal of Environmental Management, 270, 110928. https://doi.org/10.1016/j.jenvman.2020.110928

Pitlick, J., & Wilcock, P. (2001). Relations between streamflow, sediment transport, and aquatic habitat in regulated rivers. Geomorphic processes and riverine habitat, 4, 185-198. (n.d.).

Plane, E., Hill, K., & May, C. (2019). A Rapid Assessment Method to Identify Potential Groundwater Flooding Hotspots as Sea Levels Rise in Coastal Cities. Water, 11(11), 2228. https://doi.org/10.3390/w11112228

Prem Chhetri, Jonathan Corcoran, Victor Gekara, Chris Maddox & Darryn McEvoy (2015) Seaport resilience to climate change: Mapping vulnerability to sea-level rise, Journal of Spatial Science, 60:1, 65-78, DOI: 10.1080/14498596.2014.943311. (n.d.).

Ready, M. J., & Ready, R. C. (1995). Optimal Pricing of Depletable, Replaceable Resources: The Case of Landfill Tipping Fees. Journal of Environmental Economics and Management, 28(3), 307–323. https://doi.org/10.1006/jeem.1995.1020

Rosado, L., Niza, S., & Ferrão, P. (2014). A Material Flow Accounting Case Study of the Lisbon Metropolitan Area using the Urban Metabolism Analyst Model: The Urban Metabolism Analyst Model. Journal of Industrial Ecology, 18(1), 84–101. https://doi.org/10.1111/jiec.12083

R.,V. Glasow, T.,D. Jickells, A. Baklanov, G.,R. Carmichael, T.,M. Church, L. Gallardo, et al. Megacities and large urban agglomerations in the coastal Zone: Interactions between atmosphere, land, and marine ecosystems The Rolyal Swedish Academic of Scniences, 42 (2013), pp. 13-28, 10.1007/s13280-012-0343-9. (n.d.).

S. Brown, R.J. Nicholls, C.D. Woodroffe, S. Hanson, J. Hinkel, A.S. Kebede, et al. Sea-level rise impacts and responses: A global perspective (117–149) Springer, Netherlands (2013), 10.1007/978-94-007-5234-4_5. (n.d.).

Sauerwein, M. (2011). Urban soils–characterization, pollution, and relevance in urban ecosystems. NIEMELÄ, Jari; BREUSTE, Jürgen H.; ELMQVIST, Thomas, 45-58. (n.d.).

Schoellhamer, D. H., Mumley, T. E., & Leatherbarrow, J. E. (2007). Suspended sediment and sediment-associated contaminants in San Francisco Bay. Environmental research, 105(1), 119–131. Https://doi.org/10.1016/j.envres.2007.02.002. (n.d.).

Schoellhamer, D. H., Wright, S. A., & Drexler, J. Z. (2013). Adjustment of the San Francisco estuary and watershed to decreasing sediment supply in the 20th century. Marine Geology, 345, 63–71. https://doi.org/10.1016/j.margeo.2013.04.007

Schwab, O., Laner, D., & Rechberger, H. (2017). Quantitative Evaluation of Data Quality in Regional Material Flow Analysis: Data Quality in MFA. Journal of Industrial Ecology, 21(5), 1068–1077. https://doi.org/10.1111/jiec.12490

Seasholes, N. S. (2003). Gaining ground: A history of landmaking in Boston. (Environmental Design F73.3 .S46 2003). Cambridge, Mass. : MIT Press, c2003.; cat04202a. https://libproxy.berkeley.edu/login?qurl=http%3a%2f%2fsearch.ebscohost.com%2flogin.aspx%3fdirect%3dtrue%26db%3dcat04202a%26AN%3ducb.b16014820%26site%3deds-live

SFEI and SPUR. 2019. San Francisco Bay Shoreline Adaptation Atlas: Working with Nature to Plan for Sea Level Rise Using Operational Landscape Units. Publication #915, San Francisco Estuary Institute, Richmond, CA. Version 1.0 (April 2019). (n.d.).

Shellenbarger, G. G., Wright, S. A., & Schoellhamer, D. H. (2013). A sediment budget for the southern reach in San Francisco Bay, CA: Implications for habitat restoration. Marine Geology, 345, 281–293. https://doi.org/10.1016/j.margeo.2013.05.007

Shirzaei, M., & Bürgmann, R. (2018). Global climate change and local land subsidence exacerbate inundation risk to the San Francisco Bay Area. Science Advances, 4(3), eaap9234. https://doi.org/10.1126/sciadv.aap9234

Soulsby, C., Youngson, A. F., Moir, H. J., & Malcolm, I. A. (2001). Fine sediment influence on salmonid spawning habitat in a lowland agricultural stream: A preliminary assessment. Science of the Total Environment, 265(1-3), 295-307. (n.d.).

Spencer, T., Schuerch, M., Nicholls, R. J., Hinkel, J., Lincke, D., Vafeidis, A. T., Reef, R., McFadden, L., & Brown, S. (2016). Global coastal wetland change under sea-level rise and related stresses: The DIVA Wetland Change Model. Global and Planetary Change, 139, 15–30. https://doi.org/10.1016/j.gloplacha.2015.12.018

Sprankling, J. G. (2008). Owning the Center of the Earth. UCLA LAW REVIEW, 63.

Stagg, C. L., & Mendelssohn, I. A. (2011). Controls on resilience and stability in a sediment-subsidized salt marsh. Ecological Applications, 21(5), 1731-1744. (n.d.).

Staudt, F., Gijsman, R., Ganal, C., Mielck, F., Wolbring, J., Hass, H. C., Goseberg, N., Schüttrumpf, H., Schlurmann, T., & Schimmels, S. (2021). The sustainability of beach nourishments: A review of nourishment and environmental monitoring practice. Journal of Coastal Conservation, 25(2), 34. https://doi.org/10.1007/s11852-021-00801-y

Steding, D. J., Dunlap, C. E., & Flegal, A. R. (2000). New isotopic evidence for chronic lead contamination in the San Francisco Bay estuary system: Implications for the persistence of past industrial lead emissions in the biosphere. Proceedings of the National Academy of Sciences, 97(21), 11181–11186. https://doi.org/10.1073/pnas.180125697

Sun, H., Grandstaff, D., & Shagam, R. (1999). Land subsidence due to groundwater withdrawal: Potential damage of subsidence and sea level rise in southern New Jersey, USA. Environmental Geology, 37(4), 290-296. (n.d.).

Swain, D. L. (2021). A shorter, sharper rainy season amplifies California wildfire risk. Geophysical Research Letters, 48(5), e2021GL092843. (n.d.).

Taillardat, P., Thompson, B., Garneau, M., Trottier, K., & Friess, D. (2020). Climate change mitigation potential of wetlands and the cost-effectiveness of their restoration. Interface Focus: A Theme Supplement of Journal of the Royal Society Interface, 10. https://doi.org/10.1098/rsfs.2019.0129

Tarr, J. A. (1996). The Search for the Ultimate Sink. [Electronic resource]: Urban Pollution in Historical Perspective. Akron, Ohio : University of Akron Press, 1996. (Baltimore, Md. : Project MUSE, 2015); cat04202a. https://libproxy.berkeley.edu/login?qurl=http%3a%2f%2fsearch.ebscohost.com%2flogin.aspx%3fdirect%3dtrue%26db%3dcat04202a%26AN%3ducb.b21470849%26site%3deds-live

Temmerman, S., & Kirwan, M. L. (2015). Building land with a rising sea. Science, 349(6248), 588–589. https://doi.org/10.1126/science.aac8312

Tessler, Z. D., Vörösmarty, C. J., Overeem, I., & Syvitski, J. P. M. (2018). A model of water and sediment balance as determinants of relative sea level rise in contemporary and future deltas. Geomorphology, 305, 209–220. https://doi.org/10.1016/j.geomorph.2017.09.040

Torio, D.D. and Chmura, G.L., 2013. Assessing coastal squeeze of tidal wetlands. Journal of Coastal Research, 29(5), pp.1049-1061. (n.d.).

Vähäaho, I. (2016). An introduction to the development for urban underground space in Helsinki. Tunnelling and Underground Space Technology, 55, 324–328. https://doi.org/10.1016/j.tust.2015.10.001

Valiela, I., Lloret, J., Bowyer, T., Miner, S., Remsen, D., Elmstrom, E., Cogswell, C., & Robert Thieler, E. (2018). Transient coastal landscapes: Rising sea level threatens salt marshes. Science of The Total Environment, 640–641, 1148–1156. https://doi.org/10.1016/j.scitotenv.2018.05.235

Van Meirvenne, M., & Goovaerts, P. (2001). Evaluating the probability of exceeding a site-specific soil cadmium contamination threshold. Geoderma, 102(1), 75–100. https://doi.org/10.1016/S0016-7061(00)00105-1 van Slobbe, E., de Vriend, H. J., Aarninkhof, S., Lulofs, K., de Vries, M., & Dircke, P. (2013). Building with Nature: In search of resilient storm surge protection strategies. Nat Hazards, 20.

Verhoeven, J. T. A., Soons, M. B., Janssen, R., & Omtzigt, N. (2008). An Operational Landscape Unit approach for identifying key landscape connections in wetland restoration. Journal of Applied Ecology, 45(5), 1496–1503. https://doi.org/10.1111/j.1365-2664.2008.01534.x

Vileisis, A. (1999). Discovering the unknown landscape: A history of America's wetlands. Island Press. (n.d.).

Villoria Sáez, P., & Osmani, M. (2019). A diagnosis of construction and demolition waste generation and recovery practice in the European Union. Journal of Cleaner Production, 241, 118400. https://doi.org/10.1016/j.jclepro.2019.118400

Wilby, R. L. (n.d.). A Review of Climate Change Impacts on the Built Environment. CLIMATE CHANGE AND CITIES, 33(1), 15.

Williams, P. B., & Orr, M. K. (2002). Physical Evolution of Restored Breached Levee Salt Marshes in the San Francisco Bay Estuary. Restoration Ecology, 10(3), 527–542. https://doi.org/10.1046/j.1526-100X.2002.02031.x

Wong, C. S. C., & Li, X. D. (2004). Pb contamination and isotopic composition of urban soils in Hong Kong. Science of The Total Environment, 319(1), 185–195. https://doi.org/10.1016/S0048-9697(03)00403-0

Zhao, Q., Bai, J., Huang, L., Gu, B., Lu, Q., & Gao, Z. (2016). A review of methodologies and success indicators for coastal wetland restoration. Ecological Indicators, 60, 442–452. https://doi.org/10.1016/j.ecolind.2015.07.003

Conclusion

The work undertaken for this dissertation seeks both to broadly frame and deeply examine an emergent challenge of the climate change era that will come to matter dramatically to developed shorelines in coming decades. While sea level rise is employed as the umbrella term for the climate phenomenon of interest, we can understand it as wicked in the sense that it actually entails many different interacting challenges that cut across domains. Accordingly, while certain physical realities related to the material and industrial ecologies of resources are the subject of the work here, they lead us to consider their meaning and implications in deeper ways. Some basic insights connecting the core chapters may be useful to reflect upon.

First, it is interesting to consider how general notions related to adaptation discussed in chapter one relate to the particular case study and its management of sediment resources discussed in chapters two and three. The SF Bay is grappling with a clear adaptation situation as embodied by its increasingly tenuous sediment deficit—analogous to an adaptation gap. Similarly, the region recognizes that sediment is crucial in terms of its adaptive capacity; though this resource is also limited. Barriers to adaptation exist in practically every sense imaginable: from hurdles presented by outmoded regulations to the difficulty in long-term financing of equitable approaches to the problem itself. How its various adaptive management processes might play out in the context of broader adaptation planning will depend, to no small extent, on the various ways in which organizations and institutions resist or overcome the lock-in and path dependent effects that a sediment-as-waste-product paradigm will tend to perpetuate; thus reducing adaptive capacity in the overall system and region. In turn, the industrial and development processes that connect sediment supplies (and the capacity they may confer) to the demand that instrumentalizes them (as adaptation projects) embody tensions based on private sector for-profit operations that cleave to an unsustainable resource management model (and the maladaptive outcomes it promulgates) which is, to some degree, rendered at the mutual exclusion of the broader public interest.

The mechanisms by which this happens are linked to processes explored and articulated in the second chapter: wherein processes of urban development—literally the means of production of urban space—are arranged such that a dominant classification logic for dictating the flows of excavated soil and sediment render this resource as a byproduct of urban development and metabolism—perhaps (or increasingly) even urbanism itself.

Accordingly, and in a strange kind of marriage of convenience, environmental contractors, developers and landfill operators are incentivized towards a highly wasteful resource regimen: one in which considerations of the opportunity costs associated with landfilling sediment are externalized. That is, for the broader public and future generations, we can see the makings of a vexing but predictable market failure. This, of course, is also true of and applies to the environmental justice dimensions of the interconnected problem aspects illustrated herein: in particular, starkly evident in the potential calamity of coastal squeeze and wetland drowning occurring as a function of not reusing urban sediment resources in adaptation and restoration schemes.

Insofar as the work establishes the nature of multi-year construction projects that will be involved in constructing horizontal levees and ecotones with excavated sediment in San Mateo County, and especially given the profoundly outmoded governance of these resources, major innovations are both possible and increasingly important efforts in which to invest. In no small part, there is a need for leadership to mandate and streamline basic permitting and reporting standards across broad organizational fields and more meaningful spatial scales and with the intent of aiding an overall climate adaptation paradigm that will come to dominate so many resource issues in the region—whether we actively prepare for this eventuality or not. This dissertation is proof both of the willingness of government agencies and offices to help in processes geared towards adaptation, and of the severely difficult reality of doing so as a function of byzantine record-request processes, redundancy, lack of clarity and countless dead-ends. If nothing else, the research stands as its own testament and justification for the need for advances in statistical modeling techniques that can overcome some of these barriers, which is a hallmark of much applied industrial ecology work.

These entanglements—of data and offices, leadership and the status quo, resources and governance in complex socioenvironmental settings—also emphasize another lesson of the work: the all-too-familiar hot potato cliché. In short, and because of a lack of leadership, coordination and (maybe most fundamentally) communication and awareness, various actors within the overall network connected to anthropogenic sediment management in an urban shoreline act independently, and this produces enormous shortcomings in the efficiency of work that might otherwise be possible. Perhaps this is an central lesson related to the complexity of planning processes where multiple stakeholders, procurements, and various scenarios complicate problems and tend to increase uncertainty. But the factionalizing and balkanizing effects of narrowly-defined mandates that don't generate broader platforms for cooperation and coordination are, to some extent, institutional issues: and they are, as such, possible to overcome with changes in *culture*--maybe especially as it relates to the values and priorities that come to constitute a definition and understanding of the public interest.

Yet there, also, we encounter another need for adaptation; or at least another role for it to play in this context. That is, some sense of our public interest and public good must emerge and evolve as a function of the severity, enormity and complexity of climate change and the risks and hazards it poses. In chapter one, we encountered this articulated as institutional adaptation itself. In the real world, theories about how and why institutional adaptation happen may be of limited value. What is surely of immense value, on the other hand, is the illustrative power of seeing and showing how our public interest is tied to its resources and in ways that implicate multiple levels of governance and the cross-sector actors whose mission, mandate or profit margins are linked to the management of these resources. In her pioneering work on common pool resources, Elinor Ostrom explored how collective (or collectivized) sensibilities about justice and equity were at play in adjudicating aspects of the physical world which might not, at first blush, seem to speak to higher ideals and deeper meaning in terms of societal ethics and intergenerational and interspecies justice. Ostrom's work illustrates a recognition of these realities—those at the intersections of aspirational ethics and seemingly uninteresting logistics—as a profoundly rich place, both in terms of the environmental problems they frame and the possibilities for interrogating them.

Insofar as this work may hold some insights for those engaged in the strategic adaptation of systems and places to climate change, a central tenet of strategic planning is helpful to finally reflect upon and consider in context. Strategic planning requires an articulation of the goals of some enterprise (the ends) and how the resources (means) required to realize these goals are, or can become, possessed by those engaged in the undertaking. Two things are important to note about this axiomatic principle. First, in terms of how resources are captured or collected, enormous variety and flexibility can exist: thus the techniques, technologies and tools for realizing goals may be diverse, adaptive and even unprecedented. In that sense, the "how" might be a matter of practicalities, timing or sheer will—and perhaps all of the above in some measure. In this sense, slippery concepts related to chaos, chance and the human commitment to addressing some challenge come into play, and often in unexpected ways, when plans attempting to realize some future state of affairs is attempted. This echoes the notion that adaptability is, to some extent, a process of realizing and seizing opportunities as they emerge.

The second consideration of strategic planning's implied definition concerns what happens when one's ends and means do not comport. In turn, this situation demands that one of two things happen or that, all things being equal, a third inevitably will. Namely, one must identify and adopt a new goal if the resources are insufficient to achieve the original one; or else the something about the resources—their collection, allocation, definition, status, utilization, etc.—must themselves be changed in order to reach said goal. If neither of these adaptations can be made to address the disparity between means and ends, the strategy fails. Consider this in the context of the SF Bay Area explored here. The region has identified widespread wetland restoration as a crucial climate adaptation goal. It has passed legislation and funding provisions to accomplish this end. The physical (sediment) resources to realize the goal are not assessed to emerge in the expected sequence of events or state of affairs that scientists have projected will play out without massive human intervention. Thus we see the choice starkly emerging: does the region change its stated goals, or ways in which it marshals its resources?

This dissertation does not tell us the answer, of course: it serves to frame the question. And in the ever-changing context of climate change affecting an entire, complex regional landscape, there may be any number of answers that must be conjured. What we can see in the work is that even in something as mundane as the way that our society chooses (and/or fails to change its choices about) how it "throws away dirt", a wildly rich, complex and important world of possibilities also exists: wherein there lies an adaptation pathway built on something as understated and simple as a ramp of subtly sloping soil. This microtopographic feature of the landscape is a constructed landform: one that may protect our society from flooding, and our most vulnerable the most of all; it may stave off the cataclysmic collapse of our wetlands and global flyways, and resist catastrophic losses in biodiversity; it may save our region many billions of dollars in avoided costs and through protection of existing infrastructure; it might improve water quality and reduce the throughput of contaminants into the Bay itself; it may form the backbone of extensive networks of public open spaces and natural resources; and, in these ways, it may serve as a deep investment in our region's future and the health, safety, welfare and justice of countless people.

This modest landform does any of this only if it is actually constructed, of course. And it will only ever *be* constructed if the decision makers of the region decide that new modes of public, environmental and resource stewardship can and should be realized and embraced: in short, the broad, strategic inception, and deep implementation of climate change adaptation; and the myriad efforts involved in its planning.

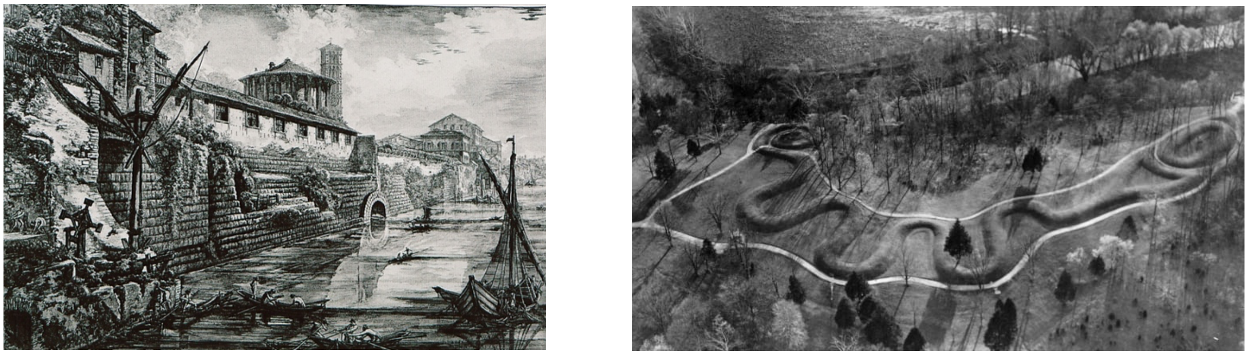
Introduction: Human Beings As Geomorphic Agents

The impetus to intervene in the landscape by physically manipulating landform was historically most pressing in settlements adjacent to waterways and waterbodies for the purposes of preventing or controlling flooding and building commercially useful space. At the shoreline, shaping the landscape to establish desirable topographic relief offered a way of capitalizing resources and space in multiple ways: initially by removing soil from steep ground considered more difficult to develop (thereby improving it) and subsequently depositing it at the shore to create flat, low, valuable real estate (by "reclaiming" it from waters and wetlands). After industrialization, the disposal practices of urban and industrial wastes increasingly utilized excavated soils as a material for 'capping' wastes – at the shoreline and inland landfill sites alike.

This dissertation expands on a central thesis: the role of managed soil and sediment is poised to change dramatically in the 21st century. As human population rises, and people increasingly settle in ever-more dense (often coastal) cities, they will expand their built environment and excavate umpteen volumes of sediment doing so. Currently, dominant regimes defining the management of this resource view and treat it as a waste-product; and it is often ultimately and irretrievably interred in landfills. The relationship between these processes and resources may dramatically change in the climate change era. We consider themes and theories for contextualizing and situating this concept in relevant processes, patterns, places and problems related to earthworks, focusing on coastal urban development, design and planning.

Beginnings of Anthropogenic Earthworks

Humans have proved prodigious shapers of the face of the earth: manipulating landform to capture and control natural processes: in the Neolithic drive towards agrarian settlements; in the building of mounds and mounts for spiritual and civic purposes; in the urban society-building process; and in myriad other endeavors of environmental alteration since (Douglas, 2000; Hooke, 2012; Morrish, 2010; Pollock, 1999; Price, 2011; Sjoberg, 1960; Yoshida, 2018; McEvoy, 2004; Wilkinson, 2014). Often credited to Napoleon Bonaparte, the axiom "geography is destiny" implies an elegant and profound idea about humans and their place on earth. Yet it risks overlooking an important aspect of the human condition: where manipulation of the landscape could alter natural processes of the site, area, or region, manifold effects might result -- intentional and otherwise (and often both) (Harrison, 1992; Reisner, 1993; Scott, 1998). In this way, humans have explored ways of engineering geography; and perhaps bending the arc of destiny to their will. Doing so inevitably seemed to entail the physical reworking of landform.



Form and Void: The 6th Century BC Cloaca Maxima of Rome's outfall at the Tiber River (Left) is still in existence and partially functional, thus sometimes referred to as the least expensive infrastructure ever built. While essentially invisible, its construction nonetheless involved extensive earthwork. (R): 3rd Century BC Adenaen Serpent Mound in Midwestern America: a notable earthwork of altogether different form and intent. University of San Francisco.

Manipulation of Landform in North American Cities: 1700-Present

Setting the Scene: Relevant Context and Trends: America in 1700-1850

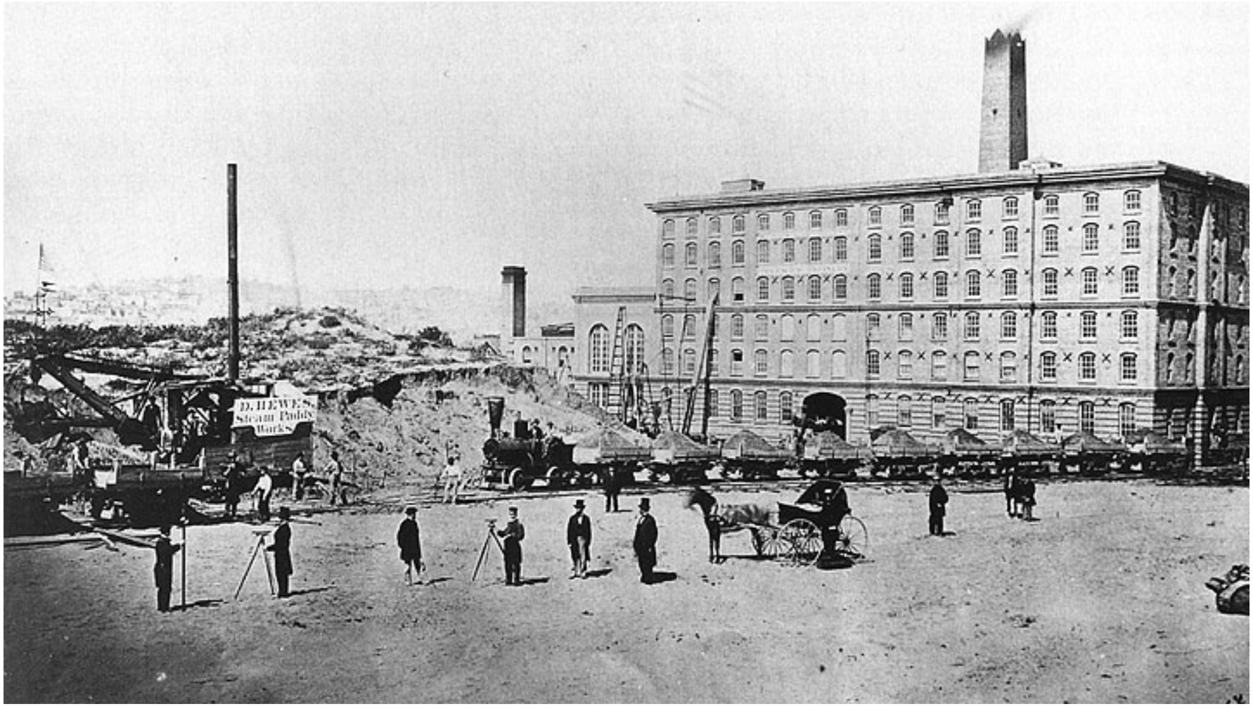
Understanding the patterns and processes of growth, industrialization and urbanization that led to the America of the mid-19th century requires consideration of several important trends and projects leading up to the era. Port cities were critical outposts in colonial times: access to natural resources, safe harbors and inland waterways made shallow bays and estuaries ideal loci of commerce, culture and the local urban development they engendered (ULI, 1983). Demand for waterfront access (wharves and docks) and flat, low ground to build urban space led to a common practice: land filling by deposition of all manner of material to establish vast swaths of constructed waterfront (Spirn, 1984). Urban development and functions found this the preferable condition for the logistical avoidance of schlepping goods uphill and the relative ease of siting and constructing buildings on flatlands and gradual grades. Laying low local hills relief yielded material for expanding land (by filling) while also producing lower, flatter ground in turn, thus improving it (Lockwood, 1978).

Extensive canals connected New England's port cities to points west. The Erie and Pennsylvania Mainline Canals were highly sophisticated, hundreds-of-miles-long constructions at the height of the "Canal Age" (Nye, 1994; Shaw, 1990). Enormous volumes of earthen material had to be dug and blasted out of their alignments, where horse carts and countless men did the digging (Haycraft, 2000). The Erie canal likely entailed the excavation of 11 million cubic yards of earth: side-casted to build a towpath levee (Clark, 1985; Shaw, 1990). Sanitation efforts in early American cities drove another suite of excavation processes that laced through cities and reached far into the hinterlands alike (Cronon, 1992; Granick, 1991; Nye, 1994). Outbreaks of typhoid, yellow fever, malaria, cholera and dysentery plagued early cities, and urban water was complicit in them all (Melosi, 2000). Inadequate drainage, tainted aquifers, and the need to convey drinking, wastewater and stormwater led to mass excavations to bury pipes and aqueducts beneath cities, in addition to the earthworks involved in trenching and tunneling through countryside, damming reservoirs and building levees (Gandy, 2002; Granick, 1991). Civil Engineering emerged as a formalized discipline to tackle these prominent and emergent challenges of the day (reclamation, transportation, sanitation), and America's first Engineering school was founded in 1820 (Melosi, 2000). Steam-powered plows began to revolutionize agriculture in North America, starting in the 1830s, and steam shovels and trains were used to reduce topography to cartloads of soil, sand and stone: very often to shunt the spoils to the shoreline (Lockwood, 1978; Spirn, 1984).

The Industrialized City: 1850-1950

Civil Systems: Infrastructure and its Earthworks

Enormous national growth and change characterized the decades leading up to the mid-19th Century, and the 1850 Gold Rush essentially began to reformat the political, population and economic dynamics of the nation (Caughey, 1975; Cronon, 1992). Millions of Europeans arrived, though the growth of cities was also due to migration from outlying rural areas -- partially a function from steam-powered agricultural machinery's rise, though increasingly it was put to use in other earthworks (Caughey, 1975; Haycraft, 2000; McKelvey, 1963; Miller, 1987; Mumford, 1961). If anything, the westward expansion and migration triggered by the Gold Rush made the imperative for large, dense, and prosperous cities on the East Coast and Great Lakes all the more important: driving towards an unprecedented level of interconnectedness, due in no small part to the 1869 transcontinental Railroad linkage, an enterprise entailing a network of innumerable earthworks to construct (Cronon, 1992; Nye, 1994; Schuyler, 1986; Tarr, 1996).

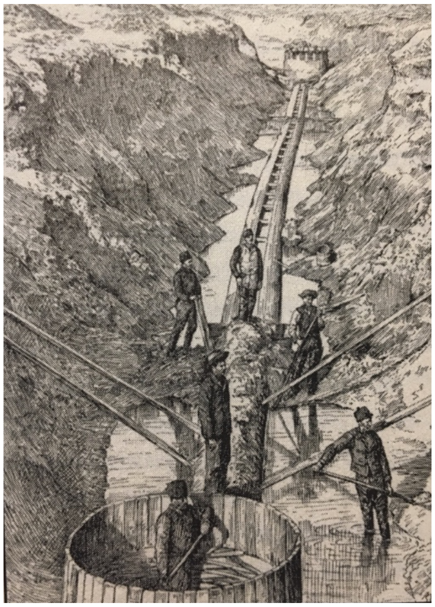


Above: San Francisco in the 1850s, as the region's extensive "wharfing out" period began in earnest. The sign reads, "D. Hewes Steam Paddy Works". Note the steam locomotive with carts full of soil surely headed to the shoreline; the flattened, barren expanse in the foreground; and the scrub-covered hill being reaped, center-left. Bancroft Library.

As the built environment spread, its infrastructural networks did too, and countless projects to underground pipelines and other provisional networks accompanied the landforms of development: graded hills and parcels; cuts through relief for roads and rails; dam-building; and excavating innumerable cellars, vaults, tunnels and basements. The trolley replaced the horse as electrification, emerging slowly in the 1880s, altered transport and energy regimes, adding layers to the underground in cities and suburbs (Granick, 1991; Kaika, 2005; Nye, 1994). Influential notions about how modernity might be physically constructed coalesced across the pond: Hausmann's 1850s "rationalization" of Parisian space established the souterrain as an urban "underground service layer" (Gandy, 2014). Bazalgette's massive 1860s sewerage and Thames River improvement project illustrated the potential balance between "cutting" and "filling" in a developed city, as trenches for sewers yielded spoils for remaking the Thames' newly bulkheaded banks and reinventing the basic hydrology of the city through the manipulation of land (Halliday, 1999).

Above: 1862 drawing of the St Martin canal (left) beneath Paris, being used for transport, which coincided with Hausmann's extensive renovation and the major sanitation infrastructure overhaul it sought to provide (middle). Photo of Thames River outfall into the River Lea (right), also in 1862. Royal College London

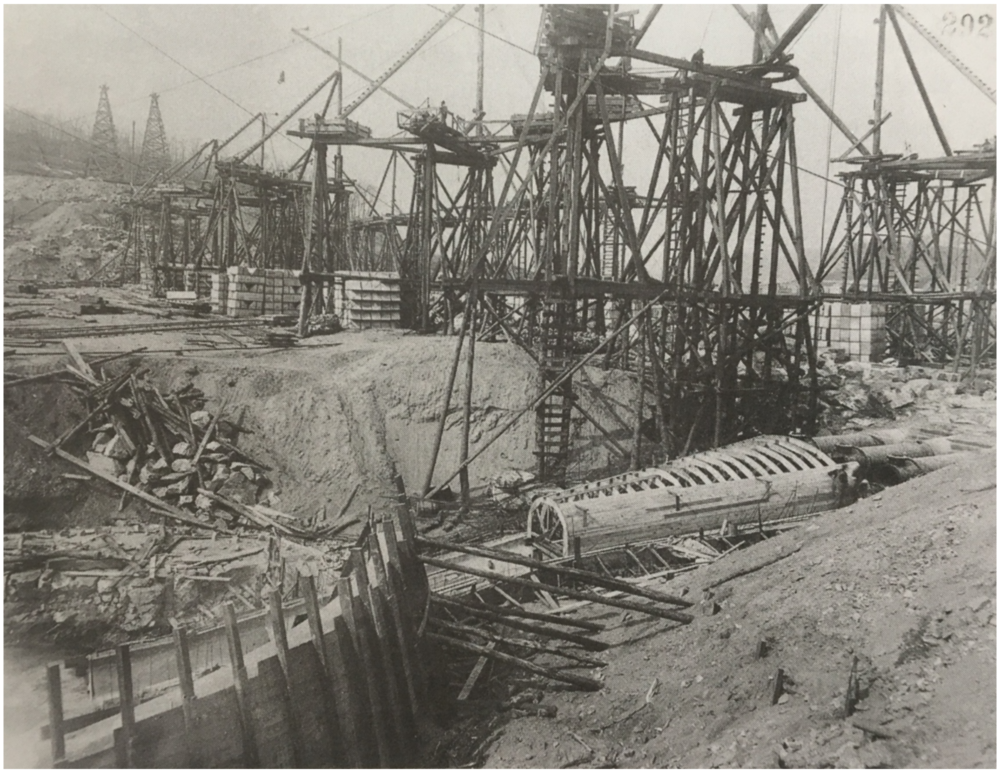
By the 1880s, centralized steam networks for municipal heat joined the urban underground, and engineers were gifted new powers with the 1890 invention of the Diesel internal combustion engine, widely deployed in endeavors ranging from agriculture (its raison d'être) to other earthmoving uses involved in mining, tunneling, and marine dredging (Granick, 1991; Haycraft, 2000; Melosi, 2000). Railroads extended suburbs, furthering their demand for civil infrastructure, much of it underground (Cronon, 1992; Miller, 1987; Spirn, 1998).



Above: A photograph (L) and drawing (R) of workers laying a 4′-diameter redwood water pipe in a ~1900 Denver, CO trench. 10,000 cubic yards of earth is displaced per-mile of pipe. In the 1880s and 1890s, the number of national waterworks increased faster than the population grew (Melosi, 2000). UCD; Engineering News.

Above: A 1910 cutaway drawing of a "city of flows", showing Paris' Place d'Opera metro and the urban underground. While intricate and impressive, the drawing actually omits numerous other layers of Hausmann's urban "service layer" that the souterrain provided to the City of Lights: including energy (hence the lights) and sanitary services. Mumford cited the "Underground City" as a natural outgrowth of urbanization. Popular Mechanics.

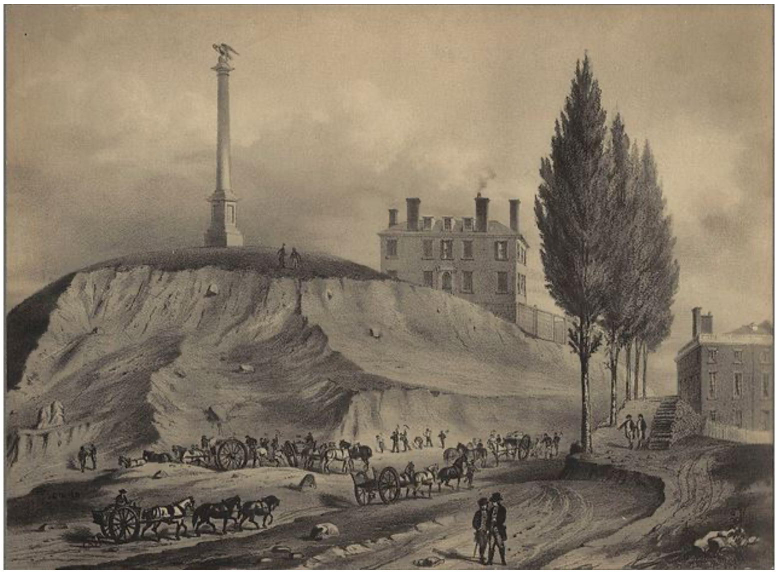
The rapid growth of the nation's cities continued to build a palimpsest of subterranean networks laced through increasingly tall, dense cities; networks inevitably requiring expansion, growth, repair and adaptation (Granick, 1991). This "city of flows" facilitated the movement of resources, goods, wastes, energy and people -- influenced by ever-expanding markets, technological mobility and a sense of control over commodities, resources, and perhaps nature itself (Cronon, 1992; Gandy, 2002; Kaika, 2005; Nye, 1994). Private automobilization redefined urban form everywhere in the 1920s and 30s, inevitably finding its way underground; and natural gas replaced coal in many cities by the 1940s, necessitating a novel underground distribution network of pipelines and storage wells (Mumford, 1961; Tarr, 1996).



Above: Croton Falls Dam, NY, 1909. Provisioning an urban enclave with various resources often entailed earthworks in the hinterlands (and connecting them, see previous picture) and many unintentional consequences for aquatic ecosystems and sediment flows to shorelines resulted. NY Historical Society.

The Making of Land near Water

Providing and ever-growing urban population with housing, services, and resources challenged growing port cities, which also contended constantly with the urban-industrial woes of the era (Melosi, 2000; Tarr, 1996). As ships grew, their drafts deepened. The sheer scale and tempo of commerce ticked up; extensive wharves, quays and proximal storage, processing and distribution facilities were built, very often on reclaimed land made from shallowing waters and wetlands (Whitehill & Kennedy, 2000).



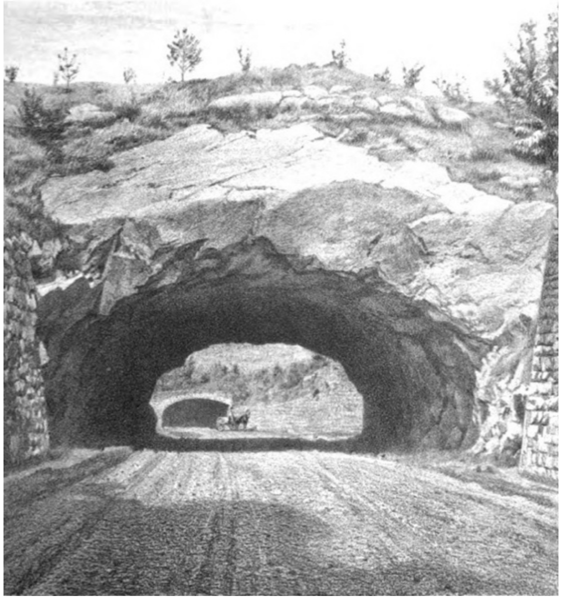
Above: Boston's Beacon Hill (~1890s) was not safe in the "wharfing-out" era, in which doing so was understood as a compound benefit: a more easily-traversed city was graded, while its waterfront expanded, and landowners were paid for the soil and sand reaped (Seasholes, 2003). Boston Historical Society.

To facilitate the near-constant rearticulation and growth of urban shorelines, waterfront cities employed all manner of technological means to source, transport and deposit materials. Commonly, earthen levees, or piles driven into the watery ground hemmed in reaches of shoreline -- in coastal estuaries, riverfronts and Great Lakes alike -- and Into these basins were deposited all manner of refuse and bulk material until a supratidal elevation was achieved: sand, soil, stone and gravel; dredged spoils; ship ballast; ashes, rubble and, increasingly, various solid wastes generated by urban and industrial life (Cronon, 1992; Melosi, 2000; Seasholes, 2003; Tarr, 1996).

Above: 1893's Columbian Exhibition on Lake Michigan's shore provided cutting-edge civil infrastructure in a reinvented swath of Chicago's waterfront as a Beaux-Arts dreamland (for a temporary event). Underpinning the plan were considerable land reclamations and earthworks overseen by Olmsted, and filling of Chicago's waterfront continued – for far-less civic-minded purposes – for decades thereafter (Larson, 2003; Taft, 2018). Chicago Public Library.

Regional Urbanism: Aesthetics and Ideals in Landform and Its Functions

Designers grappling with the emergent needs and challenges of the mid- and late-19th century embarked upon defining projects of the new American landscape. Frederick Law Olmsted's schemes for New York's Central Park was ambitious in several respects, not least of which was its sheer size and siting: a massive grading and earthwork-based "lungs" at the center of America's premier city (Schuyler, 1986). The Greensward Plan of 1858 audaciously foregrounded the simple preeminence of landscape in its own right: landforms blurred and obscured the park's boundaries, and it was the sole proposal to simply declare that surface-level roadways would be ruinous; requiring considerable tunneling and cut-and-cover operations to subordinate them (Schuyler, 1986). Landscape architecture, while not yet minted as a profession in America, had moved far beyond gardening to meet (and define) the scale of the city.

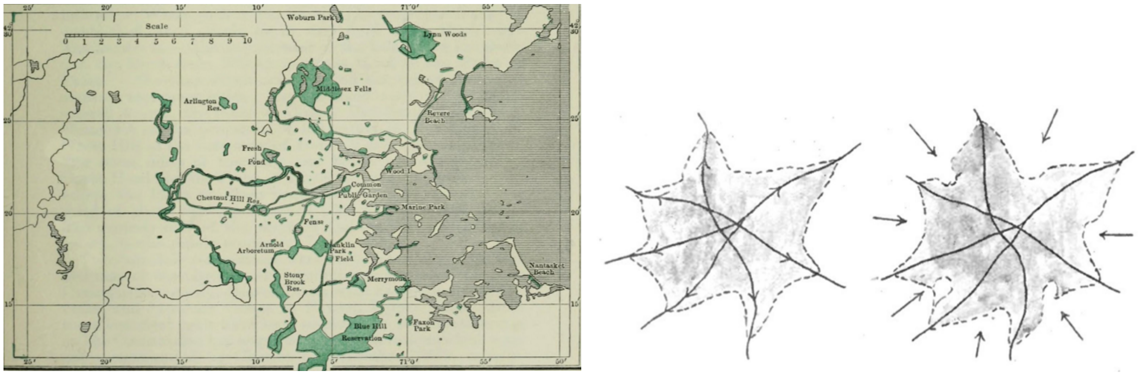


Above: While Olmsted and Vaux sought to showcase and play off the natural relief of Manhattan in their 1858 scheme for Central Park, the scale of earthwork involved is often overlooked. Shunting the transverse roads under the park (left) was unique to their Greensward Plan; construction of the new reservoir required extensive digging and grading. New York Public Library.

Concerns for the lack of quality of life in cities, echoing some of the romantic lamentations of Emmerson and Thoreau, gave voice to advocates of suburbanizing like Catharine Beecher and Andrew Jackson Downing (Marx, 2000). Waves of reimagining the relationship between nature and the city ensued, and notions about how the built environment might view, use or otherwise benefit from pastoralism, nature's aesthetics and ecological functionality evolved to herald the 20th century, and its ever-widening metropolitan regions that inevitably enveloped (and often degraded) the countryside surrounding the city (Hall, 2002; Miller, 1987). Nonetheless, leveraging advances in technology to overcome environmental inconveniences abounded, as cities in some instances took to undergrounding, and essentially denying, their fundamental hydrologic realities, often to their eventual, intergenerational detriment (Spirn, 1998). Yet this was of a pattern: while romantic notions about nature and wilderness were evolving in the American Psyche, the drive to "solve" urban problems through technocratic means was consuming (Gandy, 2014).

Above: The Undergrounding of Mill Creek in 1880s Western Philadelphia. Shunting stormwater into a massive culvert beneath the town caused extensive, multi-generational problems, and entailed an impressive earthmoving enterprise to accomplish in the first place. Note the sheer displacement of earth by the structure; and the volume required to eventually re-establish grade above it. Philadelphia Water Department

Ebenezer Howard's Garden City imagined a productive landscape adorned with agricultural self-sufficiency and modern modes of living; City Beautiful sought the injection of nature into the city, reclaiming its civic dignity and value; Progressive Era reformers promoted City Efficient to solve social and environmental problems, essentially ushering in the formalization of zoning as a central aspect of urban planning and governance (Hall, 2002; Marx, 2000; Miller, 1987; Schuyler, 1986, Taylor, 2009). The rise of metropoles perhaps demanded that regionalism and an understanding of the value of not developing land emerge, as luminaries like Charles Elliot Jr and Patrick Geddes challenged contemporary views about the role and value of ecological structures and systems -- inevitably linked to broader environmental and sociocultural wellbeing – that harmonized with a reformist Progressive era's discontented notions about urban-industrial growth and its impacts, becoming a focus of the cultural philosophies of Catherine Bauer, Lewis Mumford and others (Tyrwhitt, 1947; Hall, 2002; Ndubisi, 2002).



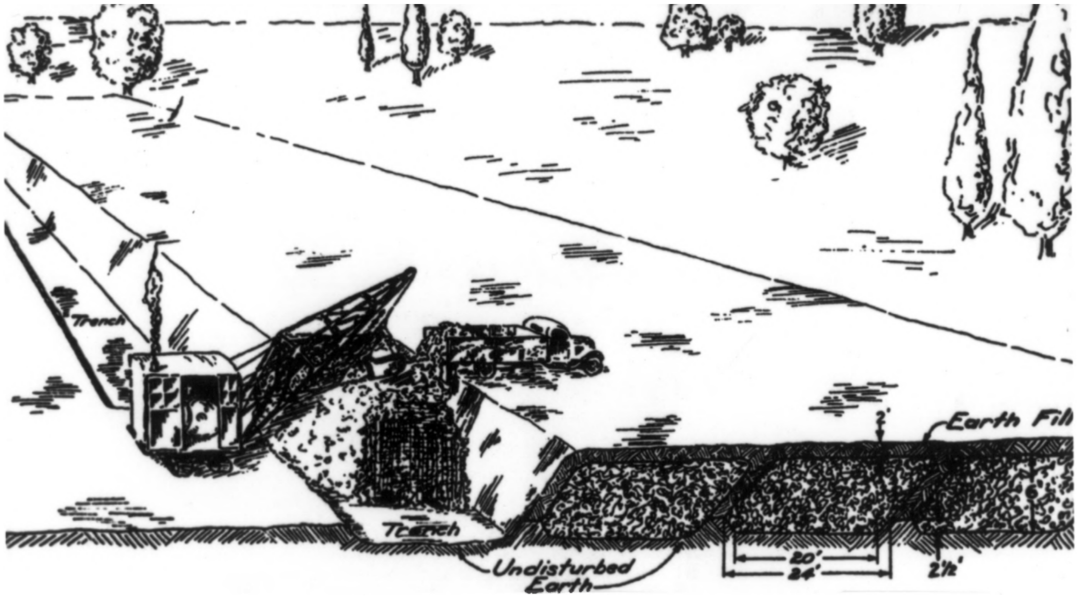
Above left: Charles Eliot Jr's networked open space sketch of the Neponset River basin (1902) and Patrick Geddes' (1915) sketch imagining the countryside constraining the sprawl of development spoke to increasing sociocultural concerns and interest in regional aspects of societal growth and development. University of Toronto.

Automobilization became a defining logic for urban form, rising hand-in-glove with technological leaps in the heavy machinery (and the scale of resultant earthworks) useful in city building projects (like linking interstate highway networks and shunting traffic below already built-out cities) including their rebuilding to address reformist concerns of the age, rural-urban migration and rising populations (Granick, 1991; Haycraft, 2000; McKelvey, 1963; Miller, 1987; Mumford, 1961). Civil engineering, ascendant in the early 21st century, sought to affect resource reallocation schemes on hitherto unknown scales, often imposing "top-down" notions of commanding and controlling nature for the benefit of humans: draining the Everglades; taming the Tennessee Valley; mastering the Mississippi and the monumental task of provisioning water out West all signified the public works projects of the New Deal (Holling, 1996; Grunwald, 2006; Hall, 2002; McPhee, 1989; Nye, 1994; Righter, 2005).

Above: Montana's 1938 Ft Peck Dam (partial) failure. The dam itself (lower left) is 250' tall at its crest with a 500-acre area. Inevitably, where control of water was concerned, manipulation of land was the medium for its realization, sometimes grandiosely. Army Corps of Engineers.

Landform Manipulation in the Modern Metropoles: 1950-Present

World War II introduced the military industrial complex to all aspects of American sociopolitical life, and processes of extraction, manufacturing and shipping exploded in their scope and scale. Strategic port cities found themselves injected anew with the imperative and impetus to grow and develop (Miller, 1987; Mumford, 1961). Rising populations in these regions engendered a bigger, denser built environment, which entailed all manner of excavation projects to construct and UUS expanded with these changes and advances in engineering's capacities and ambitions, (Jansson, 1978). A convenient, if not altogether original role for excavated soils to play in the dance of urban development emerged. "Sanitary landfills" spearheaded in Fresno and San Francisco CA in the 1930's provided a threefold solution: local municipal waste could be "capped" by earth (thus hiding its offensive aesthetics); done at the shoreline (some states had, by now, banned open ocean dumping), this formed a cornerstone of ongoing land reclamation projects; and it effectively "solved" the question of where and how to dispose of a constant and increasing flow of soils and spoils, which could be used to cap the (also increasing flow of) garbage (Melosi, 2000; Tarr, 1996).



Above: Fresno, CA's sanitary landfill, c. 1939. APWA

Numerous large-scale projects both real and imagined hinged upon this concept, which spoke to the scale of the bustling metropoles need for developable land and waste management in an expanding and ravenously hungry consumer culture (Melosi, 2000). Schemes aimed at engineering entire regional landscape dynamics and converting the world's largest landfill (Fresh Kills, NY) into valuable real estate stood as examples also of the oddly important role of soil and sediment as building material for projects of immense scale (Caro, 1974; Jackson, 1977; Trumpeter, 2012). And postwar frontiers across the country experimented with new ways of shaping, and conserving landscape in the rapid growth of the postwar period (Mozingo, 2011). Though environmental luminaries had been laying the groundwork for over a century, the troubling trends pertaining to growth, sprawl and environmental degradation coalesced in the postwar period as a "New Ecology" dawned and the environmental movement ultimately galvanized in the 1970s (Melosi, 2000; Ndubisi & ebrary Academic Complete, 2002). Insights of John Muir, Aldo Leopold and Rachel Carson were synthesized into a planning ethos by Ian McHarg and others sketching utopian merging of city and countryside into, and many environmentally-focused legislative acts were incepted into federal and state law, with implications for planning and development (De Monchaux, 2016) Fiorino, 2006).

Above: Eminent Landscape Architect Rich Haag's articulation of the elemental ethos of the landscape architect, "dig hole; build mound" at least half-evident in Seattle's Gas Works Park, opened in 1975. The "Great Mound" (right) is a cache of rubble, capped by soil and now standing as a novel landform simultaneously masking and referencing the site's past. University of Puget Sound.

A number of regulatory measures emerged; aimed at curtailing land filling and soil/sediment disposal in waterways and mostly for the protection of crucial habitat and species – regulations that persist today in many metropolitan shorelines (Platt, 1994). The Water Pollution Control and Coastal Zone Management Acts of 1972 restricted reclamation, land filling and shoreline development. The Endangered Species Act and Habitat Conservation Plans induced expanded stewardship of many national shoreline areas.

Future Directions

Physically altering the elevational profiles of shorelines is ancient, and evident in the rapid rise of America's port cities and their long legacies (Charlier, 2005; Hill 2013; Inman, 1974; Spirn, 1984). Excavated soil resources have played interesting roles in metropolitan shorelines: as a building material for physically constructing them; as byproducts of their development and growth; as components of waste management systems tied to changes in urbanization, infrastructure, technology and governance; and most recently in ecological restoration and adaptation projects. Extensive landforms are being considered for their role in coastal adaptation as multi-benefit flood barriers, and research is needed to connect an understanding of their material requirements with the soil management in urban shorelines: conceptually linking ongoing flows to an anticipated application, and exploring how their physical linkage might be accomplished.

The built environment is expected to grow at an astonishing rate in coming decades (de Monchaux, 2016). Urban development trending toward tight, dense, transit-oriented cores will concentrate excavation activities, very often in places much closer to under-nourished shorelines than landfills. The challenges of implementing (or simply planning) metropolitan shoreline adaptation schemes that might be required to meet several feet of SLR in the 21st century are immense; so complexified and contested are these geographies by actors of all stripes, operating at federal, state, regional, and local levels. Without research into the potential significance of sediment reuse in regional SLR strategies, coastal conurbations cannot compose an accurate picture of their fundamental options based on the material markets and ecology related to excavated sediment. And because of the existing regimes governing urban soils (and as a function of their nature), they are both nonrenewable and truly lost when landfilled. The drowning of coastal wetlands whose migration is impeded by the (also imperiled) built environment represents a major impetus for research into the material ecology of anthropogenically-managed urban soils and sediment.

Introduction References:

Admiraal, H., & Cornaro, A. (2016). Why underground space should be included in urban planning policy – And how this will enhance an urban underground future. Tunnelling and Underground Space Technology, 55, 214–220. https://doi.org/10.1016/j.tust.2015.11.013

Admiraal, H., & Cornaro, A. (2018). Underground spaces unveiled: Planning and creating the cities of the future. (Environmental Design NA2542.7 .A36 2018). London : ICE Publishing, [2018]; cat04202a.

Ascher, K., & Marech, W. (2007). The works: Anatomy of a city. (Environmental Design HT394.N4 A84 2007). New York : Penguin Press, 2007, c2005.; cat04202a.

Barnard, P. L., Schoellhamer, D. H., Jaffe, B. E., & McKee, L. J. (2013). Sediment transport in the San Francisco Bay Coastal System: An overview. Marine Geology, 345, 3–17. https://doi.org/10.1016/j.margeo.2013.04.005

Bartel, S., & Janssen, G. (2016). Underground spatial planning – Perspectives and current research in Germany. Tunnelling and Underground Space Technology, 55, 112–117. https://doi.org/10.1016/j.tust.2015.11.023

Besner, J. (2016). Underground space needs an interdisciplinary approach. Tunnelling and Underground Space Technology, 55, 224–228. https://doi.org/10.1016/j.tust.2015.10.025

Caro, R. A. (1974). The power broker: Robert Moses and the fall of New York. (Environmental Design NA9085.M68 C371 1974). New York, Knopf, 1974.; cat04202a.

Caughey, J. W. (1975). The California gold rush. (Asian American Studies F861.A1 C58). Berkeley : University of California Press, 1975, c1948.; cat04202a.

Charlier, R. H., Chaineux, M. C. P., & Morcos, S. (2005). Panorama of the History of Coastal Protection. Journal of Coastal Research, 211, 79–111. https://doi.org/10.2112/03561.1

Clark, R. (1985). Works of man. (Morrison T15 .C531 1985). New York : Viking, 1985.; cat04202a. \

Cronon, W. (1992). Nature's metropolis: Chicago and the Great West. (Earth Science/Map Collection F548.4 .C85 1992). New York : W. W. Norton, 1992, c1991.; cat04202a.

De Monchaux, N. (2016). Local code: 3,659 proposals about data, design & the nature of cities. (Environmental Design NA9053.E58 D4 2016). New York : Princeton Architectural Press, [2016]; cat04202a.

Delgado, J. P. (2009). Gold rush port: The maritime archaeology of San Francisco's waterfront. (Environmental Design F869.S347 D45 2009). Berkeley : University of California Press, c2009.; cat04202a.

Dixon, S. J., Viles, H. A., & Garrett, B. L. (2018). Ozymandias in the Anthropocene: The city as an emerging landform. Area, 50(1), 117–125. https://doi.org/10.1111/area.12358

Douglas, I., & Lawson, N. (2000). The Human Dimensions of Geomorphological Work in Britain. Journal of Industrial Ecology, 4(2), 9–33. https://doi.org/10.1162/108819800569771

Ferguson, L. E. (2018). A Gateway without a Port: Making and Contesting San Francisco's Early Waterfront. Journal of Urban History, 44(4), 603–624. https://doi.org/10.1177/0096144218759030

Gandy, M. (2002). Concrete and clay: Reworking nature in New York City. (Environmental Design HT243.U62 N74 2002). Cambridge, Mass. : MIT Press, c2002.; cat04202a.

Gandy, M. (2014). The fabric of space: Water, modernity, and the urban imagination. (Environmental Design TC405 .G36 2014). Cambridge, Massachusetts : The MIT Press, 2014.; cat04202a.

Geddes, P., Sir, & Tyrwhitt, J. (1947). Patrick Geddes in India; (Environmental Design NA9251 .G4). London, L. Humphries, 1947.; cat04202a.

Glacken, C. J. (1967). Traces on the Rhodian shore; nature and culture in Western thought from ancient times to the end of the eighteenth century. (Anthropology GF31 .G6). Berkeley, University of California Press, 1967.; cat04202a.

Granick, H. (1991). Underneath New York. (Environmental Design TD159.3 .G73 1991). New York : Fordham University Press, 1991.; cat04202a. h

Grunwald, M. (2006). The swamp: The Everglades, Florida, and the politics of paradise. (Main (Gardner) Stacks F317.E9 G78 2006). New York : Simon & Schuster, c2006.; cat04202a.

Haglund, K. (2003). Inventing the Charles River. (Environmental Design F72.C46 H33 2003). Cambridge, Mass. : MIT Press, c2003.; cat04202a.

Hall, P. (2002). Cities of tomorrow: An intellectual history of urban planning and design in the twentieth century. (Environmental Design HT166 .H349 2002). Oxford, UK ; Malden, MA : Blackwell Pub., 2002.; cat04202a.

Halliday, S. (1999). The great stink of London: Sir Joseph Bazalgette and the cleansing of the Victorian capital. (Main (Gardner) Stacks TD564.L6 H35 1999). Stroud : Sutton, 1999.; cat04202a.

Harrison, R. P. (1992). Forests. [Electronic resource]: The shadow of civilization. Chicago : University of Chicago Press, c1992.; cat04202a.

Hashimoto, S., Tanikawa, H., & Moriguchi, Y. (2007). Where will large amounts of materials accumulated within the economy go? – A material flow analysis of construction minerals for Japan. Waste Management, 27(12), 1725–1738. https://doi.org/10.1016/j.wasman.2006.10.009

Haycraft, W. R. (2000). Yellow steel: The story of the earthmoving equipment industry. (Institute for Research on Labor and Employment HD9715.25.U62 H39 2000). Urbana : University of Illinois Press, c2000.; cat04202a.

Hooke, R. LeB., Martín-Duque, J. F., & Pedraza, J. (2012). Land transformation by humans: A review. GSA Today, 22(12), 4–10. a9h.

Jackson, W. T., & Paterson, A. M. (1977). The Sacramento-San Joaquin Delta: The Evolution and Implementation of Water Policy: An Historical Perspective. edssch.

James, L. A. (2013). Legacy sediment: Definitions and processes of episodically produced anthropogenic sediment. Anthropocene, 2, 16–26. https://doi.org/10.1016/j.ancene.2013.04.001

Jansson, B. (n.d.). City Planning and the Urban Underground. 17.

Kaika, M. (2005). City of flows. [Electronic resource]: Modernity, nature, and the city. New York : Routledge, c2005.; cat04202a.

Katsumi, T. (2015). Soil excavation and reclamation in civil engineering: Environmental aspects. Soil Science and Plant Nutrition, 61(sup1), 22–29. https://doi.org/10.1080/00380768.2015.1020506

Larson, E. (2003). The devil in the white city: Murder, magic, and madness at the fair that changed America. (Environmental Design HV6248.M8 L37 2003). New York : Crown Publishers, ©2003.; cat04202a.

Lockwood, C. (1978). Suddenly San Francisco: The early years of an instant city. (Environmental Design F869.S3 L61 1978). San Francisco : Examiner Special Projects, c1978.; cat04202a. h

Marx, L. (2000). The machine in the garden: Technology and the pastoral ideal in America. (Environmental Design E169.1 .M35 2000). Oxford ; New York : Oxford University Press, c2000.; cat04202a.

McEvoy, D., Ravetz, J., & Handley, J. (2004). Managing the Flow of Construction Minerals in the North West Region of England.: A Mass Balance Approach. Journal of Industrial Ecology, 8(3), 121–140. https://doi.org/10.1162/1088198042442289

McKelvey, B. (1963). The urbanization of America, 1860-1915. (Environmental Design HT123 .M25). New Brunswick, N.J., Rutgers University Press [1963]; cat04202a.

McNichol, D., & Ryan, A. (2002). The Big Dig. (Environmental Design HE356.5.B6 M355 2002). New York, NY : Silver Lining Books, c2002, 2000.; cat04202a.

McPhee, J. (1989). The control of nature. (Anthropology TD170 .M361 1989). New York : Farrar, Straus, Giroux, 1989.; cat04202a.

Melosi, M. V. (2000). The sanitary city: Urban infrastructure in America from colonial times to the present. (Engineering TD223 .M45 2000). Baltimore : Johns Hopkins University Press, 2000.; cat04202a.

Miller, Z. L., & Mooney-Melvin, P. (1987). The urbanization of modern America: A brief history. (Environmental Design HT123 .M541 1987). San Diego : Harcourt Brace Jovanovich, c1987.; cat04202a.

Morrish, W. R. (2010). Civilizing terrains: Mountains, mounds and mesas. (Environmental Design SB472.7 .M67 2010). San Francisco, CA : William Stout Publishers, 2010.; cat04202a.

Mozingo, L. A. (2011). Pastoral capitalism: A history of suburban corporate landscapes. Cambridge, Massachusetts ; London, England : The MIT Press, 2011.; cat04202a.

Mumford, L. (1961). The city in history: Its origins, its transformations, and its prospects. (Environmental Design HT111 .M85). New York : Harcourt, Brace & World, ©1961.; cat04202a.

Ndubisi, F., [1955-] & ebrary Academic Complete. (2002). Ecological planning: A historical and comparative synthesis. awn.

Nye, D. E. (1994). American technological sublime. (Engineering T14.5 .N93 1994). Cambridge, Mass. : MIT Press, c1994.; cat04202a.

Platt, R. H., Rowntree, R. A., & Muick, P. C. (1994). The Ecological City: Preserving and Restoring Urban Biodiversity. University of Massachusetts Press; nlebk.

Pollock, S. (1999). Ancient Mesopotamia: The eden that never was. (Main (Gardner) Stacks DS71 .P65 1999). Cambridge : Cambridge University Press, 1999.; cat04202a.

Price, S. J., Ford, J. R., Cooper, A. H., & Neal, C. (2011). Humans as major geological and geomorphological agents in the Anthropocene: The significance of artificial ground in Great Britain. Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences, 369(1938), 1056–1084. https://doi.org/10.1098/rsta.2010.0296

Reisner, M. (1993). Cadillac desert: The American West and its disappearing water. (Bioscience & Natural Resources HD1739.A17 R45 1993). New York, N.Y., U.S.A. : Penguin Books, 1993.; cat04202a.

Righter, R. W. (2005). The battle over Hetch Hetchy: America's most controversial dam and the birth of modern environmentalism. (Bioscience & Natural Resources TD225.S25 R54 2005). New York : Oxford University Press, 2005.; cat04202a.

Schuyler, D. (1986). The new urban landscape: The redefinition of city form in nineteenth-century America. (Environmental Design HT167 .S2851 1986). Baltimore : Johns Hopkins University Press, c1986.; cat04202a.

Scott, J. C. (1998). Seeing like a state: How certain schemes to improve the human condition have failed. (Anthropology HD87.5 .S365 1998). New Haven [Conn.] : Yale University Press, c1998.; cat04202a.

Seasholes, N. S. (2003). Gaining ground: A history of landmaking in Boston. (Environmental Design F73.3 .S46 2003). Cambridge, Mass. : MIT Press, c2003.; cat04202a.

Shaw, R. E. (1990). Canals For A Nation. [Electronic resource]: The Canal Era in the United States, 1790-1860. Lexington, Ky. : University Press of Kentucky, c1990. (Baltimore, Md. : Project MUSE, 2015); cat04202a.

Sjoberg, G. (1960). The preindustrial city, past and present. (Anthropology HT113 .S46). Glencoe, Ill. : Free Press, c1960.; cat04202a.

Spirn, A. W. (1984). The granite garden: Urban nature and human design. (Environmental Design HT166 .S638 1984). New York : Basic Books, c1984.; cat04202a.

Spirn, A. W. (1998). The language of landscape. (Environmental Design SB472 .S685 1998). New Haven [Conn.] : Yale University Press, c1998.; cat04202a.

Strupp, C. (n.d.). Dealing with Disaster: The San Francisco Earthquake of 1906. 45.

Taft, C. E. (2018). Shifting shorelines: Land reclamation and economic blackmail in industrial South Chicago. Environment and Planning E: Nature and Space, 1(1–2), 186. edo.

Tanikawa, H., & Hashimoto, S. (2009). Urban stock over time: Spatial material stock analysis using 4d-GIS. Building Research & Information, 37(5–6), 483–502. https://doi.org/10.1080/09613210903169394

Tarr, J. A. (n.d.). THE METABOLISM OF THE INDUSTRIAL CITY. 35.

Tarr, J. A. (1996). The Search for the Ultimate Sink. [Electronic resource]: Urban Pollution in Historical Perspective. Akron, Ohio : University of Akron Press, 1996. (Baltimore, Md. : Project MUSE, 2015); cat04202a.

Trumpeter, K. (2012). Fresh Kills Landfill. Sage Publications, Inc; edsgvr.

Upton, D. (2008). Another city: Urban life and urban spaces in the new American republic. (Environmental Design HT123 .U68 2008). New Haven : Yale University Press, c2008.; cat04202a.

Walker, R. (2007). The Country in the City. [Electronic resource]: The Greening of the San Francisco Bay Area. Seattle : University of Washington Press, c2007. (Baltimore, Md. : Project MUSE, 2015); cat04202a.

Whitehill, W. M., & Kennedy, L. W. (2000). Boston: A topographical history. (Environmental Design F73.3 .W57 2000). Cambridge, Mass. : Belknap Press of Harvard University Press, 2000.; cat04202a.

Wilkinson, T. J., Philip, G., Bradbury, J., Dunford, R., Donoghue, D., Galiatsatos, N., Lawrence, D., Ricci, A., & Smith, S. L. (2014). Contextualizing Early Urbanization: Settlement Cores, Early States and Agro-pastoral Strategies in the Fertile Crescent During the Fourth and Third Millennia BC. Journal of World Prehistory, 27(1), 43–109. https://doi.org/10.1007/s10963-014-9072-2

Yoshida, K., Okuoka, K., & Tanikawa, H. (2018). Anthropogenic Disturbance by Domestic Extraction of Construction Minerals in Japan: Extraction of Construction Minerals in Japan. Journal of Industrial Ecology, 22(1), 145–154. https://doi.org/10.1111/jiec.12543

Chapter 1: Climate Change, Adaptation Planning and Institutional Integration: A Literature Review and Conceptual Framework

Abstract

The scale and scope of climate change has triggered widespread acknowledgement of the need to adapt to it. Out of recent work attempting to understand, define, and contribute to the family of concepts related to adaptation efforts, considerable contributions and research have emerged. Yet, the field of climate adaptation constantly grapples with complex ideas whose relational interplay is not always clear. Similarly, understanding how applied climate change adaptation efforts unfold through planning processes that are embedded in broader institutional settings can be difficult to apprehend. We present a review of important theory, themes, and terms evident in the literature of spatial planning and climate change adaptation to integrate them and synthesize a conceptual framework illustrating their dynamic interplay. This leads to consideration of how institutions, urban governance, and the practice of planning are involved, and evolving, in shaping climate adaptation efforts. While examining the practice of adaptation planning is useful in framing how core climate change concepts are related, the role of institutional processes in shaping and defining these concepts — and adaptation planning itself — remains complex. Our framework presents a useful tool for approaching and improving an understanding of the interactive relationships of central climate change adaptation concepts, with implications for future work focused on change within the domains of planning and institutions addressing challenges in the climate change era.

1. Introduction

The environmental severity and enormity of climate change is coming into sharper focus, as are considerations of crucial and complex impacts on society and daunting demands of the requisite efforts to adapt to it (Nordgren et al, 2016). Climate Change Adaptation (CCA) is understood as a challenge ensnaring numerous actors across multiple societal sectors, acting as a nexus of overlapping concerns and connections (Aylett, 2015). Significant increases in literature concerned with climate change adaptation is evident, with commensurate scholarship dedicated to exploring key concepts in the field (Einecker & Kirby, 2020; Gupta et al., 2010; Wang et al., 2018). Hurdles to effectively engaging with climate adaptation concepts run the gamut: from the inaccessibility of scientific "jargon" (Tribbia & Moser, 2008) to the need to synthesize research and identify areas lacking attention (Berrang-Ford et al., 2015; Ford & Pearce, 2010). Disentangling the roles and relationships between modes of preparing adaptive responses to climate change (planning) and the social patterns that govern these practices (institutions) reveal more areas of confusion and needed consideration; perhaps especially for examining how these practices and patterns may *themselves* adapt or be adapted (Giordano, 2012; Gupta et al., 2010; Patterson, 2021). While conceptual frameworks used to streamline and simplify complex ideas are common, frameworks constructed for the purpose of clarifying key concepts in the field of climate change adaptation planning are lacking.

Planning is a concept with wide and diverse meaning across numerous scales and disciplines (Lawrence, 2000). While climate impacts on the atmosphere and oceans of earth are increasingly severe (and entail their own planning considerations), we are concerned here with *spatial* planning, which frames the landscape as a crucial, dynamic medium—a geographic template—upon and within which effects of climate change will be experienced most acutely by humans (Ndubisi, 2002). Spatial planning uses diverse scientific methods and information to shape decisions about how features of the landscape are designed, constructed, and managed. Berkes and Folke (1998) sought to formalize the concept of *social-ecological systems* (SES) as linked human and natural systems that somehow "fit" together (Epstein et al., 2015); and a framework for "match[ing] the dynamics of *institutions* with the dynamics of *ecosystems* for mutual social-ecological *resilience* and improved performance." While earlier work on the concept was undertaken by Ratzlaff (1970) and later Cherkasskii (1988) reflects that the SES initialization is also used to denote '*socio-ecological*' or '*socioecological*' systems, Berkes and Folke sought to avoid a modifier (socio-) that would imply a subordinate role of the social features of SES (Colding, 2019). Nonetheless, they remain largely interchangeable in the literature.

The concept's presence in publications across numerous subject areas has exploded in the 21st century (Colding & Barthel, 2019), perhaps reflecting or coinciding with increasing interest in the climate crisis and the human role and responses to it. SESs are useful here as a way of examining human interactions with and within the geographic template, and determining how technical and scientific knowledge about SESs are used to inform action in order to shape it and its future states: the essence of spatial planning (Anderies et al., 2004; Gallopın, et al., 1989). Planning decisions about shaping SESs are implicitly ethical because they may generate opportunities and challenges for future generations (Leopold, 1949).

Because climate change is characterized by significant and potentially increasing uncertainty, decision-making processes are encountering complexity in planning adaptation efforts to address these "(super)wicked" problems (Albrechts, 2004; Giordano, 2012; Hallegatte, 2009; Levin et al., 2012; Toimil et al., 2020). This is especially true in urban regions complicated by the concentration, entanglement, exposure, and diversity of citizens, resources, assets, and the systems for their management evident there, as well as the numerous, multileveled and/or polycentric governance structures employed as administrative actors (Castán Broto, 2017; Pahl-Wostl, 2009). Urban areas are complex geographies, where deep and complicated histories, cultures, and institutions generate important questions about the social aspects of power, resources, and environmental health, safety, and justice (Bulkeley & Castán Broto, 2013; Rasmussen et al., 2020).

For these reasons, while we do not rigorously analyze or compare issues arising from various scales of consideration that spatial planning constantly confronts (local vs. national; site-based vs. regional), we examine central ideas and themes related to CCA that are especially evident in densely populated, developed areas. Extensive research on the role and function of multi-level governance (MLG) is evident in CCA circles, as are discussions of various traditions, processes, and planning cultures across nations and regions of the globe (including recent work by Ishtiaque (2021) and DiGreggorio (2019) useful for deeper examination of multilevel governance dynamics.) Most of the discussion within this article is derived from—and applies most directly to—developed nations and western planning traditions whose similarities and features lend toward the generalization and synthesis useful in the construction of the proposed framework.

Meadows' (1972) landmark 1972 study, *Limits to Growth*, was recently assessed to examine the "fit" between projections of troubling development trends modeled a half-century ago, and their potential implications for countless (and planetary) SESs. Specifically, the "Business as Usual" description of a scenario describing unsustainable development practices (in this instance, particularly as a function of pollution increases including atmospheric greenhouse gas concentrations) appears to be playing out today, potentially portending calamitous impacts for society by or before midcentury (Herrington, 2021). Given that countless planning endeavors have unfolded for decades within the context of a finite planet articulated in *Limits to Growth*, major questions emerge about what planning is fundamentally *for*, how it functions (or can fail), and how it is positioned to operate in the climate change era.

Moreover, insofar as planning is understood as a *practice* utilized for governing the use of resources and space, the *institutions*—rules, norms, customs, and conventions—that simultaneously overarch and undergird planning are crucial to consider, and perhaps the fundamental relationship between planning and institutions most of all (Gualini, 2001). This frames the basic question at the center of this review: how is climate change driving transformation of the human systems that must confront it? What prominent and salient concepts characterize this confrontation, and how are they related—to one another and to the planning and institutional domains grappling with climate change? This literature review draws upon important concepts and themes from these fields and areas of interest, as well as synthesizes and integrates prominent concepts into a broadly applicable framework to further research and consideration of the relationships between these fields and ideas. We demonstrate that core concerns stemming from climate change studies are commonplace and of increasing relevance in planning and institutional domains, and that logical links between them can be articulated to illustrate relationships framing notable conceptual and thematic intersections and interactions; these, in turn, work to clarify areas of emphasis, key linkages, and important "blind spots" that persist in CCA research.

This article is structured as follows: Section 2 describes the review approach, and briefly situates spatial planning within a historical and theoretical context that frames consideration of important concepts in the climate adaptation literature. Section 3 integrates these into a Climate Change Adaptation Planning (CCAP) schema, and we describe its key phases. Section 4 examines how, in turn, the practice of adaptation planning is related to theory about adaptation features of interest. Synthesis and integration of these features produces a conceptual framework that exhibits the 'nested' and covalent relationships and dynamics therein, which is followed by an examination of the role of institutions in these dynamics. We close with a brief discussion and conclusion examining insights and further questions framed by the work.

2. Climate Change Adaptation Planning: Prologue, Practice, Paradigm

Our research is focused around a literature review that examines prominent themes related across several domains of interest to CCA: spatial planning, climate change, and institutions. Comparing ideas and terminology of importance across diverse fields and phenomena involving various sociocultural dynamics is complex for a variety of reasons

(Ritchie, et al., 2014). This is especially true when theories of change in social patterns are involved because framing and contextualizing historical trends inevitably entails consideration of broad themes (Webster & Watson, 2021). Our review considered highly-cited literature in the domains of interest to assemble a network of conceptual and empirical articles and studies engaging concepts with broad prominence in CCA research. This formed the basis of an approach articulated by Paré, as geared towards "identifying, describing, and transforming [important] concepts, constructs and relationships…[to build a] higher order of theoretical structure" (Paré et al., 2015). In turn, this approach was used as a theoretical and narrative basis for constructing a *conceptual framework*. This is a common goal and outcome of research linking interdisciplinary bodies of knowledge to explore associated phenomena by articulating "key factors, constructs, or variables" to describe logical relationships among them that correspond to the main tenets of the research (Jabareen, 2009; Miles & Huberman, 1994.). Accompanying the narrative review, the framework is used to consider relevant issues in the institutional domain, as well as for framing a discussion about persistent challenges, emergent insights, and potential applications.

2.1. *A Very Brief History of Modern Spatial Planning*

Landscape architecture arose as a formal design discipline in the 19th century based partially on the increasing recognition of connections between environmental and social health, out of which the sub-discipline of *landscape planning* emerged (Hill, 2018). Landscape design and planning's interests in large-scale (watershed, regional) geographies and dynamic environmental and human (system, network) processes led to a broader rationale for incorporating ecological considerations into multi-scalar spatial planning (Ndubisi, 2002). In the postwar era, *ecological planning* entered common parlance, further shaped by the concerns of the modern environmental movement's discontent with harmful effects of unbridled development (McHarg, 1969; Swaffield, 2002). One of the overarching themes in ecological views of spatial planning is the concept of the *suitability* of landscapes: how their inherent and potential qualities predispose them to various uses by humans.

Modern perspectives focusing on Sustainable Development (SD) emerged in the late 20th century largely to address the obvious tensions between intensifying resource management practices and future prosperity (Meadows et al., 2004). Goals to achieve SD have become key concerns in the climate change era; especially in urban areas of high development intensity (Lélé, 1991; Sauvé et al., 2016). The means by which these goals are achieved—the "pathways" taken to reach them—inherently entail *strategic* planning approaches because limited resources force choices that entail tradeoffs (Albrechts, 2004; Carter et al., 2015; Rondinelli, 1976; Tyler & Moench, 2012). The scope and scale of climate change is coming into sharper focus in the 21st century, as are its implications for significant change and uncertainty over time (Chaffin et al., 2014; Fankhauser et al., 1999; Hallegatte, 2009; Toimil et al., 2020).

The failure of society to curb GHG emissions through climate mitigation has increased the need for climate adaptation, emerging as a central concern of spatial planners across the globe; with some anticipating a paradigm shift in the fields of spatial planning concerned with adaptation to more effectively address it (Birchall et al., 2021; Hill, 2016; Lawrence et al., 2018). Challenges especially evident for spatial planning in the climate era emerge when administrative units delineated in space (as municipal boundaries, borders, zones, etc.) do not adequately address or fit well with the climate phenomena that defy socio-politically conceived and articulated 'lines on the (proverbial) map' (Hannah, 2010; Wilder et al., 2010). Indeed, as the landscape itself is modified by climate change, increased flexibility will surely be required of the very planning processes meant to effectively manage it.

2.2. *Climate Change Adaptation: Central Concepts*

To situate the practice of spatial planning within CCA efforts and the diversity of interactions that SESs in the climate change era will confront, we summarize several core concepts important in climate adaptation work. These ideas serve to populate our conceptual framework in the next section, which, in turn, displays their relational and dynamic qualities within an integrated theoretical construct.

Sustainability

The harvesting, commodification, distribution, (re)uses, and disposal of resources is a ubiquitous human activity (Graedel & Allenby, 2010). This is especially true in (and for the provision of) urban areas, where intense turnover and concentration of stocks occurs, recognition of which has given rise to studies of urban ecology and metabolism (Restrepo & Morales-Pinzón, 2018; Ioppolo et al., 2013; Wu, 2014; Kennedy et al., 2011). These processes also entail significant energy footprints, and numerous environmental impacts, including pollution, result from them (Tarr, 1996). The concept of sustainability may be understood to mean the maintenance of some (economic, social, environmental) entity, process, and/or outcome over time, framed in the environmental context of SESs (Basiago, 1999; Berkes et al., 1998 & 2003). Thus, while resource management remains a central consideration of sustainability in general (and SD specifically), it is also understood as a concept with applications in broader social realms (Epstein et al., 2015).

Resource scarcity (and competition) resulting from unsustainable management practices carries equity implications – across both extant socioeconomic classes and for future generations who may be disadvantaged or disenfranchised by prior resource usage (Baccini & Brunner, 2012; Dipierri & Zikos, 2020; Stoddart, et al., 2011). Because planning is a core component of development, SD is frequently invoked as a concept to guide both the means and ends of planning-for-sustainability, a topic of increasing importance in an era of rising environmental concern, uncertainty, and flux (Gopalakrishnan & Bakshi, 2017; Lemons et al., 1998; Wheeler, 2004). Some authors argue that SES are the logical analytical unit for SD research, with others asserting that they contain inherently interrelated concepts with special relevance to adaptation, or the quality of adaptability (Anderies et al., 2004; Young et al., 2006).

Adaptation and Adaptive Capacity

Influential scholarship concerning fundamentals about adaptation is extensive. For the purposes of CCA, it entails altering or adjusting systems and behavior to "alleviate adverse impacts of change or take advantage of new opportunities" through anticipation or response to climate change impacts (Adger et al., 2005). Adaptation can be differentiated based on *who* is involved in adjustment, *what* prompts this adjustment, and *how* it is undertaken (Fischer, 2018a; Smit & Wandel, 2006). Together, they "manifest" *adaptive capacity*, through a variety of institutional and social mechanisms (Ibid.). While non-human (eco)systems may also be said to display CCA behavior (and possess adaptive capacity), we are concerned primarily with the active inception and application of human efforts to "influence the direction of change" in SESs affected by climate change (Fazey et al., 2016; Fischer, 2018b; Wilson, 2012). Pelling (2015) articulates transformation of SESs as a pathway along which adaptation may play out, arguing that adaptation may trigger fundamental changes that decouple systems from more linear modes of progression.

Efforts to manifest adaptive capacity may backfire: potentially increasing vulnerability (Eisenhauer, 2020). This is known as *maladaptation* (Oberlack, 2017; Scott et al., 2020). Maladaptive outcomes bear the double burden of generally worsening conditions (reducing resilience or increasing vulnerability) at the implied mutual exclusion of building adaptive capacity due to resource limits (Kondo & Lizarralde, 2021). While noting various viewpoints and definitions, Gallopín (2006) describes adaptive capacity in SES generally as the capability to cope with environmental change combined with the ability to improve in relation to it. Eakin (2014) argues that there are *generic* (development-focused) and *specific* (climate impact-focused) domains of adaptive capacity, and that pursuit of one may exclude, subordinate, or otherwise reduce the other. Whereas adaptation actions might be understood in intuitive ways as relating to adaptive capacity (a quality), these interact in the context of additional qualities — namely vulnerability and resilience — which define SESs in important ways.

Vulnerability and Risk

Vulnerability concerns adverse impacts that occur due to a state's "susceptibility to harm" resulting from potentially complex interplays of exposure and sensitivity to stresses; and it is amplified by a lack of adaptive capacity (Adger, 2006; Mccarthy et al., 2001; Smit & Wandel, 2006). When harmful, these stresses take the form of hazards representing threats to systems; events that "realize" hazards in significant ways by causing damage are *disasters*; and those stemming from or involving natural phenomena are natural disasters (Alexander, 1993; Oliver-Smith, 1996; Revi et al., 2014; Young et al., 2006). *Risk* essentially describes the condition and degree(s) of being vulnerable (based on exposure, sensitivity, and capacity) to hazards (Pescaroli & Alexander, 2018); and risks shape and define adaptive capacity itself (Dow, et al. 2013). Risks are generally thought to be, in some sense, quantifiable, i.e., capable of being rendered in terms of probabilities describing the likelihood of outcomes (Abbott, 2005; Haimes, 2004.; Mack, 1971.; Van Der Heijden, 1996). The concentration of people, resources, and systems in urban spaces implies increased exposure, and additional risk based on the location of urban assets (in coastal areas, for example) may arise (Carter et al., 2015; Rasmussen et al., 2020). Risk operates in and across various societal domains: it should be considered in social and economic terms in addition to physical ones, including their interactions (Martins et al., 2020).

Resilience and Robustness

Systems exposed to risk and experiencing vulnerability may cope with it by drawing upon internal resources, whose realization may reduce impacts. Since Holling's (1973) pioneering work in studying ecosystems' capacity to withstand and rebound from states of disturbance, — to "absorb" and "persist" — *resilience* has become something of a darling within adaptation circles; prompting some to caution that its over-invocation might dilute its meaning (Rose, 2007). Resilience is of particular importance in the context of climate change because it represents a desirable quality of interacting designed and natural systems, and their relationship to risk and vulnerability (Twigg, 2007); UNISDR, 2012).

Systems that are resilient possess features, including flexibility and diversity, redundancy and modularity, and safe failure characteristics (Tyler & Moench, 2012). These work to reduce risk from disasters, which manifests in various types that include interacting, interconnected, compound, and cascading risks (Pescaroli & Alexander, 2018). The UN's (2015) adoption of frameworks for identifying and evaluating these risks speaks to the centrality of disaster risk reduction (DRR) in adaptation and resilience concerns and approaches. If resilience is seen as flexibility in the face of disturbance, *robustness* might be understood as the capability to resist and withstand it (Anderies et al., 2004). According to this view, resilient and/or robust systems maintain their core structure despite disturbance, enough so as to avoid becoming vulnerable to the point of significant structural deformation or collapse (Holling & Meffe, 1996).

Uncertainty

Planning is a process of anticipating, preparing for, and influencing future states of affairs. *Uncertainty* is a critically important epistemic situation that is inherent to planning because these 'affairs' of future states are influenced by numerous processes that engender and shape events, eventualities, and exigencies (Levin et al., 2012; Lipshitz & Strauss, 1997). This is the meta-context of planning: the temporal dimension within which all socioecological systems inevitably must play out. Uncertainty intrinsically implies what is unknown and/or unknowable (Chow & Sarin, 2002). It is a matter of degree; hence, "levels" of uncertainty exist (van der Heijden, 2019). Uncertainty is generally understood to increase as more distant futures are considered; and uncertainty may reflect, or be considered as a function of, complexity (Abbott, 2005; Rauws, 2017).

As planning is intended to inform decision-making, it must ultimately confront uncertainty in that context; by influencing the selection of options for coping with or managing it in acceptable ways (Christensen, 1985; Emery & Trist. 1965; Fischhoff & Davis, 2014; van der Bles et al., 2019). In this sense, uncertainty actually produces the need to make decisions (Shackle 1969). These decisions theoretically address, but can also produce*,* uncertainty; environmental uncertainty (uncertainty *for* planning) and process uncertainty (uncertainty from planning) may also exist, emerge, and interact (Abbott, 2005; Gruber, 1994.). Christensen's (1985) elegant rendering of planning problems hinges on two related processes and their relationship with uncertainty: identifying what to do (a goal) and determining how to do it (through resources and technology), effectively invoking the "ends and means" dyad familiar across all disciplines of planning. The capacity to learn new information that changes how uncertainty is characterized (and, therefore, may change degrees of belief) is a fundamentally adaptive ability (Oppenheimer et al., 2008).

The sheer scale and scope of potential impacts that CCA seeks to address entail significant uncertainty about how and when they will play out, thus shaping the 'menu of options' for responding to them (McInerney et al., 2012; Rauws, 2017; Reeder & Ranger, 2010). Uncertainty might be epistemic (stemming from a lack of knowledge), aleatory (due to intrinsic stochasticity), or both – and it can produce delays in decision-making (van der Bles et al., 2019). A striking example of how the very conceptualization of uncertainty is evolving in the climate change era concerns the asserted "death" of stationarity (Milly et al., 2008). Stationarity refers to the statistical concept that environmental fluctuations are bounded inside a value range that is stable (or stationary) over meaningfully-long time scales, an assumption that undergirds countless modeling approaches in environmental science and engineering (Stedinger & Griffis, 2011; Stroup, 2011). Whether or not reports of stationarity's death have indeed been greatly exaggerated, uncertainty is certainly growing, in actuality and/or as a topic of interest and importance (Hallegatte, 2009).

2.3. Planning: Practice, Policy and Governance

Why Plan(ning)?

The practice of planning is the professionalized implementation of planning efforts, processes shaped by and based on the application of planning theories (Abbott, 2005; Cartwright, 1973). In exploring what the ultimate purpose of planning is, institutional perspectives have positioned it as operating, in effect, as a mode of *governing societal actions* through processes of "regulation, coordination and control" (Pierre, 1999), while others have extended this view to ideally incorporate progressive values linked to social justice and democracy more broadly (Alexander, 2009; Healey, 1998). Generally speaking, planning is practiced in order to use knowledge to shape and implement action by informing decision-making. While noting a multitude of theoretical approaches to spatial planning, Morphet (2011) acknowledges planning's inherent power as a redistributive social force, with implications for how power itself is mediated. For our purposes, planning occurs through governmentally-sanctioned processes that concern access to goods and services deemed socially beneficial, and which maintain or enhance public health, safety, and welfare within a particular place; these provisions are often simplified as public "good(s)" (Reyes Plata, 2020).

Planning's Mandate: Service to the Public Good(s) and Interest

Defining what, exactly, constitutes the public good — much less deciding how to go about achieving, maintaining, or enhancing it — is well-recognized as complex, contentious, and dynamic, involving many diverse stakeholders across multiple levels of society (Bolan, 1967; Faludi, 2000; Forester, 1980). Accordingly, Kunzmann (2000) identifies the planning process as one preferably led by the public sector. Numerous climate effects are expected to disproportionately impact (by definition) vulnerable communities, and greater concern for the wellbeing and livelihoods impacted by the products of the adaptation process are, thus, linked closely to planning (Rodima-Taylor et al., 2012). Erikson and Brown (2011) and Ribot (2010) articulate challenges for planning associated with sustainability, resilience, and vulnerability related to uncertainty and complexity in the climate era. Transformative adaptation resulting from effective planning ideally reinforces the legitimacy of the social contract underlying public consent that is granted to planning authorities, ostensibly in their efforts to protect and expand the public interest and good (Pelling, 2011).

Planning is understood on basic terms to be a collaborative process that must address what Myers and Kitsuse (2000) identified as one of planning's "twin hazards": disagreement (the other being uncertainty), which is confronted through a number of different techniques for conflict resolution in planning, including communication, collaboration, mediation, dialogue, discussion, deliberation, and debate (Leach & Sabatier (2003); Moore, 1987; Ostrom, 1990; Roberts, 1997 & 2002;; Ryan, 2001). Innes (Innes, 2004) offers an examination of consensus-building as a crucial process for approaching various planning and policy-based disagreements. These serve to discover and define that of which the public good(s) actually consist, and doing so is where the practice of planning partially derives its validity (Susskind et al., 1999). Owing to numerous factors emerging from climate impacts on the public sector, planning is being deeply reexamined in the context of climate change (Abbott, 2005; Carter et al., 2015; Macintosh, 2013).

So...What's the Plan?

A plan involves articulating and orienting towards a *vision* for the future—what some human geographers refer to as environmental or sociotechnical imaginaries. These frame discourses for structuring the relationship of human processes within places, based on societal imperatives and aspirations amounting to the "virtualities" of future states of affairs (Bulkeley & Betsill, 2013). This articulation, in the context of producing the "instrument" of a plan, might involve constructing a declarative set of goals, while orienting towards them identifies steps, stages, or strategies for their realization, though both should embody flexibility to changing circumstances, thus possibly entailing "menus" of scenarios that could be encountered (Faludi, 2000; Peterson et al., 2003). This serves to "situate" the future within an as-yet unrealized (imaginary) SES: one towards which the plan is intended to guide decision-making (Albrechts, 2006; Soden & Kauffman, 2019). Strategic plans are generally flexible, longer-term, and less fine-grained than more near-term and discrete project plans, owing partially to greater uncertainty existing in "further off" futures (Balducci et al., 2011).

Plan-making may be challenged as a function of numerous horizontal (sector and actor-related) and vertical (multi-level governance-related) connections and the legal, regulatory, and institutional standards at play (Daddi et al., 2020; Hughes, 2015; Nalau et al., 2021). Plans themselves must define and address the community they are intended to serve; and adopted plans represent, to some acceptable degree, the resolution of disputes and tensions that arise based on the interests of various stakeholders involved; as well as how they may have constructed their own visions for the future (Corfee-Morlot et al., 2011; Levin et al., 2012). From an adaptation standpoint, this principle also applies to plans that could impact broader communities, so that adaptation actions undertaken within or for one community do not unduly disadvantage another (Fankhauser et al., 1999). Resolving these overlaps, tensions, and tradeoffs is, therefore, part of mediating the planning process that shapes and, subsequently, manifests in the scope and strategy of a given adaptation plan (Turkelboom et al., 2018).

3. 'Sketching' Climate Change Adaptation Planning: Important Features of Interest

The considerations and theories outlined in the last section illustrate features of planning that are useful in apprehending the fast-emerging practices (and problems) involved in Climate Change Adaptation Planning (CCAP). In this section, we illustrate a conceptual schematic (schema), describing the interplay of notable, generalized features of CCAP (Figure 1). Walker (2001) describes a *thinking* (planning) and *implementation* (action) phase in adaptive theory applied to policy, to which we add a third phase related to the ongoing assessment of applied work: adaptive *management* (Allen & Garmestani, 2015).

These echo Peter Hall's (1993) trifurcated policy paradigm: overall goal-setting (planning), techniques or instruments (actions), and their "calibration" (management).

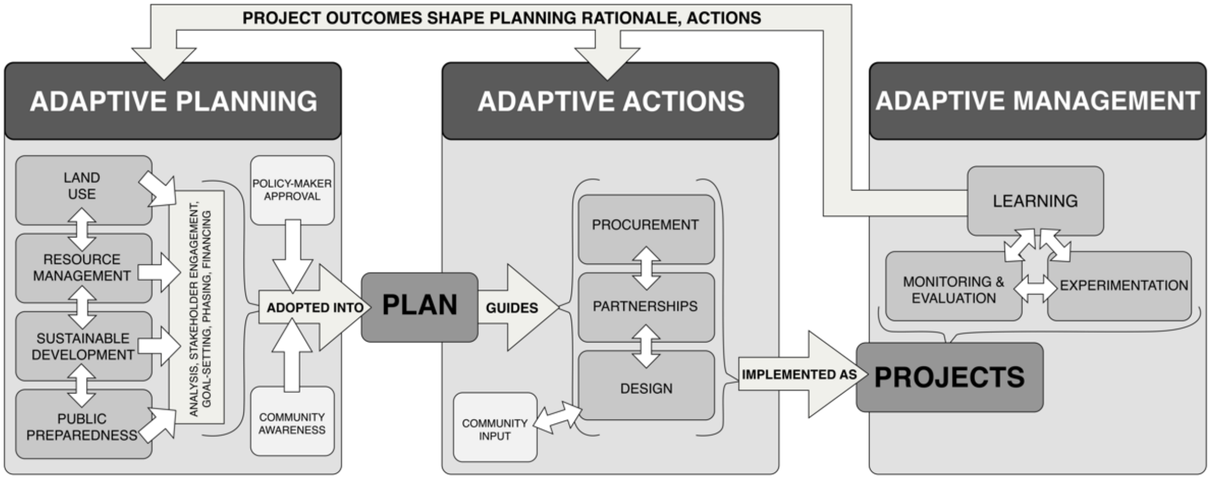


Figure 1. A Climate Change Adaptation Planning (CCAP) schema. In the *Adaptive Planning* phase, prominent planning concerns are addressed to produce a plan; Implementation based on guidance from plans yields *Adaptive Actions* in the forms of projects; these, in turn become subject to *Adaptive Management* practices for improving upstream and scaled-up efforts.

3.1. *Adaptive Planning*

Aspects of the planning process are inherently anticipatory in nature, wherein complex public policy decision-making occurs in the context of preparing for uncertain future states, thereby naturally engendering adaptive approaches (Birchall et al., 2021). As a feature of adaptive governance, adaptive planning naturally entails complexities owing to the diversity of actors and actions involved, especially in urban areas (Allen et al., 2011; Castán Broto, 2017; Folke et al., 2005). Anticipatory and planned adaptation within this phase prepare for (instead of react to) future states of affairs; in theory reducing vulnerability and costs (Burley et al., 2012; Klein & Tol, 1997; Tol et al., 2008). Adaptive planning entails stakeholder engagement that takes many forms, but the familiar top-down/bottom-up heuristic is useful in that planners operationalize the interactions of political decision makers in governance (top) and a broader public (bottom), though this group can be defined in various fashions, and based on criteria that, themselves, deserve scrutiny (Sabatier, 1986; Urwin & Jordan, 2008). Corfee-Morlot (2011), citing Mitchell (2006) and Cash (2003), identify requirements for science-policy assessments that inform and influence planning to be deemed publicly acceptable: namely that they be credible, legitimate, and salient.

Plans emerge as products of governance that identify steps for realizing goals in accordance with rules observed by the actor-networks involved, and they gain approval and adoption by passage through the "sluices of democratic and constitutional procedures" (Habermas 1998; Schroeder & Kobayashi, 2021). Adaptive planning ideally embraces learning processes concerned with the structure and effects of the overarching institutional contexts as a useful principle for improving outcomes (Huntjens et al., 2012; Schroeder & Kobayashi, 2021; Torabi et al., 2018). Adaptation plans may include financing components or supplementary plans for funding implementation (Barrett, 2013; Moser et al., 2019). "Evolutionary" processes in institutional and governance systems, in which processes of reframing and transformational learning occur, are understood as critical for adaptive and equitable systems, and are conceptually well-oriented toward adaptation (Geels 2002; Ostrom, 1990; Pahl-Wostl, 2009; van Assche et al., 2014). Limitations in validity assessment and/or forecasting methods may serve to constrain the adaptive planning applications to some extent, though climate change's overall uncertainty implies that flexible, adaptive approaches to planning for it are logical (Giordano, 2012; Goodwin & Wright, 2010; Kwakkel & van Der Pas, 2011; Hallegatte, 2009).

3.2. *Adaptive Actions*

We borrow from Aylett's (2015) description of adaptive governance as relying on distinct adaptation planning and action processes, thus echoing Ostrom's (2005) notion of the action situation. We use the term adaptive actions essentially to describe the inception of projects. Adaptation projects in urban areas might entail activities involving construction, such as urban greening to reduce heat island effects; improved shoreline defenses as approaches to coastal zone management; integration of "green" stormwater networks to mitigate upland flooding; and the regional management of "upstream" watersheds; and many municipal infrastructure systems represent adaptation imperatives and opportunities in some fashion (Chaffin et al., 2016; Erik Andersson et al., 2014; J. Lawrence et al., 2018; Storbjörk & Hedrén, 2011). Yet, adaptive actions might also include community initiatives involving outreach, education, and participation without resulting in changes to the physical environment (K. M. Allen, 2006). Thus, broad CCA interest categories in applied adaptation include land use planning (for reclamation, restoration, preservation, conservation aims, for example), natural resource management regimes (concerning water, for example), sustainable development projects (for housing, infrastructure, and public amenities), and community engagement initiatives (for educational or preparedness purposes) (Albrechts, 2010; Faludi, 2000; Fischer, 2018b; Leck, 2015; Main et al., 2021; Nalau et al., 2015; Pahl-Wostl, 2009; Satterthwaiteet al, 2009; Vogel & Henstra, 2015).

Large, complex, or costly adaptive actions that exceed the capacity of public policy and governance institutions often necessitate NGO and private sector involvement, in which planners operate at the "boundary" between the public and private entities (Bierbaum et al., 2013; Guston, 2001; Warsen, et al., 2018). Public-Private Partnerships (PPP) describe an arrangement in which collaborative, mutually-beneficial relationships are assembled; they are common in urban and municipal settings and a subject of interest in sustainable development circles, with noted promise for adaptation, despite their inherent complexities (Agrawal, 2010; Glasbergen, 2007; Leck & Simon; Harman et al., 2015; Rodima-Taylor et al., 2012). Procurement processes and partnerships are generally intended to alleviate capacity constraints of government. These arrangements can distribute risk and integrate diverse skills and resources into projects involving infrastructure, DRR, urban development, and, increasingly, adaptation projects (and which may entail some or all of the aforementioned project goals and concerns), though these arrangements in the context of CCA are still relatively novel (Bauer & Steurer, 2014; Harman et al., 2015).

3.3. *Adaptive Management*

CCA inherently acknowledges that traditional, linear project implementation "pipelines" for realizing plans may be of limited value in an era characterized by increasing uncertainty and complexity (Allen et al., 2011). While ancient in practice, recent interest in sustainable resource use, conservation, and ecosystem management have popularized the concept of adaptive management (Buck et al., 2001; Holling, 1973; Walters 1986; Williams, 2011). Other authors have stressed the ties of adaptive management to system resilience and flexibility (Gunderson, 1999). Drawing on work from Allen (2011) and his work with Garmestani (2015), Chaffin (2014) defines adaptive management as "implementation of management actions as *experiments*, followed by monitoring, evaluation and adjustment". Because of the prominence of nature-based solutions and green infrastructure in applied adaptation projects, numerous concerns of adaptive management are relevant to CCAP (Demuzere et al., 2014). Adaptive management applies flexible strategies that take into account emergent opportunities and are generally intended as modes of increasing learning and knowledge, thereby arguably building adaptive capacity and aiding adaptive governance (Hallegatte, 2009; Main et al., 2021).

Numerous approaches to understanding change in SESs exist, though central interest in investigating causal processes are especially relevant to planning, a notion termed by Dewey (1929) as "experimental knowing". Despite its experimental and flexible nature, adaptive management's potential to induce change (in broader practice and approaches) may be limited by institutional settings where change is itself problematized or opposed (Burley et al., 2012). The experimental underpinning of adaptive management may be useful for learning and information sharing across scales, theoretically aiding in expanding resourcefulness and responsiveness; and thereby increasing adaptive capacity (Bulkeley & Castán Broto, 2013; Tyler & Moench, 2012). The potential for specific adaptive actions (in the form of demonstration projects, for example) to broadly inform others might create synergies for syntheses of learning, testing, and adjustment across other sectors and policy realms (Burley et al., 2012). Experiments also may be efficient in the sense that small scales (and costs) may generate knowledge that is useful at broader scales of application, though experimentation itself — especially in large (landscape), complex (urban), and dynamic (climate-related) contexts — presents numerous challenges (Allen & Garmestani, 2015; Walters & Holling, 1990). While "scaling up" projects for broader regional application remains complex and daunting (Allan & Curtis, 2005; Garmestani et al., 2008; Lee, 2021), Hallegatte's (2009) identification of the desirable "low regret" quality of adaptation strategies and projects represents obvious conceptual correspondence with experimentation.

Adaptive management also presents opportunities to improve planning processes by incorporating enhanced social inclusiveness, including the dissemination and sharing of information (Buijs et al., 2016; Stringer et al., 2006). Monitoring that produces data useful for policy consideration is subject to a "reuptake mechanism", whereby conditions observed in adaptation actions may then inform improved planning practices of future or concurrent ones (Corfee-Morlot et al., 2011); while Fankhauser (1999) asserts that adaptation potential is predicated on having "room" (in the form of time) to change behavior. By providing the public, planners, and policymakers with real-time, real-world feedback that illustrates how selected adaptive actions are functioning, the "room" for adaptation may become better-parameterized through the reduction of uncertainty (especially relevant in the climate change era) provided by experimental observations. The "feedback loops" inherent to adaptive management suggest that CCAP is, thus, better conceived as looped processes, which are common in conceptualizations of SESs (Huntjens et al., 2012; Moser & Ekstrom, 2010; Ostrom, 1990).

4. Zooming Out: CCAP in Broader Context

Partially owing to the varied and multi-scale concerns and methods of practice, the literature exploring what CCAP is and how it operates contains no shortage of concepts and terminology for intellectualizing relevant ideas, themes, theories, and describing a diversity of applied work. While it is beyond the scope of this article and our study to exhaustively compare and square the myriad notions and constructs put forth to describe CCA, we offer a summary of important and interesting concepts, which we synthesize in this section. We then construct a conceptual, graphic framework (Figure 2) that strives to integrate these concepts into a holistic logic, offering a mode of rendering the important ideas and their relationships in a conceptual "space" that captures essential ideas of how important features and forces of CCA interact.

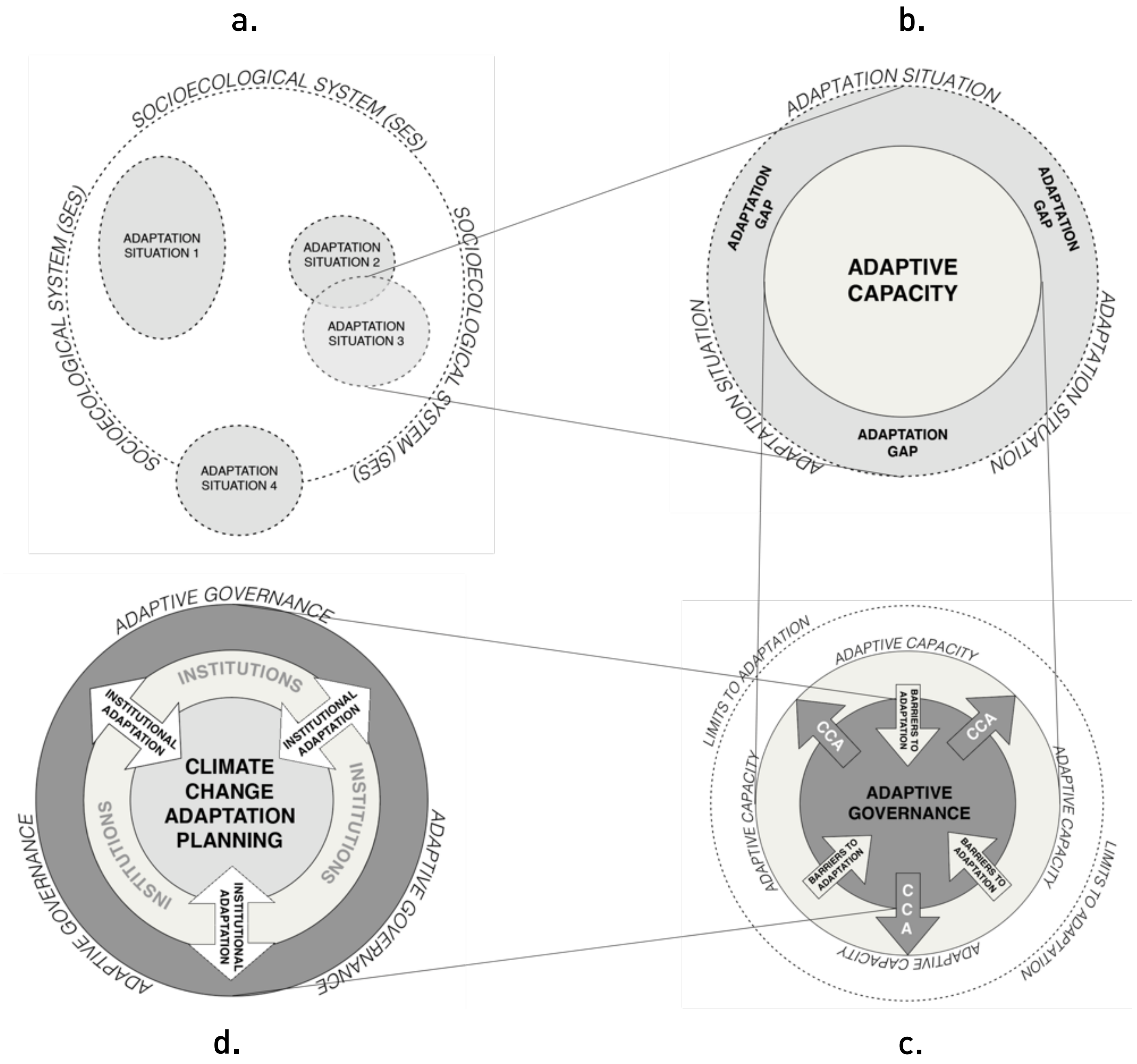


Figure 2. A framework displaying the 'nested' and 'coupled' nature of concepts and interactions of importance in climate change adaptation literature. Arrows denote force directionality; indicating how efforts or concepts "push or pull" towards and/or against other conceptual features or 'spaces'. Below is a glossary of key terms from the framework above; and a theoretical discussion follows.

'Glossary': (a) The *socioecological system* (SES) forms the basic conceptual unit of consideration for framing an adaptation situation. Numerous and interacting adaptation situations may exist within a given SES, or overlap, or "spill" into others. *Adaptation Situations* are characterized by features of the SES, including those in *sociotechnical* (human-based) and *biophysical* (natural setting and context-based) domains, which interact. Phenomena in the biophysical domain engender sociotechnical efforts to establish or expand ("realize") adaptative capacity. **(b)** *Adaptive capacity* is generated by sociotechnical efforts to adapt to biophysical features of the adaptation situation. In general, it is realized by building resilience/robustness and thus reducing vulnerability. An *adaptation gap* exists in the portion of the adaptation situation that lies beyond the adaptive capacity realized within it: it represents the amount of *unrealized* adaptive capacity. **(c) Adaptive governance** describes sociotechnical efforts in shaping the adaptation situation: when effective, adaptive governance increases adaptive capacity, thereby, ideally, shrinking the adaptation gap. Maladaptive (ineffective or counter-productive) efforts reduce adaptive capacity. ***Barriers to adaptation*** are produced, encountered, and addressed by the sociotechnical and biophysical domains, and in their interactions. Barriers constrain and shrink adaptive capacity, often by hindering adaptive governance or exceeding its reach; they exert restrictions and limits to the expansion of adaptive capacity that Climate Change Adaptation Planning (for example) seeks to realize. ***Limits to adaptation*** describe the extents of possible adaptation efforts, beyond which increasing adaptive capacity is (actually or considered) infeasible or impossible. Limits may be unknown. **(d)** Within the ***adaptive governance*** sphere, formal *organizational* practices *(planning)* are employed as modes of realizing efforts; and it is shaped by broader characteristic cultural features and processes called *institutions*. Its efficacy is the sum of institutional and organizational planning efforts performed in the interest of CCA. ***Integrated adaptation*** refers to the coordination and feedback between adaptation planning organization-based practices and institutional processes of adaptive change that coexist and combine.

4.1. Conceptualizing Climate Change Adaptation: Framework Features and Forces

4.1.1. Context: Defining Social-Ecological Systems

Pioneering work by Berkes and Folke (2003; 1998) to articulate the interactive dimensions and interplay between humans and their environments introduced the keystone concept of *social-ecological systems* (SES), based partly on work regarding the systematic nature of aspects of the human-nature interaction illustrated by concepts, including vulnerability, resilience, and sustainability (Füssel & Klein, 2006; Gallopín, et al., 1989; Young et al., 2006). These insights became key components of numerous interpretive framework approaches to understanding socioecological interdependencies. Of particular importance to planners is that SESs are inherently *spatially contextualized*. That is, because of the entanglement of particular and countless effects of some given environmental situation on sociotechnical (human) systems (and vice versa), they are understood as being in some way at play within a spatially distinct or discernible setting. However, this quality is also, by implication, malleable; and its definition or delimiting is based partially on the interest and perspective of those considering or using it as a construct for understanding, planning and managing actions to intentionally alter SESs—the basis of adaptation (Moser & Ekstrom, 2010).

4.1.2. Problem: Emergence of Adaptation Situations

Insofar as SESs contain or capture the dynamics between human drives to utilize natural resources and systems, dilemmas stemming from these drives and the capacity of the environment to accommodate them emerge constantly (Andereis, 2003; Hardin,1968). This produces phenomena in which the social and ecologic system aspects relate (or are situated with respect) to one another, generally impelling tensions regarding resources and governance, and thus engendering situations in which, according to Ostrom (2005), actions may be taken to address or resolve them — generating the concept of the *action situation* (Andersson et al., 2021; Marshall, 2013; Obeng-Odoom, 2016).

The magnitude of climate change on earth's biogeophysical systems has compelled some authors to refine Ostrom's original notion to define *adaptation situations* as a particular form of action situation (Reyes Plata, 2020). Citing previous work, Bisaro and Hinkel (2015) describe the adaptation situation as one involving "one or more actors interacting within a common biophysical and institutional environment in which outcomes are altered through climate change". This implies that social features of the situation may be interested in adapting *to* climate change, as well as that, regardless of their interest or efforts, outcomes will be shaped by biophysical effects *of* climate change; and this view resonates with other scholarship describing the centrality of human endeavors to shape the adaptation situation (Eakin, 2005; Roggero, 2015; Roggero et al., 2018).

4.1.3. Manifesting Adaptive Capacity: Adaptive Governance

The sociotechnical (human) features of SESs address the adaptation situation by making decisions about taking actions. These actions amount to Smit and Wandel's (2006) description of adaptation(s) as the "manifestation of adaptive capacity". The dominant means by which adaptive capacity is manifested by the sociotechnical entities of an SES is through adaptive governance, in large part because of the scale at which governmentally-organized action (and governmental organizations themselves) can operate, (Adger et al., 2003; Pahl-Wostl, 2009; Pelling & High, 2005). Chaffin (2014), in reviewing adaptive governance and synthesizing the perspectives of others, describes adaptive governance as emerging from the search for "modes of managing uncertainty and complexity in SESs". Adaptive governance might be understood as the exercised portion of adaptive capacity — the part that "people use" (Wamsler & Brink, 2014). Accordingly, depending on how and when adaptive capacity is used, it is dynamic over time; unfolding across scales in "coupled cycles of change" (Gunderson & Holling, 2002; Smit & Wandel, 2006). While we examine adaptive governance through the lens of climate change, concepts from theories of evolutionary governance may also be useful to consider and apply.

Though adaptive capacity is doubtless considered a desirable quality to possess, the particular and various ways in which adaptive governance is conceived and practiced may give rise to effects that tend to reduce or constrain adaptive capacity; or to outcomes that are maladaptive (Ekstrom & Moser, 2014; Juhola et al., 2016; Macintosh, 2013). Likewise, while adaptive capacity may reflect or express component qualities of the adaptation situation, including vulnerability, resilience, and sustainability, understanding how adaptive capacity is designed or generated (or not) remains complex (Anderies et al., 2004; Gunderson & Holling, 2002). Carter (Carter et al., 2015), drawing upon work by Rosenzweig (2011), after Mehrotra (2009), positions adaptive capacity in relation to vulnerability and hazards, the interactions of all three in essence serving to define risk. In this view, a system's adaptive capacity serves as a kind of counterweight against its vulnerability. While capacity intuitively refers to the *amount* of something (of which one might possess more or less), governance is not the only *source* of adaptive capacity, which can be possessed or provided by non-human features of an adaptation situation, or through non-governance-mediated human actions (Torabi et al., 2018; Tyler & Moench, 2012). We focus on adaptive governance because of its centrality to CCAP.

4.1.4. Aspirations: The Adaptation Gap

Lying between the optimal and actual adaptive capacity characterized within a given adaptation situation is a "*gap*", wherein the potential actions and outcomes of becoming optimally or fully adapted have not (yet) been realized. Moser and Eckstrom (2014), echoing Burton (2009), note this as a form of "adaptation deficit". In describing the analytical methodology of gap analysis for assessing climate hazards, Chen (2016) defines the adaptation gap as a "difference between existing adaptation efforts and adaptation need". The United Nations' recently published Adaptation Gap Report focuses on nature-based solutions in conceptualizing and further defining the adaptation gap, though previous volumes with different emphases all include the adaptation gap as a centralizing theme (UNEP, 2021). Numerous complications arise from attempts to quantify subjective, complex, and dynamic features of an adaptation situation that, in theory, define the adaptation gap; including the potential "unknowability" of what, precisely, the gap actually entails and includes (Chow, & Sarin, 2002; Davoudi, et al., 2011). Nonetheless, the concept of the adaptation gap is intuitive and useful in the same sense that adaptive capacity is: the former describing an amount of adaptation work *to* be done, and the latter describing the work that *has been* done (thereby establishing existing capacity) or *can be* done as a function of this work. If adaptive governance and other adaptation-oriented sociotechnical efforts are understood as seeking to build adaptive capacity, what forces and phenomena serve to constrain or diminish it?

4.1.5. Challenges: Barriers and Limits to Adaptation

A subject of broad interest is *barriers* to adaptation. Moser and Eckstrom (2010) define these as "impediments that can stop, delay, or divert the adaptation process", specifying that they may be surmounted through "concerted effort, creative management, change of thinking, prioritization, and related shifts in resources, land uses, institutions, etc.". Work from Anderies (2004), Ostrom (2007), and Adger (2009) helps situate this concept within the SES literature which, by extension, we project and integrate as features of adaptation situations (Hinkel & Bisaro, 2015). Some authors have invoked the notion of adaptation "obstacles", which we consider essentially analogous to barriers (Corfee-Morlot et al., 2011). Barriers arise at different stages and levels of adaptation; and they may emerge because of features of governance itself — potentially influencing exactly how adaptive such governance can claim to be — and, by extension, defining its degree of adaptive capacity (Burley et al., 2012; Fischer, 2018b; Moser & Ekstrom, 2010). Importantly, Bisaro (2018), questioning the utility of the concept, points out that barriers that are easily identified might mask larger, structural, and *institutional* forces that produce the effect(s) of barriers without presenting obvious modes of addressing them.

A common phenomenon that arises from and promulgates barriers to adaptation (thus, in theory, reducing adaptive capacity) is *path dependency*, which occurs when institutions or organizations "fail to effectively adapt established practices to face changing circumstances", a pattern of behavior observed across numerous sectors and organizational endeavors, though maladaptive outcomes are a common effect — with obvious and sector-specific implications for CCA, especially in urban settings (Aylett, 2015; Barnett et al., 2015; Healey, 2006). From an economic perspective, situations in which inferior practices perpetuated by path dependency may serve to "lock-in" inefficient (or maladaptive) behaviors and outcomes (Arthur, 1994). Citing Pierson (2000) and Wilson (2012), among others, Fischer (2018b) notes path dependency as a kind of *inertia* that results when future actions are shaped in profound or pernicious ways by previous ones. Path dependency, in this sense, is of particular importance for CCAP because of planning's stepwise, cyclical, discursive, and constantly-unfolding nature; the ubiquity of decision-making points and processes therein; diverse sets of actors taking part in the process(es); and the variety of "embedded" cultural features and forces that steer and constrain them (Booth, 2011; Harman et al., 2015; Sanyal, 2005; Tilly,1984).

Whereas the notion of barriers (and obstacles) naturally conjures ideas about surmounting them, *limits* to adaptation refer to bounds that describe "level(s) of adaptive capacity…that cannot be surpassed", potentially defining the boundary between acceptable and intolerable risks, and those which might require transformative change to avoid (Dow et al., 2013; Klein et al., 2014). Barnett (2015) distinguishes between "hard" limits that are essentially defined by the environment and "soft" ones that are socially determined and, thus, theoretically malleable. Indeed, Eisenhauer (2020), in defining these limits as "factors that prevent adaptation from succeeding", points out that they have been articulated as both objectively identifiable (as in the case of certain biotic and economic examples) and, from a more constructivist perspective, presenting as difficult-to-define endogenous effects emerging from societies' "goals, values, risk perceptions and actions". Limits are perhaps also worth considering as "blended" between hard and soft characterizations because sociopolitical conceptualizations of limits emerge in response to environmental ones; which may then be redefined by human intervention. In general, limits define the extent to which adaptive capacity *could* be realized — apart from how effectively barriers *are* overcome in the practice of adaptive governance (to increase adaptive capacity). Again, this resonates with Adger's (2009a) view that limits are situational thresholds beyond which "adaptation actions fail to protect things stakeholders care about", which we take to include non-physical "things", such as social cohesion, morale, trust in institutions, etc.

4.2. CCAP: Integrating Institutional Adaptation

4.2.1. The Role of Institutions

Gupta (2010) elegantly renders institutions as "social patterns", while a more expansive view, according to Oberlack (2017), citing several others, describes institutions as "rules and procedures that structure action situations within which individual and collective decision-making [is affected to] constrain, enable and incentivize actions; link individual actions, events and outcomes; distribute authority and power; define reciprocal rights and duties; and shape beliefs, motivations and social learning" (Hagedorn, 2008; Ostrom, 2005; Paavola, 2007; Pahl-Wostl, 2009). Accordingly, institutions may be formal or informal (Schroeder & Kobayashi, 2021). Vatn (2005) describes the invisible or even unselfconsciously natural instantiation of institutions in behavior as conventions that are observed, referencing work by Crawford and Ostrom (1995), to compose a "grammar" of institutions and their functions. Institutions might be understood as self-reinforcing "regularities": patterns of behavior evident in networks of social actors who "tacitly create [them] to solve a wide variety of recurrent problems" (Schotter, 2000). Yet, despite regularities and recurrences, institutions are not static; they "distribute obligations and entitlements to resources as well as the power to change such obligations and entitlements" (Basili et al., 2006). Though they may be nonmaterial (informal), institutions reify actual, tangible outcomes.

Institutional analyses focused on resources (components or products of the environment) and how the notion of property (which entails ownership, often of the landscape itself) factors into their management, is a well-established field of interest, and planning has been articulated as a mode of "bundling the rights" of ownership associated with property in this sense (Sorensen, 2018). From an economic perspective, the linkages between humans and their environment are mediated by countless rules that shape and reinforce beliefs and values, but these are dynamic and responsive (Knight & North, 1997). Where public policy is concerned, this dynamic quality of institutions has important implications because the question of how power and influence are distributed within society — including this critical capacity to alter existing situations and arrangements — is of enormous importance in the climate change era (Oberlack, 2017); insofar as planning efforts are understood as being shaped by larger cultural and institutional forces, and because these may fail to present obvious, accessible, and discrete decision-making processes themselves (Bisaro et al., 2018; Storbjörk & Hedrén, 2011).

4.2.2. Institutions and Change

In theorizing about the evolutionary nature of governance, Van Assche (2014) positions institutions as being designed for change; even postulating that the essence of democracy lies in the "rules of self-transformation; *rules to change the rules*". As institutions occupy important features of SESs and spatial discourse generally, they are tightly linked with conceptions of the environmental imaginary (Milkoreit, 2017), entailing consideration of the distribution and access to power and influence involved in its realization, recalling Bromley's (2006) obligations and entitlements (Ekers & Loftus, 2008). In other words, institutions structure *what is possible* based partially on how society *mediates the tensions arising from multitudes* (citizens, actors) shaping and *sharing something more unified*: the environment (Swyngedouw, 2009). Institutions influence aspirations (for a more healthy and just environment, for example), even while subject to inertia (perpetuating the status quo), and the outright resistance to change, termed the *precautionary principle*, which is important in situations involving uncertainty (Chhetri et al., 2010; Gollier & Treich, 2003; Lempert & Collins, 2007). Similar to the concept of path dependency in organizational endeavors, institutional inertia and "lock in" may occur when regimes and patterns of behavior become ossified due to various factors (Knight, & North 1997; Pierson, 2000). Institutions within or across SESs may constrain or delimit the actions of organizations by conformation and homogenization, producing institutional *isomorphism* (Scott, 2003), which may be induced by coercive, mimetic, or normative means (Daddi et al., 2020). Storbjörk and Hedrén (2011) describe clashing cultures, knowledge claims, and cross-sectoral integration problems as several notable barriers to institutional change.

While approaches to determining how institutions resist change are evident (in inertial, oppositional, and isomorphic ways), factors that instigate change within and across institutions are complex to identify, perhaps owing to requisite "concatenations" of underlying mechanisms (Smets et al., 2012; Tilly, 2001). Hodgson (2006) identified two dominant institutional modes: agent-*sensitive* and agent-*insensitive*, the latter describing an institution in which significant change affected by institution-shaping actors (agents) is unlikely or difficult. Individuals, organizations, and governance structures that cut across public and private sectors constantly respond to environmental change (thereby engendering change); thus, environmental change does not occur in an "institutional vacuum" (Agrawal, 2008; Smets et al., 2012). Influential individuals (leaders) (Mimura, et al., 2014), sociopolitical mobilization (Keskitalo, 2010), and/or catalytic or vivid events (Bazerman, 2005) that impose or focus urgency upon some situation may induce institutional change by creating or framing a state of urgency, though other factors have been identified as important "drivers" precipitating change dynamics (Biesbroek et al., 2009; Patterson, 2021; Smets et al., 2012). Aggregating these behavioral changes across scales and social structures — and mediating or coordinating them through planning mechanisms — in turn changes the institutional environment itself, in theory providing conditions for *institutional adaptation* (Morphet, 2011). Planning that attempts to engage these institutional change dynamics confronts a duality in that institutions are both behavior patterns "out in the world" (actions) and internal ones "in the head" (thoughts and feelings), which obviously presents complexities to planners attempting to derive institutional origins (Hodgson & Knudsen, 2006; MacKinnon et al., 2009). All of these qualities speak to the difficulty in clearly formalizing or mapping institutional dynamics, made especially complex when applied to situations in which the underlying environmental context is also in a state of flux.

4.2.3. Institutions, Climate Adaptation, Planning

Smit and Wandel (2006) note that adaptive capacity may be increased through improvements in technology and/or institutions, while Rodima-Taylor (2012) echoes Koppel's (1995) position that technological innovation is *induced* by institutional change. Christensen (1985) considers technology in the context of planning to be the "knowledge of how to do something"—literally, the *means*. Our CCAP schema illustrates that these means might be expanded by integrating adaptive principles into planning that make it more "nimble" (thus, resistant to path-dependence). Yet, how these qualities relate to an institutional adaptation discourse remains complex, in part owing to the need to disentangle the functions and mechanics of institutions themselves (Patterson, 2021; Petersen-Rockney et al., 2021; Voigt, 2013). In developing a framework for assessing institutional adaptive capacity, Gupta (2010) identifies two core characteristics: one essentially describing their inherent, extant qualities; and the second relating to the degree to which they "allow or encourage" their own (institutional) change, essentially describing adaptability itself. The *rate* of change, or timing, also matters: disparities between non-institutional changes that occur within SESs and that at which institutions are fundamentally *able to affect change* may lead to missed opportunities, including from a lack of timely collaboration and cooperation (Barnett et al., 2015; Ekstrom & Moser, 2014; Gupta et al., 2010).

Roggero (2015) explores how one aspect of institutional change is positioned with respect to CCA in his iteration of Hagedorn's (2008) notion of *integrative* institutions (that address climate-related *interdependencies*) versus *segregative* ones (that focus only on climate-impacted *resources* under their effective purview). Institutional complexity itself may work against institutional change or adaptation simply as a function of the increased "work" required to do so in complex networks, though structured learning processes may be useful (Lubell et al., 2014; Pahl-Wostl, 2009; Urwin & Jordan, 2008). Informal, 'behind-the-scenes' "shadow" processes may be important factors for inducing institutional change (Leck, 2015), in addition to the identification and inception of "additional or adjusted institutional design propositions" to address climate uncertainties and complexities (Huntjens et al., 2012).

A critical question for CCAP and its role in building adaptive capacity seems to concern the scope of its *influence* and *intentions*, particularly in relation to institutional forces that define, delimit, and direct them; as well as how these may differ from, or mesh with, planning practices and processes as traditionally understood. For example, failures to adapt may be due to issues of governance more so than the planned, technical implementation of applied adaptation efforts (projects), reflecting complexity inherent to multi-level governance (Armitage, 2015; Huitema et al., 2016; Pahl-Wostl, 2009). Patterson's (2021) work investigating dimensions and possible drivers of institutional adaptation in urban governance reveals that, in formal terms, "planning" is limited in its role: for example, it is not the job of planners to cultivate charismatic leaders, nor to foment community pressure (much less political disruptions), even though these may occur partially as a function of adaptation planning. The lack of real or perceived alignment of institutions with climate change adaptation risks the governance processes for achieving it being less adaptive and/or less strategic than optimal: a condition describing – or producing – institutional "voids" (Biesbroek et al., 2009).

5. Discussion

5.1. Central Insights

As explored and illustrated in this review, planning and institutional domains are being challenged or are changing because of the emergence, intensity, and importance of climate change within policy and governance spheres. The core goal of this review is to explore complicated topics across several domains and, based on thematic and conceptual linkages prominent in the literature, to construct an integrative perspective to increase clarity in comprehension of complex and related topics relevant to CCA. Several insights based on this work are notable. First, important concepts of climate change literature have been increasingly encountered and integrated into spatial planning practices, which have led to distinct *forms* of planning. Our CCAP schema demonstrates how, for example, uncertainty is being addressed not only as an increasing "fact of life" for planners to manage but one that can be understood and approached opportunistically and as a force driving innovation and learning processes that can increase adaptive capacity. In other words, the emphasis and engagement with climate change issues is leading to adaptation in the *practice* of planning itself.

Second, prominent and complex concepts of interest evident in climate change literature can be organized into a holistic construct that displays important tenets of the research; and displayed in such a fashion as to clarify their interplay, as through the proposed framework. These interplay may take the form of *positional* properties of features within a framework that group or separate concepts; nest or embed them in one another; or imply some connective linkage(s) or couplings. They can also be rendered in *mechanistic* terms: whereby dynamics of some feature of interest logically or implicitly affect others, thus illustrating *causal* relationships. These are of particular importance in adaptation work in a similar fashion to features of our CCAP schema, in that, fundamentally, *being adaptive* entails processes of feedbacks and responses in *systems*. Thus, in the same way that features of some given environmental context tend to exert pressures on the organizations and institutions within it, these, too, can exert forces that shape the environment itself. Because our framework's foundational feature (within and through which other features interact) are SESs, we can intuitively grasp this systematic structure and behavior. The framework, in this regard, is useful in two primary ways: it organizes and simplifies information; and it provides its own *logic* that is both emergent (arising from themes and ideas in the literature examined) and can be utilized, altered, adapted or critiqued by practitioners for case-specific or applied work; or as a basis for expansion or alteration through introducing additional or different theoretical components.

Finally, as a function of the deeply complex, subtle, and dynamic nature of institutions (including merely identifying or agreeing upon them), we display the limits of the framework; prompt consideration of how planning and institutions are, in theory and reality, bound together; and provide context for considering relevant connections or patterns as theses domains unfold and interact through CCA endeavors. For example, we discuss that organizational path dependency and institutional lock-in both serve to reduce adaptive capacity, while the modes of surmounting these barriers to adaptation are nonetheless domain-distinct, in terms of the means for assessing, addressing, or ameliorating them. Likewise, planning and institutions must be understood in a temporal context: planning because its legitimacy and efficacy depend on the results of its implementation and "follow through"; and institutions because their social utility, acceptance and adherence are derived, at least partially, by way of their durability. The examination of key features of the climate change era, namely uncertainty and change itself, present vexing questions and prompt provocative, perhaps even subversive, perspectives from which to consider the practice of planning and its institutional context. Insofar as the lack of change and innovation in so many organizational and institutional cultures has led to the unfolding climate catastrophe, which of them (or what components of them) should be challenged, adapted or even discarded for the sake of aiding the planning processes that must cope with the limits organizations and institutions impose upon them in the interest of supporting and expanding the public good(s)?

5.2. Adoption, Application, Adaptation of the Framework

This article seeks to articulate the ways in which important concepts relevant to climate adaptation might be more clearly differentiated and understood in their relational dynamics, partially through illustrating schema that can be adapted to various actual situations or case studies, and linking these with prominent themes and patterns from our literature review. An overarching challenge in CCA, planning, and institutional change (especially) is measuring or quantifying the magnitude or effects of concepts that, to some extent, resist or defy efforts to do so. Certain aspects of SESs are, after all, based on informal, constantly-changing, and nonmaterial qualities with which it is, nonetheless, important to grapple. Our "schematizing" of concepts in ways that can be visualized, to some extent, might provide interesting opportunities for researchers seeking to understand how individuals (within or across organizations, levels of government, and/or demographic groups) comprehend, or (literally) "picture", some of these concepts.

Future use of the framework along these lines might take the form of research employing templates that are used to gauge (for example) how different groups render adaptive capacity inside an adaptation situation, define magnitudes of effects for various barriers; order hierarchies of adaptation planning issues, "connect" causal influences or tensions between features and how they are situated relative to others, or articulate the "distance(s)" they imagine limits lie from adaptive capacity. Clearly, these exercises would yield abstractions: sketches or diagrams, that stand in for more nuanced work. Yet, these might reveal insights and/or patterns valuable to managers seeking to understand institutional or organizational dynamics, public sentiment, or differences across divisions, or even the age or career seniority of individuals. While not the focus of this article, social science methods applied to constructing impressions and understanding of how various groups apprehend the concepts explored here—and their relationships to each other—may be illuminating. A consistent theme of this research seems to be that what people believe is *possible* (and the institutional ramifications therein) is strongly linked with problem definition and framing, with obvious impacts on decision-making and commensurately dramatic implications for CCAP.

5.3. Critical Considerations and Questions

One of the appeals of institutions that are not only adaptive but well-integrated into CCAP is that their influence and capacity to "structure…political decision-making…[and] shape practices and behaviors" is understood as being vital for the success of large-scale, strategic efforts necessary in complex urban settings (Bulkeley & Betsill, 2013; Castán

Broto, 2017; Patterson, 2021). In this context, the utility of local knowledge and local institutions has been emphasized as a driver of adaptive capacity but also as *processes*, not merely information or rules (or *content*) (Berkes, 2009; Naess, 2013; Smit & Wandel, 2006). In one sense, planning is a practice of more than instrumentalizing content; it inherently represents engagement with ongoing processes. Yet, precisely because planning entities (individuals, agencies, departments, divisions, authorities) are empowered *by and within* overarching institutional milieus, questions emerge about planning as a force for transformational, fundamental change in the ongoing adaptation quest, which some see as amounting to the proposition of a paradigm shift for planning itself (Hill, 2016). In other words, can planning "unlock" institutions from nonadaptive tendencies, and, if so, how and to what degree?

We have examined the relationships between these concepts and their underlying theories to situate planning in a critical light, insofar as we question its agency and the scope of its traditionally-conceived responsibilities. Planning, in the face of massive environmental change and uncertainty, may itself obscure the clarity of future visions and complicate the steps for manifesting them, in no small part due to institutional inertia and dynamics. That is, uncertainties rooted in the institutional domain may amplify overall situational uncertainty and complicate planning processes attempting to address it. Dovers (2010) points out that even constructing an understanding of the limits to adaptation is fraught, in part, because of the institutional dimension; whose sheer complexity grows with the scale considered (Ostrom, 2012). With climate change altering resource regimes and shaping the public interest(s) and good(s) of citizens linked through institutional behavior and (ideally) aligned through adaptation planning practices, crucial questions about how common-pool resources and common-pool institutions can or should shape planning's role in allocating entitlements and obligations emerge (Armitage, 2015; Bromley, 1998; Dipierri & Zikos, 2020; van Klingeren & de Graaf, 2021; Wilson, 2012). This, in turn (and in ways beyond the scope of this chapter), ensnares any number of private sector considerations and the need to, among other things, understand how planning and institutions are positioned to address or adapt to markets relevant in adaptation (Hughes, 2015; Neil Adger et al., 2005).

6. Conclusions

Our review examined important concepts related to the CCA plight by exploring the theoretical and applied linkages between the practice of spatial planning and role of institutions in the governance of adaptation, with an emphasis on issues and dynamics broadly relevant in urban regions. Through this process, we sought to illustrate and situate prominent themes and concepts in climate adaptation work that connect to planning and institutional dynamics; as well as their effects on SESs, which Berkes and Folke originally termed the "linkages between ecosystems and institutions" (1998). Epstein expanded on this concept and considered the differentiation between social and ecological systems as reconciled by "fitting" them together through institutions themselves; and, in doing so, revealing strengths and limitations of the institutional *couplings* of these systems (2015). Planning, as we have discussed, represents a mode of instrumentalizing adaptive governance largely in the interest of increasing adaptive capacity; and, in the climate era, our schema demonstrates how planning employs various techniques to do so in the context of uncertainty and change, by embracing it and approaching it opportunistically. Likewise, our framework illustrates the nested and linked — or *coupled* — positionality and mechanics of planning to larger concepts and displaying how their interconnections might be understood. For their part, institutions, while playing important roles in shaping and constraining planning and defining various aspects of SESs, remain difficult to fully comprehend and describe when the same considerations of uncertainty and change characterize the (conceptual) landscape in which they exist and are realized.

In his treatise articulating the global, intergenerational ethical and moral implications of climate change, Stephen Gardiner (2006) identifies *institutional inadequacy* as a key characteristic; one that, for various reasons, cannot simply be overcome by better governance. This article situates adaptation planning as a critical link between governance and institutions: in the case of the former, as a "downstream" tool for facilitating policy through decision-making; in the latter, by triggering feedback from features of the SESs that have "upstream" implications for the "rules of the game" themselves, which define and constrain what futures are considered possible or desirable (Greif & Kingston, 2011). Planning, as a field seeking to integrate science and knowledge into decision-making, is surely constrained in its capacity to do so by various political and institutional arrangements and realities, though Roggero (2018) asserts that organizing knowledge in "*institutionally meaningful ways* can advance…understanding of the link between institutions and adaptation". What precisely constitutes institutional meaningfulness in the context of climate change remains complex, dynamic, and, surely, case-specific, to some degree.

Insofar as we consider institutions to be collectivized social patterns of behavior that are "rendered durable" over time by routine and habits, the task for planning to break from reinforced tendencies that reduce adaptive capacity seems pressing (Hodgson, 2006; MacKinnon et al., 2009). These reflections position planning in a crucial position that prompts consideration about the nature or characterization of planning entities themselves: are they primarily *agents* within Hodgson's (2006) reckoning (to whom institutions may be sensitive/responsive in terms of change), or merely a *means* by which those agents interact? If they fall into the former category (or if they are understood to be both), the question of intent emerges: is it the role and responsibility of planning to actively, aggressively attempt to alter — or even do away with — institutions in light of the knowledge planning inevitably encounters and frames? If so, which institutions? According to whose values, decisions or standards? In what circumstances, to what degree, why, and — critically — how? While this last question involves what Dover & Herzi (2010) term the *practicalities* of institutional change, the challenge for adaptation planning in the 21st century may be poised to be as much about principles as practicalities.

Ch. 1 References

Abbott, J. (2005). Understanding and Managing the Unknown: The Nature of Uncertainty in Planning. Journal of Planning Education and Research, 24(3), 237–251. https://doi.org/10.1177/0739456X04267710

Adger, W. N. (2006). Vulnerability. Global Environmental Change, 16(3), 268–281. https://doi.org/10.1016/j.gloenvcha.2006.02.006

Adger, W. N., Huq, S., Brown, K., Conway, D., & Hulme, M. (2003). Adaptation to climate change in the developing world. Progress in Development Studies, 3(3), 179–195. https://doi.org/10.1191/1464993403ps060oa

Adger, W. N., S. Dessai, M. Goulden, M. Hulme, I. Lorenzoni, D. R. Nelson, L. O. Naess, J. Wolf, and A. Wreford. 2009a. Are there social limits to adaptation to climate change? Climatic Change 93:335-354. (n.d.).

Agrawal, A. (2008). The Role of Local Institutions in Adaptation to Climate Change. World Bank. https://doi.org/10.1596/28274

Agrawal, A. (2010). Local institutions and adaptation to climate change. In R. Mearns, & A. Norton (Eds.), Social dimensions of climate change: Equity and vulnerability in the warming world (pp. 173e198).Washington, DC: TheWorld Bank. (n.d.).

Albrechts, L. (2004). Strategic (Spatial) Planning Reexamined. Environment and Planning B: Planning and Design, 31(5), 743–758. https://doi.org/10.1068/b3065

Albrechts, L. (2006). Bridge the Gap: From Spatial Planning to Strategic Projects. European Planning Studies, 14(10), 1487–1500. https://doi.org/10.1080/09654310600852464

Albrechts, L. (2010). More of the same is not enough! How could strategic spatial planning be instrumental in dealing with the challenges ahead? Environment and Planning B: Planning and Design, 37(6), 1115–1127. https://doi.org/10.1068/b36068

Alexander, D. E. (1993). Natural disasters. Boston, MA: Kluwer Academic Publishers. (n.d.).

Alexander, E. (2009). Dilemmas in Evaluating Planning, or Back to Basics: What is Planning For? Planning Theory & Practice, 10(2), 233–244. https://doi.org/10.1080/14649350902884177

Allan, C., & Curtis, A. (2005). Nipped in the Bud: Why Regional Scale Adaptive Management Is Not Blooming. Environmental Management, 36(3), 414–425. https://doi.org/10.1007/s00267-004-0244-1

Allen, C. R., Fontaine, J. J., Pope, K. L., & Garmestani, A. S. (2011). Adaptive management for a turbulent future. Journal of Environmental Management, 92(5), 1339–1345. https://doi.org/10.1016/j.jenvman.2010.11.019

Allen, C. R., & Garmestani, A. S. (Eds.). (2015). Adaptive Management of Social-Ecological Systems. Springer Netherlands. https://doi.org/10.1007/978-94-017-9682-8

Allen, K. M. (2006). Community-based disaster preparedness and climate adaptation: Local capacity-building in the Philippines: Community-Based Disaster Preparedness and Climate Adaptation. Disasters, 30(1), 81–101. https://doi.org/10.1111/j.1467-9523.2006.00308.x

Andereis, J. M. (2003). Economic development, demographics, and renewable resources: A dynamical systems approach. Environment and Development Economics, 8(2), 219–246. JSTOR. http://www.jstor.org.libproxy.berkeley.edu/stable/44379301

Anderies, J. M., Janssen, M. A., & Ostrom, E. (2004). A Framework to Analyze the Robustness of Social-ecological Systems from an Institutional Perspective. Ecology and Society, 9(1), art18. https://doi.org/10.5751/ES-00610-090118

Andersson, D., Bratsberg, S., Ringsmuth, A. K., & de Wijn, A. S. (2021). Dynamics of collective action to conserve a large common-pool resource. Scientific Reports, 11(1), 9208. https://doi.org/10.1038/s41598-021-87109-x

Armitage, D. (n.d.). Governance and the commons in a multi-level world. 26.

Arthur, W.B., 1994. Increasing Returns and Path Dependence in the Economy. University of Michigan Press, Ann Arbor. (n.d.).

Aylett, A. (2015). Institutionalizing the urban governance of climate change adaptation: Results of an international survey. Urban Climate, 14, 4–16. https://doi.org/10.1016/j.uclim.2015.06.005

Baccini, P., & Brunner, P. H. (2012). Metabolism of the anthroposphere: Analysis, evaluation, design. Cambridge, Mass. : MIT Press, ©2012; cat04202a.

Balducci, A., Boelens, L., Hillier, J., Nyseth, T., & Wilkinson, C. (2011). Introduction: Strategic spatial planning in uncertainty: theory and exploratory practice. Town Planning Review, 82(5), 481–501. https://doi.org/10.3828/tpr.2011.29

Barnett, J., Evans, L. S., Gross, C., Kiem, A. S., Kingsford, R. T., Palutikof, J. P., Pickering, C. M., & Smithers, S. G. (2015). From barriers to limits to climate change adaptation: Path dependency and the speed of change. Ecology and Society, 20(3), art5. https://doi.org/10.5751/ES-07698-200305

Barrett, S. (2013). Local level climate justice? Adaptation finance and vulnerability reduction. Global Environmental Change, 23(6), 1819–1829. https://doi.org/10.1016/j.gloenvcha.2013.07.015

Basiago, A. D. (1999). Economic, social, and environmental sustainability in development theory and urban plan- ning practice: The environmentalist. Boston: Kluwer Academic Publishers. (n.d.).

Basili, M., Franzini, M., & Vercelli, A. (2006). Environment, inequality and collective action. Routledge.

Bauer, A., & Steurer, R. (2014). Innovation in climate adaptation policy: Are regional partnerships catalysts or talking shops? Environmental Politics, 23(5), 818–838. https://doi.org/10.1080/09644016.2014.924196

Bazerman, M. (2005). Climate Change as a Predictable Surprise. Climatic Change, 77, 179–193. https://doi.org/10.1007/s10584-006-9058-x

Berkes, F. (2009). Indigenous ways of knowing and the study of environmental change. Journal of the Royal Society of New Zealand, 39(4), 151–156. https://doi.org/10.1080/03014220909510568

Berkes, F., Colding, J., Folke, C. (Eds.), 2003. Navigating Social- Ecological Systems: Building Resilience for Complexity and Change. Cambridge University Press, Cambridge. (n.d.).

Berkes, Fikret; Folke, Carl (1998). Linking Social and Ecological Systems: Management Practices and Social Mechanisms for Building Resilience. Cambridge University Press. (n.d.).

Berrang-Ford, L., Pearce, T., & Ford, J. D. (2015). Systematic review approaches for climate change adaptation research. Regional Environmental Change, 15(5), 755–769. https://doi.org/10.1007/s10113-014-0708-7

Bierbaum, R., Smith, J. B., Lee, A., Blair, M., Carter, L., Chapin, F. S., Fleming, P., Ruffo, S., Stults, M., McNeeley, S., Wasley, E., & Verduzco, L. (2013). A comprehensive review of climate adaptation in the United States: More than before, but less than needed. Mitigation and Adaptation Strategies for Global Change, 18(3), 361–406. https://doi.org/10.1007/s11027-012-9423-1

Biesbroek, G. R., Termeer, C. J. A. M., Kabat, P., & Klostermann, J. E. M. (2009). Institutional governance barriers for the development and implementation of climate adaptation strategies. https://edepot.wur.nl/108132

Birchall, S. J., MacDonald, S., & Slater, T. (2021). Anticipatory planning: Finding balance in climate change adaptation governance. Urban Climate, 37, 100859. https://doi.org/10.1016/j.uclim.2021.100859

Bisaro, A., Roggero, M., & Villamayor-Tomas, S. (2018). Analysis: Institutional Analysis in Climate Change Adaptation Research: A Systematic Literature Review. Ecological Economics, 151, 34–43. edselp.

Bolan, R. S. (1967). Emerging Views of Planning. Journal of the American Institute of Planners, 33(4), 233–245. https://doi.org/10.1080/01944366708977924

Booth, P. (2011). Culture, planning and path dependence: Some reflections on the problems of comparison. Town Planning Review, 82(1), 13–28. https://doi.org/10.3828/tpr.2011.4

Bromley, D. W. (1998). Searching for sustainability: The poverty of spontaneous order. Ecological Economics, 10.

Buck et al., 2001 L.E. Buck, C.C. Geisler, J. Schelhas, E. Wollenberg Biological diversity: Balancing interests through adaptive collaborative management CRC Press, Boca Raton, FL (2001). (n.d.).

Buijs, A. E., Mattijssen, T. J., Van der Jagt, A. P., Ambrose-Oji, B., Andersson, E., Elands, B. H., & Steen Møller, M. (2016). Active citizenship for urban green infrastructure: Fostering the diversity and dynamics of citizen contributions through mosaic governance. System Dynamics and Sustainability, 22, 1–6. https://doi.org/10.1016/j.cosust.2017.01.002

Bulkeley, H., & Betsill, M. M. (2013). Revisiting the urban politics of climate change. Environmental Politics, 22(1), 136–154. https://doi.org/10.1080/09644016.2013.755797

Bulkeley, H., & Castán Broto, V. (2013). Government by experiment? Global cities and the governing of climate change: Government by experiment? Transactions of the Institute of British Geographers, 38(3), 361–375. https://doi.org/10.1111/j.1475-5661.2012.00535.x

Burley, J. G., McAllister, R. R. J., Collins, K. A., & Lovelock, C. E. (2012). Integration, synthesis and climate change adaptation: A narrative based on coastal wetlands at the regional scale. Regional Environmental Change, 12(3), 581–593. https://doi.org/10.1007/s10113-011-0271-4

Burton I (2009) Climate change and the adaptation deficit. Earthscan Reader on Adaptation to Climate Change, eds Schipper ELF, Burton I (Earthscan, Sterling, VA), pp 89–95. (n.d.).

Carter, J. G., Cavan, G., Connelly, A., Guy, S., Handley, J., & Kazmierczak, A. (2015). Climate change and the city: Building capacity for urban adaptation. Progress in Planning, 95, 1–66. https://doi.org/10.1016/j.progress.2013.08.001

Cartwright, T. J. (1973). Problems, Solutions and Strategies: A Contribution to the Theory and Practice of Planning. Journal of the American Institute of Planners, 39(3), 179–187. https://doi.org/10.1080/01944367308977852

Cash DW, Clark WC, Alcock F, Dickson NM, Eckley N, Guston DH, Jaeger J, Mitchell RB (2003) Knowledge systems for sustainable development. PNAS 100(14):8086–8091. (n.d.).

Castán Broto, V. (2017). Urban Governance and the Politics of Climate change. World Development, 93, 1–15. https://doi.org/10.1016/j.worlddev.2016.12.031

Céspedes Restrepo, J. D., & Morales-Pinzón, T. (2018). Urban metabolism and sustainability: Precedents, genesis and research perspectives. Resources, Conservation and Recycling, 131, 216–224. https://doi.org/10.1016/j.resconrec.2017.12.023

Chaffin, B. C., Gosnell, H., & Cosens, B. A. (2014). A decade of adaptive governance scholarship: Synthesis and future directions. Ecology and Society, 19(3), art56. https://doi.org/10.5751/ES-06824-190356

Chaffin, B. C., Shuster, W. D., Garmestani, A. S., Furio, B., Albro, S. L., Gardiner, M., Spring, M., & Green, O. O. (2016). A tale of two rain gardens: Barriers and bridges to adaptive management of urban stormwater in Cleveland, Ohio. Journal of Environmental Management, 183, 431–441. https://doi.org/10.1016/j.jenvman.2016.06.025

Chen, C., Doherty, M., Coffee, J., Wong, T., & Hellmann, J. (2016). Measuring the adaptation gap: A framework for evaluating climate hazards and opportunities in urban areas. Environmental Science & Policy, 66, 403–419. https://doi.org/10.1016/j.envsci.2016.05.007

Chhetri, N., Easterling, W. E., Terando, A., & Mearns, L. (2010). Modeling path dependence in agricultural adaptation to climate variability and change. Annals of the Association of American Geographers, 100(4), 894e907. (n.d.).

Chow, C. C.; Sarin, R. K. (2002): Known, unknown, and unknowable uncertainties. Theory and Decision, 52, pp. 127–138. (n.d.).

Christensen, K. S. (1985). Coping with Uncertainty in Planning. Journal of the American Planning Association, 51(1), 63–73. https://doi.org/10.1080/01944368508976801

Colding, J., & Barthel, S. (2019). Exploring the social-ecological systems discourse 20 years later. Ecology and Society, 24(1). https://doi.org/10.5751/ES-10598-240102

Corfee-Morlot, J., Cochran, I., Hallegatte, S., & Teasdale, P.-J. (2011). Multilevel risk governance and urban adaptation policy. Climatic Change, 104(1), 169–197. https://doi.org/10.1007/s10584-010-9980-9

Crawford, S. E. S., & Ostrom, E. (1995). A Grammar of Institutions. American Political Science Review, 89(3), 582–600. https://doi.org/10.2307/2082975

Daddi, T., Bleischwitz, R., Todaro, N. M., Gusmerotti, N. M., & De Giacomo, M. R. (2020). The influence of institutional pressures on climate mitigation and adaptation strategies. Journal of Cleaner Production, 244, 118879. https://doi.org/10.1016/j.jclepro.2019.118879

Davoudi, S., Mehmood, A., Brooks, E., 2011. The London climate change adaptation strategy: Gap analysis. (n.d.).

Demuzere, M., Orru, K., Heidrich, O., Olazabal, E., Geneletti, D., Orru, H., Bhave, A. G., Mittal, N., Feliu, E., & Faehnle, M. (2014). Mitigating and adapting to climate change: Multi-functional and multi-scale assessment of green urban infrastructure. Journal of Environmental Management, 146, 107–115. https://doi.org/10.1016/j.jenvman.2014.07.025

Dewey, J. (1929) The Quest for Certainty: A Study of the Relation of Knowledge and Action. The Journal of Philosophy Volume 27, Issue 1, January 1930Pages 14-25. (n.d.).

Dipierri, A. A., & Zikos, D. (2020). The Role of Common-Pool Resources' Institutional Robustness in a Collective Action Dilemma under Environmental Variations. Sustainability, 12(24), 10526. https://doi.org/10.3390/su122410526

Dovers, S. R., & Hezri, A. A. (2010). Institutions and policy processes: The means to the ends of adaptation. WIREs Climate Change, 1(2), 212–231. https://doi.org/10.1002/wcc.29

Dow, K., Berkhout, F., Preston, B. et al. Limits to adaptation. Nature Clim Change 3, 305–307 (2013). Https://doi.org/10.1038/nclimate1847. (n.d.).

Eakin, H. (2005), 'Institutional change, climate risk, and rural vulnerability: Cases from central Mexico', World Development 33(11): 1923–38. (n.d.).

Eakin, H. C., Lemos, M. C., & Nelson, D. R. (2014). Differentiating capacities as a means to sustainable climate change adaptation. Global Environmental Change, 27, 1–8. https://doi.org/10.1016/j.gloenvcha.2014.04.013

Einecker, R., & Kirby, A. (2020). Climate Change: A Bibliometric Study of Adaptation, Mitigation and Resilience. Sustainability, 12(17), 6935. https://doi.org/10.3390/su12176935

Eisenhauer, D. C. (2020). Climate Change; Adaptation. In International Encyclopedia of Human Geography (pp. 281–291). Elsevier. https://doi.org/10.1016/B978-0-08-102295-5.10756-5

Ekers, M. and Loftus, A. (2008). The power of water: Developing dialogues between Foucault and Gramsci. Environment and Planning D: Society and Space 26 (4), pp. 698–718. (n.d.).

Ekstrom, J. A., & Moser, S. C. (2014). Identifying and overcoming barriers in urban climate adaptation: Case study findings from the San Francisco Bay Area, California, USA. Urban Climate, 9, 54–74. https://doi.org/10.1016/j.uclim.2014.06.002

Emery, Fred, and Eric Trist. 1965. The causal texture of organisational environments. Human Relations 18:21-32. (n.d.).

Epstein, G., Pittman, J., Alexander, S. M., Berdej, S., Dyck, T., Kreitmair, U., Rathwell, K. J., Villamayor-Tomas, S., Vogt, J., & Armitage, D. (2015). Institutional fit and the sustainability of social–ecological systems. Current Opinion in Environmental Sustainability, 14, 34–40. https://doi.org/10.1016/j.cosust.2015.03.005

Erik Andersson, Stephan Barthel, Sara Borgström, Johan Colding, Thomas Elmqvist, Carl Folke, & Åsa Gren. (2014). Reconnecting Cities to the Biosphere: Stewardship of Green Infrastructure and Urban Ecosystem Services. Ambio, 43(4), 445. edsjsr.

Eriksen, S., & Brown, K. (2011). Sustainable adaptation to climate change. Climate and Development, 3, 3e6. (n.d.).

Faludi, A. (2000). The Performance of Spatial Planning. Planning Practice and Research, 15(4), 299–318. https://doi.org/10.1080/713691907

Fankhauser, S., Smith, J. B., & Tol, R. S. J. (1999). Weathering climate change: Some simple rules to guide adaptation decisions. Ecological Economics, 30(1), 67–78. https://doi.org/10.1016/S0921-8009(98)00117-7

Fazey, I., Wise, R. M., Lyon, C., Câmpeanu, C., Moug, P., & Davies, T. E. (2016). Past and future adaptation pathways. Climate and Development, 8(1), 26–44. https://doi.org/10.1080/17565529.2014.989192

Fischer, A. P. (2018a). Pathways of adaptation to external stressors in coastal natural-resource-dependent communities: Implications for climate change. World Development, 108, 235–248. https://doi.org/10.1016/j.worlddev.2017.12.007

Fischer, A. P. (2018b). Pathways of adaptation to external stressors in coastal natural-resource-dependent communities: Implications for climate change. World Development, 108, 235–248. https://doi.org/10.1016/j.worlddev.2017.12.007

Fischhoff, B., & Davis, A. L. (2014). Communicating scientific uncertainty. Proceedings of the National Academy of Sciences, 111(Supplement_4), 13664–13671. https://doi.org/10.1073/pnas.1317504111

Folke, C., Hahn, T., Olsson, P., & Norberg, J. (2005). ADAPTIVE GOVERNANCE OF SOCIAL-ECOLOGICAL SYSTEMS. Annual Review of Environment and Resources, 30(1), 441–473. https://doi.org/10.1146/annurev.energy.30.050504.144511

Ford, J. D., & Pearce, T. (2010). What we know, do not know, and need to know about climate change vulnerability in the western Canadian Arctic: A systematic literature review. Environmental Research Letters, 5(1), 014008. https://doi.org/10.1088/1748-9326/5/1/014008

Forester, J. (1980). Critical Theory and Planning Practice. Journal of the American Planning Association, 46(3), 275–286. https://doi.org/10.1080/01944368008977043

Füssel, H.-M., & Klein, R. J. T. (2006). Climate Change Vulnerability Assessments: An Evolution of Conceptual Thinking. Climatic Change, 75(3), 301–329. https://doi.org/10.1007/s10584-006-0329-3

Gallopín, G. C. (2006). Linkages between vulnerability, resilience, and adaptive capacity. Global Environmental Change, 16(3), 293–303. https://doi.org/10.1016/j.gloenvcha.2006.02.004

Gallopı n, G.C., Gutman, P., Maletta, H., 1989. Global impoverishment, sustainable development and the environment: A conceptual approach. International Social Science Journal 121, 375–397. (n.d.).

Gardiner, S. M. (2006). A Perfect Moral Storm: Climate Change, Intergenerational Ethics and the Problem of Moral Corruption. Environmental Values, 15(3,), 397–413. http://www.jstor.org/stable/30302196

Garmestani, A. S., Allen, C. R., & Cabezas, H. (n.d.). Panarchy, Adaptive Management and Governance: Policy Options for Building Resilience. 20.

Geels, F.W., 2002. Technological transitions as evolutionary reconfiguration processes: A multi-level perspective and a case-study. Research Policy 31, 1257– 1274. (n.d.).

Giordano, T. (2012). Adaptive planning for climate resilient long-lived infrastructures. Utilities Policy, 23, 80–89. https://doi.org/10.1016/j.jup.2012.07.001

Giuseppe Ioppolo, Reinout Heijungs, Stefano Cucurachi, Roberta Salomone, & René Kleijn. (2013). Urban Metabolism: Many Open Questions for Future Answers. Pathways to Environmental Sustainability : Methodologies and Experiences, 23. edssjb. https://doi.org/10.1007/978-3-319-03826-1_3

Glasbergen P: Setting the scene: The partnership paradign in the making. In Partnerships, Governance and Sustainable Development: Reflections on Theory and Practice. Edited by Glasbergen P, Biermann F, Mol A. Edward Elgar Publishing; 2007: 314. (n.d.).

Gollier, C., Treich, N., 2003. Decision-making under scientific uncertainty: The economics of the precautionary principle. Journal of Risk and Uncertainty 27 (1), 77–103. (n.d.).

Goodwin, P.,Wright, G., 2010. The limits of forecasting methods in anticipating rare events. Technological Forecasting and Social Change 77, 355e368. (n.d.).

Gopalakrishnan, V., & Bakshi, B. R. (2017). Including Nature in Engineering Decisions for Sustainability. In Encyclopedia of Sustainable Technologies (pp. 107–116). Elsevier. https://doi.org/10.1016/B978-0-12-409548-9.10039-9

Graedel, T. E., & Allenby, B. R. (2010). Industrial ecology and sustainable engineering. (Engineering TS161 .G7425 2010). Upper Saddle River, NJ : Prentice Hall, c2010.; cat04202a.

Greif, A., & Kingston, C. (2011). Institutions: Rules or Equilibria? In N. Schofield & G. Caballero (Eds.), Political Economy of Institutions, Democracy and Voting (pp. 13–43). Springer Berlin Heidelberg. https://doi.org/10.1007/978-3-642-19519-8_2

Gruber, Judith. 1994. Coordinating growth management through consensus- building: Incentives and the generation of social, intellectual, and political capital. Berkeley: Institute of Urban and Regional Development (IURD), University of California, Berkeley. (n.d.).

Gualini, E. (2001). Planning and the Intelligence of Institutions: Interactive Approaches to Territorial Policy-Making Between Institutional Design and Institution-Building (1st ed.). Routledge. Https://doi.org/10.4324/9781315201726. (n.d.).

Gunderson, L & Holling, C.S. (eds), 2002. Panarchy: Understanding Transformations in Human and Natural Systems; Island Press. (n.d.).

Gunderson, L. 1999. Resilience, flexibility and adaptive management—- Antidotes for spurious certitude? Conservation Ecology 3(1): 7. (n.d.).

Gupta, J., Termeer, C., Klostermann, J., Meijerink, S., van den Brink, M., Jong, P., Nooteboom, S., & Bergsma, E. (2010). The Adaptive Capacity Wheel: A method to assess the inherent characteristics of institutions to enable the adaptive capacity of society. Environmental Science & Policy, 13(6), 459–471. https://doi.org/10.1016/j.envsci.2010.05.006

Guston DH. Boundary organizations in environmental policy and science: An introduction. Sci Technol Hum Values 2001, 26:339–408. (n.d.).

Habermas J (1998) Between facts and norms: Contributions to a discourse theory of law and democracy. MIT, Cambridge. (n.d.).

Hagedorn, K. (2008). Particular requirements for institutional analysis in nature-related sectors. European Review of Agricultural Economics, 35(3), 357–384. https://doi.org/10.1093/erae/jbn019

Haimes, Y.Y., 2004. Risk Modeling, Assessment, and Management. Wiley, Hoboken. (n.d.).

Hall, P.A., 1993. Policy paradigms, social learning, and the state: The case of economic policymaking in Britain. Comparative Politics 25, 275–296. (n.d.).

Hallegatte, S. (2009). Strategies to adapt to an uncertain climate change. Global Environmental Change, 19(2), 240–247. https://doi.org/10.1016/j.gloenvcha.2008.12.003

Hannah, L. (2010). A Global Conservation System for Climate-Change Adaptation. Conservation Biology, 24(1), 70–77. JSTOR. http://www.jstor.org.libproxy.berkeley.edu/stable/40419631

Hardin, G. (1968). The Tragedy of the Commons. Science, 162, 1243-1248. Http://dx.doi.org/10.1126/science.162.3859.1243. (n.d.).

Harman, B. P., Taylor, B. M., & Lane, M. B. (2015). Urban partnerships and climate adaptation: Challenges and opportunities. Current Opinion in Environmental Sustainability, 12, 74–79. https://doi.org/10.1016/j.cosust.2014.11.001

Healey, P. (1998) Planning: Shaping Places in Fragmented Societies (Bassingstoke, Macmillan). (n.d.).

Healey, P. (2006). Transforming governance: Challenges of institutional adaptation and a new politics of space. European Planning Studies, 14(3), 299–319. (n.d.).

Herrington, G. (2021). Update to limits to growth: Comparing the World3 model with empirical data. Journal of Industrial Ecology, 25(3), 614–626. https://doi.org/10.1111/jiec.13084

Hill, K. (2016). Climate Change: Implications for the Assumptions, Goals and Methods of Urban Environmental Planning. Urban Planning, 1(4), 103–113. https://doi.org/10.17645/up.v1i4.771

Hill, Kristina (2018). Oxford Bibliographies. DOI: 10.1093/obo/9780199363445-0099. (n.d.).

Hinkel, J., & Bisaro, A. (2015). A review and classification of analytical methods for climate change adaptation: Analytical methods for climate change adaptation. Wiley Interdisciplinary Reviews: Climate Change, 6(2), 171–188. https://doi.org/10.1002/wcc.322

Hodgson, G. M. (2006). What Are Institutions? Journal of Economic Issues, 40(1), 1–25. JSTOR. http://www.jstor.org.libproxy.berkeley.edu/stable/4228221

Hodgson, G. M., & Knudsen, T. (2006). Why we need a generalized Darwinism, and why generalized Darwinism is not enough. Journal of Economic Behavior & Organization, 61(1), 1–19. https://doi.org/10.1016/j.jebo.2005.01.004

Holling, C. S. (1973) Resilience and stability of ecological systems, Annual Review of Ecological Systems, 4, pp. 1–23. (n.d.).

Holling, C. S., & Meffe, G. K. (1996). Command and Control and the Pathology of Natural Resource Management. Conservation Biology, 10(2), 328–337. https://doi.org/10.1046/j.1523-1739.1996.10020328.x

Hughes, S. (2015). A meta-analysis of urban climate change adaptation planning in the U.S. Urban Climate, 14, 17–29. https://doi.org/10.1016/j.uclim.2015.06.003

Huitema, D., Adger, W. N., Berkhout, F., Massey, E., Mazmanian, D., Munaretto, S., Plummer, R., & Termeer, C. C. J. A. M. (2016). The governance of adaptation: Choices, reasons, and effects.

Introduction to the Special Feature. Ecology and Society, 21(3), art37. https://doi.org/10.5751/ES-08797-210337

Huntjens, P., Lebel, L., Pahl-Wostl, C., Camkin, J., Schulze, R., & Kranz, N. (2012). Institutional design propositions for the governance of adaptation to climate change in the water sector. Global Environmental Change, 22(1), 67–81. https://doi.org/10.1016/j.gloenvcha.2011.09.015

Innes, J. E. (2004). Consensus Building: Clarifications for the Critics. Planning Theory, 3(1), 5–20. https://doi.org/10.1177/1473095204042315

Jabareen, Y. (2009). Building a Conceptual Framework: Philosophy, Definitions, and Procedure. International Journal of Qualitative Methods, 8(4), 49–62. https://doi.org/10.1177/160940690900800406

Jianguo Wu. (2014). Urban ecology and sustainability: The state-of-the-science and future directions: Actionable urban ecology in China and the world: Integrating ecology and planning for sustainable cities. Landscape and Urban Planning, 209. edscal.

Juhola, S., Glaas, E., Linnér, B.-O., & Neset, T.-S. (2016). Redefining maladaptation. Environmental Science & Policy, 55, 135–140. https://doi.org/10.1016/j.envsci.2015.09.014

Kennedy, C., Pincetl, S., & Bunje, P. (2011). The study of urban metabolism and its applications to urban planning and design. Environmental Pollution, 159(8/9), 1965–1973. 8gh.

Keskitalo, E. C. H. (Ed.). (2010). Developing Adaptation Policy and Practice in Europe: Multi-level Governance of Climate Change. Springer Netherlands. https://doi.org/10.1007/978-90-481-9325-7

KLEIN, R.J.T. and TOL, R.S.J., 1997. Adaptation to Climate Change: Options and Technologies. An Overview Paper. Technical Paper FCCC/TP/1997/3. Bonn, Germany: United Nations Framework Convention on Climate Change Secretariat, 36p. (n.d.).

Klein RJT, Midgley GF, Preston BL, Alam M, Berkhout FGH, Dow K, Shaw MR (2014) Adaptation opportunities, constraints, and limits. In: Barros V et al (eds) Climate change 2014: Impacts, adaptation, and vulnerability. Part A: Global and sectoral aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, New York, pp 899–943. (n.d.).

Knight, J., & Douglass North [1997], "Explaining Economic Change: The Interplay Be- tween Cognition and Institutions," Legal Theory, 3, 211-226. (n.d.).

Kondo, T., & Lizarralde, G. (2021). Maladaptation, fragmentation, and other secondary effects of centralized post-disaster urban planning: The case of the 2011 "cascading" disaster in Japan. International Journal of Disaster Risk Reduction, 58, 102219. https://doi.org/10.1016/j.ijdrr.2021.102219

Koppel, B. M. (1995). Induced innovation theory, agricultural research, and Asia's green revolution: A reappraisal. In B. M. Koppel (Ed.), Induced innovation theory and international agricultural development: A reassessment (pp. 56e72). The John Hopkins University Press. (n.d.).

Kunzmann, K. (2000) Strategic spatial development through information and communication, in: W. Salet & A. Faludi (Eds) The Revival of Strategic Spatial Planning, pp. 259–265 (Amsterdam: Royal Netherlands Academy of Arts and Sciences). (n.d.).

Kwakkel, J., van der Pas, J.W.GH.M., 2011. Evaluation of infrastructure planning approaches: An analogy with medicine. Futures 43 (9), 934e946. (n.d.).

Lawrence, D. P. (2000). Planning theories and environmental impact assessment. Environmental Impact Assessment Review, 20(6), 607–625. https://doi.org/10.1016/S0195-9255(00)00036-6

Lawrence, J., Bell, R., Blackett, P., Stephens, S., & Allan, S. (2018). National guidance for adapting to coastal hazards and sea-level rise: Anticipating change, when and how to change pathway. Environmental Science & Policy, 82, 100–107. https://doi.org/10.1016/j.envsci.2018.01.012

Leach, W. and Sabatier, P. (2003) 'Facilitators, Coordinators, and Outcomes', in R. O'Leary and L.B. Bingham (eds) The Promise and Performance of Environmental Conflict Resolution, pp. 148–71. Washington, DC: Resources for the Future. (n.d.).

Leck, H. (2015). What lies beneath: Understanding the invisible aspects of municipal climate change governance. Current Opinion in Environmental Sustainability, 7.

Leck H, Simon D: Fostering multiscalar collaboration and co-operation for effective governance of climate change adaptation. Urban Stud 2013, 50:1221-1238. (n.d.).

Lee, K. N. (2021). Appraising Adaptive Management. 22.

Lemons, J., Westra, L., & Goodland, R. (Eds.). (1998). Ecological Sustainability and Integrity: Concepts and Approaches (Vol. 13). Springer Netherlands. https://doi.org/10.1007/978-94-017-1337-5

Lempert, R.J., Collins, M.T., 2007. Managing the risk of uncertain thresholds responses: Comparison of robust, optimum, and precautionary approaches. Risk Analysis 27, 1009–1026. (n.d.).

Leopold, Aldo, 1886-1948 and Charles Walsh, Schwartz. 1966. A Sand County Almanac: With Other Essays On Conservation From Round River.. New York: Oxford University Press. (n.d.).

Levin, K., Cashore, B., Bernstein, S., & Auld, G. (2012). Overcoming the tragedy of super wicked problems: Constraining our future selves to ameliorate global climate change. Policy Sciences, 45(2), 123–152. https://doi.org/10.1007/s11077-012-9151-0

Lipshitz, R., & Strauss, O. (1997). Coping with Uncertainty: A Naturalistic Decision-Making Analysis. Organizational Behavior and Human Decision Processes, 69(2), 149–163. https://doi.org/10.1006/obhd.1997.2679

LtLt, S. M. (n.d.). Sustainable Development" A Critical Review. WORLD DEVELOPMENT, 15.

Lubell, M., Robins, G., & Wang, P. (2014). Network structure and institutional complexity in an ecology of water management games. Ecology and Society, 19(4), art23. https://doi.org/10.5751/ES-06880-190423

Macintosh, A. (2013). Coastal climate hazards and urban planning: How planning responses can lead to maladaptation. Mitigation and Adaptation Strategies for Global Change, 18(7), 1035–1055. https://doi.org/10.1007/s11027-012-9406-2

Mack, Ruth. 1971. Planning on uncertainty: Decision making in business and government administration. New York: Wiley Interscience. (n.d.).

MacKinnon, D., Cumbers, A., Pike, A., Birch, K., & McMaster, R. (2009). Evolution in Economic Geography: Institutions, Political Economy, and Adaptation. Economic Geography, 85(2), 129–150. https://doi.org/10.1111/j.1944-8287.2009.01017.x

Main, K. L., Mazereeuw, M., Masoud, F., Lu, J., Barve, A., Ojha, M., & Krishna, C. (2021). Climate action zones: A clustering methodology for resilient spatial planning in climate uncertainty. In

Enhancing Disaster Preparedness (pp. 241–258). Elsevier. https://doi.org/10.1016/B978-0-12-819078-4.00013-7

Marshall, G. R. (2013). Transaction costs, collective action and adaptation in managing complex social–ecological systems. Ecological Economics, 88, 185–194. https://doi.org/10.1016/j.ecolecon.2012.12.030

Mccarthy, J., Canziani, O., Leary, N., Dokken, D., & White, K. (2001). Climate Change 2001: Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, 19.

McHarg, I. L. (1969). Design with nature. (Bioscience & Natural Resources HM206 .M18). Garden City, N.Y., Published for the American Museum of Natural History [by] the Natural History Press, 1969.; cat04202a.

McInerney, D., Lempert, R., & Keller, K. (2012). What are robust strategies in the face of uncertain climate threshold responses?: Robust climate strategies. Climatic Change, 112(3–4), 547–568. https://doi.org/10.1007/s10584-011-0377-1

Meadows, D. H. (1972). The Limits to growth: A report for the Club of Rome's project on the predicament of mankind. (Institute of Governmental Studies 90 01642). [S.l.] : Earth Island, 1972.; cat04202a.

Meadows, D. H., Randers, J., & Meadows, D. L. (2004). The limits to growth: The 30-year update. (Environmental Design HD75.6 .M437 2004). White River Junction, Vt : Chelsea Green Pub., c2004.; cat04202a.

Mehrotra, S., Natenzon, C., Omojola, A., Folorunsho, R., Gilbride, J., & Rosenzweig, C. (2009). Framework for city climate risk assess- ment. Fifth Urban Research Symposium. World Bank. Retrieved from. (n.d.).

Miles, M. B. , & Huberman, A. M. (1994). Qualitative data analysis: An expanded source book (2nd ed.). Newbury Park, CA: Sage. (n.d.).

Milkoreit, M. (2017). Imaginary politics: Climate change and making the future. Elementa: Science of the Anthropocene, 5, 62. https://doi.org/10.1525/elementa.249

Milly, P. C. D., Betancourt, J., Falkenmark, M., Hirsch, R. M., Kundzewicz, Z. W., Lettenmaier, D. P., & Stouffer, R. J. (2008). Stationarity Is Dead: Whither Water Management? Science, 319(5863), 573–574. https://doi.org/10.1126/science.1151915

Mimura, N., Pulwarty, R.S., Duc, D.M., Elshinnawy, I., Redsteer, M.H., Huang, H.Q., Nkem, J.N., Sanchez Rodriguez, R.A., 2014. Chapter 15: Adaptation planning and implementation, Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA. (n.d.).

Mitchell RB, Clark WC, Cash DW, Dickson N (eds) (2006) Global environmental assessments: Information, institutions, and influence. MIT, Cambridge. (n.d.).

Moore, C. W. (1987). The Mediation Process: Practical Strategies for Resolving Conflict. San Francisco: Jossey-Bass. (n.d.).

Morphet, J. (2011). Effective practice in spatial planning. Routledge.

Moser, S. C., & Ekstrom, J. A. (2010). A framework to diagnose barriers to climate change adaptation. Proceedings of the National Academy of Sciences, 107(51), 22026–22031. https://doi.org/10.1073/pnas.1007887107

Moser, S. C., Ekstrom, J. A., Kim, J., & Heitsch, S. (2019). Adaptation finance archetypes: Local governments’ persistent challenges of funding adaptation to climate change and ways to overcome them. Ecology and Society, 24(2), art28. https://doi.org/10.5751/ES-10980-240228

Myers, Dowell, and Alicia Kitsuse. 2000. Constructing the future in planning: A survey of theories and tools. Journal of Planning Education and Research 19:221-31. (n.d.).

Naess, L. O. (2013). The role of local knowledge in adaptation to climate change: Role of local knowledge in adaptation. Wiley Interdisciplinary Reviews: Climate Change, 4(2), 99–106. https://doi.org/10.1002/wcc.204

Nalau, J., Preston, B. L., & Maloney, M. C. (2015). Is adaptation a local responsibility? Environmental Science & Policy, 48, 89–98. https://doi.org/10.1016/j.envsci.2014.12.011

Nalau, J., Torabi, E., Edwards, N., Howes, M., & Morgan, E. (2021). A critical exploration of adaptation heuristics. Climate Risk Management, 32, 100292. https://doi.org/10.1016/j.crm.2021.100292

Ndubisi, F., [1955-] & ebrary Academic Complete. (2002). Ecological planning: A historical and comparative synthesis. awn. https://libproxy.berkeley.edu/login?qurl=http%3a%2f%2fsearch.ebscohost.com%2flogin.aspx%3fdirect%3dtrue%26db%3dawn%26AN%3dSO-1603-914281%26site%3deds-live

Neil Adger, W., Arnell, N. W., & Tompkins, E. L. (2005). Successful adaptation to climate change across scales. Global Environmental Change, 15(2), 77–86. https://doi.org/10.1016/j.gloenvcha.2004.12.005

Nordgren, J., Stults, M., Meerow, S., 2016. Supporting local climate change adaptation: Where we are and where we need to go. Environ. Sci. Pol. 66, 344–352. (n.d.).

Nuno Martins Mahmood Fayazi Faten Kikano Liliane Hobeica, (2020) Enhancing Disaster Preparedness From Humanitarian Architecture to Community Resilience, 1st Edition. Elsevier. (n.d.).

Obeng-Odoom, F. (2016). The Meaning, Prospects, and Future of the Commons: Revisiting the Legacies of Elinor Ostrom and Henry George: The Meaning, Prospects, and Future of the Commons. American Journal of Economics and Sociology, 75(2), 372–414. https://doi.org/10.1111/ajes.12144

Oberlack, C. (2017). Diagnosing institutional barriers and opportunities for adaptation to climate change. Mitigation and Adaptation Strategies for Global Change, 22(5), 805–838. https://doi.org/10.1007/s11027-015-9699-z

Oliver-Smith, A. (1996). ANTHROPOLOGICAL RESEARCH ON HAZARDS AND DISASTERS. Annual Review of Anthropology, 25(1), 303–328. https://doi.org/10.1146/annurev.anthro.25.1.303

Oppenheimer, M., O'Neill, B. C., & Webster, M. (2008). Negative learning. Climatic Change, 89(1–2), 155–172. https://doi.org/10.1007/s10584-008-9405-1

Ostrom, E. (2005). Doing Institutional Analysis Digging Deeper Than Markets and Hierarchies. In C. Menard & M. M. Shirley (Eds.), Handbook of New Institutional Economics (pp. 819–848). Springer US. https://doi.org/10.1007/0-387-25092-1_31

Ostrom, E. (2012). Nested externalities and polycentric institutions: Must we wait for global solutions to climate change before taking actions at other scales? Economic Theory, 49(2), 353–369. https://doi.org/10.1007/s00199-010-0558-6

Ostrom, E. (1990) Governing the Commons: The Evolution of Institutions for Collective Action. Cambridge, MA: Cambridge University Press. (n.d.).

Ostrom E (2007) A diagnostic approach for going beyond panaceas. Proc Natl Acad Sci USA 104:15181–15187. (n.d.).

Paavola, J. (2007). Institutions and environmental governance: A reconceptualization. Ecological Economics, 63(1), 93–103. https://doi.org/10.1016/j.ecolecon.2006.09.026

Pahl-Wostl, C. (2009). A conceptual framework for analysing adaptive capacity and multi-level learning processes in resource governance regimes. Global Environmental Change, 19(3), 354–365. https://doi.org/10.1016/j.gloenvcha.2009.06.001

Paré, G., Trudel, M.-C., Jaana, M., & Kitsiou, S. (2015). Synthesizing information systems knowledge: A typology of literature reviews. Information & Management, 52(2), 183–199. https://doi.org/10.1016/j.im.2014.08.008

Patterson, J. J. (2021). More than planning: Diversity and drivers of institutional adaptation under climate change in 96 major cities. Global Environmental Change, 68, 102279. https://doi.org/10.1016/j.gloenvcha.2021.102279

Pelling M (2011) Adaptation to climate change: From resilience to transformation. Routledge, London. (n.d.).

Pelling, M., & High, C. (2005). Understanding Adaptation: What Can Social Capital Offer Assessments of Adaptive Capacity? Global Environmental Change, 15, 308–319. https://doi.org/10.1016/j.gloenvcha.2005.02.001

Pelling, M., O'Brien, K., & Matyas, D. (2015). Adaptation and transformation. Climatic Change, 133(1), 113–127. https://doi.org/10.1007/s10584-014-1303-0

Pescaroli, G., & Alexander, D. (2018). Understanding Compound, Interconnected, Interacting, and Cascading Risks: A Holistic Framework: A Holistic Framework for Understanding Complex Risks. Risk Analysis, 38(11), 2245–2257. https://doi.org/10.1111/risa.13128

Petersen-Rockney, M., Baur, P., Guzman, A., Bender, S. F., Calo, A., Castillo, F., De Master, K., Dumont, A., Esquivel, K., Kremen, C., LaChance, J., Mooshammer, M., Ory, J., Price, M. J., Socolar, Y., Stanley, P., Iles, A., & Bowles, T. (2021). Narrow and Brittle or Broad and Nimble? Comparing Adaptive Capacity in Simplifying and Diversifying Farming Systems. Frontiers in Sustainable Food Systems, 5, 564900. https://doi.org/10.3389/fsufs.2021.564900

Peterson, G.D., Cumming, G.S., Carpenter, S.R., 2003b. Scenario planning: A tool for conservation in an uncertain world. Conservation Biology 17, 358–366. (n.d.).

Pierre, N.J. (1999) Models of urban governance: The institutional dimension of urban politics, Urban Affairs Review, 34(3), pp. 372–396. (n.d.).

Pierson, P. (2000). Increasing Returns, Path Dependence, and the Study of Politics. American Political Science Review, 94(2), 251–267. Cambridge Core. https://doi.org/10.2307/2586011

Rasmussen, D. J., Oppenheimer, M., Kopp, R. E., & Shwom, R. (2020). The political complexity of coastal flood risk reduction: Lessons for climate adaptation public works in the U.S. [Preprint]. Climatology (Global Change). https://doi.org/10.1002/essoar.10502705.3

Rauws, W. (2017). Embracing Uncertainty Without Abandoning Planning: Exploring an Adaptive Planning Approach for Guiding Urban Transformations. DisP - The Planning Review, 53(1), 32–45. https://doi.org/10.1080/02513625.2017.1316539

Reeder, T., & Ranger, N. (n.d.). How do you adapt in an uncertain world? Lessons from the Thames Estuary 2100 project. 16.

Revi, A., Satterthwaite, D., Aragón-Durand, F., Corfee-Morlot, J., Kiunsi, R. B. R., Pelling, M., Roberts, D., Solecki, W., Gajjar, S. P., & Sverdlik, A. (2014). Towards transformative adaptation in cities: The IPCC's Fifth Assessment. Environment and Urbanization, 26(1), 11–28. https://doi.org/10.1177/0956247814523539

Reyes Plata, J. A. (2020). Urban Planning, Urban Design, and the Creation of Public Goods. In W. Leal Filho, A. Marisa Azul, L. Brandli, P. Gökçin Özuyar, & T. Wall (Eds.), Sustainable Cities and Communities (pp. 899–905). Springer International Publishing. https://doi.org/10.1007/978-3-319-95717-3_82

Rianne Warsen, José Nederhand, Erik Hans Klijn, Sanne Grotenbreg & Joop Koppenjan (2018) What makes public-private partnerships work? Survey research into the outcomes and the quality of cooperation in PPPs, Public Management Review, 20:8, 1165-1185, DOI: 10.1080/14719037.2018.1428415. (n.d.).

Ribot, J. C. (2010). Vulnerability does not fall from the sky: Toward multi-scale propoor climate policy. In R. Mearns, & A. Norton (Eds.), Social dimensions of climate change: Equity and vulnerability in a warming world (pp. 47e74). Washington, DC: The World Bank. (n.d.).

Ritchie, J., Lewis, J., Nicholls, C.M. & Ormston, R., 2014, Qualitative research practice: A guide for social science students and researchers, 2nd edn., Sage, London. (n.d.).

Roberts, N. (1997) 'Public Deliberation: An Alternative Approach to Crafting Policy and Setting Direction', Public Administration Review 57(2): 124–32. (n.d.).

Roberts, N. (2002) 'Keeping Public Officials Accountable through Dialogue: Resolving the Accountability Paradox', Public Administration Review 62(6): 658–69. (n.d.).

Rodima-Taylor, D., Olwig, M. F., & Chhetri, N. (2012). Adaptation as innovation, innovation as adaptation: An institutional approach to climate change. Applied Geography, 33, 107–111. https://doi.org/10.1016/j.apgeog.2011.10.011

Roggero, M. (2015). Adapting institutions: Exploring climate adaptation through institutional economics and set relations. Ecological Economics, 118, 114–122. https://doi.org/10.1016/j.ecolecon.2015.07.022

Roggero, M., Bisaro, A., & Villamayor-Tomas, S. (2018). Institutions in the climate adaptation literature: A systematic literature review through the lens of the Institutional Analysis and

Development framework. Journal of Institutional Economics, 14(3), 423–448. https://doi.org/10.1017/S1744137417000376

Rondinelli, D. A. (1976). Public planning and political strategy. Long Range Planning, 9(2), 75–82. https://doi.org/10.1016/0024-6301(76)90080-7

Rose, A. (2007). Economic resilience to natural and man-made disasters: Multidisciplinary origins and contextual dimensions. Environmental Hazards, 7(4), 383–398. https://doi.org/10.1016/j.envhaz.2007.10.001

Rosenzweig, C., Solecki, W. D., Hammer, S. A., & Mehrohtra, S. (Eds.). (2011). Climate change and cities first assessment report of the urban climate change research network. Cambridge: Cam-bridge University Press. (n.d.).

Ryan, C.M. (2001) 'Leadership in Collaborative Policy Making: An Analysis of Agency Roles in Regulatory Negotiation', Policy Sciences 34(3): 221–45. (n.d.).

Sabatier, P.A., 1986. Top-down and bottom-up approaches to implementation research: A critical analysis and suggested synthesis. Journal of Public Policy 6, 21–48. (n.d.).

Sanyal, B. (2005). Planning as Anticipation of Resistance. Planning Theory, 4(3), 225–245. https://doi.org/10.1177/1473095205058495

Satterthwaite, D., Dodman, D., & Bicknell, J. (2009). Conclusions: Local development and adaptation. In J. Bicknell, D. Dodman, & D. Satterthwaite (Eds.), Adapting cities to climate change: Understanding and addressing the development challenges (pp. 359–383). London: Earthscan. (n.d.).

Sauvé, S., Bernard, S., & Sloan, P. (2016). Environmental sciences, sustainable development and circular economy: Alternative concepts for trans-disciplinary research. Environmental Development, 17, 48–56. edselp.

Schotter, A. (2000). The Economic Theory of Social Institutions. In Southern Economic Journal (Vol. 48). https://doi.org/10.2307/1058295

Schroeder, H., & Kobayashi, Y. (2021). Climate change governance: Responding to an existential crisis. In The Impacts of Climate Change (pp. 479–489). Elsevier. https://doi.org/10.1016/B978-0-12-822373-4.00006-9

Scott, C. A., Shrestha, P. P., & Lutz-Ley, A. N. (2020). The re-adaptation challenge: Limits and opportunities of existing infrastructure and institutions in adaptive water governance. Current Opinion in Environmental Sustainability, 44, 104–112. https://doi.org/10.1016/j.cosust.2020.09.012

Scott, W. (2003). Institutions and Organizations. Leadership & Organization Development Journal, 24, 469–470. https://doi.org/10.1108/01437730310505902

Shackle, G. L. S. 1969. Decision order and time in human affairs. Cambridge: Cambridge University Press. (n.d.).

Smets, M., Morris, T., & Greenwood, R. (2012). From Practice to Field: A Multilevel Model of Practice-Driven Institutional Change. Academy of Management Journal, 55(4), 877–904. https://doi.org/10.5465/amj.2010.0013

Smit, B., & Wandel, J. (2006). Adaptation, adaptive capacity and vulnerability. Global Environmental Change, 16(3), 282–292. https://doi.org/10.1016/j.gloenvcha.2006.03.008

Soden, R., & Kauffman, N. (2019). Infrastructuring the Imaginary: How Sea-Level Rise Comes to Matter in the San Francisco Bay Area. Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems, 1–11. https://doi.org/10.1145/3290605.3300516

Sorensen, A. (2018). Institutions and Urban Space: Land, Infrastructure, and Governance in the Production of Urban Property. Planning Theory & Practice, 19(1), 21–38. https://doi.org/10.1080/14649357.2017.1408136

Stedinger, J. R., & Griffis, V. W. (2011). Getting From Here to Where? Flood Frequency Analysis and Climate1: Getting From Here to Where? Flood Frequency Analysis and Climate. JAWRA Journal of the American Water Resources Association, 47(3), 506–513. https://doi.org/10.1111/j.1752-1688.2011.00545.x

Stoddart, H., Schneeberger, K., Dodds, F., Shaw, A., Bottero, M., Cornforth, J., & White, R. (2011). A pocket guide to sustainable development governance. Stakeholder Forum 2011. (n.d.).

Storbjörk, S., & Hedrén, J. (2011). Institutional capacity-building for targeting sea-level rise in the climate adaptation of Swedish coastal zone management. Lessons from Coastby. Ocean & Coastal Management, 54(3), 265–273. https://doi.org/10.1016/j.ocecoaman.2010.12.007

Stringer, L. C., Dougill, A. J., Fraser, E., Hubacek, K., Prell, C., & Reed, M. S. (2006). Unpacking “Participation” in the Adaptive Management of Social–ecological Systems: A Critical Review. Ecology and Society, 11(2), art39. https://doi.org/10.5751/ES-01896-110239

Stroup, L. J. (2011). Adaptation of U.S. Water Management to Climate and Environmental Change. The Professional Geographer, 63(4), 414–428. https://doi.org/10.1080/00330124.2011.604010

Susskind, L., McKearnan, S. and Thomas-Larmer, J. (eds) (1999) The Consensus Building Handbook: A Comprehensive Guide to Reaching Agreement. Thousand Oaks, CA: Sage. (n.d.).

Swaffield, S. R. (2002). Theory in landscape architecture: A reader. (Environmental Design SB472 .T44 2002). Philadelphia : University of Pennsylvania Press, c2002.; cat04202a.

Swyngedouw, E. (2009). The Antinomies of the Postpolitical City: In Search of a Democratic Politics of Environmental Production. International Journal of Urban and Regional Research, 33(3), 601–620. https://doi.org/10.1111/j.1468-2427.2009.00859.x

Tarr, J. A. (1996). The Search for the Ultimate Sink. [Electronic resource]: Urban Pollution in Historical Perspective. Akron, Ohio : University of Akron Press, 1996. (Baltimore, Md. : Project MUSE, 2015); cat04202a.

Tilly, C. (2001). Mechanisms in Political Processes. 22.

Tilly, C. (1984) Big Structures, Large Processes, Huge Comparisons. New York, NY. Russel Sage. (n.d.).

Toimil, A., Losada, I. J., Nicholls, R. J., Dalrymple, R. A., & Stive, M. J. F. (2020). Addressing the challenges of climate change risks and adaptation in coastal areas: A review. Coastal Engineering, 156, 103611. https://doi.org/10.1016/j.coastaleng.2019.103611

Tol, R. S. J., Klein, R. J. T., & Nicholls, R. J. (2008). Towards Successful Adaptation to Sea-Level Rise along Europe's Coasts. Journal of Coastal Research, 242, 432–442. https://doi.org/10.2112/07A-0016.1

Torabi, E., Dedekorkut-Howes, A., & Howes, M. (2018). Adapting or maladapting: Building resilience to climate-related disasters in coastal cities. Cities, 72, 295–309. https://doi.org/10.1016/j.cities.2017.09.008

Tribbia, J., & Moser, S. C. (2008). More than information: What coastal managers need to plan for climate change. Environmental Science & Policy, 11(4), 315–328. https://doi.org/10.1016/j.envsci.2008.01.003

Turkelboom, F., Leone, M., Jacobs, S., Kelemen, E., García-Llorente, M., Baró, F., Termansen, M., Barton, D. N., Berry, P., Stange, E., Thoonen, M., Kalóczkai, Á., Vadineanu, A., Castro, A. J., Czúcz, B., Röckmann, C., Wurbs, D., Odee, D., Preda, E., … Rusch, V. (2018). When we cannot have it all: Ecosystem services trade-offs in the context of spatial planning. Ecosystem Services, 29, 566–578. https://doi.org/10.1016/j.ecoser.2017.10.011

Twigg, J. (2007). Characteristics of a disaster-resilient community: A guidance note. London: DFID DRR Interagency Coordination Group. (n.d.).

Tyler, S., & Moench, M. (2012). A framework for urban climate resilience. Climate and Development, 4(4), 311–326. https://doi.org/10.1080/17565529.2012.745389

UNISDR. (2012). How to make cities more resilient: A handbook for local government leaders. Geneva: Author. (n.d.).

UNISDR. (2015). Sendai Framework for disaster risk reduction. Geneva: UNISDR. Retrieved from www.unisdr.org. UNISDR. (2017). National disaster risk assessment. Geneva: UNISDR. Retrieved from www.unisdr.org. (n.d.).

United Nations Environment Programme (2021). Adaptation Gap Report 2020. Nairobi. (n.d.).

Urwin, K., & Jordan, A. (2008). Does public policy support or undermine climate change adaptation? Exploring policy interplay across different scales of governance. Global Environmental Change, 18(1), 180–191. https://doi.org/10.1016/j.gloenvcha.2007.08.002

van Assche, K., Beunen, R., & Duineveld, M. (2014). Evolutionary Governance Theory. Springer International Publishing. https://doi.org/10.1007/978-3-319-00984-1

van der Bles, A. M., van der Linden, S., Freeman, A. L. J., Mitchell, J., Galvao, A. B., Zaval, L., & Spiegelhalter, D. J. (2019). Communicating uncertainty about facts, numbers and science. Royal Society Open Science, 6(5), 181870. https://doi.org/10.1098/rsos.181870

van der Heijden, J. (2019). Studying urban climate governance: Where to begin, what to look for, and how to make a meaningful contribution to scholarship and practice. Earth System Governance, 1, 100005. https://doi.org/10.1016/j.esg.2019.100005

Van der Heijden, Kees. 1996. Scenarios: The art of strategic conversation. Chichester, UK: John Wiley. (n.d.).

van Klingeren, F., & de Graaf, N. D. (2021). Heterogeneity, trust and common-pool resource management. Journal of Environmental Studies and Sciences, 11(1), 37–64. https://doi.org/10.1007/s13412-020-00640-7

Vatn, A. (2005). Institutions and the Environment / A. Vatn.

Vogel, B., & Henstra, D. (2015). Studying local climate adaptation: A heuristic research framework for comparative policy analysis. Global Environmental Change, 31, 110–120. https://doi.org/10.1016/j.gloenvcha.2015.01.001

Voigt, S. (2013). How (Not) to measure institutions. Journal of Institutional Economics, 9(1), 1–26. Cambridge Core. https://doi.org/10.1017/S1744137412000148

Walker, W. E., Rahman, S. A., & Cave, J. (2001). Adaptive policies, policy analysis, and policy-making. European Journal of Operational Research, 128(2), 282–289. https://doi.org/10.1016/S0377-2217(00)00071-0

Walters, C. J., & Holling, C. S. (1990). Large-scale experimentation and learning by doing. Ecology, 71, 2060–2068. (n.d.).

Walters, C. J. (1986). Adaptive management of renewable resources. New York: McGraw Hill. (n.d.).

Wamsler, C., & Brink, E. (2014). Interfacing citizens' and institutions' practice and responsibilities for climate change adaptation. Urban Climate, 7, 64–91. https://doi.org/10.1016/j.uclim.2013.10.009

Wang, Z., Zhao, Y., & Wang, B. (2018). A bibliometric analysis of climate change adaptation based on massive research literature data. Journal of Cleaner Production, 199, 1072–1082. https://doi.org/10.1016/j.jclepro.2018.06.183

Webster, J., & Watson, R. T. (2021). Analyzing the Past to Prepare for the Future: Writing a Literature Review. 12.

Wheeler, S. M. (n.d.). Planning for Sustainability: Creating Livable, Equitable, and Ecological Communities. 289.

Wilder, M., Scott, C. A., Pablos, N. P., Varady, R. G., Garfin, G. M., & McEvoy, J. (2010). Adapting Across Boundaries: Climate Change, Social Learning, and Resilience in the U.S.–Mexico Border Region. Annals of the Association of American Geographers, 100(4), 917–928. JSTOR. http://www.jstor.org.libproxy.berkeley.edu/stable/40863611

Williams, B.K., 2011. Adaptive management of natural resourceseframework and issues. Journal of Environmental Management 92 (5), 1346e1353. (n.d.).

Wilson, G. A. (2012). Community resilience, globalization, and transitional pathways of decision-making. Geoforum, 43(6), 1218–1231. (n.d.).

Wilson, J. (n.d.). Scientific Uncertainty, Complex Systems, and the Design of Common-Pool Institutions. 24.

Young, O. R., Berkhout, F., Gallopin, G. C., Janssen, M. A., Ostrom, E., & van der Leeuw, S. (2006). The globalization of socio-ecological systems: An agenda for scientific research. Global Environmental Change, 16(3), 304–316. https://doi.org/10.1016/j.gloenvcha.2006.03.004

Chapter 2: Urban Sediment Systems in Coastal Adaptation Planning
A Concept and Case Study

Abstract

Systems and strategies for improving Urban Metabolism (UM) are being challenged by climate change. While most considerations of industrial ecology (IE) as applied to climate issues focus on mitigation, there are significant ways in which climate adaptation outcomes may be improved utilizing IE approaches. In developed shorelines, a fundamental tension is emerging between the drive to develop dense, compact city cores designed to improve efficiency and reduce wastes; and the threat of sea level rise (SLR) in reducing the availability land. This spatial aspect of adapting to rising waters, and its planning and policy considerations offer significant challenges and emerging opportunities for prominent IE concepts, tools and techniques to aid in the challenge of adapting populous, dense coastal cities. We describe the relationship between space as a basic resource in planning, and increasing flows of excavated soils in urban shorelines, which may be useful as a building material for SLR barriers. We consider the San Francisco Bay Area of California as an example of a metropolitan region experiencing rapid urban development as new coastal flooding imposes spatial constraints on it. The region's planning agencies lack a mass balance framework allowing efficient use of excavated material flows for adaptation to flooding. We examine the human-driven processes affecting soils and sediment management in a developed shore and consider their relevance to climate adaptation planning. We discuss the conceptual potential of the circular economy (CE), urban metabolism (UM), and material flow analysis (MFA) to inform and improve adaptation outcomes for urban shorelines.

Introduction

Global SLR is forcing developed shorelines everywhere to plan strategies for adapting to it, and cities are facing numerous, pressing sustainability challenges in the 21st century (Reese and Wackernagel 1994; Moffatt 2000; Kennedy et al. 2014). As global population rises, so too does the proportion of people settling in cities and most the planet's largest cities are located on or near coastlines, where physiographic and sociopolitical factors often constrain the growth boundaries of cities (Bianchi and Allison 2009). A focus on centralized, dense urban cores has been widely adopted by many of the world's major metropolitan areas, (Rees 1999) even as SLR threatens to inundate them and devastate coastal ecosystems delivering major flood protection to adjacent urban areas (Valiela et al. 2018). Expansion of urban underground space (UUS) is rapidly expanding in many population centers (Admiraal and Cornaro 2016). The construction of UUS yields geomaterials, including soils and sediment, which are important resources in ecologically-based adaptation strategies. Certain themes and approaches evident in IE may be useful in adaptation planning that incorporates these resources to achieve sustainable development (SD) goals.

Within city boundaries, resource extraction is usually considered null or residual (Niza, Rosado, and Ferrão 2009), as the hinterlands have historically served as the sources of raw materials provided to cities (Hodson et al. 2012) . Though cities generally consume a narrow range of most raw materials, certain mineral resources like sand and gravel (which are elemental material inputs of the modern built environment) still represent major inflows (Douglas and Lawson 2000). Indeed, cities currently consume the majority of extracted material resources by volume for building housing stock and infrastructure (Fischer-Kowalski et al. 2011; Hu, Van Der Voet, and Huppes 2010) : a trend likely to increase with the construction of higher density urban spaces. Recent decades have seen greater focus emerge on the efficiency of the Circular Economy (CE), and where local waste reduction and increased reuse and recycling of material is possible, urban sustainability may be improved (Acselrad 1999; Céspedes Restrepo and Morales-Pinzón 2018). Urban symbiosis has served as a conceptual link for CE applied to the urban context, where one sector's waste stream becomes another's resource (Chertow 2008). This reasoning may extend past goods and products to regional resource management and municipal public works, the subject of this paper.

White's (1994) description of IE as "the study of the flows of materials and energy…of the effects of these flows on the environment, and of the influences of economic, political, regulatory, and social factors on the flow, use, and transformation of resources" serves to frame its broad, institution-spanning relevance. Specifically, in recognizing the spatiotemporal dynamics, complexity, and geographic context-dependency of resource management, the importance of "strategic resource optimization" is evident and of major interest here (Cerceau, Mat, and Junqua 2018). We consider the promise of IE to improve the technical and strategic capacity of cities to optimize a particular resource flow intimately connected to development and UM, and frame a discussion about the complexities and challenges evident in applying IE to problems paradigmatic of the climate change era. As such, we focus on the systematic aspects of spatial planning components of UM as it relates to regional/territorial resource flows.

Our discussion of IE draws on the aforementioned disciplinary definition offered by White while integrating perspectives from several fields to offer interpretations of IE concepts and embracing a view of IE that frames its proven utility while pointing to its expanded potential in environmental planning processes. To do so, Ramaswamy's (2003) articulation that, "an Industrial Ecology based system-level perspective is essential to identify the major flows of materials in a region for planning resource optimization and for solving environmental problems" is considered salient and relevant herein. Moreover, adaptation planning's clear harmonization with these themes presents possibilities for IE to advance efforts in schematizing a resource-optimization system, address relevant data challenges, and recognizing its utility as a planning tool for improving adaptation outcomes.

Sustainable Development in the era of Rising Seas: Key Challenges

Because of IE's disciplinary concern with systems, urban infrastructure's importance in effectively integrating planning and adaptation has been noted as an opportunity for planners to "overcome fragmentation through integration" (Neuman 2009; Hodson et al. 2012; Ness and Xing 2017). The construction of novel adaptation infrastructure may represent a convergent opportunity of this type, and one reliant upon the systems perspective implicit in IE. Though focused on climate mitigation, Seto and colleagues (2014) recognize that spatial planning advances are possible where interlinked efforts can essentially yield a "whole" outcome greater than the sum of its parts. As Wíjkman and Skånberg (2015) emphasize, "climate change mitigation strategies need to become more holistic and consider resource efficiency as a key instrument" (Ness and Xing 2017), potentially through climate adaptation efforts, which are often less evident (Reckien et al. 2018). The impetus to seek and develop creative solutions to pressing problems effecting and effected by UM is evident in the impacts on the built and natural environments in developed shorelines, and linked through the possible innovations in resource management practices and adaptation planning.

SLR Impacts on the Built Environment

SLR in the 21st century will worsen flooding globally, in more frequent and sustained nuisance flooding and during extreme weather events (Ruggiero 2008; Moftakhari et al. 2017). In addition to surface flooding of private property and major transportation infrastructure, subsurface changes induced by rising groundwater in coastal zones may threaten subterranean infrastructure and prompt its retrofitting and repair (Fletcher 2012; Hoover et al. 2017). In many coastal zones, urban development built on filled wetlands is also physically sinking: subsiding as soils compress (Hoover et al. 2017). In many coastal conurbations, the majority of coastal protective infrastructure was designed assuming a static sea surface elevation, and without SLR in mind.

SLR Impacts on Ecosystems

Alterations in landscape composition, changes in surface cover and impacts on ecosystems as a function of the built environment are recognized as effects of urbanization (MEA 2005). Pereira et al. (2010) identified habitat destruction and species distribution shifts as two major spatially-linked drivers of biodiversity loss likely to affect countless ecosystems in the 21st century. Habitat destruction, biodiversity loss, and fragmentation of ecosystems as effects of urbanization are well-recognized, and the effect of these trends are compounded by the richness and variation evident in shorelines, where biodiversity is high, ecosystem services are rich, complex and linked to broader, global systems (Spencer et al. 2016; Singh and Kennedy 2018). Coastal wetlands are also sensitive to land use change and important landscape complexes for muting upland flooding (Bilskie et al. 2014; Ding 2017; Bigalbal et al. 2018).

The Coastal Wetland "Squeeze"

As sea levels change, tidal wetlands naturally migrate and reestablish their biogeophysical processes accordingly, demarcating novel shorelines in the process (Crosby et al. 2016). A major ecological concern for developed (and developing) coastal cities is that the built environment is often situated in close proximity to the shoreline. Rising seas that trigger the inland and upward migration of wetlands on developed shorelines will drive them toward physical barriers like highways, urban centers and other developed spaces whose current configurations and design do not support wetlands. Tidal wetlands that cannot successfully migrate with rising waters will destabilize and drown, and their capacity to adapt to rising waters is of global concern (Sánchez-Arcilla et al. 2016; Phillips 2018; Reed et al. 2018).

Coastal Sediment Deficits: a "Mass Imbalance"

Douglas and Lawson (2000) estimated that human beings actively transport more than three times as much earthen material than the natural geomorphic processes of the planet, and most extracted material is bound for cities, where It is capitalized into building stock, infrastructure and other materials in the evolution of "urban morphology". At the same time, numerous human endeavors aimed at industrial processes and "command and control" of natural systems have substantially reduced the "throughput" of sediment that reaches coastal waters and nourish shorelines, whose profiles play major roles in governing the severity of coastal flooding, and where sediment loss has been linked to coastal erosion, more severe storm impacts, and damage to coastal ecosystems (Holling and Meffe 1996; Schoellhamer, Wright, and Drexler 2013; Florsheim et al. 2013; Voss, Christian, and Morris 2013). The impacts described above are based on the projected inability of developed shorelines to "keep pace" with SLR as a function of a shortage of sediment flowing to the shore – creating a localized "mass imbalance".

To make coastal ecosystems and cities more resilient to climate impacts, there is interest in increasing sediment flows to shorelines. In addition to nourishing existing shorelines, establishment of multi-benefit flood protection barriers will require considerable volumes of soils and sediment to construct. Urban development constantly yields geomaterial resources (through excavation), which can both bolster the viability of the built environment (through construction of SLR barriers) and improve the resilience of ecological systems (through wetland restoration and construction). The spatial proximity of the processes of excavation to the sites of material reuse is significant. Kenway et al (2011) acknowledge the need for cities to "source from within" resources where possible, echoed in the "urban harvest" approach (Agudelo-Vera et al. 2012). Indeed, the concept of reclaiming and reusing material resources gleaned in urban metabolic process for adapting the urban fabric to climate change is a critical challenge that IE is well-suited to address.

2. Case Study Area

The San Francisco Bay Area and Estuary (SF Bay) is a large, fast-growing metropolitan "megaregion" of Northern California, which encircles its namesake waterway (Florida et al. 2008). Development patterns of the modern era focused development near the Bay's shoreline, and destroyed the majority of its tidal marshes, which are now a major focus of ecological restoration. The SF Bay is experiencing a severe housing crises, and pressure to build homes and implement land use controls to meet demand in a region projected to host 2 million more residents by 2040 is widely recognized (Mackenzie et al. 2017). Planning efforts aimed at preventing sprawl and developing dense, transit-oriented urban centers have identified Priority Development Areas (PDAs), to serve as the urban cores to accommodate population increase and an intensification of the built environment's use and demands [Figures I and II]. Much of the region's major civil infrastructure is built near the shoreline, and faces increased strains from age and use, in addition to major threats posed by SLR (Biging, Radke and Lee 2012).

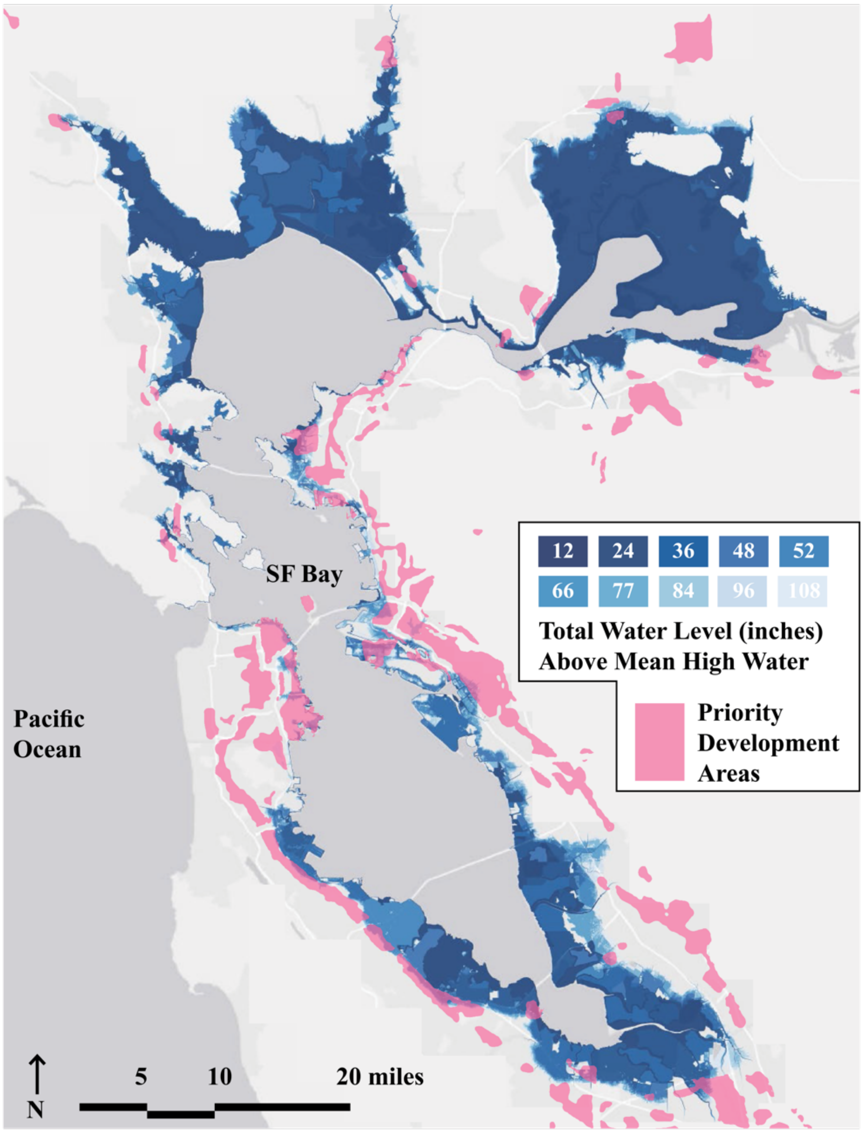
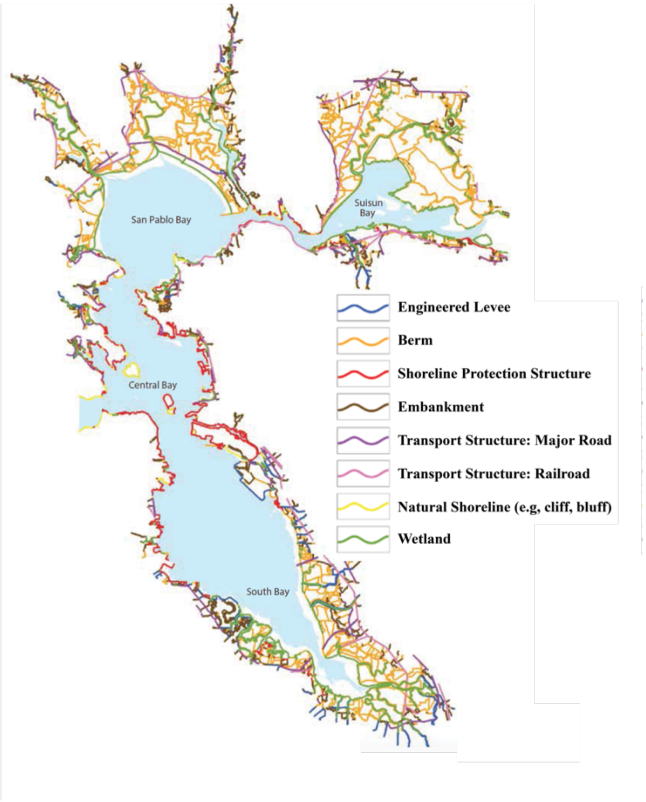


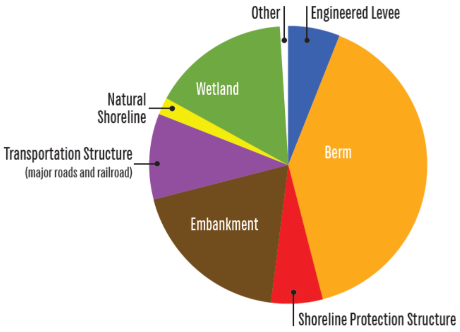
Figure 1 : A map showing the placement and proximity of regional Priority Development Areas (PDAs) in pink within 10 miles of the existing shoreline; and their proximity and position relative to potential flooding extents, displayed in blue, which includes a wide range of possible SLR-induced inundation. Sources : Sea Level Rise Data: BCDC, MTC, AECOM, Adapting to Rising Tides Bay Area Sea Level Rise Analysis and Mapping Project 2017, SF Greenbelt Alliance.

	2010	2015	2040	Change 2010-40	Change 2015-40	2010-2040 (%)	2015-2040 (%)
Population[1]	7,150.7	7,609.0	9,522.3	2,371.6	1,913.3	33.2%	25.1%
Households[2]	2,606.3	2,699.3	3,388.6	782.8	689.8	30.0%	25.6%
[1] 2015 Is July 2015 estimate from the California Department of Finance. [2] 2015 is Association of Bay Area Governments estimate for mid-year, based on 2015 January data and growth estimates.							

Table 1: Table showing projected regional population and households. Source : Association of Bay Area Governments, Plan Bay Area 2040 Report. If excavation processes and their commensurate yield of excavated soils are indeed a proxy for building and infrastructure construction projects, a rising population driving demand for housing should correlate to increased volumes of excavated soils.

Developed shorelines inevitably feature coastal infrastructure to prevent flooding. SF Bay's development necessitated an extensive network of earthen berms and levees (built from indigenous soils and sediment), and hardened protection structures. The impact of a rising Bay on the region's shore is already evident in places, and projected to become widespread and severe by midcentury (Heberger et al. 2012.). Regional interest in the need to improve the shoreline was ratified in a 2016 ballot measure that will direct $500 million dollars to its improvement in coming decades. Using this financing to establish ecological structures and systems that deliver flood protection benefits under anticipated SLR conditions is understood as a regional priority.





Class	Percent	Miles
Engineered Levee	6%	170
Berm	40%	1,215
Shoreline Protection Structure	6%	175
Embankment	19%	558
Transportation Structure (major roads, railroad)	10%	313
Natural Shoreline	2%	66
Wetland	16%	486
Other	1%	29
TOTAL	**100%**	**3,012**

Figures 2 and 3: Extent and type of shoreline reaches in the SF Bay, displaying the abundance of earthen berms and shoreline protection structures (Note: The San Pablo, South, Central and Suisun Embayments comprise the SF Bay Estuary). Source: San Francisco Estuary Institute, Bay Shore Inventory, 2016.

2.1 Landforms as Flood Barriers : The Ecotone Slope and its Material Demands

Armoring and "hard" treatments for shoreline protection may telegraph floodwaters to adjacent reaches of the shore, potentially worsening flooding in neighboring areas, whereas ecological structures like wetlands tend to dissipate and absorb erosive energy (Neil Adger, Arnell, and Tompkins 2005; Foster-Martinez et al. 2018). While restoring tidal marsh plains remains a regional priority, a novel strategy for doing so is the construction of landforms as SLR barriers, which is currently being piloted. An "ecotone slope" (also regionally referred to as a "horizontal levee") is a landform featuring a bay-facing, gradually-sloped face (at a 1:30 to 1:50 slope ratio) that provides several regional benefits (Lowe et al. 2013). Ecotones' biogeophysical processes allow them to trap sediment and build incrementally upwards in the process of accretion. The ecotone's wetland edge attenuate waves, may reduce overtopping potential of storm surge, and can be more economical to construct than a traditional levee (Lowe 2013; Hirschfeld and Hill 2017;

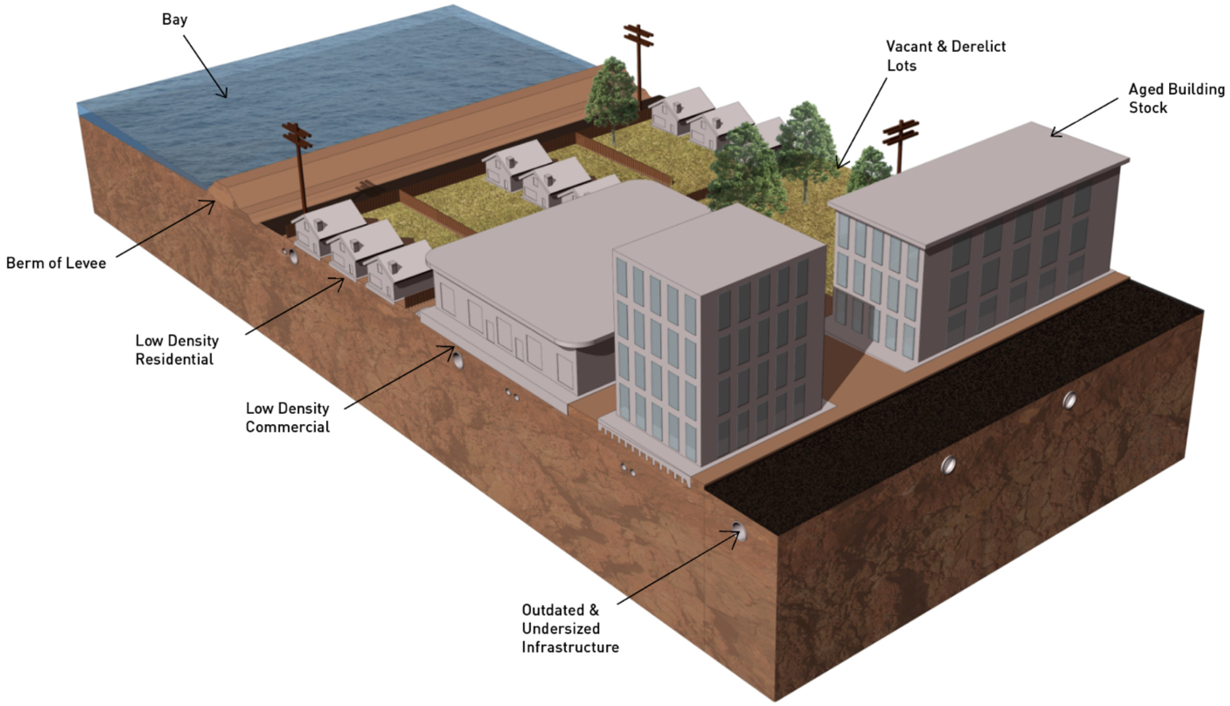
Foster-Martinez et al. 2018). The volume of material required to construct ecotones on a regional scale depends on many factors, and the topic remains under-researched, in part because of unclear adaptation planning goals. A widely-circulated white paper estimates the gross volume of sediment required to build the barriers in question encircling the Bay, and considering a range of SLR rates and subsequent ecotone heights. It estimates a range between three hundred million and two billion cubic yards of material will be required (Gunther 2014). How and where the material for this massive construction operation would be sourced remains unclear.

2.2 Excavation Processes in Urban Shorelines: Regional Material Supplies

Effects of modern anthropogenic actions affecting the mass balance of sediment in various regions is well-known (Happ et al. 1945; Knox 1972; Douglas and Lawson 2000), but the implication of these understandings as relevant for climate change adaptation is unclear. James (2013) proposes a broad definition of the activities and processes that produce or interact with "legacy sediment" (material impacted or activated by human activities) to encompass urbanization, and we consider urban morphology's relationship to a particular type of legacy sediment: excavated urban soils. Excavated urban soils are often yielded as locally-produced construction wastes, while many UM material flows are directed towards cities to meet the need of people within them (Hodson, 2012; Tukker et al. 2014; Gorgolewski 2018). Few raw material resources emerge from within cities and travel for use to the hinterlands. Excavated urban soils are rather idiosyncratic in this respect. Trends driving excavation processes to establish an increasingly dense built environment will continue to produce these materials: a resource stock whose potential has not been evaluated in the context of SLR adaptation planning.

2.2.1 Urban Underground Space

The relationship between urban underground space (UUS) and the possible reuse of geomaterials evident there have not been deeply considered in urban planning, though dense cities are increasingly considering these resources (Parriaux et al. 2004; Li et al. 2016), and UUS has been extensively developed and studied in a variety of geographic settings over many decades (Jansson 1978). Drivers of large-scale excavation processes include public works projects in addition to expansion of building stock, and these processes will increase with the need of cities to house more people. Likewise, extensive infrastructure projects are important to consider, as cities adapt their civil systems to meet greater demands and stress from population increases (Heller 2001; Kaliampakos et al. 2016). UUS is established for diverse purposes [Figure 5], but the re-use of the resources extracted in their construction varies widely by region, geology and potential re-use strategies and needs. While UUS has been built in numerous geographic settings with varied underlying geologic conditions (Bartel and Janssen 2016), consideration of the suitability of the physical subsurface strata is critical to understand in attempting to estimate or articulate a likely or maximal intensity and extent UUS, and its commensurate yield of excavated material. Nonetheless, surveying, tunneling, and other technologies involved in establishing UUS continue to advance, as do building techniques and processes that may increase the feasibility and sustainability of UUS construction (Makana et al. 2016; Nelson 2016).



Urban Shoreline 'Fabric':
Pre-2025

Figure 4: Block diagram illustration of an urban shoreline parcel, showing an arrangement of typical elements of recent (pre-2025) development patterns. Low-slung, low-density development associated with suburban "sprawl" may feature limited exploitation of subsurface space and the soil and sediment resources present therein.

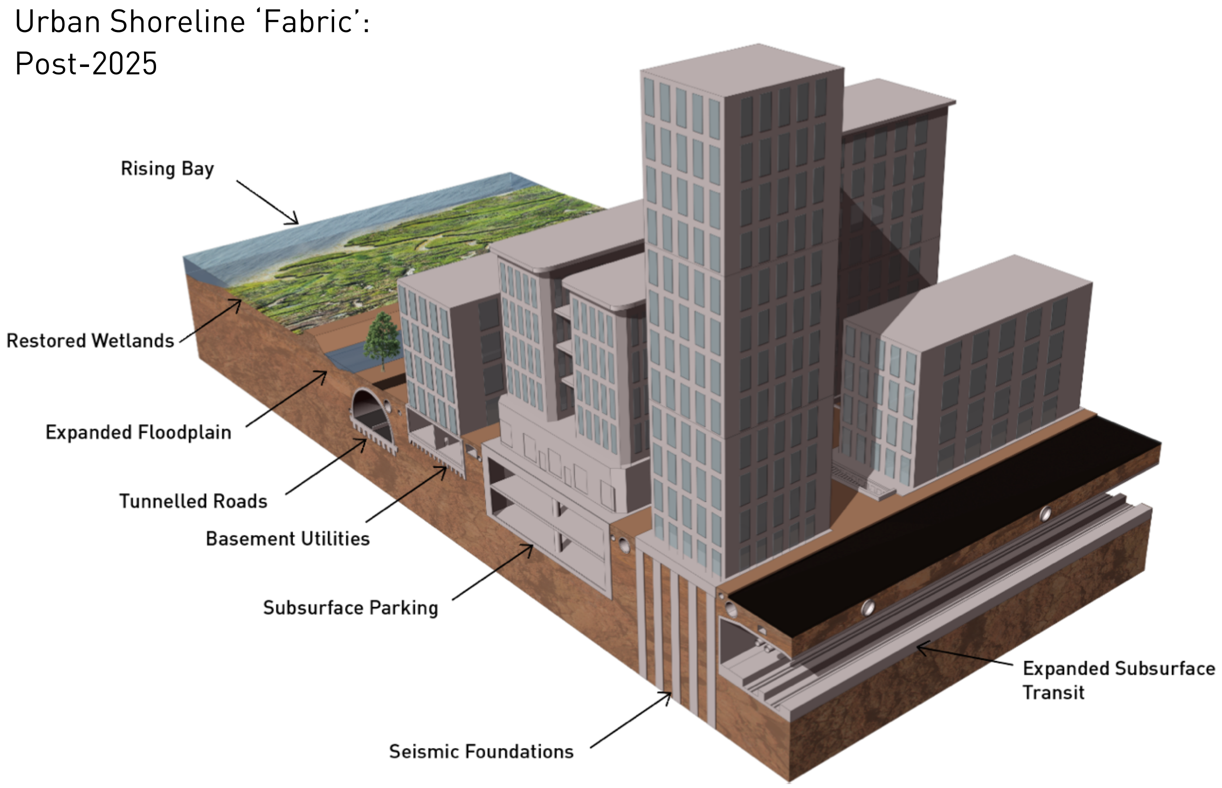


Figure 5 : Block diagram showing features of urban development in more dense and vertical arrangements of building and infrastructure stock. These are elements typical in the SF Bay's Priority Development Areas (PDAs) and their orientation towards both sustainable development practices and orientation towards public/mass transit.

Schiller et al. (2017) observes that knowledge gaps persist regarding the "construction technologies and qualitative and procedural aspects that govern the recovery of recycled materials", while inefficiencies in urban development and waste reduction in development booms have been noted (Ness and Xing 2017). Van Timmeren's (2008) contemplates the (often) overlooked resources in "interrelated networks" for insights into creative ways of viewing materials and spatially-extensive infrastructure systems, as advances in UUS construction is facilitating more extensive projects and the need for connections between them (Broere 2016; Zhao and Künzli 2016; Labbé 2016). Some major cities are advanced in their subterranean planning and development processes. Helsinki, hosts some 10 million cubic meters of UUS, including public attractions and major public infrastructure, with plans for further expansion (Vähäaho 2016). Singapore expects to double its municipal rail service length by 2030, the majority of which will be underground (Zhou and Zhao 2016). Hong Kong has conducted a territory-wide study to assess the utility of UUS in its planning implications, a spatial resource that it has already heavily utilized (Wallace and Ng 2016). These cities face major inundation by rising seas, and UUS may play a role in maximizing SD goals as their density increases (Hunt et al. 2016).

Process scale	Process example
micro	Residential construction earthwork (seismic retrofits, home expansions); local utility repairs and retrofits; geologic hazard management (bank control, slump removal); local flood control work (dredging, clearing channels)
meso	Large building stock replacement, expansion, improvement (undergrounding parking structures, utilities, seismic work); municipal works (undergrounding public utilities and local transport infrastructure); large-scale flood control work (dredging dam-impounded sediment; removing flood control structures for broadened floodplains).
macro	Regional dredge regimes; extensive infrastructure undergrounding (electric power lines or long-distance tunneling and boring for passenger or public transportation systems)

Table 2 : Table listing known UM processes involving excavated urban soils and sediment, as interpreted through CE scales emphasized by Yuan et al. (2006), Su et al. (2013) and synthesized by Ghiselini (2016). Note: "Process scale" refers to operational size for individual project type. A total volume of the soils and sediment governed by these processes remains publicly unknown for the SF Bay's regional UM, as a function of proprietary data protection and the nonintegrated nature of relevant information.

Landfill or Landform?

In dense cities, demand for spatial resources due to surface scarcity will tend to discourage or limit local re-use or recycling possibilities of excavated materials. Accordingly, excavated urban soils are often transported to landfills and applied as "daily cover" for dust and odor suppression, and preventing windblown trash and scavenging. Comparing the functional utility of landfilling soils against possible alternative uses is complex, especially where this alternative might deliver widespread, diverse regional benefits if effectively used to construct SLR adaptation landforms.

To adequately establish a rationale for comparing the possible end-of-life (EOL) impacts or utility of excavated soils requires regional, cross-disciplinary examination of the potential of excavated soils to benefit society in some way. Currently, though the sediment shortfall of the Bay Area (and many developed shorelines around the globe) is well-recognized, strategic planning efforts remain nascent, and thus a rigorous understanding of the comparative economic, social and ecological impacts of different EOL scenarios for excavated soils remains a topic in need of greater consideration. Nonetheless, the simple, axiomatic relationship between resource proximity and system efficiency evident in IE provides a basic premise for further exploring this concept (Metson, Aggarwal, and Childers 2012), specifically for marrying excavated soils proximal to sediment-starved shorelines. Also, the possibility that wastes gleaned in the establishment of some civil infrastructures might represent the foundation of a material ecology for constructing another in the form of an landform-based coastal flood protection system is compelling from a resource-efficiency perspective.

Methods and Data Modeling

To understand the potential significance of excavated soil resources, and their utility and scale as a landform-building material, we collected and analyzed data on a known "sink" for this material: regional landfills (for the purposes of this paper, "landfill" refers to a "dump" for solid waste disposal, not sites or applications using earthen material as "fill" in reclamation or construction). California's Department of Resources Recycling and Recovery (CalRecycle) provided data recoding the tonnage of soils, received quarterly, at seven of the nine Bay Area counties' landfills. San Francisco county contains no active landfills (and disposes of their soils in adjacent counties), and Sonoma County's data was rejected because of low confidence in fidelity due to anomalies and inconsistencies (thus our total volume estimates may be lower than the actual volumes received by regional landfills). We analyzed the overall trend in soil volumes received by regional landfills for years 2007 – 2017, and compared these volumes across counties, and over this timeframe. We then compared these volumes to average annual sediment-inputs (to the estuary) estimates to contextualize our results in a regional earthen material flow and expanded sediment budget.

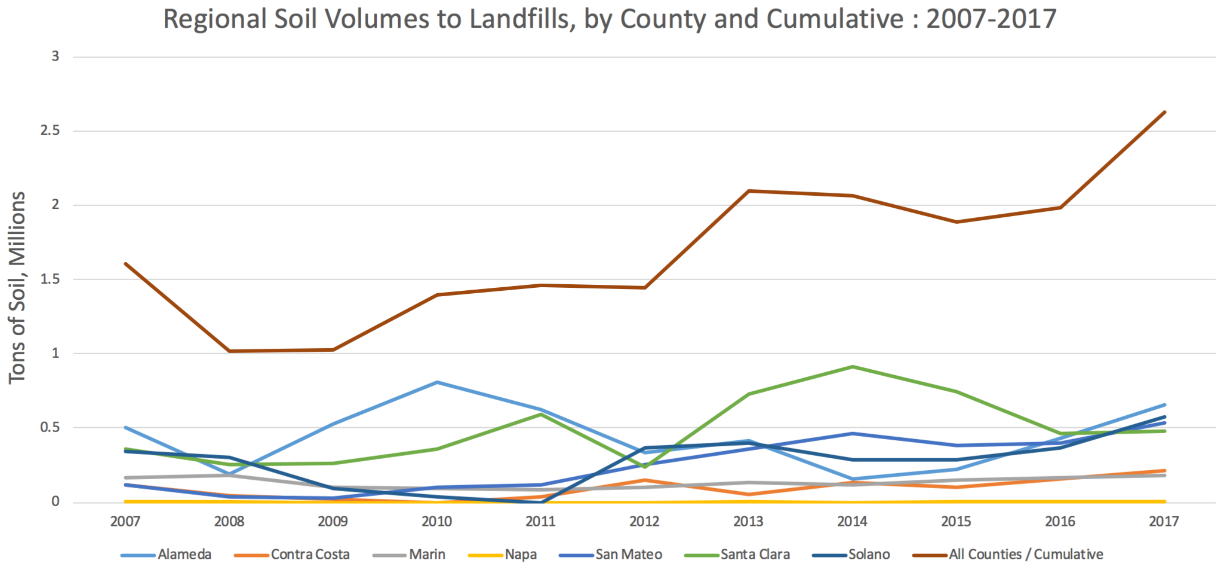


Figure 6 : Comparison chart of the seven Bay Area counties surveyed for their disposal of soils at regional landfills. The top (red) line indicates a net volume of this material.

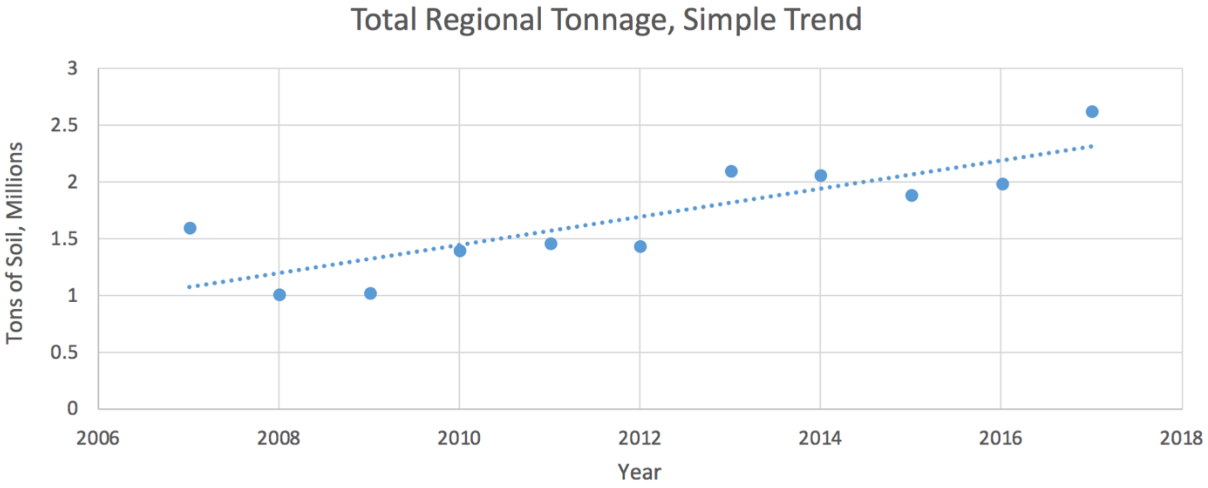


Figure 7 : A simple trend line displaying the total volume of landfilled soils from the counties surveyed (see Figure 4, above) over a recent ten year period. Note the drop in the 2008-09 range, correlating to the economic downturn, and the upward trend, potentially illustrating the relationship between economic activity and construction processes, and their commensurate soil yields by proxy.

Discussion

Interpretation and Limits of Data Analysis, and Next Steps for Ongoing Research

To thoroughly assess the potential utility and scale of excavated soils being reused as the building material for flood-protection landforms in an adaptation scheme, numerous aspects of the planning rationale and approach of a given study region must be identified and assumed, which is not the focus of this paper. Similarly, because of this nascence in the development of building ecotones beyond pilot projects (i.e. on a large scale deployed along some portion of the SF Bay's 500-mile shoreline, and over an extended time period), there does not exist a firm set of parameters for their optimal (or average) size, nor the exact geotechnically-acceptable characteristics of suitable soils for their construction. Additionally, soils and sediment reused in ecological restoration projects must pass stringent testing and permitting processes that prevent a wide range of contaminants being introduced to critical habitat areas, a major concern in reusing earthen materials in an historically industrialized port region. Neither the geotechnical composition nor contaminant presence or type is tracked by CalRecycle for the purposes of receiving soils for daily cover at regional landfills.

As such, our analysis is intended to provide a general sense of the volumes of these materials, and to contextualize this volume in the other known or estimated flows that govern the "sediment budget" for the estuary and its effects in nourishing the region's shoreline. Research has demonstrated that the average annual volume of waterborne sediment flowing into the Bay from local tributaries and the San Joaquin Delta complex (~2M tons/year) is comparable to the volume of soils annually interred in regional landfills, though landfilled soil volume is both greater and rising (Barnard et al. 2013; McKee et al. 2013; Schoellhamer, Wright, and Drexler 2013; Schoellhamer et al., 2018). This suggests that, in the context of a material flow examination of soil and sediment transport by human and natural processes, excavated soil volumes can be viewed as a significant component of the regional sediment budget. Since the regional yield volume of these soils is increasing on average, intensifying demands for construction (in increased building stock for a growing population) and the need to protect these assets from flooding (as a function of SLR) presents a compelling reason to further study and consider the flows, fate transport and resource reuse potential of these soils as possible building materials unto themselves.

IE Tools and Frameworks : Utility and Challenges in SLR Adaptation Planning

Though some aspects of the material flow of sediment can be observed in instances where volumes are tracked and recorded (as discussed the previous section), these publicly available data provide an incomplete picture of the total material ecology of excavated soils in a developed shoreline. SF Bay and coastal cities everywhere contemplating adaptation planning strategies involving landforms as SLR barriers face difficulties in surveying, sourcing and supplying soil and sediment for their construction. Though the focus of this paper is excavated soils due to the regional geomorphology and geologic composition of the estuary, other extracted geomaterials including sand, gravel and stone abundant in other coastal cities may be assessed using similar approaches and tools. Methods and models for advancing this endeavor, and modes of revealing the underlying costs, benefits and efficiencies possible on several fronts are evident in prominent IE scholarship and applications. We discuss CE, UM and MFA as concepts and tools that may aid planners, revealing climate adaptation opportunities.

The Circular Economy and Urban/Industrial Symbioses

CE's inclusion of multi-scale actors and processes is well-suited to informing optimized urban soils management, where a system's efficiency of scale and scope will need to recognize flows of various magnitudes, frequencies and rates of change (Ghisellini, Cialani, and Ulgiati 2016). While many IE tools and approaches have focused on stocks and flow processes, interest in more nuanced and potentially efficient systems has also emerged (Van Berkel et al. 2009; Jiao and Boons 2014). Soils gleaned in processes of coastal urban development being re-used or recycled locally to improve sustainability and adaptation outcomes aligns well with foundational concepts of a CE (with roots in environmental and ecological economics), and may be especially relevant in real estate and construction industries (Boulding 1966; Pearce and Turner 1989; Yang and Feng 2008; EMF 2015; Ghiselini et al. 2016). Supporting CE are the implementation tools offered by industrial and urban symbioses for improving material recycling, and useful when applied to larger scales than typical corporate or consumer operations (Ghiselini et al. 2016; Ness and Xing 2017) and Chertow and Lombardi's (2005) definition of industrial symbiosis as a concept useful in working across individual boundaries to maximize "efficient use of material, energy and facility resources at a broader systems level" serves as a useful perspective for positioning industrial symbiosis in the broader IE field.

Urban Metabolism

Wolman's (1965) popular thesis of UM as a mode of understanding the web of relationships between cities and their wider environment remains a powerful and important thematic framework for studying cities, whose rich, complex, interconnected spaces, defined by their many and varied flows may be seen as the "milieu defining the urban ecosystem"

(Rudolf 2008; Cerceau, Mat, and Junqua 2018) and wherein Wu (2014) identifies the adaptive processes required to promote human well-being and ecosystem services in response to urban land use change as one key aspect of the relationship between sustainable development and the ecologic health of surrounding regions. Singh and Kennedy (2018) also recognize the impact of UM processes on complex natural systems, and note metrics like biodiversity as indicators of ecosystem health that are complex, dynamic and perhaps an underdeveloped aspects of UM. The optimized reuse of urban soils illustrates an relationship between an urban waste product (or byproduct of development) and its potential to bolster the threatened ecosystems on the urban fringe.

Modeling resource flows and UM, and gathering, sharing, accessing, and integrating of data remains a challenge in efforts to accurately model UM at an urban scale (Niza, Rosado, and Ferrão 2009). Recent and emerging technological improvements are clearly tools for improving the resolution and fidelity of data and models -- or for calculating their uncertainties (Patrício et al. 2015) -- but cooperation between actors and across sectors and institutional divides is also necessary not only for an accurate understanding of UM, but a basic consensus on how (or why) to shape it: a fundamental concern of environmental planning in this context. The Stockholm Royal Seaport's use of a framework of "smart" UM approach aims to capture and utilize vast amounts of data at high resolution and in real-time, to improve the sustainability of urban development outcomes and incorporating a variety of stakeholder concerns and goals (Shahrokni et al. 2015).

Material Flow Analysis (MFA)

Brunner and Rechberger (2004) describe MFA's system elements as the "components of material flow systems" which include "flows, processes, stocks, and materials." Assessment or design of a systems-level approach to optimizing the reuse potential of urban soils for adaptation landform building depends on evaluating the quantity of material involved and its quality (Schiller, Gruhler, and Ortlepp 2017). Quantifying the total material volume is a data-dependent task complicated by numerous factors, and the quality of soils excavated in urban development processes across a region are likely variable in their geologic origin and composition, geotechnical fitness and potential contaminants. Though Sibley (2009) suggests that a comprehensive MFA should "take into account in-ground stocks" of extracted resources, the responsibility for doing so in the case of "hibernating" urban soil stocks is unclear, as is an understanding of the future market for these and other buried resources (Niza, Rosado, and Ferrão 2009). How in-ground urban soils should be assessed and evaluated in the context of current or future markets – as wastes or byproducts of construction, or as a foundational material resource for a future landform-based flood protection system – should employ MFA to reveal possible planning opportunities as a function of spatial relationships and their significance in various use scenarios.

Hurdles to Applying MFA for Adaptation Planning

While CE and UM themes generally align well with adaptation planning goals, successful application of MFA in the case of urban soils presents certain technical challenges. They include:

Unbounded, Complex System

Where a resource or its flows are not limited or contained within stark physical or political boundaries, its modelling becomes complicated. Cerceau (2018), citing numerous authors, asserts that "For most of the IE scientific community, geographic issues are reduced to the question of system boundaries." A major challenge for MFA at a regional or urban scale is the unclear boundaries of cities, where numerous physical, regulatory, and political borders – some of which change over time – are at play, and do not necessarily correspond to one another (Niza et al 2009; Rosado et al. 2014). Insights into "bounding" a system whose dynamics are defined by urban land use (and sea level) change, and the materials flowing in it may depend on novel ways of defining spatial components of systems as a function of their resource availability and needs.

The proper spatial scale of a system to optimize urban soils for adaptation planning is variable based on technological, political and geographic factors. Where regional modeling is possible, the task of policy implementation may fall to political "sub systems" composing the region. Sharifi and Murayama (2014) argue that city districts are the "suitable geopolitical entities" most fit to incorporate or introduce sustainable urban development practices. Improvements in a broader system for optimizing excavated soils use in adaptation landforms will almost certainly depend on the innovation of the "sub systems" (through local action and implementation), to achieve "system innovation" (Ness and Xing 2017) through regional adoption.

Where modelling across urban boundaries is possible, other problems may arise, including the potential to ignore certain UM processes like storage or local material distribution (Kennedy et al. 2007; Keirstead and Sivakumar 2012). Effectively capturing both the static components and active flows of the system is complex in the case of urban soils because of the variety of processes, regulations and actors involved. Rosado et al. (2014) cites the dynamic nature of resource flows often rendered as static for the purposes of information interpretation and which may exclude or obviate insights into a material's possible end-of-life. This may be especially important in thinking about the transport networks of urban soils and their relationship to possible sites of need. Urban soil management reuse options are limited by logistics, market forces, regulations and regional planning uncertainties, and scenario analyses demonstrate that accurate MFAs depend on numerous sociotechnical and underlying economic dynamics (Hu et al. 2010).

Inadequate Information Infrastructure

MFA are based on the interpretation of information to improve operations and applications. The UN's Millenium Development Goals report recognizes that data is crucial for decision making to achieve sustainable development goals. Indeed, to this end, the report recognizes the need for "(A) data revolution to improve the availability, quality, timeliness and disaggregation of data" (UN 2015; Malik et al. 2018). The accurate assessment of the potential for urban soils to aid adaptation planning is complicated by numerous factors. Rebitzer et al. (2004) describe some of many challenges in simply collecting data, and the complex interactions of people, media, technology and sociopolitical structures involved. And while some operations, regions or even nations may track their extracted and reused soils (Katsumi 2015), assessment of their comparative utility or usefulness in reuse roles is under-researched, a reality which may change in the era of rising seas and worsening storms.

Other challenges include the sheer availability of data; its quality and reliability; scale and resolution; and various degrees and sources of uncertainty. In instances where a system is well-defined, the quality and uncertainty of data may be mostly a function of limited knowledge (Laner et al. 2016). "Defects of information" arising from these knowledge limitations are recognized as a distinct type of uncertainty, not one arising from natural variability (Dubois and Prade 2010; Schwab and Rechberger 2018). In their study of the New York/New Jersey Harbor and its sediment loads, Boehme et al. (2009) describe the importance of evaluating data "richness" for surveying key contaminants in a complex, dynamic geographic setting. Laner (2016) lays out a method for data quality assessment and characterization of uncertainty for effective MFA. Rebitzer (2004) identifies a number of difficulties and hurdles in data processing necessary to assess a functional unit's life cycle.

Problems may arise from data confidentiality issues when few firms manage a given resource (Hammer et al. 2003). Where possible, a centralized databank tracking relevant resources is a desirable feature for "harmonizing" MFA concepts and methods (Patrício et al. 2015). In the United States the USGS might serve as a logical institution to track information on in-ground resource reserves that are "economical to recover", yet it does not directly measure reserves nor do governments directly report to them (Sibley 2009). Likewise, in the Environmental Protection Agency's Resource Conservation and Recovery Act, urban soils occupy an apparent "blind spot". It appears that without a broader awareness of the potential utility of these materials, the need to accurately survey them on a large scale is lacking. Malik et al. (2018) observe that the recent surge in computational capacity has theoretically increased the efficacy of tools and techniques for large-scale input-output modeling, but that integration with "small data" is nonetheless necessary at local and regional scales : a clear priority for cities managing local resources while facing regional impacts.

While small-scale data gathering may be logistically easier, Patrício et al. (2015) note the increasing difficulty in data availability and uncertainty as smaller spatial and systems scales are considered, though Pincetl et al. (2014) demonstrate a method for statistically inferring larger trends from small data sets. Keirstead and Sivakumar (2012) identify some of the advantages and efficiencies possible in using specialized land use and transportation techniques to glean data of high spatiotemporal resolution. Aspects of all of these challenges are evident in constructing a clear picture of the urban soils flows in the SF Bay, and these and other examples of applied IE methods should be considered in formulating how best to assess a region's excavated soil resources.

Translating IE Insights into Policy and Planning

Though sediment deficits are a recognized and increasingly problematic reality in developed global shorelines, efforts to understand excavated urban soil's significance as an adaptation resource remain underdeveloped. Binder (2009) posits that the ultimate function of MFA should be to influence policy or practices that increase sustainability and generally improve the relationship between natural and human-made environments, specifically through the wise use of materials evident in cities. For the purposes of translating IE insights into improvements in SLR adaptation planning using urban soils, developed shorelines might consider:

Novel System Definition and Demarcation

Borrowing notions from Inddigo (2012) and Cerceau et al. (2018), a SLR adaptation-oriented system may be spatially understood as a specialized “territorial resource basin” established to optimize and manage material flows over time and across political jurisdictions, and in which spatial constraints on the basin naturally impose restriction of the volumes of material and possible flows therein (Eckelman and Chertow 2009). A “basin” implies that certain resources flow in but not out– they remain and are used therein. Various institutions may cooperate to define a territorial basin that contains the resources required to achieve the particular goal of constructing SLR barriers. Factors including spatial proximities, logistical factors, planning phase and financial mechanisms including incentives or subsidies to capture, gather and redirect soils may shape the basin. In this way, applying IE might serve as a mode of enacting governance and adaptation actions based on the “territoriality” of SLR impacts, and a societal response: localized urban soils reuse for regional benefit (Beaurain and Brullot, 2011; Brullot et al. 2017).

Adaptation-Based Information Infrastructure

IE tools and techniques for understanding resource flows in human systems is advancing technically by harnessing computing power and “big” data, theoretically improving public access and planning insights (Baynes 2009; Fischer-Kowalski, 2011). Establishing adaptation planning as a regional priority with access to databases maintained by private firms (developers, transportation contractors) and integration with relevant public databases (waste management, flood control agencies, the dredging industry) is a necessary step toward framing the realistic “menu of options” based on the soil and sediment flows in a territorial basin. Updating and reconfiguring data and its collection methods to respond to changes in development, SLR projections, or institutional reconfiguration will be important for modeling achievable outcomes given uncertain future environmental conditions.

IE as Adaptation Planning Decision-Support Toolkit

IE can be viewed as a component of local planning strategy that fosters interactions among various actors, by providing a “shared understanding” of how an infrastructure transition might look, and its relationship to local resources involved in its inception (Beaurain and Brullot 2011; Buclet 2011; Hodson 2012; Cerceau 2018). Cross-disciplinary embrace of visions of novel, multi benefit, resource-wise, infrastructure and its spatial effects might redefine sociecological relationships thereby “resignifying” the urban environment (Broto, Allen, and Rapoport 2012; Ranhagen and Groth 2012) or revealing emergent power dynamics shaping the sociopolitical relationships of a new kinds of territories or “terrains” (Elden 2010): ones that will inevitably involve collaboration to the community level (Cheng et al. 2003). These novel territories, and their resource flows, infrastructures and sociopolitical relationships will require common tools and platforms for evaluating and enacting policy. In the same way that IE may schematize systems or the information infrastructure of SLR adaptation planning, so too might its role expand to underpin this “common ground” for decision-making.

Discussion

Relevant aspects of urban soil and sediment management, and tools for their assessment, were not examined here but bear mention to frame future discussions. For an IE-based approach to urban soils as an adaptation resource, Life Cycle Assessment (LCA) may reveal broader economic, energy, and environmental impacts with major policy and planning implications (Curran 1996; European Commission 2003; Ardente et al. 2007). In the SF Bay, the impact of passenger vehicles on the region’s waste, energy and environmental quality have been assessed and considered (Chester, Horvath, and Madanat 2010), and long-distance highway transport of heavy material (soils) obviously contributes to these impacts. The ability to render a “menu of options” by modeling various possible uses of a resource (or system) can significantly improve efficiencies and may reveal “win wins” for the SD goals of coastal cities (Wilson et al. 1998). In imagining the effect of redirecting soils from landfills, the material ecology of alternative daily cover materials must be considered.

Extensive research and IE tools have been applied to the dredge regimes and cycles of coastal cities. These should be examined for their systems components and cyclical nature, in addition to the beneficial re-use of dredged sediment. Resource extraction processes in general are receiving greater scrutiny in the climate change era (Hatfield-

Dodds et al. 2017; Krausmann et al. 2018), and though Calvo (2018) offers an example of mineral resource modelling can account for scarcity and energy profiles, these materials' utility to society is generally mediated through their commoditization, not as components of public-benefit infrastructure. Notably, commercial sand mining in SF Bay and other coastal zones has been contested as a resource flow "blurring the line" between an extraction process and depletion of a natural resource that may lie in the public trust, for its regional role in mitigating coastal erosion.

Conclusion

As some of the planet's most vibrant, populous places, sociopolitical resources for innovation are clearly evident in coastal cities (Major, Lehmann, and Fitton 2018). At the same time, inefficient, even counterproductive management of space and resources engendered by historic, bureaucratic and technocratic complexities present opportunities for policy improvement, which may come in part through de-emphasizing the focus on individual components of a given system (O'Brien et al. 2011; Admiraal and Cornaro 2016; Ness and Xing 2017). Coastal cities are intense process landscapes (Hägerstrand 1993; Anderberg 1998) whose sustainability and adaptation goals are constantly evolving, and where the sovereignty of a current generation or regimes' values and goals is fleeting (Norton, Costanza, and Bishop 1998).

Linking spatial patterns of development to UM, and operationalizing systems that present future generations with more options towards prosperity, not fewer, should inform near-term adaptation goals. Similarly, bolstering the resilience of coastal wetland ecosystems for the benefit of future generations is a pressing and important task (Crosby et al. 2016; Gopalakrishnan and Bakshi 2017; Liu et al. 2017; Leonardi et al. 2018). As traditional notions of cost and value are challenged by climate change, novel methods for "situating" the economy in the (changing) physical world to organize its complexities are sorely needed (Forrester 1969; Baynes 2009; Rochat et al. 2013). IE appears clearly disposed technically and in its core ethos to increasingly inform, improve, and influence climate adaptation planning.

Ch. 2 References:

Acselrad, H., 1999. Sustentabilidad y Ciudad. EURE 25, 36–46. http://dx.doi.org/10.4067/S0250-71611999007400003.

Admiraal, Han, and Antonia Cornaro. 2016. "Engaging Decision Makers for an Urban Underground Future." Tunnelling and Underground Space Technology 55 (May): 221–23. https://doi.org/10.1016/j.tust.2015.08.009.

Agudelo-Vera, Claudia Marcela, Adriaan Mels, Karel Keesman, and Huub Rijnaarts. 2012. "The Urban Harvest Approach as an Aid for Sustainable Urban Resource Planning: Urban Harvest Approach." Journal of Industrial Ecology 16 (6): 839–50. https://doi.org/10.1111/j.1530-9290.2012.00561.x.

Anderberg, Stefan. 1998. "Industrial Metabolism and the Linkages between Economics, Ethics and the Environment." Ecological Economics 24 (2–3): 311–20. https://doi.org/10.1016/S0921-8009(97)00151-1.

Ardente, Fulvio, Maurizio Cellura, Valerio Lo Brano, and Marina Mistretta. 2007. "Multidiscipline LCA Application to an Experience of Industrial Symbiosis in South of Italy." Integrated Environmental Assessment and Management preprint (2009): 1. https://doi.org/10.1897/IEAM_2008-065.1.

Barnard, Patrick L., David H. Schoellhamer, Bruce E. Jaffe, and Lester J. McKee. 2013. "Sediment Transport in the San Francisco Bay Coastal System: An Overview." Marine Geology 345 (November): 3–17. https://doi.org/10.1016/j.margeo.2013.04.005.

Bartel, Sebastian, and Gerold Janssen. 2016. "Underground Spatial Planning – Perspectives and Current Research in Germany." Tunnelling and Underground Space Technology 55 (May): 112–17. https://doi.org/10.1016/j.tust.2015.11.023.

Baynes, Timothy M. 2009. "Complexity in Urban Development and Management." Journal of Industrial Ecology 13 (2): 214–27. https://doi.org/10.1111/j.1530-9290.2009.00123.x.

Bianchi, T. S., and M. A. Allison. 2009. "Large-River Delta-Front Estuaries as Natural 'Recorders' of Global Environmental Change." Proceedings of the National Academy of Sciences 106 (20): 8085–92. https://doi.org/10.1073/pnas.0812878106.

Binder, Claudia R., Ester van der Voet, and Kirsten Sinclair Rosselot. 2009. "Implementing the Results of Material Flow Analysis." Journal of Industrial Ecology 13 (5): 643–49. https://doi.org/10.1111/j.1530-9290.2009.00182.x.

Boehme, Susan E., Marta A. Panero, Gabriela R. MuÃ±oz, Charles W. Powers, and Sandra N. Valle. 2009. "Collaborative Problem Solving Using an Industrial Ecology Approach." Journal of Industrial Ecology 13 (5): 811–29. https://doi.org/10.1111/j.1530-9290.2009.00166_2.x.

Broere, Wout. 2016. "Urban Underground Space: Solving the Problems of Today's Cities." Tunnelling and Underground Space Technology 55 (May): 245–48. https://doi.org/10.1016/j.tust.2015.11.012.

Broto, Vanesa Castán, Adriana Allen, and Elizabeth Rapoport. 2012. "Interdisciplinary Perspectives on Urban Metabolism: Interdisciplinary Perspectives on Urban Metabolism." Journal of Industrial Ecology 16 (6): 851–61. https://doi.org/10.1111/j.1530-9290.2012.00556.x.

Brullot, Sabrina, Guillaume Junqua, and Bertrand Zuindeau. 2017. "Écologie industrielle et territoriale à l'heure de la transition écologique et sociale de l'économie." Revue d'Économie Régionale & Urbaine Décmbr (5): 771. https://doi.org/10.3917/reru.175.0771.

Brunner, Paul H., and Helmut Rechberger. 2004. Practical Handbook of Material Flow Analysis. Advanced Methods in Resource and Waste Management 1. Boca Raton, Fla.: Lewis.

Calvo, Guiomar, Alicia Valero, and Antonio Valero. 2018. "Thermodynamic Approach to Evaluate the Criticality of Raw Materials and Its Application through a Material Flow Analysis in Europe: Evaluation of Critical Raw Materials Using Rarity." Journal of Industrial Ecology 22 (4): 839–52. https://doi.org/10.1111/jiec.12624.

Cerceau, Juliette, Nicolas Mat, and Guillaume Junqua. 2018. "Territorial Embeddedness of Natural Resource Management: A Perspective through the Implementation of Industrial Ecology." Geoforum 89 (February): 29–42. https://doi.org/10.1016/j.geoforum.2018.01.001.

Céspedes Restrepo, Juan D., and Tito Morales-Pinzón. 2018. "Urban Metabolism and Sustainability: Precedents, Genesis and Research Perspectives." Resources, Conservation and Recycling 131 (April): 216–24. https://doi.org/10.1016/j.resconrec.2017.12.023.

CHENG, ANTONY S., LINDA E. KRUGER, and STEVEN E. DANIELS. 2003. "'Place' as an Integrating Concept in Natural Resource Politics: Propositions for a Social Science Research Agenda." Society & Natural Resources 16 (2): 87–104. https://doi.org/10.1080/08941920309199.

Chertow, Marian R. 2008. "'Uncovering' Industrial Symbiosis." Journal of Industrial Ecology 11 (1): 11–30. https://doi.org/10.1162/jiec.2007.1110.

Chertow, Marian R. n.d. "Quantifying Economic and Environmental Benefits of Co-Located Firms," 7.

Chester, Mikhail V., Arpad Horvath, and Samer Madanat. 2010. "Comparison of Life-Cycle Energy and Emissions Footprints of Passenger Transportation in Metropolitan Regions." Atmospheric Environment 44 (8): 1071–79. https://doi.org/10.1016/j.atmosenv.2009.12.012.

Crosby, Sarah C., Dov F. Sax, Megan E. Palmer, Harriet S. Booth, Linda A. Deegan, Mark D. Bertness, and Heather M. Leslie. 2016. "Salt Marsh Persistence Is Threatened by Predicted Sea-Level Rise." Estuarine, Coastal and Shelf Science 181 (November): 93–99. https://doi.org/10.1016/j.ecss.2016.08.018.

Daniella Hirschfeld, and Kristina Hill. 2017. "Choosing a Future Shoreline for the San Francisco Bay: Strategic Coastal Adaptation Insights from Cost Estimation." Journal of Marine Science and Engineering 5 (3): 42. https://doi.org/10.3390/jmse5030042.

Ding, Yan. n.d. "Sea-Level Rise and Hazardous Storms: Impact Assessment on Coasts and Estuaries," 45.

Douglas, Ian, and Nigel Lawson. 2000. "The Human Dimensions of Geomorphological Work in Britain." Journal of Industrial Ecology 4 (2): 9–33. https://doi.org/10.1162/108819800569771.

Eckelman, Matthew J., and Marian R. Chertow. 2009. "Using Material Flow Analysis to Illuminate Long-Term Waste Management Solutions in Oahu, Hawaii." Journal of Industrial Ecology 13 (5): 758–74. https://doi.org/10.1111/j.1530-9290.2009.00159.x.

Elden, Stuart. 2010. "Land, Terrain, Territory." Progress in Human Geography 34 (6): 799–817. https://doi.org/10.1177/0309132510362603.

Fischer-Kowalski, M., F. Krausmann, S. Giljum, S. Lutter, A. Mayer, S. Bringezu, Y. Moriguchi, H. Schütz, H. Schandl, and H. Weisz. 2011. "Methodology and Indicators of Economy-Wide Material Flow Accounting: State of the Art and Reliability Across Sources." Journal of Industrial Ecology 15 (6): 855–76. https://doi.org/10.1111/j.1530-9290.2011.00366.x.

Florsheim, Joan L., Anne Chin, Karen Gaffney, and Dennis Slota. 2013. "Thresholds of Stability in Incised 'Anthropocene' Landscapes." Anthropocene 2 (October): 27–41. https://doi.org/10.1016/j.ancene.2013.10.006.

Foster-Martinez, M.R., J.R. Lacy, M.C. Ferner, and E.A. Variano. 2018. "Wave Attenuation across a Tidal Marsh in San Francisco Bay." Coastal Engineering 136 (June): 26–40. https://doi.org/10.1016/j.coastaleng.2018.02.001.

Ghisellini, Patrizia, Catia Cialani, and Sergio Ulgiati. 2016. "A Review on Circular Economy: The Expected Transition to a Balanced Interplay of Environmental and Economic Systems." Journal of Cleaner Production 114 (February): 11–32. https://doi.org/10.1016/j.jclepro.2015.09.007.

Gopalakrishnan, Varsha, and Bhavik R. Bakshi. 2017. "Including Nature in Engineering Decisions for Sustainability." In Encyclopedia of Sustainable Technologies, 107–16. Elsevier. https://doi.org/10.1016/B978-0-12-409548-9.10039-9.

Gorgolewski, Mark. 2018. Resource Salvation: The Architecture of Reuse. http://www.myilibrary.com?id=1044761.

Hatfield-Dodds, Steve, Heinz Schandl, David Newth, Michael Obersteiner, Yiyong Cai, Tim Baynes, James West, and Petr Havlik. 2017. "Assessing Global Resource Use and Greenhouse Emissions to 2050, with Ambitious Resource Efficiency and Climate Mitigation Policies." Journal of Cleaner Production 144 (February): 403–14. https://doi.org/10.1016/j.jclepro.2016.12.170.

Heberger, Matthew, Heather Cooley, Eli Moore, and Pablo Herrera. n.d. "THE IMPACTS OF SEA LEVEL RISE ON THE SAN FRANCISCO BAY," 32.

Hinterberger, Friedrich, Stefan Giljum, and Mark Hammer. n.d. "Material Flow Accounting and Analysis (MFA)," 21.

Hodson, Mike, Simon Marvin, Blake Robinson, and Mark Swilling. 2012. "Reshaping Urban Infrastructure: Material Flow Analysis and Transitions Analysis in an Urban Context." Journal of Industrial Ecology 16 (6): 789–800. https://doi.org/10.1111/j.1530-9290.2012.00559.x.

Holling, C.S., and Gary K. Meffe. 1996. "Command and Control and the Pathology of Natural Resource Management." Conservation Biology 10 (2): 328–37. https://doi.org/10.1046/j.1523-1739.1996.10020328.x.

Hoover, Daniel J., Kingsley O. Odigie, Peter W. Swarzenski, and Patrick Barnard. 2017. "Sea-Level Rise and Coastal Groundwater Inundation and Shoaling at Select Sites in California, USA." Journal of Hydrology: Regional Studies 11 (June): 234–49. https://doi.org/10.1016/j.ejrh.2015.12.055.

Hu, Mingming, Ester Van Der Voet, and Gjalt Huppes. 2010. "Dynamic Material Flow Analysis for Strategic Construction and Demolition Waste Management in Beijing." Journal of Industrial Ecology 14 (3): 440–56. https://doi.org/10.1111/j.1530-9290.2010.00245.x.

Hunt, D.V.L., L.O. Makana, I. Jefferson, and C.D.F. Rogers. 2016. "Liveable Cities and Urban Underground Space." Tunnelling and Underground Space Technology 55 (May): 8–20. https://doi.org/10.1016/j.tust.2015.11.015.

"IMPACTS OF PREDICTED SEA-LEVEL RISE AND EXTREME STORM EVENTS ON THE TRANSPORTATION INFRASTRUCTURE IN THE SAN FRANCISCO BAY REGION." n.d., 80.

"Intergovernmental Panel on Climate Change - 2014 - Climate Change 2014 Mitigation of Climate Change .Pdf." n.d.

James, L. Allan. 2013. "Legacy Sediment: Definitions and Processes of Episodically Produced Anthropogenic Sediment." Anthropocene 2 (October): 16–26. https://doi.org/10.1016/j.ancene.2013.04.001.

Jansson, Birger. n.d. "City Planning and the Urban Underground," 17.

Kaliampakos, D., A. Benardos, A. Mavrikos, and G. Panagiotopoulos. 2016. "The Underground Atlas Project." Tunnelling and Underground Space Technology 55 (May): 229–35. https://doi.org/10.1016/j.tust.2015.03.009.

Katsumi, Takeshi. 2015. "Soil Excavation and Reclamation in Civil Engineering: Environmental Aspects." Soil Science and Plant Nutrition 61 (sup1): 22–29. https://doi.org/10.1080/00380768.2015.1020506.

Keirstead, James, and Aruna Sivakumar. 2012. "Using Activity-Based Modeling to Simulate Urban Resource Demands at High Spatial and Temporal Resolutions: Activity-Based Modeling of Urban Resource Demands." Journal of Industrial Ecology 16 (6): 889–900. https://doi.org/10.1111/j.1530-9290.2012.00486.x.

Kennedy, Chris, Iain D. Stewart, Nadine Ibrahim, Angelo Facchini, and Renata Mele. 2014. "Developing a Multi-Layered Indicator Set for Urban Metabolism Studies in Megacities." Ecological Indicators 47 (December): 7–15. https://doi.org/10.1016/j.ecolind.2014.07.039.

Kennedy, Christopher, John Cuddihy, and Joshua Engel-Yan. 2007. "The Changing Metabolism of Cities." Journal of Industrial Ecology 11 (2): 43–59. https://doi.org/10.1162/jie.2007.1107.

Kenway, Steven, Alan Gregory, and Joseph McMahon. 2011. "Urban Water Mass Balance Analysis." Journal of Industrial Ecology 15 (5): 693–706. https://doi.org/10.1111/j.1530-9290.2011.00357.x.

Krausmann, Fridolin, Christian Lauk, Willi Haas, and Dominik Wiedenhofer. 2018. "From Resource Extraction to Outflows of Wastes and Emissions: The Socioeconomic Metabolism of the Global Economy, 1900–2015." Global Environmental Change 52 (September): 131–40. https://doi.org/10.1016/j.gloenvcha.2018.07.003.

Labbé, Monique. 2016. "Architecture of Underground Spaces: From Isolated Innovations to Connected Urbanism." Tunnelling and Underground Space Technology 55 (May): 153–75. https://doi.org/10.1016/j.tust.2016.01.004.

Laner, David, Julia Feketitsch, Helmut Rechberger, and Johann Fellner. 2016. "A Novel Approach to Characterize Data Uncertainty in Material Flow Analysis and Its Application to Plastics Flows in Austria: Characterization of Uncertainty of MFA Input Data." Journal of Industrial Ecology 20 (5): 1050–63. https://doi.org/10.1111/jiec.12326.

Leonardi, Nicoletta, Iacopo Carnacina, Carmine Donatelli, Neil Kamal Ganju, Andrew James Plater, Mark Schuerch, and Stijn Temmerman. 2018. "Dynamic Interactions between Coastal Storms and Salt Marshes: A Review." Geomorphology 301 (January): 92–107. https://doi.org/10.1016/j.geomorph.2017.11.001.

Li, XiaoZhao, Congcong Li, Aurèle Parriaux, Wenbo Wu, HuanQing Li, Liping Sun, and Chao Liu. 2016. "Multiple Resources and Their Sustainable Development in Urban Underground Space." Tunnelling and Underground Space Technology 55 (May): 59–66. https://doi.org/10.1016/j.tust.2016.02.003.

Liu, Wen, Andrew C. Chang, Weiping Chen, Weiqi Zhou, and Qi Feng. 2017. "A Framework for the Urban Eco-Metabolism Model - Linking Metabolic Processes to Spatial Patterns." Journal of Cleaner Production 165 (November): 168–76. https://doi.org/10.1016/j.jclepro.2017.07.055.

Mackenzie, Jake, Scott Haggerty, Alicia C Aguirre, Tom Azumbrado, Jeannie Bruins, Damon Connolly, Dave Cortese, Carol Dutra-Vernaci, and Dorene M Giacopini. n.d. "Metropolitan Transportation Commission," 96.

Major, David C., Martin Lehmann, and James Fitton. 2018. "Linking the Management of Climate Change Adaptation in Small Coastal Towns and Cities to the Sustainable Development Goals." Ocean & Coastal Management 163 (September): 205–8. https://doi.org/10.1016/j.ocecoaman.2018.06.010.

Makana, L.O., I. Jefferson, D.V.L. Hunt, and C.D.F. Rogers. 2016. "Assessment of the Future Resilience of Sustainable Urban Sub-Surface Environments." Tunnelling and Underground Space Technology 55 (May): 21–31. https://doi.org/10.1016/j.tust.2015.11.016.

McKee, L.J., M. Lewicki, D.H. Schoellhamer, and N.K. Ganju. 2013. "Comparison of Sediment Supply to San Francisco Bay from Watersheds Draining the Bay Area and the Central Valley of California." Marine Geology 345 (November): 47–62. https://doi.org/10.1016/j.margeo.2013.03.003.

Metson, Geneviève, Rimjhim Aggarwal, and Daniel L. Childers. 2012. "Efficiency Through Proximity: Changes in Phosphorus Cycling at the Urban-Agricultural Interface of a Rapidly Urbanizing Desert Region." Journal of Industrial Ecology 16 (6): 914–27. https://doi.org/10.1111/j.1530-9290.2012.00554.x.

Moffatt, Ian. 2000. "Ecological Footprints and Sustainable Development." Ecological Economics, 4.

Moftakhari, Hamed R., Amir AghaKouchak, Brett F. Sanders, and Richard A. Matthew. 2017. "Cumulative Hazard: The Case of Nuisance Flooding: CUMULATIVE HAZARD: NUISANCE FLOODING." Earth's Future 5 (2): 214–23. https://doi.org/10.1002/2016EF000494.

Neil Adger, W., Nigel W. Arnell, and Emma L. Tompkins. 2005. "Successful Adaptation to Climate Change across Scales." Global Environmental Change 15 (2): 77–86. https://doi.org/10.1016/j.gloenvcha.2004.12.005.

Nelson, Priscilla P. 2016. "A Framework for the Future of Urban Underground Engineering." Tunnelling and Underground Space Technology 55 (May): 32–39. https://doi.org/10.1016/j.tust.2015.10.023.

Ness, David A., and Ke Xing. 2017. "Toward a Resource-Efficient Built Environment: A Literature Review and Conceptual Model: Towards a Resource Efficient Built Environment." Journal of Industrial Ecology 21 (3): 572–92. https://doi.org/10.1111/jiec.12586.

Neuman, Michael. 2009. "Spatial Planning Leadership by Infrastructure: An American View." International Planning Studies 14 (2): 201–17. https://doi.org/10.1080/13563470903021241.

Niza, Samuel, Leonardo Rosado, and Paulo Ferrão. 2009. "Urban Metabolism: Methodological Advances in Urban Material Flow Accounting Based on the Lisbon Case Study." Journal of Industrial Ecology 13 (3): 384–405. https://doi.org/10.1111/j.1530-9290.2009.00130.x.

Norton, Bryan, Robert Costanza, and Richard C Bishop. 1998. "The Evolution of Preferences Why 'Sovereign' Preferences May Not Lead to Sustainable Policies and What to Do about It." Ecological Economics, 19.

Patrício, João, Yuliya Kalmykova, Leonardo Rosado, and Vera Lisovskaja. 2015. "Uncertainty in Material Flow Analysis Indicators at Different Spatial Levels: Uncertainty in Material Flow Analysis Indicators at Different Spatial Levels." Journal of Industrial Ecology 19 (5): 837–52. https://doi.org/10.1111/jiec.12336.

Pereira, H. M., P. W. Leadley, V. Proenca, R. Alkemade, J. P. W. Scharlemann, J. F. Fernandez-Manjarres, M. B. Araujo, et al. 2010. "Scenarios for Global Biodiversity in the 21st Century." Science 330 (6010): 1496–1501. https://doi.org/10.1126/science.1196624.

Ramaswamy, Ramesh. n.d. "Industrial Ecology – A New Platform for Planning Sustainable Societies," 11.

Reckien, Diana, Monica Salvia, Oliver Heidrich, Jon Marco Church, Filomena Pietrapertosa, Sonia De Gregorio-Hurtado, Valentina D'Alonzo, et al. 2018. "How Are Cities Planning to Respond to Climate Change? Assessment of Local Climate Plans from 885 Cities in the EU-28." Journal of Cleaner Production 191 (August): 207–19. https://doi.org/10.1016/j.jclepro.2018.03.220.

Reed, Denise, Bregje van Wesenbeeck, Peter M.J. Herman, and Ehab Meselhe. 2018. "Tidal Flat-Wetland Systems as Flood Defenses: Understanding Biogeomorphic Controls." Estuarine, Coastal and Shelf Science, August. https://doi.org/10.1016/j.ecss.2018.08.017.

Rees, William E. 1999. "FORUM: Consuming the Earth: The Biophysics of Sustainability." Ecological Economics 29 (1): 23–27. https://doi.org/10.1016/S0921-8009(98)00074-3.

Rochat, David, Claudia R. Binder, Jaime Diaz, and Olivier Jolliet. 2013. "Combining Material Flow Analysis, Life Cycle Assessment, and Multiattribute Utility Theory: Assessment of End-of-Life Scenarios for Polyethylene Terephthalate in Tunja, Colombia." Journal of Industrial Ecology, May, n/a-n/a. https://doi.org/10.1111/jiec.12025.

Rosado, Leonardo, Samuel Niza, and Paulo Ferrão. 2014. "A Material Flow Accounting Case Study of the Lisbon Metropolitan Area Using the Urban Metabolism Analyst Model: The Urban Metabolism Analyst Model." Journal of Industrial Ecology 18 (1): 84–101. https://doi.org/10.1111/jiec.12083.

Sánchez-Arcilla, Agustín, Manuel García-León, Vicente Gracia, Robert Devoy, Adrian Stanica, and Jeremy Gault. 2016. "Managing Coastal Environments under Climate Change: Pathways to Adaptation." Science of The Total Environment 572 (December): 1336–52. https://doi.org/10.1016/j.scitotenv.2016.01.124.

Schiller, Georg, Karin Gruhler, and Regine Ortlepp. 2017. "Continuous Material Flow Analysis Approach for Bulk Nonmetallic Mineral Building Materials Applied to the German Building Sector: Continuous MFA for Nonmetallic Mineral Materials." Journal of Industrial Ecology 21 (3): 673–88. https://doi.org/10.1111/jiec.12595.

Schoellhamer, David H., Scott A. Wright, and Judith Z. Drexler. 2013. "Adjustment of the San Francisco Estuary and Watershed to Decreasing Sediment Supply in the 20th Century." Marine Geology 345 (November): 63–71. https://doi.org/10.1016/j.margeo.2013.04.007.

Schoellhamer, David, Mathieu Marineau, Lester McKee, Sarah Pearce, Pete Kauhanen, Micha Salomon, Scott Dusterhoff, Letitia Grenier, and Philip Trowbridge. n.d. "Sediment Supply to San Francisco Bay, Water Years 1995 through 2016: Data, Trends, and Monitoring Recommendations to Support Decisions about Water Quality, Tidal Wetlands, and Resilience to Sea Level Rise," 91.

Schwab, Oliver, and Helmut Rechberger. 2018. "Information Content, Complexity, and Uncertainty in Material Flow Analysis: Uncertainty and Complexity in MFA." Journal of Industrial Ecology 22 (2): 263–74. https://doi.org/10.1111/jiec.12572.

Shahrokni, Hossein, Louise Årman, David Lazarevic, Anders Nilsson, and Nils Brandt. 2015. "Implementing Smart Urban Metabolism in the Stockholm Royal Seaport: Smart City SRS: Implementing SUM in the Smart City SRS." Journal of Industrial Ecology 19 (5): 917–29. https://doi.org/10.1111/jiec.12308.

Sharifi, Ayyoob, and Akito Murayama. 2014. "Neighborhood Sustainability Assessment in Action: Cross-Evaluation of Three Assessment Systems and Their Cases from the US, the UK, and Japan." Building and Environment 72 (February): 243–58. https://doi.org/10.1016/j.buildenv.2013.11.006.

Shirzaei, Manoochehr, and Roland Bürgmann. 2018. "Global Climate Change and Local Land Subsidence Exacerbate Inundation Risk to the San Francisco Bay Area." Science Advances 4 (3): eaap9234. https://doi.org/10.1126/sciadv.aap9234.

Sibley, Scott F. 2009. "Using U.S. Geological Survey Data in Material Flow Analysis." Journal of Industrial Ecology 13 (5): 670–73. https://doi.org/10.1111/j.1530-9290.2009.00160.x.

Singh, Shweta, and Christopher Kennedy. 2018. "The Nexus of Carbon, Nitrogen, and Biodiversity Impacts from Urban Metabolism: Nexus of Carbon, Nitrogen, and Biodiversity Impacts from Urban Metabolism." Journal of Industrial Ecology 22 (4): 853–67. https://doi.org/10.1111/jiec.12611.

Spencer, Thomas, Mark Schuerch, Robert J. Nicholls, Jochen Hinkel, Daniel Lincke, A.T. Vafeidis, Ruth Reef, Loraine McFadden, and Sally Brown. 2016. "Global Coastal Wetland Change under Sea-Level Rise and Related Stresses: The DIVA Wetland Change Model." Global and Planetary Change 139 (April): 15–30. https://doi.org/10.1016/j.gloplacha.2015.12.018.

Vähäaho, Ilkka. 2016. "An Introduction to the Development for Urban Underground Space in Helsinki." Tunnelling and Underground Space Technology 55 (May): 324–28. https://doi.org/10.1016/j.tust.2015.10.001.

Valiela, Ivan, Javier Lloret, Tynan Bowyer, Simon Miner, David Remsen, Elizabeth Elmstrom, Charlotte Cogswell, and E. Robert Thieler. 2018. "Transient Coastal Landscapes: Rising Sea

Level Threatens Salt Marshes." Science of The Total Environment 640–641 (November): 1148–56. https://doi.org/10.1016/j.scitotenv.2018.05.235.

Voss, Christine M., Robert R. Christian, and James T. Morris. 2013. "Marsh Macrophyte Responses to Inundation Anticipate Impacts of Sea-Level Rise and Indicate Ongoing Drowning of North Carolina Marshes." Marine Biology 160 (1): 181–94. https://doi.org/10.1007/s00227-012-2076-5.

Wallace, M.I., and K.C. Ng. 2016. "Development and Application of Underground Space Use in Hong Kong." Tunnelling and Underground Space Technology 55 (May): 257–79. https://doi.org/10.1016/j.tust.2015.11.024.

Wolman, A. 1965. The Metabolism of Cities. https://books.google.com/books?id=XNuqNwAACAAJ.

Yang, Shanlin, and Nanping Feng. 2008. "A Case Study of Industrial Symbiosis: Nanning Sugar Co., Ltd. in China." Resources, Conservation and Recycling 52 (5): 813–20. https://doi.org/10.1016/j.resconrec.2007.11.008.

Zhao, Jian, and Olivia Künzli. 2016. "An Introduction to Connectivity Concept and an Example of Physical Connectivity Evaluation for Underground Space." Tunnelling and Underground Space Technology 55 (May): 205–13. https://doi.org/10.1016/j.tust.2015.12.017.

Zhou, Yingxin, and Jian Zhao. 2016. "Assessment and Planning of Underground Space Use in Singapore." Tunnelling and Underground Space Technology 55 (May): 249–56. https://doi.org/10.1016/j.tust.2015.12.018.

.

Landfill or Landform? The Management of Excavated Sediment in a Developed Shoreline: Case Study Insights for Climate Adaptation Planners

Abstract: Dominant management regimens of excavated soil and sediment are unsustainable and potentially incompatible with coastal adaptation demands. Excavated sediment is generally treated as a waste product; thus constantly received in significant volumes by municipal waste landfills. In the context of emerging and expected climate change impacts, this is an especially wasteful and regressive material management model. Sea level rise is forcing developed coastal regions to reconsider landforms that may be constructed and augmented as shoreline adaptation strategies: by raising barriers, restoring subsided wetlands and nourishing existing ones including tidal marsh plains. Actions intended to construct and maintain these structures and ecological complexes require the sourcing, transport and application of enormous amounts of geomaterials – namely various sediment resources. Our analysis demonstrates that long-term SLR adaptation goals in a study region require strategically planning the future management of excavated sediment; and we demonstrate that various applications and timeframes for successful adaptation plans will require significant shifts in the current management practices of these resources. By considering the likely amounts of reusable excavated sediment currently being received at landfills and modeling alternative uses as adaptation applications, our case study makes clear that the industrial and material ecologies of these resources must change to meet adaptation goals – as will the environmental governance involved in the urban and landscape planning related to these resources. While the study area entails specific geophysical and developmental conditions, the implications of the broad trends and underlying rationales are of global importance and applicability for adaptation planners to consider.

1. Introduction

Global sea surface elevations will rise significantly in the 21st century, an issue of increasing concern and importance for coastal developments (Hallegatte et al., 2013). Approximately half of the global population and the majority of the world's most populous cities are sited in and around the coastal zone, with important implications for the exposure and risk of large populations and the substantial infrastructure assets concentrated in coastal conurbations (Barragán & de Andrés, 2015; McGranahan et al., 2007; Seto et al., 2011). Rising seas and their associated biogeophysical processes and impacts will lead to dramatic changes in the built and natural environments of coastlines everywhere on earth. Adaptation to these changes is an increasingly pressing imperative in the planning of both urban and ecological landscapes (Brown et al., 2013; Tessler et al., 2018; Wilby, 2007). In the United States alone, costs associated with sea level rise (SLR) adaptation will constitute the majority of national adaptation costs by 2100 (Neumann et al., 2014).

Developed shorelines, where hydrologic, geomorphic and ecological processes interact with structures and processes of the built environment, exemplify coupled human and natural systems that entail complex environmental governance approaches. They often encompass landscapes with rich and contested cultural histories and display significant evolution and flux as a function of development pressures and patterns (Bianchi & Allison, 2009; Liu et al., 2007). Moreover, many are directly vulnerable not only to SLR and other climate change-induced phenomena (including urban heat islands, wildfire and drought), but environmental risks like earthquakes and tsunamis, in addition to other mass movement events such as mudslides and erosion which may be exacerbated by climate impacts (Lawrence et al., 2018, 2020). The concentration of infrastructure, capital, resources, and the populations they serve and sustain, complicates and intensifies coastal climate hazard mitigation and risk management practices applied to developed shorelines (Macintosh, 2013).

Rising seas pose flood risks not only to shoreline settlements, but also threaten coastal landscapes, ecosystems, biodiversity and habitat that have frequently been degraded, depleted and fragmented by prior industrial processes and urban development, often in ways that now predispose shoreline communities to significant flood exposure and impacts (Foster-Martinez et al., 2018; Valiela et al., 2018). Historically, typical means of flood protection included the construction of static barriers including levees and sea walls (Hill, 2015). More recently, major tensions have emerged in considering options for protecting a given site, community, or shoreline reach using engineered defenses because constructed barriers may prevent flooding in one location while worsening it in others by "telegraphing" floodwaters, thus complicating matters regarding jurisdictional mandates, collective action in planning processes, and how environmental justice is assessed and addressed as a function of interplays between these considerations and proposals (Hummel et al., 2021; Lubell et al., 2021).

Tidal wetlands act to reduce wave energy by creating frictional drag, which saps destructive energy from surging waterbodies, in turn reducing wave heights (eg. mitigating the overtopping of landward barriers) and/or by reducing erosion and preventing coastal land loss, delivering two crucial ecosystem services highly valued by coastal settlements (Barbier, 2013; Möller,et al., 2014). In light of widespread research indicating the relative cost-effectiveness and multiple-benefit qualities of nature-based shoreline "green infrastructure" systems in the form of preserved, restored or constructed wetlands, much attention has focused on the feasibility of maintaining or fundamentally creating these ecological complexes and landscapes in an era of rising seas (Bayraktarov, et al., 2016; Taillardat et al., 2020; Zhao et al., 2016). However, this focus has also served to further illuminate several troubling realities: tidal wetlands are increasingly vulnerable to destabilization and drowning via SLR; their restoration is often in tension with urban developments; and these developments themselves are generally, and increasingly, made more vulnerable to costly impacts of rising seas in the absence of wetlands to buffer them (Kirwan & Megonigal, 2013; Narayan et al., 2017; Nicholls, 2004).

Attempts to address these tensions often encounter an underlying and problematic planning paradigm rooted in the tradeoffs between allowing wetlands to "migrate" upland as rising sea surface elevations force their spatial realignments towards inland areas (creating land use conflicts with development) and/or the proclivity to armor urban shorelines with barriers which may further degrade wetlands that *cannot* migrate. This attenuation of the spatial "band" in which wetlands can endure is a situation colloquially known as coastal or wetland "squeeze" (Spencer et al., 2016; Torio et al., 2013). Management approaches that allow tidal wetlands to accrete (build up) matter and establish and maintain critical elevations relative to rising seas is a cornerstone of the restoration ecology and engineering involved in sustaining these landscapes, approaches that hinge on the provision and availability of *sediment, loose earthen material* (Fagherazzi et al., 2012; Stagg & Mendelssoh. 2011). Indeed, sediment represents a material backbone of countless coastal restoration and, increasingly, adaptation projects (Aarninkhof et al., 2010; Brand et al., 2012).

Because of the diversity of shoreline landscapes (and their associated topographic forms, and ecologic, urban and biogeophysical processes) that will inevitably experience increased SLR pressures, coastal landscape and urban planners across the globe, are modeling, planning, and testing a variety of strategies are being modeled, planned and tested by (Diaz, 2016. Kleint et al., 2022; Spencer et al., 2016). And while the physical realignment of urban shorelines based on managed retreat scenarios may become broadly necessitated by SLR, the use of landforms as adaptation applications represent a common and widely evident suite of strategies for addressing SLR in the near-term (van Slobbe et al., 2013). Construction of large-scale landform-based networks functioning as multi-benefit shoreline infrastructure systems require considerable material demands for sediment that can be gathered, transported and placed by ecological and/or human processes.

Troublingly, the supply of naturally occurring sediment is dwindling or insufficient to meet SLR demands in many urban shoreline regions, prompting consideration of other sources and supplies, including the strategic management of excavated (upland) sediment (Milligan & Holmes, 2017). Yet to date, the emerging role of this material in SLR adaptation has been considerably overlooked and/or underestimated in the literature. This represents a significant blind spot and knowledge gap for planners that imposes limitations both in forecasting future conditions based on sediment budgets, and the adaptation objectives and options linked to them. We explore the ways in which sediment materials that are ubiquitous byproducts of urban development might be reconsidered as physical resources that will surely grow in global importance as SLR adaptation projects unfold in the 21st century and beyond. Our study examines how supplies and demand for this increasingly important resource presents challenges, and shapes the adaptation planning paradigm, in a case study of interest.

The paper's five sections present our findings. The introduction section summarizes and situates the research problem and prominent trends and issues in the urban and landscape adaptation planning of developed shorelines, including the importance of sediment dynamics for constructed coastal landforms in these regions; and we describe a case study region and site. Our methods section explores a research approach applied to data related to our socio-ecological phenomena of interest, in addition to a description of an alternative resource management regime. The next section interprets and considers our analytical results, and frame them in the context of a forecasted decade in the case study and its resource dynamics. A section discusses the implications of these results and future research areas of importance to adaptation planning illuminated by the study. A brief conclusion summarizes key takeaways and recommendations from the work.

1.1 Historical Patterns and Processes of Shoreline Development and their Effects

Patterns of urban development sited in proximity to floodplains have consistently depended upon the use or creation of higher ground (areas situated above flood stages or supratidal elevations) as basic flood prevention strategies. At the same time, proximity to waterways and waterbodies is universally understood as a condition conferring multiple beneficial socioeconomic qualities, including the facility of accessing navigable channels (in the siting of industrial ports, for example) in addition to the desirability of proximity to water for aesthetic and cultural reasons (as with commercial urban waterfront districts). This tension is present in many of the world's largest and most dense cities, where shoreline development and the concentration of assets is a prominent, perhaps even consistent, urban situation, often characterizing extensive metropolitan regions surrounding core cities (Biging et al., 2012; Chhetri, et al., 2015; Hallegatte, et al., 2011). Accordingly, in the world's largest and most rapidly-developing coastal cities, considerable socio-environmental impacts are emerging as function of climate change (Glasow, et al., 2013).

The planning, development and protection processes of myriad coastal areas around the world required the intentional, physical movement of enormous volumes of sediment resources (Charlier et al., 2005). Historically, raising the elevations of local shorelines has been accomplished by the accumulation and deposition of various materials to "reclaim" land from water by the placement of soil, sand, rock, ballast, various forms of refuse, and any number of other material masses at the shoreline (Ferguson, 2018; Han et al., 2013; Martín-Antón et al., 2016). Seaward land reclamation was often accomplished by using fill material to bury and obliterate wetlands whose ecologic and environmental functions were generally and profoundly under-valued or altogether unrecognized (Vileisis, 1999). Soil resources generated by grading, digging and land-clearing projects in upland areas were very often directed to shorelines and used to "cap" solid waste and debris for the establishment of novel real estate near the shore, property of increasing, multifunctional utility and value for urban development schemes (Seasholes, 2003).

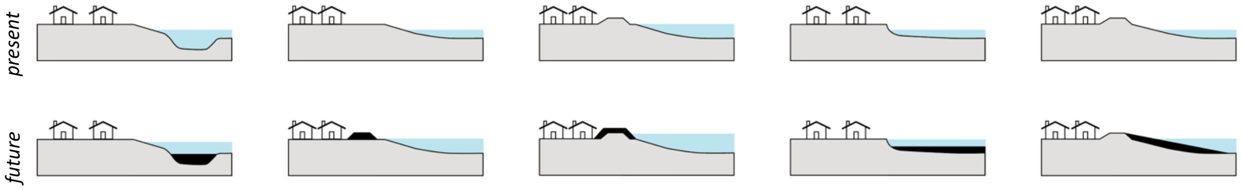
Taken together, these development patterns and practices in urban shoreline regions have resulted in several prominent challenges for SLR adaptation planners to consider. These include: land subsidence due to settlement of fill material and subsurface compaction (Shirzaei & Bürgmann, 2018; Sun, 1999); the rise and emergence of groundwater due to SLR, and its potential to mobilize subsurface contaminants (Hoover et al., 2017; Plane et al., 2019); and the deprivation of sediment throughput from upper watersheds into receiving waterbodies including estuaries, as a function of historic and ongoing upstream flood control, development and water management schemes (Barnard et al., 2013).

1.2 Future Shoreline Adaptation Strategies Using Constructed Landforms

Examples of linking anthropogenically managed sediment to large-scale coastal restoration, maintenance, and flood control projects and systems are evident in the beneficial reuse of dredged benthic sediment and thin-layer placement on wetlands to help them accrete matter and maintain critical elevations (Ford et al., 1999; Mchergui et al., 2014); beach nourishment projects to mitigate coastal erosion (Staudt et al., 2021); the construction of barriers including dikes and levees to prevent inundation of landward areas (Temmerman & Kirwan, 2015); and use of breakwaters to protect vital infrastructure from waves and surges (Becker et al., 2016). In regional networks of constructed and augmented landform-based strategies to build "elevation capital", enormous physical material supplies are required due to the spatiotemporal scales involved (Cahoon et al., 2019).

Examination of *anthropogenic sediment budgets,* those based primarily on human management processes and practices, is a critical aspect to strategically plan how (and where and when) these extensive construction endeavors may be undertaken even though work to assess sediment budgets that function based on natural processes are also useful to consider (Cappucci et al., 2020; Shellenbarger et al., 2013). The considerable scale of the resources involved in these projects is a function not only of their spatial extents, but the long-term, often cyclical nature of adaptively managed sediment placement. SLR means that the magnitude of material, frequency of application and physical size of landforms are expected to increase dramatically this century, driving commensurate cost increases (Hirschfeld & Hill, 2017; Perry et al., 2020). A future characterized by higher sea surface elevations, densifying coastal development, and intensifying storm regimes will inevitably entail a reworking of the physical form and elevational profile of shorelines where protection of development is intended (Du et al., 2020; Hill, 2015). While certain climatic, physiographic and socio-environmental characteristics of developed shorelines will vary widely by region, coastal planner will need to consider several broad categories of adaptation strategies related to landforms. These categories may be useful to consider as typological classifications that apply to certain spatial, temporal and planning conditions.

A number of prominent strategies for shoreline restoration and adaptation may be helpful to consider to illustrate the interplay of sediment resources and landforms that are constructed or augmented. In the case study region (See section 1.4), recent work to understand the impacts of SLR on the watershed and its shoreline processes and form have considered the filling of subsided ponds, called polders, and other diked wetlands that are starved of sediment delivered by natural processes, as well as the nourishment of existing wetlands (Dusterhoff et al., 2021; Williams & Orr, 2002). Ongoing work in the case study area to raise existing flood-protection levees by raising their elevations is also evident, as are planning processes considering the construction of novel landforms including ecotone and horizontal levees (discussed in section 1.3).



a. polder fill b. build levee c. raise levee d. nourish wetlands e. Ecotone

Figure 1: Several common and contemplated landform-based SLR adaptation strategies for coastal and shoreline development. The top row shows typical conditions of the present day; the bottom row illustrates where material applied as fill (in black) might be placed to accomplish various goals including flood protection and habitat restoration. Because of the extensive spatial nature of many SLR strategies, these approaches entail significant volumes of material deployed as landscape-based infrastructural networks. And because many approaches may entail repeated treatments (raising, nourishing) on a long temporal scale, the need to adequately source and procure the physical material for landform constructions along these lines is an increasingly important task for planners. Illustration by Nate Kauffman.

While landscape designers and planners are accustomed to engaging with landscapes as topologic structures representable as surficial fields (through site plans and analytical "layers") and profiles (cross-sections) like those above, the central spatial dimension of interest at the intersection of land and water is, of course, three-dimensional. This intersection is defined by *volumes* that water bodies represent and which meet and resolve at shorelines with certain topographic forms, themselves volumes of land. And insofar as environmental planners and designers embrace their role in proposing *novel* landforms as adaptation strategies, understanding the systematic and logistical realities related to sourcing and manipulating volumes of land reveals numerous avenues for planners to explore. These include: practicalities related to sourcing, procurement, stockpiling and delivery; resource management practices related to long-term forecasting and conservation; considerations tied to the market and political economies involved; and the public policies that shape all of these aspects. Our study explores how some of these considerations are at play in the strategic landscape and urban planning involved in SLR adaptation and how the industrial and material ecologies of excavated sediment present environmental planners with an emergent realm of critical consideration and innovation.

1.3 Sediment Dynamics in Developed Coastal Watersheds

An extensive literature has studied natural processes related to sediment supply within and through watersheds. Fluvial and marine transport of sediment has been extensively examined for its multiplicity of roles in sustaining ecological biodiversity and habitat composition in various waterways (Milhous, 1998; Pitlick & Wilcock, 2001; Soulsby, 2001). In addition, investigation of wetland restoration and survival link adequate sediment resources to receiving bodies and landscapes in the lower watershed (Allison et al., 2012; Haltiner et al., 1996). The biogeochemistry and contaminant profiles of sediment used in restoration projects has also been noted as an important issue in urbanized shorelines (Berkowitz et al., 2016; Morris et al., 2014). The effects of flood control processes on sediment transport, and vice versa, have also been studied as problematic issues in the context of conveyance and containment structures associated with urban development including dams, lined canals, engineered channels and subsurface stormwater structures (Griggs & Paris 1982; Meade & Moody, 2010; Taylor et al., 2009; Smith, 2001).

The prevalence of socioenvironmental issues involving sediment lead to interventions devised to physically gather, remove, stockpile, remediate, sort, guide, distribute, apply and otherwise manage various types of sediment resources to balance development and infrastructural operations with environmental concerns (Kondolf et al., 2014). As the tidal prism rises to higher elevations via SLR, coastal resource managers and planners are increasingly recognizing that more active, ambitious, creative, and long-term coordinated efforts may be required to ensure that critical elevations of important landscapes and ecosystems are established and persist in managed shorelines, and that excavated sediment will have a role to play in this endeavor (Dusterhoff et al., 2021). Indeed, excavated sediment resources represent a useful and versatile building material for constructing ecologically-based landform structures with the potential to aid the adaptation and sustainability efforts of urban regions.

1.3.1 Excavated Sediment Dynamics in Developed Shorelines

Supply: Characteristics of Excavated Sediment

Soil and sediment resources extracted through excavation are ubiquitous and increasingly common byproducts of the growth and *urban metabolism* of cities. They constitute the vast majority, by mass, of construction and demolition "wastes" generated by urban development processes and projects (Hu et al., 2010; Kennedy et al., 2011). In shoreline developments, these resources are often the in situ products of depositional geomorphological processes that have accumulated and weathered alluvial and colluvial material that can be relatively easily withdrawn from the ground, in contrast to consolidated bedrock, for example. The sector of environmental contracting and its global fleet of earthmoving machinery has largely developed as a direct result of the ubiquitous and constant need for settlements and societies to physically shape the landscape (Haycraft, 2000).

Surficial soils and sediment that is excavated in urban areas may contain legacy contaminants as a function of prior industrial uses of the landscape--an important material feature to consider where environmental applications may be the ultimate goal of reuse (Katsumi, 2015; McClintock, 2015). This is especially true for reuse projects at the shoreline because various contaminant may be mobilized by the effects of exposure to waterbodies, and stringent regulations are therefore common in these zones and projects (Bolan et al., 2014). Nonetheless, excavated sediment is a useful building material, and one whose geotechnical and geochemical qualities predisposes it for certain applications that other sediment managed and encountered in urban watersheds may not (Craul, 1992; Hale et al., 2021). In fact, precisely because this material is generally classified as a waste product, certain permitting and record-keeping processes are employed in places where environmental concerns drive regulations. Excavated sediment can be seen as a resource whose dynamics are shaped by the interplay of stocks and flows useful to consider (Myers et al., 2019).

Stocks - Sediment and its Excavation as a Function of Urban & Sustainable Development

As cities develop and densify, the removal of earthen material from in-ground stocks is a ubiquitous and increasing phenomena. This removal serves the construction of myriad subsurface constructions collectively known as Urban Underground Space (UUS) (Admiraal, 2006; Admiraal & Cornaro, 2018). Sediment is excavated from the ground to accommodate the placement of foundations, parking garages, stormwater and wastewater systems, various utility infrastructure utilities including multimodal transportation tunnels and entire multifunctional municipal districts in some cases (Vähäaho, 2016). Compact, dense urban design and construction practices inevitably increase the proportion of UUS, which aligns with various sustainability goals but entails complex planning issues, including the need to manage massive amounts of excavated sediment, typically the greatest proportion, by far, of construction and demolition waste-generating projects (Bobylev, 2009; Llatas, 2011; Magnusson et al., 2019; Villoria Sáez & Osmani, 2019).

Flows - Resource Ownership, Stewardship and Markets

Subsurface sediment is generally considered a substance that is owned by the purchaser of property in the same sense as the surficial area of the site itself (Sprankling, 2008). Upon being withdrawn from the in-ground stocks via excavation, sediment in urban environments is almost invariably managed by environmental contractors who take stewardship of the payload to transport it out of dense and developed districts due to a lack of nearby sites for reuse or stockpiling. This sediment stewardship model creates various economic opportunities for private-sector environmental contractors, who seek to pay less to dispose of sediment than they were paid to haul it, effectively their profit margin. Or, potentially, to be paid twice once to remove it as “cut” (material withdrawn) from a site, and again to provide it as “fill” (material deposited) needed at another site (Cox & Ireland, 2006). This, in turn, creates a situation in which the fleets of trucks used to transport sediment have obvious incentives to dispose of their payload as quickly and inexpensively as possible while being limited to doing so only at sites that able to receive it, most often at solid waste landfills outside of cities and far from the source of excavation (McDonald & Smithers 1998; Hao at al., 2007).

Flux – Interplay of Stocks and Flows

Our data demonstrate that while overall trends in the amounts of sediment documented by grading permits may imply net production of cut or fill, (cut representing an influx into the overall material flow of the study region; fill representing net imports to construction sites) two aspects of their interplays are important to consider. First construction sites that are proximate to each other may trade excavated sediment between them. Material is excavated, documented in the site's cut grading permit) and then directly redeposited at another site, documented as fill in that site's permits. In this way, these flows between sites do not contribute to the accumulated end-of-life phase (or sink) of excavated sediment, discussed below. Secondly, this means that balanced cut and fill or net-negative cut does not imply a lack of excavation but, rather, that whatever the magnitude of that material extraction, it can "cancel out" when balanced by commensurate demand for fill in other construction processes unrelated to municipal landfill facilities. In this sense, when similar rates of supply and demand for cut/fill on projects exist within a given study area (i.e. when the states of flux are comparable) flows may be difficult to plot as individual vectors, their dynamics creating a kind of internal homeostatic balance.

Sinks - The Sustainability and Adaptation Problem for Planners: Landfill or Landform?

While construction sites in need of fill do represent locations of final destination for excavated sediment, solid waste landfills have traditionally been highly receptive of soils and sediment resources, which are distributed as a layer of material called "daily cover" to mitigate odors, windblown trash, and scavenging (Christensen et al., 1989). These facilities, many privately owned, charge a "tipping fee" for their receipt of sediment, Aspects of landfill economics may engender resistance to resource recovery and recycling programs that might divert uncontaminated soils from being permanently interred in landfills, what some scholars have termed the "ultimate sink" (Ready & Ready, 1995; Tarr, 1996). And while dramatic improvements in recycling and diversion of various consumer goods, products, and wastes have occured in recent decades, various characteristics of sediment resources (including their aforementioned utility in landfill operations) dramatically shape and constrain their flows through the urban metabolism of developed regions (Peng, et al., 1997; Magnusson et al., 2015; Rosado et al., 2014).

Taken together, these material, urban, and economic dynamics sketch the contours of a chaotic marketplace whose varied, complex, and inconsistent policy features define the current standard of excavated sediment management: one in which characteristics of the resource's industrial ecology heavily incline towards the constant and ongoing landfilling of excavated sediment in massive quantities. Environmental concerns triggered by rising seas, and associated implications for sustainable development and adaptation efforts, are presenting imperatives and opportunities for innovative resource management approaches, illustrated by increasing demand for coastal protection landforms that will form a central strategy of SLR adaptation work around the globe in the decades to come.

As such, more coherent and consistent policies regarding if and how sediment resources can, should or must be reused for various socioenvironmental benefits–ones that have not been traditionally foregrounded as societal imperatives–may illuminate areas of potential innovation and improvement for various efforts tied to sediment resources.

Emergent Demand of Adaptation Landforms: Ecotone & Horizontal Levees

Our study assesses the potential of excavated sediment to be used as a building material for the construction of "ecotone" levees: landforms that employ a gradually sloping seaward face that acts as a flood mitigating complex. The underlying principle of ecotone levees is the mimicry of natural wetlands, whose extensive lateral dimension saps wave and surge energy through attrition (Costanza et al., 2008). In engineered applications, these landforms can also restore wetland habitat, recycle and scrub treated effluent as an irrigation supply, and create a subtle ramp up which wetlands may migrate in futures characterized by higher waters (Cecchetti et al., 2020). In that sense, this constructed landform represents a bridge between the upland and wetland biomes, an ecological principle from which its name (ecotone) is derived. While still the subject of experimentation, Ecotones have been incorporated into flood and climate adaptation planning schemes (Holmes et al., 2022). The feasibility or rollout of these projects will depend on the sourcing of sediment material to physically construct them.

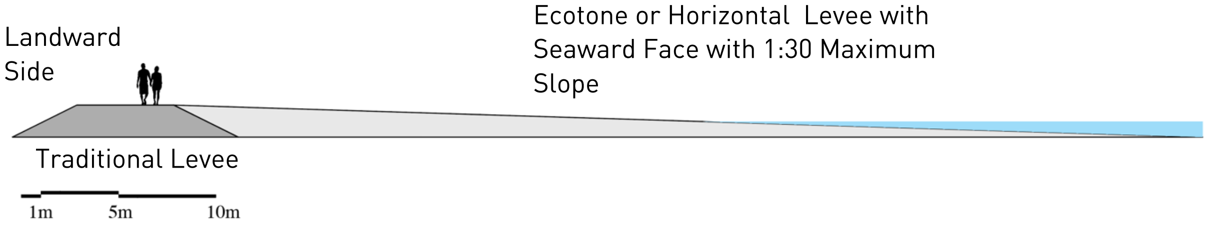


Figure 2. The notable feature of the ecotone levee (light grey wedge, above) is its extensive seaward face, which is prominently horizontally extended (relative to the steep face of traditional levees, shown in dark grey) and which creates its flood-protection benefits, but also delineates a considerable three-dimensional volume when extruded in space along a shoreline reach: illustrating the material demands involved in construction of Ecotone Levees at scale. It should be noted that ecotone levees may be constructed with more subtle slopes – and, therefore, possess larger cross-sectional areas – that would translate into larger volume demands. Illustration by Nate Kauffman.

A particular type of ecotone levee being pioneered in the case study region (described in the following section) is called a *horizontal levee*. Its basic landform is identical to the ecotone (illustrated in Figure 2, above) but which incorporates a wastewater-treatment seepage slope that involves irrigating vegetation on its seaward (horizontal) face (Cecchetti, 2022). This vegetation sequesters compounds and metabolizes nutrients that are problematic when discharged directly into the receiving waters of the adjacent estuary, as typically occurs currently. Wastewater treatment plants are municipal infrastructural assets that face major impacts as a function of SLR, as they are often being sited at extremely low elevations to take advantage of gravity-aided collection of storm- and wastewaters (Heberger et al., 2011; Hummel, 2018). As such, major interest in relieving or avoiding costs involved in replacing or retrofitting the traditional infrastructure used for treatment, pumping and discharging has come into focus as a regional priority, one potentially possible using the green infrastructure of horizontal levees.

In the context of planning adaptation measures that employ large-scale restoration and adaptation strategies that utilize landforms like ecotone and horizontal levees, shortfalls in coastal sediment supply are problematic. The sheer size of these levees as constructed earthworks is considerable and, as they work as an adaptation network in the landscape along extensive reaches of shoreline, the understanding of sourcing, allocating, transporting and applying sediment material is crucial. How are planners working at the intersection of flood protection and restoration ecology approaching the systematic study of anthropogenic sediment dynamics that are linked to landform construction? What tools and insights might aid their work and potentially open new avenues for innovation and improvements in efficiency and sustainability?

Our study examines a region grappling with these questions and issues, and the implications of a natural sediment supply shortfall, even as it plans extensive restoration work. We examine the system of excavated sediment flows within a case study on a systematic level and demonstrate a set of methods for estimating the quantities of sediment in various states within that system. Underpinning the work are central questions about the nature of excavated sediment in a developed shoreline region that may increasingly rely on it as a resource. What is the magnitude of the material involved, and how does it move through, or operate within, urban and industrial systems? By examining these questions and employing methods for surveying, modeling, and forecasting material *flows*, we illustrate the potential of excavated sediment that typically has been landfilled, for reuse in coastal adaptation to sea level rise.

1.4 Case Study Geographic Context

SF Bay Metropolitan Region

Assessing the potential of excavated sediment as a resource which might be optimized for landform construction as a component of a regional SLR adaptation strategy is grounded in estimating the *yield* of this material over time: an amount generated as a function of development projects that entail excavation processes. To explore this potential, we present a case study framing the management of this material, and investigate whether an alternative reuse strategy could be feasible or meaningful in accomplishing local benefits and regional goals. Accordingly, this study involves examining trends in known data related to recent excavated sediment yields and a plausible, causal relationship to known patterns and processes of urban development, namely population.

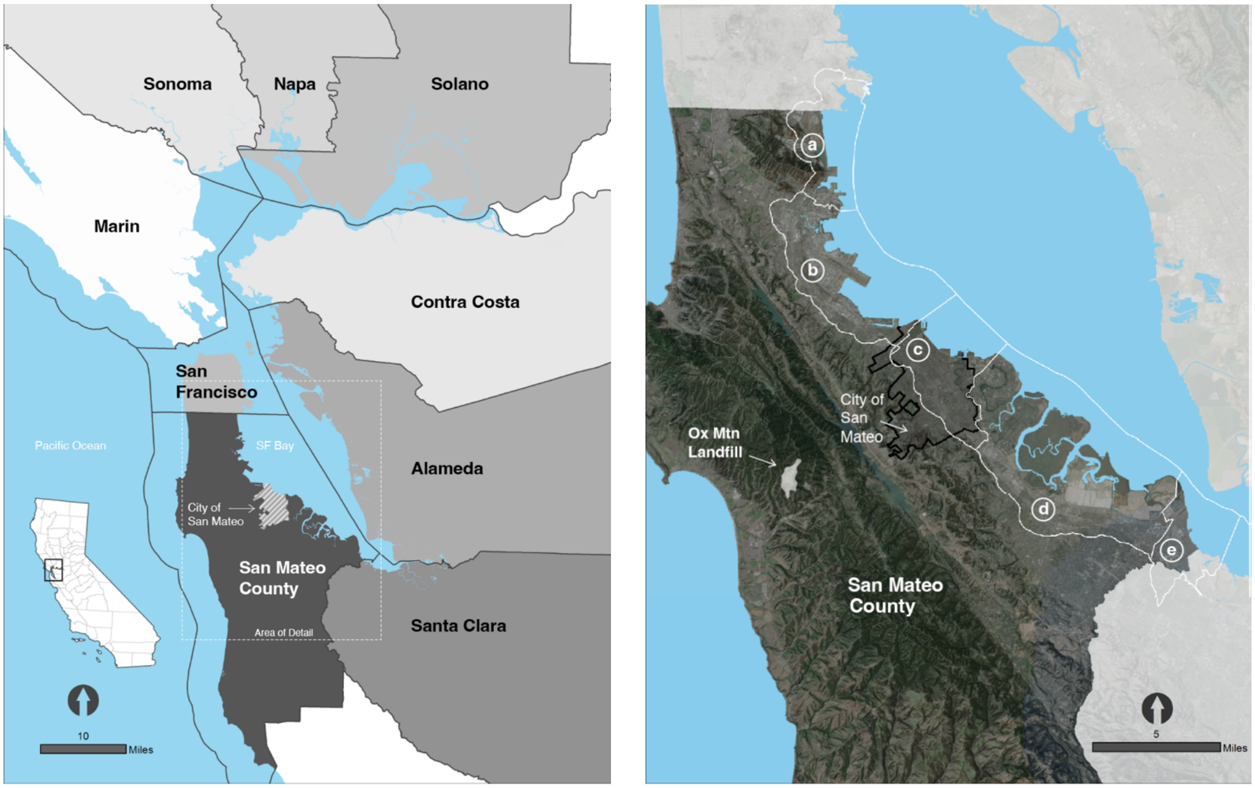
The San Francisco Bay Area of Northern California encompasses the largest deltaic estuary complex in the Americas, whose extensive watershed encompasses an enormous diversity of land uses, settlements, and physiographic regions straddling the state. The broader metropolitan agglomeration of the most-developed heart of the watershed is centered around San Francisco's namesake Bay (Bay Area), formally composed of 9 counties. Development of the Bay Area in the 19th and 20th century substantially depleted many of the region's ecological complexes, none more important to expected SLR impacts than the region's tidal wetlands and their associated ecological complexes including seaward mudflats and shoreward uplands, a landscape band regionally known as the Baylands (Goals Report, 2015). As a function of upstream development projects and dwindling natural sediment supplies flowing to the Bay, large-scale wetland restoration based on connecting Baylands to sediment supplies has come into focus as a regional adaptation priority (Brew &, Williams, 2010; Schoellhamer et al., 2013).

In recent years, the Bay Area has experienced impacts from wildfires spurred by a megadrought, upland flooding associated with atmospheric river events, exacerbation of urban heat island effects, biodiversity declines and increases in coastal erosion, tidal flooding and the rise of groundwater associated with SLR (Moser & Eckstrom, 2012; Swain, 2021; Cloern et al., 2011). These dynamics clearly illustrate the Bay Area finds itself grappling with numerous climate change-related challenges expected to intensify in the 21st century, even as its population and urban environment is expected to grow considerably. The siting of urban development in low-lying areas formerly occupied by the Baylands is a common condition of the Bay Area's urbanized tracts and their various infrastructural assets–and one with troubling implications in the climate change era.

Recent work to evaluate the capacity of the broader SF Bay watershed to link adaptation and restoration work has seized on the concept of Operational Landscape Units (OLUs) as an approach to identify landscape types of paired hydrologic and ecologic features as spatially-distinct units in places where development patterns have significantly altered biogeophysical processes (Verhoeven et al., 2008). OLUs may be understood as spatial components helpful in analyzing and planning resource management and development of SF Bay's shoreline and have been broadly adopted as a useful framework by the restoration and adaptation circles for this purpose (SFEI & SPUR, 2019).

A shoreline inventory of OLUs identified within San Mateo County forms the basis of our assessment of one county's ability to construct horizontal levees (SFEI, 2021). The assessment of the use five OLUs entirely or mostly within the county bounds the determine the potential of various possibilities linked to landform and landscape processes near the shoreline, and their interactions with the built environment. Of particular interest for our study are the linear miles of horizontal levee building opportunities. These reaches of the shoreline are essentially those in which ecotones might be constructed within approximately 2 miles of wastewater treatment plants, thus making possible the incorporation of the horizontal levee's seepage slope features and function.

Significantly, OLUs are not delineated based on municipal boundaries except when they relate to geographic features that the OLU employs in its classification logic. How might the SLR challenges faced by the region and the opportunities for horizontal levee construction play out on a local level with respect to sediment resources? We examine this question on the scale of a county grappling with significant SLR exposure, and examine aspects of its growth and development that may offer insights into its adaptative capacity (Adger et al., 2009).



Figures 2 & 3: A context map (above, left) showing the counties of the SF Bay Area and including their offshore extents. The Area of Detail is expanded (above, right) to show the County of San Mateo in greater detail, and the positions of its Ox Mtn Landfill facility and the City of San Mateo (outlined in black). The white lines correspond to Operational Landscape Units of San Mateo County, and the horizontal levee building opportunities identified within them: a) Yosemite-Visitacion, 0 miles; b) Colma-San Bruno; 2.2 miles; c) San Mateo, 0.7 miles; d) Belmont-Redwood, 3.3 miles; and e) San Francisquito, 4.2 miles. There are 10.4 miles of horizontal levee opportunity identified within OLUs that exist entirely or partially within San Mateo County's bounds. Note that OLUs incorporate offshore tracts as part of their geographic logic, as they are applied for study of Bayshore areas and processes. Images by Nate Kauffman.

1.4.1 Case Study Area:

San Mateo County

San Mateo County (SMC) straddles a large peninsula that includes both coastal exposure to the Pacific Ocean and a considerable stretch of shoreline frontage on the Bay itself, where the majority of SMC's population in centered. SMC is home to twenty incorporated cities and includes prominent regional assets including the multibillion-dollar San Francisco International Airport (SFO) and two highway bridge landings. SMC's population as of the 2020 Census was listed as 764,442; making it the 15th most populous of California's fifty-eight counties. It is part of the region's globally renown technology hub, a considerable concentration of jobs and private-sector investment. Partially a function of necessity given its extensive shoreline, SMC is recognized as a regional leader in environmental restoration and adaptation efforts aimed at addressing expected climate change impacts. SMC is notable also for its recent efforts to restore degraded and subsided wetlands by raising their elevational profiles to inter-tidal levels through the active placement of enormous quantities of sediment. The 1,400-acre restoration of Inner Bair Island, a project initiated by the US Department of Fish and Game and San Francisco Bay's Wildlife Society, involved the importation and placement of hundreds of thousands of cubic yards of fill including large volumes of excavated upland sediment to raise marsh elevations into the intertidal zone (Duke et al., 2004). Plans for protecting SFO and ongoing levee improvement and construction projects also involve the placement of fill sediments to build flood-mitigating landforms.

2. Methods

Our central hypothesis is that population growth and increasing density drive development processes that yield sediment resources as a byproduct. To test this hypothesis, we first investigate the relationship between an example city's population and the number of building permits issued in development projects. Then we examine the share of these permits that are related to known excavation processes and permitting. Next, to assess the potential for excavated sediment flows to be used for the development of landform-based adaptation strategies including the construction of horizontal levees in the San Mateo County region, we present a characterization and analysis of sediment material flows of interest within our case study.

We use permits and records of the stocks and flows of excavated sediment, and describe how the recorded sources, sinks and flows of sediment and the hidden, unrecorded flows are represented in the overall material ecology. We employ methods of analyzing material flows to test these known flows against our central hypothesis that increasing population drives sediment excavation in an urban region. The City of San Mateo is used as a proxy for other smaller cities and towns in the case study area. Using this proxy and extrapolating based on population change leads to an estimate of sediment yields associated with the County as a whole. Subtracting known flows from the volume of the primary sink allows us to estimate hidden flows in the County. Finally, we consider the potential of only the modeled flows, which we have estimated based on the recorded flows, to aid in the construction of horizontal levees. Hidden flows are not used for this comparison of urban sediment supply and the coastal adaptation demand.

2.1 System Description

Material Flow Schema: System Description and Components of Importance

Developing an understanding of the socioenvironmental system governing the uses of excavated sediment involves several methodological approaches. Material Flow Analyses (MFA) are a suite of mixed-method approaches for illustrating how movements and interactions of matter, energy and wastes are related, often for considering development patterns and processes for provisioning goods and services to society. As is typical of many MFA, our study employed literature review of similar studies and material management processes; including the reuse of excavated soil and its relationship to development projects (For example, see Hale et al., 2021; Hu et al., 2010; Magnusson et al., 2015) in combination with a process of logically testing and iteratively developing the components (stocks and flows) of the study and how they are articulated inside the system (Baccini & Brunner, 2012). Consultation with municipal offices, whose furnished data was used directly and indirectly in our quantitative analysis phase, and interviews with industry experts was also conducted to ensure the theoretical logic, and descriptive plausibility of the constructed MFA schema, and certain estimations that informed modeling (section 2.3).

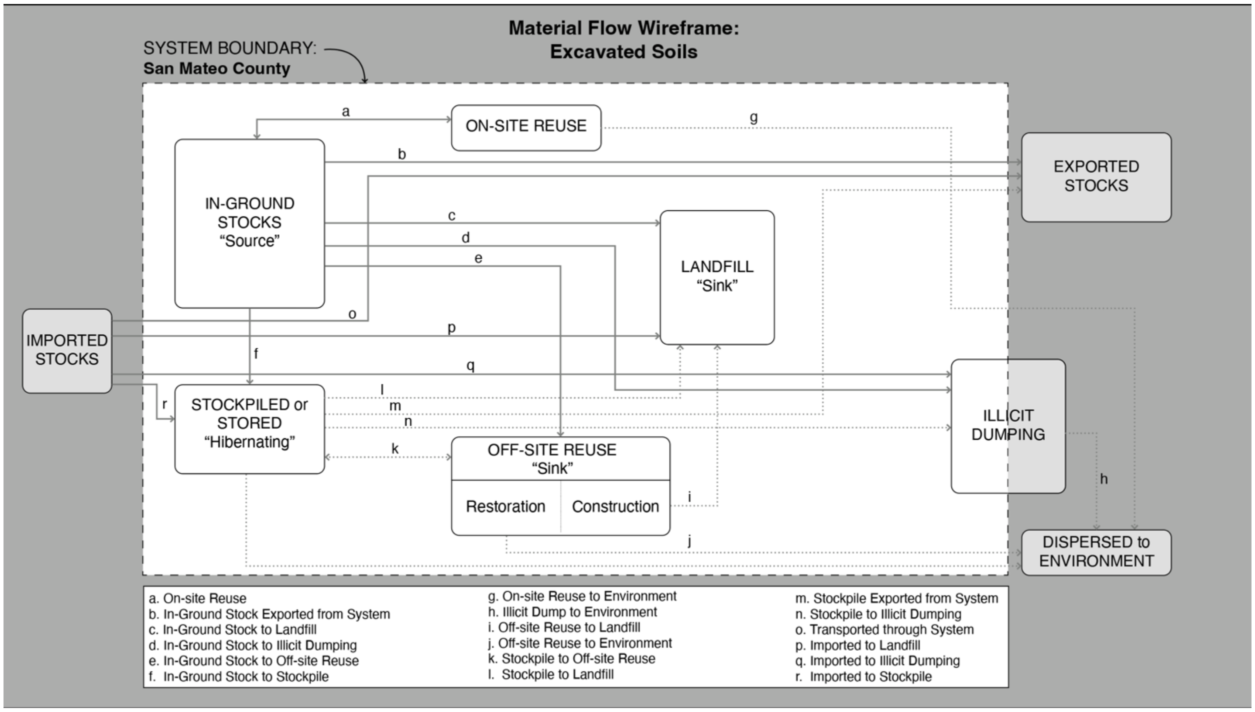


Figure 4: Material Flow Analysis Schema: The figure above represents an analytical tool common in studying the industrial ecology of various resources, substances and products: a conceptual Material Flow Analysis schematic 'wireframe'. The dashed line around the inner white rectangle represents an idealized system boundary corresponding

to San Mateo County; and the boxes within it therefor correspond to features contained therein. Dotted lines show flows that are secondary, and imply that material being moved has already been moved at least once before. The key at the bottom of the image describes flows connecting stocks. Image by Nate Kauffman.

System Features & Analysis: Stocks, Flows, Sources, Sinks and their Characterizations

MFAs necessarily simplify complex sets of elements and dynamics to convey approaches to illustrate central features of a system and the relationships between them, as is typical of conceptual frameworks applied in many fields (Paré et al., 2015). Especially when attempting to describe complex socioecological systems, MFA confront limitations prominently including the notion of system boundaries, which are simultaneously needed to scope a process of interest, and are generally also imperfect (Bartrola et al., 2001). Insofar as we rely upon data that is gathered by municipal and regional actors (as opposed to directly observing and measuring excavation in a study area), we have idealized San Mateo County as our system of interest, essentially as a spatially-discrete administrative unit charged with certain data collection practices within its bounds, while recognizing that boundaries are complex, porous and "fuzzy" with respect to the actual movement of material. These are illustrated as various *flows* that excavated sediment may take in and through the study area. Flows originate at a *source* from which they emanate, movements that can be idealized and pictured as general system behaviors or specific events or known trends during a given window of time.

Material at rest at some given location for some period exist as *stocks*. Stocks may represent a resource pool that is untapped (previously undisturbed in-ground sediment); sediment that has been relocated as a component of another project or process (as in the case of the Bair Island project, fill material used at a construction site, or as daily cover in landfills); and/or material that has been temporarily stockpiled for future reuse or movement. Because of their systematic nature, MFA often employ secondary analytical techniques to examine and emphasize particular material stocks, flows and/or system components in greater detail. Our study aims to do so by considering the interplay between two system components–certain *flows* and an end-of life stock called a *sink*–related to known data tracking processes that describe some aspects of the metabolism of excavated soils and the flows of excavated sediment and stocks of landfilled sediment occurring and existing within San Mateo County over a decade.

Hidden Flows

Stocks and flows of non-valuable, waste material on a large scale and in complex socioecological systems are often difficult to observe directly and, thus, rigorously track. Some authors have described flows as "hidden" in cases where they do not effectively "enter" the economy as commodified products or are understood as having little economic value, notably including excavated soils (Aoki-Suzuki et al., 2012; Matthews, 2000). While disagreement might exist over whether or not excavated sediment effectively do, in fact, enter the economy, the underlying notion is that hidden flows exist, especially regarding certain classes of materials. The conceptual and practical implication of hidden flows is that studies attempting to grapple with these materials will likely encounter incomplete and otherwise problematic records and data-tracking procedures for analysis. In that respect, hidden flows might be characterized as *unknown* from an analytical standpoint, but only insofar as they may not be directly measured. That is, the existence and systematic behavior or articulation of hidden flows might be known while their magnitude is not. We use the term hidden for this reason: our MFA recognizes them as being at play, while our methods attempt to quantify their gross magnitude, in part by tallying those that are not hidden.

Assessing these known and unknown sources and sinks–and the known, estimated, and inferred flows that connect them systematically–is useful for developing insights about the status of materials; specifically where they are positioned or concentrated in a system, or how various activities in the urban and industrial processes at play relate to materials of interest (Rosado et al., 2014). In our case study, examination of available data is necessary to develop an estimate of material quantities that could influence future policies and regulations that would support excavated sediment reuse in constructed adaptation landforms. This would require the re-routing of existing flows to novel sinks in a future shoreline with ecotone levees that reduce the impacts of sea level rise.

2.2 Data Collection & Analysis

Overview, Timeframe, Uncertainty

Our study gathered data related to the 10-year period between 2010 and 2019 to capture recent trends, while avoiding significantly poorer-quality datasets prior to this period. It omits the unique events of the 2008-09 recession and COVID-19 outbreak. Quantifying the amount of sediment excavated in our case study area within this time period is complicated by several issues. Fist, excavation is not directly observed and recorded by any office. Rather, norms and regulations based on self-reporting expectations and official receipt of documentation and permits defines the culture of practice associated with excavated sediment management. This documentation, in the form of permits and records, is not centrally documented and must be gathered from a variety of county, municipal and private offices. Then the data can be examined and compared to other data, such as population, to assemble an indirect impression of the material flows of interest. Second, not all excavation projects require permitting, as is the case with projects occurring in the public right of way and/or those performed by municipal service providers (for infrastructure, utilities, transport, etc.). In fact, in general, the excavation of earthen material is recorded if and when it exceeds some given amount on a given project. A minimum threshold is used to trigger certain permitting requirements. In San Mateo County, this amount is often designated as 50 cubic yards of "soil disturbance." Excavation projects below this threshold or those that do not comply with reporting procedures (see flow vectors *d, n,* and *q* in Figure 5) effectively escape cataloging altogether and therefor represent a hidden flow of unknown magnitude within the system, producing an underestimate when assessments are based on documented records.

A third set of complications arises as a function of variations in tracking, permitting and reporting procedures, including the heterogeneity of data types; the related variations in standards (procedures for data generation, collection, and archiving followed or enforced by local government entities), adherence (the degree to which said standards or requirements are observed by private sector actors), and the management and accessibility of data (if and how records are constructed, curated and shared). Incomplete, heterogenous, varied, fragmented and inaccessible information is a constant and common challenge for studying material flows in complex socioenvironmental contexts (Schwab et al., 2017), particularly when the flow represents a material considered a waste rather than a resource.

Accordingly, our study represents a coarse-resolution estimate of the material flows of interest, serving as both an initial evaluation of material yields and dynamics and as a starting point for future research. Since the ultimate aim of this study is to advance knowledge for planners and resource managers about how existing material flows and the regimes that track data related to these processes may change to advance adaptation outcomes, we apply the methods developed in this section to a forecasting approach that attempts to recognize uncertainty and sensitivity related to the supply of sediment. To examine these sensitivities, we close with a study of how the amount of sediment that would be of sufficient quality within these urban flows may vary, using estimates from previous studies. We also consider the sensitivity of the demand for sediment, using the potential height of ecotone levees to represent a range of different goals for adaptation. These considerations are presented in the results and discussion sections.

2.2.1 Acquisition, Processing & Composition of Data

Acquisition: Sources and Collection of Datasets

Available data were gathered from permitting processes and records tracked and collected by public offices. In all cases, the data used in our study was obtained through research to determine which offices held what data records (sourcing) establishing lines of communication with the offices to describe and parameterize our experimental design and data request (collection). This data was then screened to standardize and streamline datasets by eliminating duplicates and any other evident recording errors. In all instances, data were provided electronically as spreadsheets and accompanying documents related to permitting processes, etc. and consultation with office representatives provided insight and context for interpretation of data. The information we used in our modeling involved comparing and combining data provided by offices operating at various levels of government.

	SYSTEM FEATURE		
DATA FEATURE	**Flows**	**Flows**	**Stocks** (end-of-life)
Data Scale & *Agent*	County-wide *San Mateo County* unincorporated areas (**SMC**)	*City-wide* *City of San Mateo* (**CSM**)	State-Wide *Ox Mountain Landfill* (**Ox Mtn**)
Data Source(s)	San Mateo County ("SMC") Department of Building and Planning	City of San Mateo ("CSM") Dept. Public Works	Department of Resources, Recycling & Recovery "CalRecycle"; California Environmental Protection Agency
Data Element	Grading Permits (as component of Building Permits issued)	Waste Recycling Permits (REC); Stormwater Permits (STOPPP); Building Permits	Daily Cover Records
Data Attribute(s) Used	Permit #, Date Issued; Number of permits; *Volume* of "cut" produced from sitework (Cubic yards)	Permit #, Date Issued; Number of permits; Mass (Waste recycling -- direct) and volume (STOPPP -- estimated)	Quarterly Reports of mass received (tonnage)

Table 1. Data collected from various sources within the Case Study Area were analyzed and combined to estimate flows of excavated sediment from known sources within the County to the Ox Mountain landfill facility (tracked by the state of California) during the study period.

Data from nested jurisdictions

City-Level Data: City of San Mateo ("CSM")

Construction and Demolition Waste (CDW) Recycling Plans are (officially) required for new residential construction and demolition projects in the City of San Mateo, which is overseen by the Recycling division of the Public Works department (RecycleWorks). Waste Recycling Permits (RECs) track, among other things, the mass (in tons) and percentage (of total waste masses) of CDW identified and tracked as "Inert" materials consisting of soil and rubblized concrete. Stormwater Pollution Prevention Permits (STOPPPs) are also collected by CSM. These records reflect the incidence of projects that trigger permitting based on water quality regulations, and in which a "soil disturbance" exceeding 20 cubic yards occurs.

County-Level Data: Unincorporated San Mateo County ("SMC")

The County of San Mateo's Planning and Building department issues grading permits for construction projects related to private property development in unincorporated areas of the county in which 50 cubic yards or more soil is "disturbed". These permits record the cut/fill quantities of soil in cubic yards, thus reflecting which projects export sediment off-site, and in what quantities.. We examined only the "cut" component of these projects – those that become a known source contributing to material flows. Thus our SMC fill numbers are not incorporated into the model, though we do consider the implications of this logic in the Discussion section.

State-Level Data: CalRecycle & Ox Mountain Landfill ("Ox Mtn")

The Corinda Los Trancos Landfill, referred to as Ox Mountain, is SMCs only operational solid waste landfill. While privately owned and operated, a division within California's Environmental Protection Agency (CalRecycle) requires reporting on all landfills in the state, specifically related to their receipt of waste masses (recorded in tons). One of the material classifications tracked is the amount of soil received; this material is used by landfills as daily cover (see section 1.3.1).

2.3 Analyses and Modeling

Assumptions, Integration, and Use of the City of San Mateo as a Proxy

The underlying hypothesis of our study, that increases in population are an important driver of increases in the quantity of excavated urban sediment, is rooted in the observation that while development and construction projects are shaped by zoning and other land use regulations, they are driven by housing and commercial projects constructed by the private sector within the fixed boundaries of a given county. These private sector-led developments in the San Francisco Bay region are associated with the region's increasing population density, particularly in cities and counties on the Bay. Regional public sector initiatives within the study area guide local planning processes. These planning processes incentivize private-sector development projects in dense urban cores clustered around key transportation corridors, so-called Transit Oriented Development (TOD). New construction that increases urban residential, retail and commercial density requires excavation of foundations and underground spaces that produce sediment as a byproduct. We tested this hypothesis for San Mateo County by comparing population changes with sediment yields for the City of San Mateo during our study period.

Our model adds the sum of three known and estimated *sources* of sediment (yields in tons) and compares this number to a known *sink* (tons received at the Ox Mtn Landfill). First, we represented known and estimated yields of excavated sediment from the City of San Mateo (CSM) using the recorded number of building permits that involve sediment excavation. Building permits are associated with a secondary permit triggered in certain situations where earthwork, the hauling of soils/sediment, and/or impacts on stormwater as a function of grading occurs. The proportion of these secondary permits as a percentage of total building permits remained remarkably stable over the study period (12, 12, 12, 11, 13, 12, 12, 13, 11, and 6%, respectively).

Then, we used these numbers from the City of San Mateo as a proxy for calculating other unknown yields from the other incorporated cities in San Mateo County (CsSM). We used a per capita scaling number based on records in the City of San Mateo to estimate total building and secondary permit numbers using the population of incorporated cities in CsSM as our base, in all years of the study. The rationale for using CSM as a useful proxy for comparison to CsSM is based on several observations. CSM represents 14% of the county's overall population (a proportion that has remained stable over the decade of our study) making it a useful sample in and of itself. It is ranked 6th in the county in terms of its density with respect to other 19 incorporated cities and 9th in comparison with all 33 cities including those that are unincorporated. Therefore, we assume that the percentage of building permits that involve sediment excavation in all San Mateo cities (CsSM) will be comparable to that percentage of building permits in the City of San Mateo (CSM). Having an estimate of the number of permits that include sediment excavation allows us to estimate total sediment yield for all the incorporated cities of San Mateo County.

There are important differences in the data recorded at each nested jurisdictional scale. County-level data included information about cut and fill operations explicitly referring to earthwork–in other words, these permits track only excavated sediment. By contrast, the City of San Mateo includes rubblized concrete in its sediment export records. Based on their analyst's best estimate, we accepted a 4:1 ratio of sediment to rubblized concrete for the City of San Mateo's permit records. This number corresponded closely with landfill managers' estimates of 75-80% sediment and 20% rubblized concrete as a proportion of their daily cover. For our estimates of sediment yield from cities in San Mateo County and our estimates of sediment included in daily cover at the landfill, we used an 80% proportion to estimate the mass of sediment (minus concrete rubble) flowing out of the City of San Mateo and into the Ox Mountain Landfill.

Data Modeling

We built a simple material flow model to represent these data and the various assumption we applied. Our assumptions are listed below, along with a description of the data used estimate the volume of each model component:

I. Population and building permits

a. As population rises over the study period, so do the number of building permits that track development and construction.

The data on population and building permits reveal a positive correlation between building permits and population in our city-scale case study, the City of San Mateo (CSM). We calculated the annual rate of change in population and in the number of building permits year-over-year. We also calculated the average rate of growth for each variable.

b. *Within a known sample (CSM) and over the study period, a relatively stable proportion of building permits include secondary permits associated with excavation.*

    i. One set of these, waste recycling permits (RECs) directly measures excavated sediment tons as a flow.

RECs track Construction and Demolition Waste (CDW) mass totals in tons; and we apply an assumption that 80% of this is soil/sediment as opposed to rubblized concrete.

$$\text{CSM REC tonnage, year } a = (\text{Total known mass in year } a) \times (0.8)$$

    ii. The second set of these, stormwater pollution prevention permits (STOPPPs) do not directly track tonnage, but an average (per permit) is estimated.

Based on our interviews with experts from the City and County of San Mateo surveyed for this project, we assume that STOPPP permits yield an average of 50 tons of sediment per permit. Multiplying the number of STOPPP permits by this amount yields an estimate of the total mass of excavated sediment tracked by STOPPPs.

$$\text{CSM STOPPP total tonnage, year } a = (n\,\text{STOPPP in year } a) \times (50)$$

c. *We used the number of RECs and STOPPPs in the City of San Mateo to estimate their respective percentages as a share of building permits in each year of the study period and as averages.*

Using City of San Mateo data, we divided the total number of STOPPPs by the number of building permits in a given year, and divided the total number of RECs by the number of building permits in a given year.

$$\text{Percentage secondary permits of total building permits year a} = \left(\frac{n\text{ secondary permits in year } a}{n\text{ building permits in year } a}\right)(100)$$

d. *The City of San Mateo is a reasonable proxy for the other cities of San Mateo County because it likely has similar distributions of building permits per capita.*

The City of San Mateo represents 14% of the county's overall population, and as its population has grown that percentage has remained stable over the decade of our study. It is ranked 6th in the county in density with respect to 19 other incorporated cities; and 9th in comparison with all 33 cities including those that are unincorporated. The same regional and county-level planning processes and incentives that encourage dense transit-oriented development are in place across all of these communities.

II. Extrapolation of building permit numbers based on population

e. Since population is correlated with the total number of building permits, as we have observed in section I.a. above, then the number of total building permits in the cities of San Mateo County can be estimated using our previous estimates of sediment yield per permit, number of building permits per capita (both from the City of San Mateo), and the population of these other small cities.

Population totals for the other cities of San Mateo County (CsSM) are calculated by subtracting the sum of the populations of unincorporated San Mateo County and the City of San Mateo from the total County population for each year of the study. By dividing the number of building permits in the City of San Mateo by its population in a given year, we produce a coefficient that we then multiply by the population of the other small cities of the County (CsSM) for that same year. The process is repeated for all years.

$$n \text{ population Total County in year } a - ((n \text{ population SMC in year } a) + (n \text{ population CSM in year } a))$$

$$= n \text{ population CsSM in year } a$$

and

$$\frac{(n \text{ building permits CSM in year } a)}{(n \text{ population CSM in year } a)} = k^a$$

therefore

$$(k^a) \times (n \text{ population CsSM in year } a) = n \text{ building permits CsSM in year } a$$

f. The total number of secondary – STOPPP and REC – permits can be estimated for CsSM using their typical percentages of total building permits for a given area *(as observed in CSM). An average volume for these permits (on a volume per-permit basis) based on CSM permit volumes can be applied and converted to tonnages. These can be tallied on an annual basis.*

Multiplying CsSM's estimated building permit totals in a given year by the percentages calculated in the proxy case yields an estimate of the number of secondary permits (STOPPPs and RECs, respectively). Multiplying these respective totals by the proxy tonnage-per-permit values produces a tonnage estimate. The process is repeated for all years.

For RECs:

$$\left[(n\ \text{building permits CsSM in year } a) \times \left(\frac{n\ \text{RECs CSM in year } a}{n\ \text{building permits CSM in year } a}\right)(100)\right] \times 41 = \text{RECs total tons CsSM in year } a$$

and

For STOPPPs:

$$\left[(n\ \text{building permits CsSM in year } a) \times \left(\frac{n\ \text{STOPPPs CSM in year } a}{n\ \text{building permits CSM in year } a}\right)(100)\right] \times 50 = \text{STOPPPs total tons CsSM in year } a$$

therefore

$$\text{Total CsSM flows in year } a = (\text{RECs total tons CsSM in year } a) + (\text{STOPPPs total tons CsSM in year } a)$$

g. *The sum of these annual sediment yields from the City of San Mateo and the other cities of San Mateo County (CSM and CsSM) can be added to known flows from unincorporated San Mateo County (SMC) to represent total annual flows estimated from recorded sources (not including hidden flows).*

We combined the tons of sediment yield per year that we estimated for the City of San Mateo (CSM) and the other cities of San Mateo County (CsSM), and added them to the recorded tons of sediment yield from unincorporated San Mateo County (SMC). Conveniently, soil and sediment volumes recorded as cubic yards are analogous to mass tonnage (both in terms of the recording standards in our case study and as an industry standard broadly): whereby one cubic yard is assumed to be equivalent to one (US or "short") ton: 2,000 lbs. Total flows may be estimated as tons for any given year, span or range within the study period.

$$\text{Total modeled flows in year } a =$$

$$(\text{total CsSM flows in year } a + \text{total CSM flows in year } a + \text{total SMC Flows in year } a)$$

III. Comparison of our modeled sediment flows to actual tons of sediment arriving at the landfill (sink)

h. Subtracting our total modeled sediment flows from the recorded sink totals at the Ox Mountain landfill estimates the magnitude of total hidden flows into the landfill for a given year, which we can use to estimate the volume of those hidden flows produced within our study period.

The tons of material received by the Ox Mountain landfill were recorded in each year of our study period. We applied an 80% filter because expert estimates noted that about 20% of the total sediment inflow is concrete composition by mass. This percentage, estimated by Ox Mountain staff, is the same as the percentage estimated by staff in the City of San Mateo with regard to REC permits. We subtracted the sum of all known and estimated sediment flows sums (from SMC, CMS and CsSM) from 80% of the total material received by the landfill.

$$\text{Total hidden flows year } a = \text{Ox Mtn total sediment sink in year } a - \text{ total modeled flows in year } a$$

IV. Estimation of the demand for sediment required for adaptation landforms on the San Mateo shoreline

i. The total magnitude and annual yield of these excavated urban sediment flows can be compared to the need for excavated sediment required in the construction horizontal levees that have been proposed in the region. This will allow an assessment of whether excavated sediment flows can make a meaningful contribution to coastal adaptation using horizontal levee, a strategy which is currently limited by the lack of sediment availability.

To assess the comparative magnitudes of modeled flows and the emergent demand for sediment that would support horizontal levee construction, we take the length of shoreline that is suitable for horizontal levees from existing literature (SFEI & SPUR, 2019), and calculate the volume of ecotones that have three different cross-sectional areas as a function of their crest heights: 1m, 1.5m, and 2m respectively. All incorporate a 1:30

seaward slope. Using the cross-sectional areas of these profiles, we calculated volumetric extrusions for mile-long reaches; and used these volumes to estimate sediment demand in tons. Our findings are discussed in the following section.

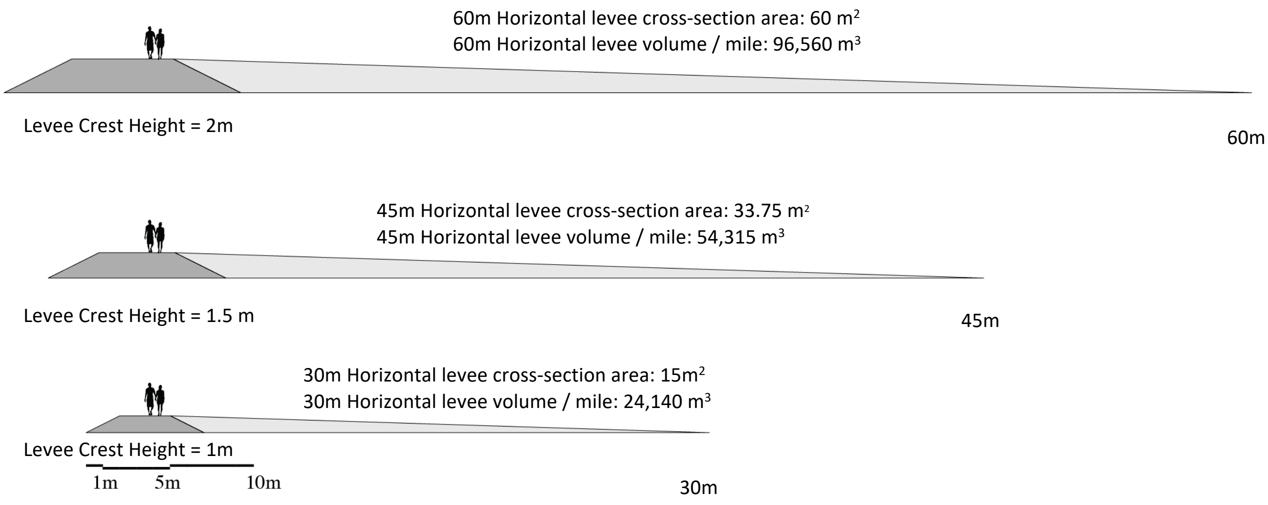


Figure 5: The sketches above represent the cross-sectional areas (in light grey) of three ecotone profiles with slopes of 30:1 that are constructed on the seaward face of traditional levees (dark grey) that have face slopes of 2:1. The ecotone width is measured from the toe of the existing levee.

3. Results

Our analytical findings demonstrate several relevant trends and relationships in the data, material and system of interest. In this section, we discuss the results of the modeling efforts and frame several important outcomes and prominent insights from the work.

a. *As population rises over the study period, so does the number of building permits that track development and construction:*

Year	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**Correlation Coefficient**
Population CSM (*n*)	97,207	95,957	97,322	98,601	100,114	101,335	102,224	103,500	104,035	104,333	**0.90**
Building permits CSM (*n*)	1,696	1,816	1,936	2,218	2,310	2,834	2,788	2,700	2,590	2,729	

Table 2. A strong positive correlation (0.0900) exists between the growth rates of population and building permits issued in the City of San Mateo.

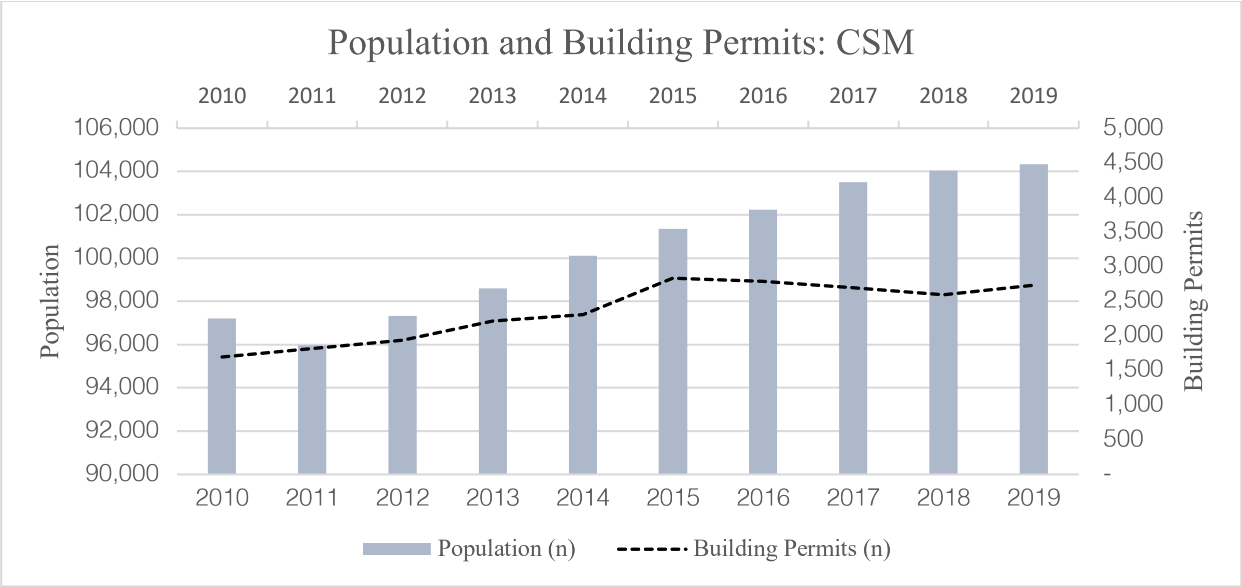


Figure 6: The overall trends in growth of population and number of building permits. Over the study period, the average annual growth rate increase was 1%. The average number of building permits issued grew by 6% per year.

b. *Within a known sample (City of San Mateo), a relatively stable proportion of building permits over the study period include secondary permits associated with sediment excavation.*

	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	**Average**
Building permits total (n)	1,696	1,816	1,936	2,218	2,310	2,834	2,788	2,700	2,590	2,729	**2,362**
REC permits total (n)	49	58	49	45	48	48	56	61	65	47	**53**
Percentage REC of building permits	3%	3%	3%	2%	2%	2%	2%	2%	3%	2%	**2.29%**
STOPPP permits total (n)	161	164	191	188	257	283	289	297	232	106	**217**
Percentage STOPPP of building permits	9%	9%	10%	8%	11%	10%	10%	11%	9%	4%	**9.22%**
Total percentage REC + STOPPP	**12%**	**12%**	**12%**	**11%**	**13%**	**12%**	**12%**	**13%**	**11%**	**6%**	11.51%

Table 3. Percentages of REC and STOPPP permits as a proportion of total building permits, by year and total averages, in the City of San Mateo.

c. *Using RECs and STOPPPs permits, we estimated an average sediment yield per permit within the City of San Mateo during our study period.*

	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	Average
REC permits total (n)	49	58	49	45	48	48	56	61	65	47	**53**
REC total tonnage*	1,178	6,040	2,009	3,476	1,127	3,784	771	1,396	604	715	**2,110**
STOPPP permits total (n)	161	164	191	188	257	283	289	297	232	106	**217**
STOPPP total tonnage†	8,050	8,200	9,550	9,400	12,850	14,150	14,450	14,850	11600	5,300	**10,840**
Average total tonnage (REC+STOPPP)	9228	14240	11559	12876	13977	17934	15221	16246	12204	6015	9,228

Table 4. Using known secondary permit totals for City of San Mateo, tonnages are calculated as averages, annual and overall totals. RECs are waste recycling permits. STOPPPs are stormwater pollution prevention permits.
*REC totals are calculated as 80% proportion of totals recorded to eliminate concrete constituency.
† STOPPP totals are estimated based on an average 50ton/permit assumption.

d. *The City of San Mateo (CSM) is logical for use as a proxy for the other cities of SMC because it resembles the typical urban form of the conglomeration of cities forming the county's population center.*

City	**Population 2010**	**Population 2020**	**% Growth**
San Mateo	97,207	105,806	9%
Daly City	101,123	105,024	4%
Redwood City	76,815	84,476	10%
South San Francisco	63,632	66,184	4%
San Bruno	41,114	43,947	7%
Pacifica	37,234	38,674	4%
Foster City	30,567	33,841	11%
Menlo Park	32,026	33,830	6%
Burlingame	28,806	31,416	9%
San Carlos	28,406	30,748	8%
East Palo Alto	28,155	30,139	7%
Belmont	25,835	28,361	10%

Millbrae	21,532	23,227	8%
Half Moon Bay	11,324	11,814	4%
Hillsborough	10,825	11,393	5%
Atherton	6,914	7,194	4%
Woodside	5,287	5,313	0%
Brisbane	4,282	4,858	13%
Portola Valley	4,353	4,457	2%
Colma	1,792	1,510	-16%

Table 5. Populations of San Mateo County's incorporated cities in 2010 and 2020 and their growth rates. Source: US Census

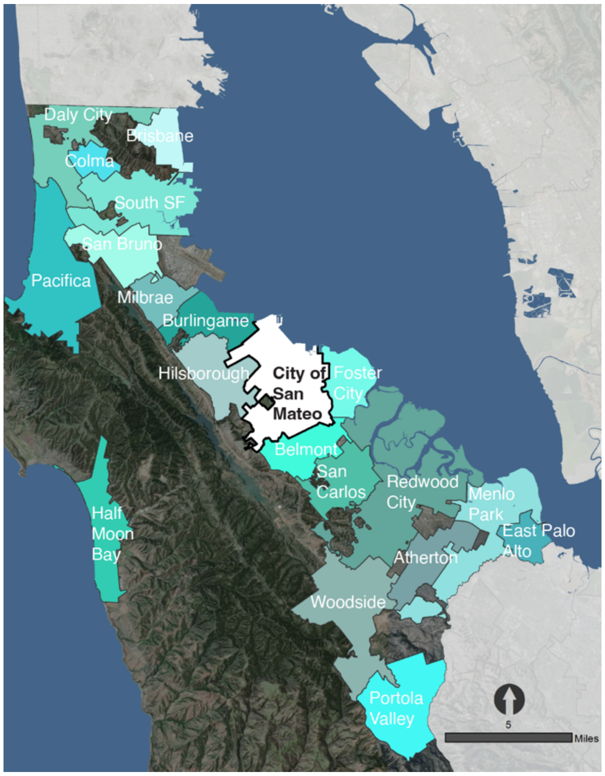


Figure 7 . The location of San Mateo County's incorporated cities. Notice their clustering along the eastern side of the peninsula and Bayshore.

e. Since we have observed a correlation in population and the number of building permits, we estimated the number of total building permits over the same period in CsSM (not including CSM) based on their population.

	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	Average
CsSM Population*	565145	574672	583202	590600	596927	602906	604270	603665	602902	593310	**591,760**
Estimated building permits total (n)	9860	10,876	11,601	13285	13773	16861	16481	15748	15010	15519	**13,901**

Table 6. Estimated building permits, tallied annually and as totals, in the other cities of San Mateo County using the City of San Mateo as a proxy case.
* CsSM is calculated by subtracting the populations of unincorporated SMC and CSM from total county population.

f. The total number of REC and STOPPP permits are estimated for the other cities of San Mateo County (CsSM) using the typical number of building permits per person (as observed in the records of the City of San Mateo). An average volume for these permits (estimated on a volume per-permit basis based on City of San Mateo permit volumes) is applied and converted to tons. These are tallied on an annual basis:

	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	Average
Estimated REC permits total (n)	226	249	266	304	315	386	377	361	344	355	**318**
REC total tonnage*	9258	10211	10893	12474	12932	15831	15474	14786	14092	14571	**13,052**
Estimated STOPPP permits total (n)	909	1003	1070	1225	1270	1555	1520	1452	1384	1431	**1,282**
STOPPP total tonnage	45456	50137	53483	61246	63495	77730	75975	72597	69194	71543	**64,086**
Average total estimated tonnage (REC+STOPPP)	**54,714**	**60348**	**64375**	**73719**	**76427**	**93561**	**91449**	**87,383**	**83,286**	**86,113**	**77,138**

Table 7: Estimated totals of secondary building permits in the other Cities of San Mateo, tallied annually and as totals, using recorded numbers from CSM as proxy.
* REC tonnage assumes 41tons/permit (previously calculated).
† STOPPP tonnage assumes 50ton/permit (estimation).

g. The sum of excavated sediment flows from the City of San Mateo (CSM) and the other cities of San Mateo County (CsSM), added to recorded flows from unincorporated San Mateo County:

	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
Total SMC Tonnage	2,978	2,990	2,902	4,075	4,853	9,223	17,128	30,447	10,021	25,486
Total CSM Tonnage*	9,228	14,240	11,559	12,876	13,977	17,934	15,221	16,246	12,204	6,015
Total CsSM Tonnage†	54,714	60,348	64,375	73,719	76,427	93,561	91,449	87,383	83,286	86,113
Total Modeled Flow Tonnage	**66,919**	**77,578**	**78,836**	**90,670**	**95,257**	**120,719**	**123,798**	**134,076**	**105,512**	**117,614**

Table 8: Sums of modeled and recorded flows from unincorporated San Mateo County, the City of San Mateo and other cities in San Mateo County, tallied annually and as totals for the study period.
* Includes recorded and estimated flows.
†Based on estimated flows.

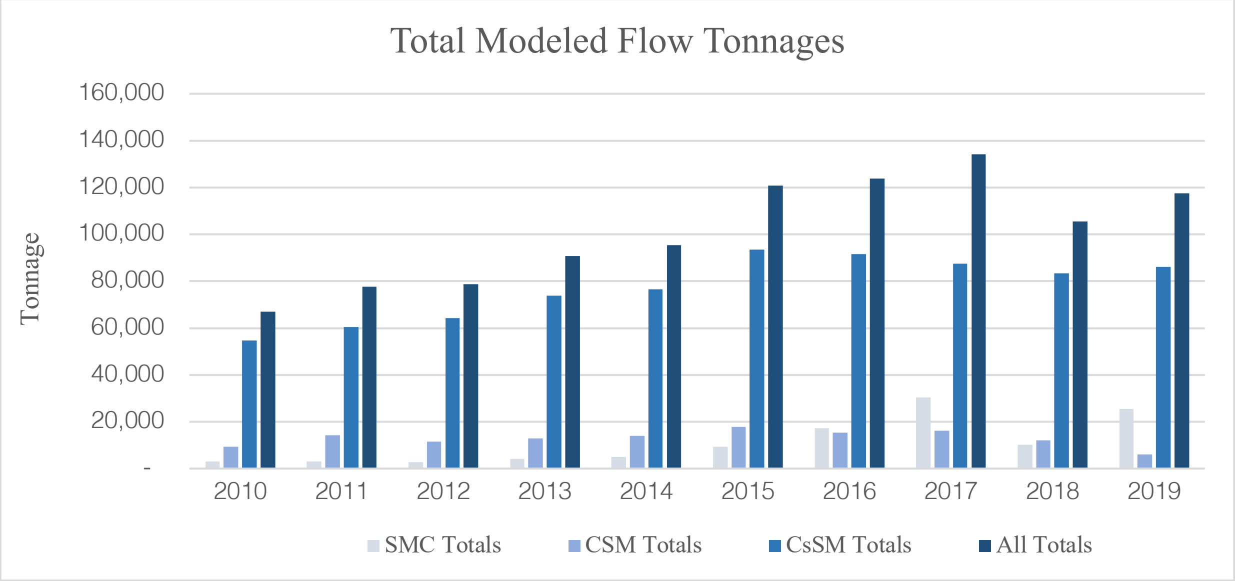


Figure 8: Bar chart showing recorded and estimated sediment yields from unincorporated San Mateo County, the City of San Mateo, and other incorporated Cites in the County of San Mateo by year.

h. Subtraction of these modeled flows from the recorded sink totals at the Ox Mountain landfill provides an estimate of the magnitude of total hidden sediment flows entering the landfill as daily cover.

	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
Total modeled Flow tonnage	66,919	77,578	78,836	90,670	95,257	120,719	123,798	134,076	105,512	117,614
Total sink tonnage*	82,055	94,032	204,711	286,532	370,038	304,947	321,242	425,879	469,364	500,194
% Total sink sodeled as flows	**82%**	**83%**	**39%**	**32%**	**26%**	**40%**	**39%**	**31%**	**22%**	**24%**
Total hidden flow tonnage	15,136	16,454	125,875	195,862	274,781	184,228	197,444	291,803	363,852	382,580

Table 9: Percentages of total modeled flows (dark grey band) as proportions of the total tons of landfilled soils, by year. The total unmodeled flow tonnage (hidden flows) is calculated as the difference between total modeled flow and total recorded sink tonnages, by year (lowermost row).

* Sink tonnage of sediment is estimated by using the assumption that 80% of the material received for daily cover is actual sediment, while 20% is rubblized concrete that is also classed as "soils" in landfill records.

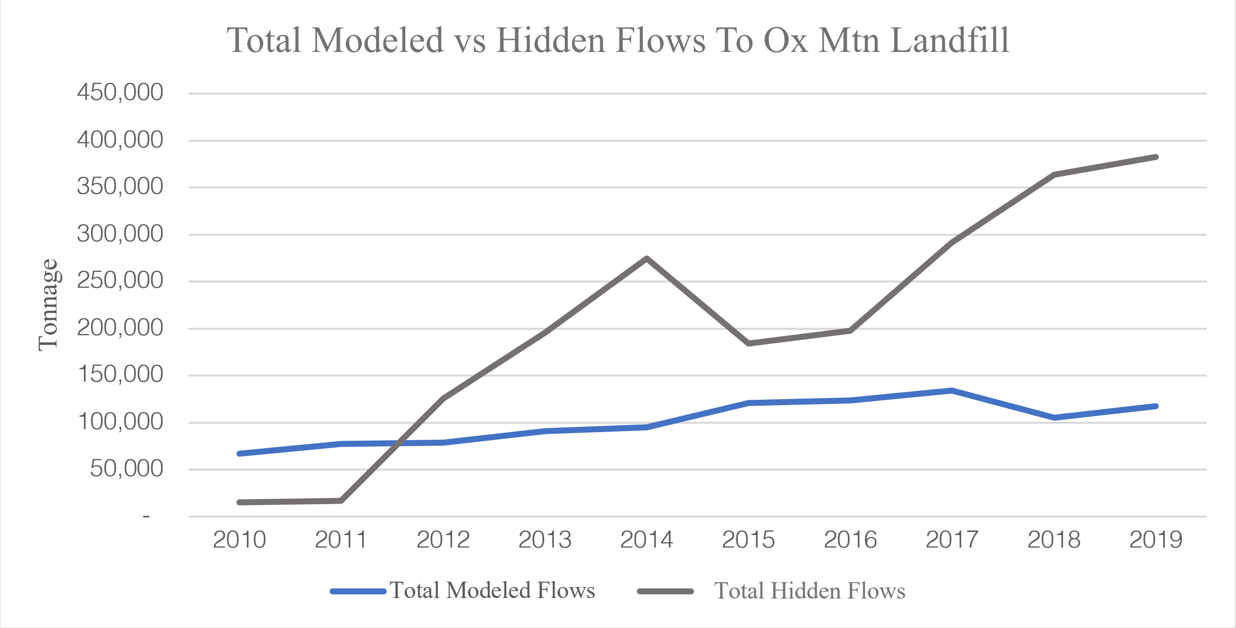


Figure 9: Graph of the trends in total modeled flows (blue line) to Ox Mountain Landfill compared to the inferred hidden flows (grey line) over the study period. According to our estimate, the proportion of hidden flows that are not recorded at the source has increased by a large amount over the past decade.

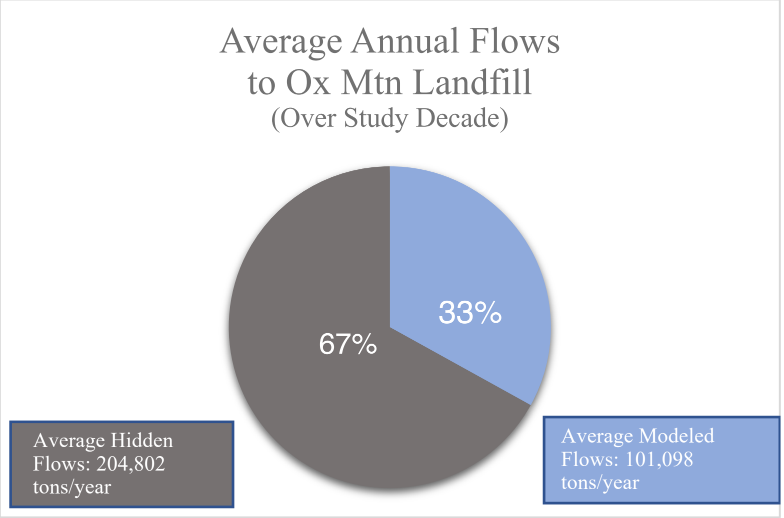


Figure 10: An average of 305,900 tons of excavated sediment flowed to the Ox Mountain Landfill, per year, over the study period. One third of these are the modeled flows from our material flow analysis, which averaged 101,098 tons/year.

i. The magnitude of these urban sediment flows is comparable to the need for excavated sediment required in the construction of horizontal levees that have been proposed in the region; facilitating an assessment of whether excavated sediment flows can make a meaningful contribution to coastal adaptation using horizontal levees, a strategy which is currently limited on the regional scale by a lack of sediment availability.

Horizontal Levee Height (meters)	**Horizontal Levee Sediment Demand** (tons per mile)	**SMC Total: 10.4 Miles Horizontal Levee Demand** (tons)	**Average *Annual* Modeled Flows as Percentage of SMC Total Horizontal Levee Demand**
1m	24,140	251,056	40%
1.5m	54,315	564,876	18%
2m	96,560	1,004,224	10%

Table 10: Comparing the supply of annual modeled flows in San Mateo County to demand for horizontal levees on the San Mateo County shoreline. Columns show (from left) three levee height cases; the per-mile tonnage demand for sediment under those height assumptions; total demand from all of SMCs currently identified miles of horizontal levee opportunity; and the percentage of modeled excavated sediment flows as a proportion of the total estimated demand for SMC's horizontal levees. At 1 m of levee height, the modeled sediment yield from the County's building permits makes a significant contribution. For the highest levees, more of the hidden flows would need to be harnessed in order to provide a significant input.

4. Discussion

Our modeling reveals several trends of interest in the study area that directly reflect and link population, permits and excavated sediment yields. Given our assumptions, excavated sediment in urbanizing San Mateo County could be a significant source of material for coastal adaptation projects.

The results also raise a set of obvious and fundamental questions: where do the hidden flows originate that comprise the majority of flows into the Ox Mtn landfill? What factors and forces effectively work to "hide" them in terms of the processes of excavation or sediment hauling at work, and the procedures for tracking these practices in the form of data records that might be further analyzed? Why are such wide variations evident in the tonnage of total modeled flows as a percentage of total sink tonnage, ranging from 83% in 2011 to 22% in 2018? Does this gap indicate that the percentage of hidden flows has increased significantly over the study period, or do other factors generate this apparent gap? In this section, we reflect on these questions and consider the potential contribution of modeled flows that might be redirected for use in horizontal levee construction (Table 10, above), considering future population dynamics and questioning the likely proportion of these flows that might be suitable for sensitive environmental applications like shoreline restoration. Our Conclusion section then frames our key takeaways and the central insights and challenges of this analysis as a whole.

4.1 Comparing Known Sources and Sinks: Hidden Flows and Leaky Systems

Mass Balances

A central concept in industrial ecology and its related methods concerns the notion of "mass balance," which describes the constancy of matter despite its movement and/or transformation within a system of study (Brunner & Rechberger, 2004). A mass balance principle is especially important to consider for studies in which the known input and output from a given process differ. This would lead to a so-called mass *im*balance, indicating that some portion of the material has been "lost" from an informational perspective (i.e. material whose state, position or situation is unclear). Our work has illustrated that estimating excavated urban sediment flows in a case study region using recorded data and estimates based on per capita sediment yields can only account for the minority of flows arriving at a prominent sink. Several features of the study and system may explain the difference in these recorded and estimated (modeled) flows and the records of landfill receipts. An overall picture emerges of a system that is very "leaky," one in which, for a variety of reasons, a lack of rigorous understanding persists regarding various features.

The first relates to the scope of the study. Specifically, because the sink at the heart of our analysis – the Ox Mountain landfill facility – is located in San Mateo County, it is reasonable to assume that a considerable proportion of its daily cover resources are the result of flows of sediment excavated within the County. However, this does not prevent other counties from disposing of sediment at Ox Mountain. In fact, the adjacent and relatively population-dense county of San Francisco (SF) has no landfill. So, it is logical to assume that they export their excavated sediment to other counties. San Mateo County's proximity and ease of access (not requiring trucks to travel across congested bridges, for example) may predispose it to receive a large amount of SFs excavated sediment resources. The other two adjacent counties, Santa Clara and Santa Cruz, are also not modeled or assessed here in terms of their potential contribution to overall flows of sediment to Ox Mtn. Records that track both the county-of-origin and material mass categorized by type (municipal wastes, green waste, shredded tires, daily cover, construction and demolition wastes, etc.) would be needed in order to make a meaningful estimate of actual inter-county flows. The boundaries of the system we defined for this material flow analysis would need to be expanded to include all three counties, at least, in order to represent the area that contributes to the major sink at Ox Mountain.

Similarly, SMC is surely also a source of hidden flows. That is, not all projects producing excavated soil and sediment that occur within the County will find their way to Ox Mtn as flows. Some are exported out of the County to landfill facilities or construction sites, depending on the economics of the contracting for doing so. A potentially complex calculus linked to and based on aspects of the project portfolios of numerous private sector actors and firms of various sizes, ranging from independent contractors who are essentially drivers that own or rent a dump truck to companies that own a fleet of trucks and may employ many drivers as staff in addition to contracting with independent drivers. There are also hidden *intra-county flows:* those that originate from sources within SMC but are routed to sinks or stocks within the county other than Ox Mtn. These may be illegal dump sites, stockpiles of material, and construction or environmental projects in need of fill material. Both the inter-county and intra-county flows are effectively hidden from our data survey and modeling efforts. Additional consideration should be given to any record keeping and permitting requirements that may not apply, may not be clear to permit staff, or may not be adequately observed or enforced.

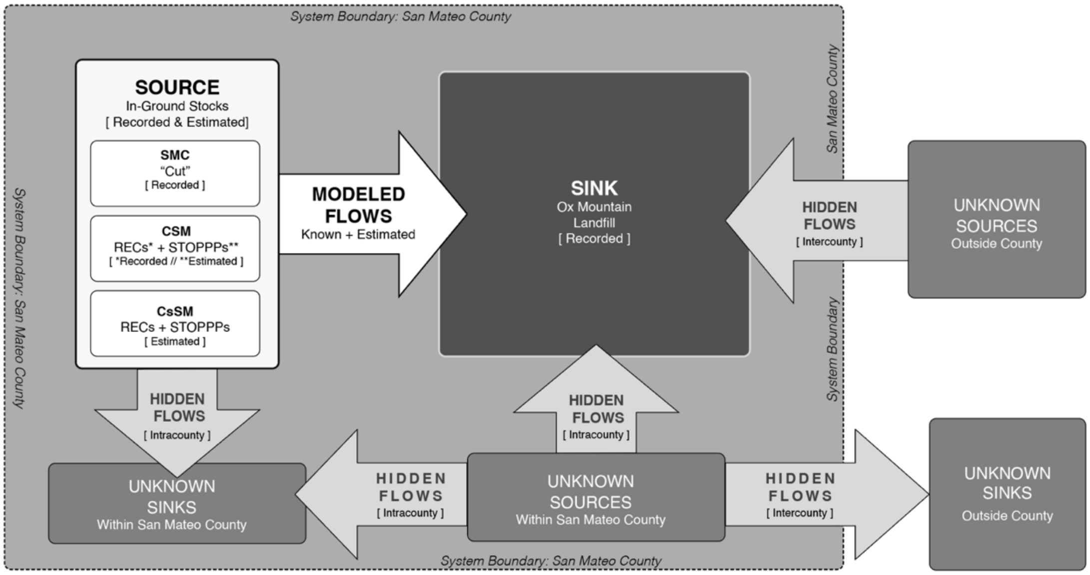


Figure 11: A portion of the overall MFA showing the sources, sinks and flows of interest and importance. In particular, our study examined the sources of in-ground stocks of excavated sediment that could be quantified or estimated as Modeled Flows (white arrow). The figure above also displays a secondary set of stock and flow features that are at play; and, in fact, constitute the majority of material that eventually makes its way to Ox Mtn, on average, during our study period. The system is "leaky": unknown sources, flows and sinks all affect the overall mass balance of excavated sediment in the study region, though as a function of numerous issues related to data that correspond to these material dynamics, it is difficult to rigorously appraise more fine-grained features of hidden flows and unknown sources and sinks, including their respective magnitudes.

An entire category of hidden flows might be collectively termed *unpermitted flows*, reflecting the primary challenge in estimating their magnitude: a lack of records and information associated with their potential share of total flows arriving at the Ox Mtn sink. Unpermitted flows occur for several reasons. One is that certain permitting requirements and their application to various types and locations of projects are initiated only when a minimum threshold of soil/sediment is disturbed. For example, unincorporated SMC's grading permits (usually issued as a secondary permit associated with building permits) include a 50 cubic yard threshold that triggers the permitting process, and projects under these thresholds effectively escape voluntary reporting and cataloguing. If a large proportion of excavation projects are smaller than this volume threshold, that could account for significant hidden flows.

Projects of various sizes routinely fail to follow proper permitting procedures, according to the consulting analysts we spoke with from the County and City of San Mateo. In fact, it was observed by more than one of these experts that unpermitted projects likely outnumber those properly permitted. In some instances, this may be due to a simple oversight or lack of clarity as to whose responsibility the permitting is (especially in cases of secondary permit procedures, notably including the RECs of SMC, for example). In other instances, failure of landowners and contractors to file for permits may simply reflect a lack of incentives for doing so (or, more to the point, a lack of disincentives for not doing so). Some permitting procedures rely on voluntary self-reporting practices and warnings are usually issued as first steps to correct lack of permits. Permitting procedures also cost money and time, and even in instances where a fine might be assessed, paying the fine for not following permitting procedures (including consideration of the odds of getting cited, and the time involved in following the rules) might be simply understood as worth the associated risk and costs. Across the experts surveyed about this phenomenon, the lack of enforcement resources was cited as a perpetual challenge that surely leads to under permitting.

A third and important category of unpermitted flows relates to the projects that involve excavation in the public Right-Of-Way (ROW), which is a publicly-owned section of land generally defined as the total width of streets, sidewalks and the utilities clustered within them. These are interesting to consider in several respects, not least of which is that in the case study area (and in other cities and counties in the case study region), projects in the ROW are not required to follow many of the permitting processes associated with private development projects. Underground utilities are concentrated in ROWs, including various water conveyance structures (drinking water pipes, sewers, storm drains) and other lines and conduits (gas lines, electrical cables, etc.). These networks are subject to upgrading, repair and replacement procedures that often entail significant excavation projects unfolding across considerable linear distances in urban settings.

Roadwork in the ROW and projects associated with low-impact-development and urban greening are also projects that produce excavated materials. Partially as a function of the lack of external revenue generation (municipalities would not assess fees against their own municipal service providers), these projects are not diligently recorded for their contribution to flows of excavated sediment. Notably, precisely because of the close working relationship of municipal offices to those that do routinely track construction permits (in fact, in many cases these are both integrated into municipal Public Works divisions), major improvement in resource tracking might be possible to implement.

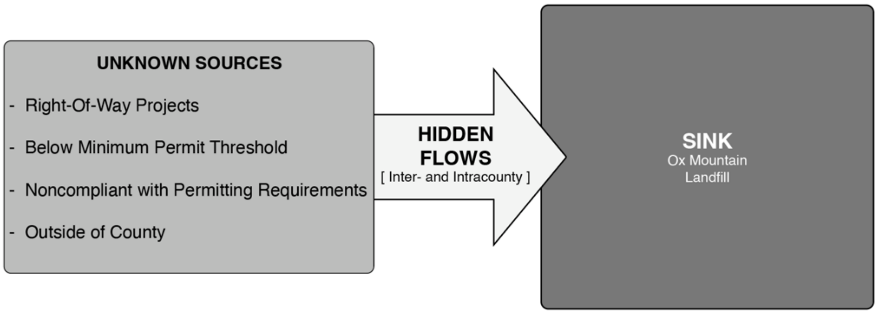


Figure 12: A portion of the overall MFA schema displaying a major contributor to the Ox Mtn soil and sediment receipt totals in a given year (and often representing the majority of the resources): Hidden Flows. Hidden flows emanate from sources within and outside of San Mateo County, and are generated from a variety of processes that are, for various reasons, not rigorously tracked and recorded by public-sector offices.

4.2 Scenario Forecasting: Future Supply and Demand of Excavated Sediment

One of the central sustainability issues that this work illustrates relates to the linear nature of the *excavation-to-landfill* paradigm of sediment management. This paradigm leads to a terminal point of permanent, irretrievable internment of resources in waste facilities like Ox Mtn. In short, there is no "going back and getting" the soil and sediment resources that have been consigned as daily cover in landfills: that material is forever lost in terms of its reuse in an alternative application and more circular economic reckoning of its life cycle. In this respect, and to better understand the potential contribution of modeled flows of excavated urban sediment to the construction of horizontal levees in SMC, requires forecasting their yields over a future timeframe and assessing the overall portion of likely yields in that timeframe that might realistically be captured for adaptation purposes.

SMC Population Projections and Future Yields: Will we have more or less?

Our study decade (2010-2019) saw an average rise in SMCs total county-wide population of about 1% per year. Since the study period, the population in SMC experienced a net negative growth period probably due to the COVID-19 pandemic. We used population projections from the 2018 Association of Bay Area Government's Plan Bay Area 2040 report to establish a plausible time series of total population in SMC over the next decade (Mackenzie et al., 2018). Because this study was published before COVID-19, we used a linear interpolation technique to plot populations for all years between 2020 (using US Census data from that year) and the ABAG projections, and adjusted the annual estimates by reducing them by 3% (the proportion of population overestimation in the ABAG report for 2020), thus attempting to correct the baseline for their projection estimation method while still assuming overall growth rates of ~ +0.7% per year in accordance with our prior data set and ABAGs projections.

To estimate the number of likely building permits that will be issued in the coming decade, we applied a forecasting method based on known population numbers for the case study decade and our estimates of total building permits issued in the County of San Mateo. On average, the number of building permits in the county is rising 6% per year. This makes sense because of the dense development pressures and incentives previously described. Using the case study timeframe to establish an average increase of this coefficient per-year, we extended coefficient values into the forecasting window, in-effect providing a number by which out population estimates can be multiplied to produce a likely number of building permits. Applying the method previously described for calculating the tonnage associated with secondary permits that can be derived as a percentage of total building permits, we estimated yields for the coming decade.

	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032
SMC* Population Projections	774,672	780,373	786,074	791,776	797,477	803,179	808,880	814,582	820,283	825,984	831,686
Estimated Building Permits Total (n)	23624	25041	26543	28136	29824	31614	33510	35521	37652	39911	42306
Forecasted Yield (tons)	**131085**	**138950**	**147287**	**156124**	**165491**	**175421**	**185946**	**197103**	**208929**	**221465**	**234753**

Table 11: Projections of potential yields (bottom row) by year in the coming decade, estimated using population trends and the previously-described methods for assessing the likely share of secondary building permits associated with grading as a share of total building permits issued.
* SMC in this table denotes the entire county and its populace, as opposed to only the unincorporated areas.

4.3 Effects of Quality Standards on Estimated Yields

While we have discussed landfill facilities as *sinks* for the receipt of material including large amounts of sediment resources, these sediment materials act as "substance sinks" themselves, defined as physical media that receive and effectively store numerous compounds (Fellenberg 1994; Sauerwein, 2011). These compounds may include arsenic and other hazardous metals, petroleum products, and herbicides, among other potential chemicals. In our case study region, strict screening protocols are applied to the use of imported fill material in areas where water quality may be impacted, including fill that would be placed in the Bay itself. A number of different environmental agencies and organizations track and enforce the standards by which material used in sensitive areas, including the Baylands, is assessed for various pollutants, including legacy contaminants from industrial activities and naturally occurring compounds including certain heavy metals (Katsumi, 2015; McClintock, 2015; Schoellhamer, et al., 2007). Water quality concerns regarding SF Bay, which serves as a receiving body of a vast watershed, have demonstrated the long-term effects of pollution in the estuary (Connor et al., 2007; Steding et al., 2000). In the region's active restoration projects, the concentration of various contaminants associated with legacy impacts (including those from manufacturing, industrial dumping, land development, local waste disposal, and excessive pesticide or fertilizer use) have been studied to inform ongoing testing and screening procedures; and overall concern about concentrating contaminants in the food webs that wetlands support persists (Davis et al., 2007; Grenier & Davis 2010; Miles & Ricca, 2010).

Based on the environmental concerns in the region and the nature of urban soils pollution, upland excavated sediment volumes – especially those withdrawn from urban environments – are likely to contain some portion in which contaminants are present that may exceed standards for reuse in restoration applications including ecotone levees (McClintock, 2015). For example, significant lead concentrations stemming from leaded gasoline use is widely evident in surficial soils of urban areas (Wong & Li, 2004). Mapping surficial sediment in developed regions, and the complexities associated with historical impacts on these resources has led to work attempting to characterize "urban soils" in a variety of settings (Bullock & Gregory 1991; Craul, 1992; Effland & Pouyat, 1997). Unfortunately, generalizing about the likely portion of excavated urban sediment that contains contamination in a broad and varied geographic region (as in the case of our sources of interest) is difficult. A number of considerations illustrate why this is so.

For one thing, many different *kinds* of contaminants are present in the urban pedosphere, and these vary both *spatially* in terms of their distributions across the urban landscape, and in their concentrations within a given *volume* of sediment based on the *depth* of their presence through infiltration into soils from biogeochemical processes or as a function of being previously buried by human activity, etc. In this sense, a small volume of surficial sediment might be quite contaminated, while more volumes extracted from deeper layers of the same dig site might be significantly less so, both as a function of "skimming" the most-problematic surficial layer, and because contaminant thresholds are often assessed based on concentrations, that is, compounds-per-volume/amount of overall material. In other words, larger excavation projects might effectively dilute contaminants as a function of their sheer volume, and/or the depths from which they are extracted.

However, in areas with high water tables, including our study region, certain labile compounds can be motivated and transported into previously uncontaminated areas and their underlying sediment volumes by groundwater–a problem made significantly worse by SLR's effect in elevating groundwater tables and especially in areas with previously buried contaminants that may be inundated by evolving groundwater dynamics (Plane et al., 2019). Because of these trends and dynamics, it is logical to assume that contaminant spread in subsurface sediment is yet another impact of climate change that may intensify in coming decades, and potentially reduce the supply of sediment useful in restoration and adaptation applications.

Clearly, multiple complications exist as a function of the physical nature and processes of urban excavated sediment, not least of which is the set of challenges associated with analyzing which sediment sources might be contaminated, since the permitting requirements for some projects simply do not take account of contaminant issues. Indeed, as we have repeatedly discussed, overall tracking and records in the context of many, if not most, construction sites and excavation processes is an afterthought, in no small part because excavated soils are broadly understood as waste products bound for landfills, a categorization that surely generally serves to reduce the likelihood of screening for contaminants. Common analytical approaches that directly address these problematic compounds found in soils are frequently based on large-scale site mapping of contamination based on past land use and surficial presence of hazardous compounds or on site-scale remediation efforts in which soil volumes are tested, treated, sequestered or removed (Dermont, et al., 2008; Lin 2002; Van Meirvenne & Goovaerts, 2001).

Given the wide variety of excavated sediment sources (in terms of their geographic, geophysical and geochemical profile) present in our modeled flows of the study region, and owing to the lack of information regarding contamination prevalence and concentrations that can be definitely correlated to these sources, we assess a range of the potential proportions of contaminants that might be present in the modeled flows. This would likely disqualify these portions of overall yields from reuse in ecotone and horizontal levees. While certain sites encountering urban fill material in excavation may yield volumes that are all, to some extent, contaminated, we would expect these to only comprise a portion of overall yields in the study area over a given year (Boudreault et al., 2010). Review of literature concerning contaminant concentrations in projects associated with soil excavation range widely, and considerable uncertainty must be managed on any given project (Goovaerts, 2001).

We reviewed literature discussing instances of urban, brownfield redevelopment and post-heavy industrial projects involving management of polluted sediment volumes. The cases ranged widely in their percentages of contaminated sediment as proportions of total volumes excavated or otherwise managed. For example, in post-industrial projects, established contaminated volumes were equivalent to 16% of total project volume; to upper estimate proportions ranging from 34% to 44% of site volumes that were likely contaminated past an acceptable threshold (Boudreault et al., 2010; D'Or et al., 2009; Hendriks et al., n.d.). Urban sites that have experienced fewer or less severe impacts from industry but still reflect anthropogenic contaminants in surficial sediment have commonly shown the top layer (10-30cm) to contain significant amounts of toxins including lead, thus constituting, by volume, 10% - 30% of a cubic yard excavated at the surface (Chen et al., 1997; Meuser, 2010). However, because of the likelihood that deeper and potentially less-contaminated volumes are a constituent of excavated sediment, and due to the fact that greenfield development processes also contribute to overall yields and flows, the overall share of contaminated sediment is likely somewhat reduced from the higher (30%) bound of this range.

4.4 Sensitivity Analyses

Effects of Sediment Quality Screens and Levee Heights on Future Ecotone Construction

For the purposes of planning how forecasted supply yields, quality standards and material demands (based on horizontal levee heights) will impact the potential to build these structures for adaptation to rising seas over the next decade, we assessed the duration of construction project cycles that will likely be associated with these variables. This effectively demonstrates the sensitivity of a dependent variable (construction timeframe) to the independent variables (quality screening and levee heights) associated with the respective supply and demand variation included in our model. Doing so involved several assumptions and methods to incorporate key variables into the modeling process.

Given the particularity of cases from the literature wherein the concentration of highly-polluted post-industrial soils was a large proportion of *overall* excavated volumes, we deemed the highest percentage (44%) encountered in the literature to be an unlikely proportion to apply to total forecasted flows in our case study area. On the other hand, given the broad ubiquity of contaminants evident in urban surficial soils, we adopted the 10% lower limit for our screening and sensitivity methodology. As an upper limit, we adopted a 30% screening level and calculated yields based on 5% increments to estimate total yields that might be disqualified from reuse in ecotone construction, which we subtracted from annual tonnage yields.

Maximum Construction Duration in Years (beginning various years)						
Year	Horizontal levee height (m)	Contamination screen (%)				
		10%	15%	20%	25%	30%
2022	1m	2.1	2.3	2.4	2.6	2.7
	1.5m	4.8	5.1	5.4	5.7	6.2
	2m	8.5	9.0	9.6	10.2	10.9
2023	1m	2.0	2.1	2.3	2.4	2.6
	1.5m	4.5	4.8	5.1	5.4	5.8
	2m	8.0	8.5	9.0	9.6	10.3
2024	1m	1.9	2.0	2.1	2.3	2.4
	1.5m	4.3	4.5	4.8	5.1	5.5
	2m	7.6	8.0	8.5	9.1	9.7
2025	1m	1.8	1.9	2.0	2.1	2.3
	1.5m	4.0	4.3	4.5	4.8	5.2
	2m	7.1	7.6	8.0	8.6	9.2
2026	1m	1.7	1.8	1.9	2.0	2.2
	1.5m	3.8	4.0	4.3	4.6	4.9
	2m	6.7	7.1	7.6	8.1	8.7
2027	1m	1.6	1.7	1.8	1.9	2.0
	1.5m	3.6	3.8	4.0	4.3	4.6
	2m	6.4	6.7	7.2	7.6	8.2
2028	1m	1.5	1.6	1.7	1.8	1.9
	1.5m	3.4	3.6	3.8	4.1	4.3
	2m	6.0	6.4	6.8	7.2	7.7
2029	1m	1.4	1.5	1.6	1.7	1.8
	1.5m	3.2	3.4	3.6	3.8	4.1
	2m	5.7	6.0	6.4	6.8	7.3
2030	1m	1.3	1.4	1.5	1.6	1.7
	1.5m	3.0	3.2	3.4	3.6	3.9
	2m	5.3	5.7	6.0	6.4	6.9
2031	1m	1.3	1.3	1.4	1.5	1.6
	1.5m	2.8	3.0	3.2	3.4	3.6
	2m	5.0	5.3	5.7	6.0	6.5
2032	1m	1.2	1.3	1.3	1.4	1.5
	1.5m	2.7	2.8	3.0	3.2	3.4
	2m	4.8	5.0	5.3	5.7	6.1

Table 12: Using the overall forecasted yields for the coming decade, various levee height scenarios will entail different years-long construction processes based on the percentage of sediment screened for quality standards. The light grey cells in the main body of the chart show the overlapping middle estimates of important variables: those of a 1.5m levee height and 20% screening proportion, respectively. This chart shows the maximum construction durations (in years) because it does not factor in increasing supplies that might become available as construction projects proceed.

We then calculated the volumes associated with our three levee design heights under the various screening levels to establish the maximum number of years that construction, initiated in any given year, would take to build the 10.4 miles of horizontal levees at various heights based on the availability of sediment. These calculations are based on the forecasted flow yields for the coming decade (see Table 10). This method stipulates a *maximum* number of years because it does not factor in the anticipated annual increases in sediment over successive years (which would, in theory, reduce build times). A second set of methods to incorporate the effects of increasing supply year-over-year was also applied, and is discussed below.

Finally, and using the same variables described above (levee heights, screening percentages, forecasted flow yields), we modeled the effects of incorporating *increases in sediment supply* as a function of overall yield increases year-over-year, assuming that levee construction began in 2022. This approach essentially subtracts total demand from previous forecasted yield years for each successive year; and, in this sense, reflects a situation in which increasing supply effectively shortens levee construction timeframes. However, and as we have seen, while sediment flows do indeed trend upwards with population increases, their increases are not linear. It should therefore be noted that whereas in the previous approach (see Table 12) was hindered by a lack of an updating annual supply function, it also tested for the potential for levee building projects initiated in a *future* year.

This difference reflects the theoretical assumptions at play. For instance, whereas the former approach estimated that, starting in 2022, it would take over a decade (10.9 years) to construct the full (10.4) miles of 2m levees when the screening was most stringent (30%), the latter approach estimated that initiating the process in the same year (under the same assumptions) would take 8.7 years. The difference is due to the former process stipulating a *maximum* construction duration that assumes supply yields do not fall in future years, but also does not assume that they rise. The subtlety here is meaningful because sediment supply does not actually occur in a step-wise process (whereby on the first day of the year all sediment resources that will be yielded that year suddenly are available for levee construction) but also is not predictably linear (whereby a new and greater total becomes available on a rolling basis). Thus, while it would be possible to use a linear interpolation technique to build more fine-grained timeframes into the model, the results from doing so would be of limited value because of the non-linear nature of sediment flows which do, indeed, ebb also. Both processes can be used to frame realities related to the years-long nature of projects based on the tranche of forecasted sediment supplies considered available for reuse in this study, and as a coarse-grained estimation logic.

	Construction duration starting in 2022 based on estimated sediment yields (years)		
	Height of horizontal levee (meters)		
Contamination screen (%)	**1 m**	**1.5 m**	**2 m**
10%	2.1	4.3	7.1
15%	2.2	4.6	7.4
20%	2.3	4.8	7.8
25%	2.4	5.1	8.2
30%	2.6	5.4	8.7

Table 13: Estimation of construction duration to construct 10.4 miles of horizontal levees in the Case Study Region, using a method that incorporates an annual increase in forecasted supply yields. The light grey cell in the middle of the main body of the chart shows the middle ranges for the screening (20%) and horizontal levee height (1.5) variables used.

5. Conclusion

Our study frames an important set of material flows occurring in the study region and illustrates that numerous factors effectively conceal a large magnitude of these flows, indeed the *majority* of them, according to our survey and modeling entering or emerging from the county whose end-of-life phase is reached at the Ox Mountain landfill facility. Our work outlines a material flow analysis that is populated by a complex set of actors and agents whose work is involved both in the physical management of sediment resources and the informational "landscape" that can be examined to describe and assess the system overall. As previously discussed, MFA that concern low-value resources are relatively rare for a variety of reasons. Though we also present a contextual logic for supporting the expectation that excavated sediment may, in fact, be or become seen as a more valuable resource in coming decades.

Notwithstanding the prominence of unknown sources and stocks and the nature of hidden flows in the overall MFA (and, perhaps more to the point, the lack of data to sufficiently identify and substantiate them), we present a method for using available data from public offices to build an estimation of excavated sediment flows that can be modeled and compared to known overall flows. Population and development trends linked to certain urban density initiatives in the region, and increasingly common in many others, can be understood as a driving force of flows that might be broadly publicly valuable in their optimization as SLR protection, adaptation and restoration applications. One of the interesting insights of the work is that, while excavated sediment flows exhibit flux–changes in the *rate* at which they are produced–scrutiny of secondary permits that track excavation suggest that they also exhibited very low variation across the study period in relation to total building permits issued in our proxy example.

Use of the illustrated methods also serve as a forecasting tool, and the work suggests that San Mateo County is well-positioned to construct the majority or full extent of horizontal levees (10.4) identified as opportunities in the case study context area in the coming decade if sediment yields continue to rise and if adequate time for construction durations are factored in given the central variables used as assumptions that will reflect sediment supply (quality assurance screening) and demand (levee heights). Interestingly, using the mid ranges of those variables (20% and 1.5m, respectively), we've estimated that a project to construct all horizontal levee miles that is initiated in 2022 would take 4.8 years to complete, while one begun halfway through the forecast window (2026) would take 4.3 years, a rather close correspondence, ceteris paribus. As previously discussed, both approaches entail uncertainty as a function of the non-linear flux of supply yields.

How resources are marshalled to accomplish or satisfy goals is a fundamental aspect of strategic planning, broadly speaking. The study and features of interest here illustrate this in specific ways as it relates to a physical material resource and regional adaptation and restoration goals and initiatives linked to it. Moreover, their interplay should be considered in the context of the considerable uncertainty and change that global warming represents. For example, catastrophic warming in coming decades might simultaneously drive SLR to greater elevations necessitating higher levees (and thus resource *demands*), while at the same time potentially leading to increased in-migration to the relatively stable micro-climate of the SF Bay region (with commensurate impacts on development and thus resource *supplies*). While our study focused on a more narrow or conservative set of scenarios (with respect to population trends and likely levee heights), planning as a professionalized practice is increasingly confronting previously unforeseen pressures and complications in the public realm.

As such, a number of interesting policy and planning considerations might stem from this work. While, to-date, rigorous understanding of the material and industrial ecologies that functionally comprise the life cycles of excavated soils is still lacking, increased coordination across municipal offices and departments could advance knowledge concerning the classification of resources that are, and will be, directly implicated in large spatiotemporal schemes for regional resilience and public benefit. Seeking collaborative opportunities that might be of interest to private sector contractors might also reveal opportunities for building more robust data tracking and records practices. For example, by incentivizing (or potentially requiring) disclosure of certain records and coordinating operations by pointing contractors towards active or planned restoration projects. By helping illuminate the connections between the logistical realities and resource and information management considerations that involve sediment resources, this work may aid in advancing future plans, policies and research to more deeply consider and understand this increasingly important subject and area of study.

Ch 3. References:

Aarninkhof, S. G. J., van Dalfsen, J. A., Mulder, J. P. M., & Rijks, D. (2010). Innovations in project design and realisation. 12.

Adger, W. N., S. Dessai, M. Goulden, M. Hulme, I. Lorenzoni, D. R. Nelson, L. O. Naess, J. Wolf, and A. Wreford. 2009a. Are there social limits to adaptation to climate change? Climatic Change 93:335-354. (n.d.).

Admiraal, H., & Cornaro, A. (2018). Underground spaces unveiled: Planning and creating the cities of the future. (Environmental Design NA2542.7 .A36 2018). London : ICE Publishing, [2018]; cat04202a. https://libproxy.berkeley.edu/login?qurl=http%3a%2f%2fsearch.ebscohost.com%2flogin.aspx%3fdirect%3dtrue%26db%3dcat04202a%26AN%3ducb.b24425606%26site%3deds-live

Admiraal, J. B. M. (2006). A bottom-up approach to the planning of underground space. Safety in the Underground Space - Proceedings of the ITA-AITES 2006 World Tunnel Congress and 32nd ITA General Assembly, 21(3), 464–465. https://doi.org/10.1016/j.tust.2005.12.102

Allen, F. W., Halloran, P. A., Leith, A. H., & Lindsay, M. C. (2009). Using Material Flow Analysis for Sustainable Materials Management. Journal of Industrial Ecology, 13(5), 662–665. https://doi.org/10.1111/j.1530-9290.2009.00168.x

Allison, M. A., Demas, C. R., Ebersole, B. A., Kleiss, B. A., Little, C. D., Meselhe, E. A., Powell, N. J., Pratt, T. C., & Vosburg, B. M. (2012). A water and sediment budget for the lower Mississippi–Atchafalaya River in flood years 2008–2010: Implications for sediment discharge to the oceans and coastal restoration in Louisiana. Journal of Hydrology, 432–433, 84–97. https://doi.org/10.1016/j.jhydrol.2012.02.020

Aoki-Suzuki, C., Bengtsson, M., & Hotta, Y. (2012). International Comparison and Suggestions for Capacity Development in Industrializing Countries: Policy Application of Economy-Wide Material Flow Accounting. Journal of Industrial Ecology, 16(4), 467–480. https://doi.org/10.1111/j.1530-9290.2012.00480.x

Baccini, P., & Brunner, P. H. (2012). Metabolism of the anthroposphere: Analysis, evaluation, design. Cambridge, Mass. : MIT Press, ©2012; cat04202a. https://libproxy.berkeley.edu/login?qurl=http%3a%2f%2fsearch.ebscohost.com%2flogin.aspx%3fdirect%3dtrue%26db%3dcat04202a%26AN%3ducb.b20558662%26site%3deds-live

Barbier, E. (2013). Valuing Ecosystem Services for Coastal Wetland Protection and Restoration: Progress and Challenges. Resources, 2(3), 213–230. https://doi.org/10.3390/resources2030213

Barnard, P. L., Schoellhamer, D. H., Jaffe, B. E., & McKee, L. J. (2013). Sediment transport in the San Francisco Bay Coastal System: An overview. Marine Geology, 345, 3–17. https://doi.org/10.1016/j.margeo.2013.04.005

Barragán, J. M., & de Andrés, M. (2015). Analysis and trends of the world's coastal cities and agglomerations. Ocean & Coastal Management, 114, 11–20. https://doi.org/10.1016/j.ocecoaman.2015.06.004

Bartrola, J., Martin, M. J., & Rigola, M. (2001). Issues in System Boundary Definition for Substance Flow Analysis: The Case of Nitrogen Cycle Management in Catalonia. The Scientific World JOURNAL, 1, 892–897. https://doi.org/10.1100/tsw.2001.260

Bayraktarov, E., Saunders, M.I., Abdullah, S., Mills, M., Beher, J., Possingham, H.P., Mumby, P.J. and Lovelock, C.E. (2016), The cost and feasibility of marine coastal restoration. Ecol Appl, 26: 1055-1074. Https://doi.org/10.1890/15-1077. (n.d.).

Becker, A., Chase, N. T. L., Fischer, M., Schwegler, B., & Mosher, K. (2016). A method to estimate climate-critical construction materials applied to seaport protection. Global Environmental Change, 40, 125–136. https://doi.org/10.1016/j.gloenvcha.2016.07.008

Berkowitz, J. F., Green, L., VanZomeren, C. M., & White, J. R. (2016). Evaluating soil properties and potential nitrate removal in wetlands created using an Engineering With Nature based dredged material placement technique. Ecological Engineering, 97, 381–388. https://doi.org/10.1016/j.ecoleng.2016.10.022

Bianchi, T. S., & Allison, M. A. (2009). Large-river delta-front estuaries as natural "recorders" of global environmental change. Proceedings of the National Academy of Sciences, 106(20), 8085–8092. https://doi.org/10.1073/pnas.0812878106

Biging, G. S., Radke, J. D., & Lee, J. H. (n.d.). IMPACTS OF PREDICTED SEA-LEVEL RISE AND EXTREME STORM EVENTS ON THE TRANSPORTATION INFRASTRUCTURE IN THE SAN FRANCISCO BAY REGION. 83.

Bobylev, N. (2009). Mainstreaming sustainable development into a city's Master plan: A case of Urban Underground Space use. Land Use Policy, 26(4), 1128–1137. https://doi.org/10.1016/j.landusepol.2009.02.003

Bolan, N., Kunhikrishnan, A., Thangarajan, R., Kumpiene, J., Park, J., Makino, T., Kirkham, M. B., & Scheckel, K. (2014). Remediation of heavy metal(loid)s contaminated soils – To mobilize or to immobilize? Journal of Hazardous Materials, 266, 141–166. https://doi.org/10.1016/j.jhazmat.2013.12.018

Boudreault, J.-P., Dubé, J.-S., Chouteau, M., Winiarski, T., & Hardy, É. (2010). Geophysical characterization of contaminated urban fills. Engineering Geology, 116(3), 196–206. https://doi.org/10.1016/j.enggeo.2010.09.002

Brand, L. A., Smith, L. M., Takekawa, J. Y., Athearn, N. D., Taylor, K., Shellenbarger, G. G., Schoellhamer, D. H., & Spenst, R. (2012). Trajectory of early tidal marsh restoration: Elevation, sedimentation and colonization of breached salt ponds in the northern San Francisco Bay. Ecological Engineering, 42, 19–29. https://doi.org/10.1016/j.ecoleng.2012.01.012

Brew DS, Williams PB. 2010. Predicting the impact of large-scale tidal wetland restoration on morphodynamics and habitat evolution in South San Francisco Bay, California. Journal of Coastal Research 26:912–924. (n.d.).

Bruce Mcdonald & Mark Smithers (1998) Implementing a waste management plan during the construction phase of a project: A case study, Construction Management and Economics, 16:1, 71-78, DOI: 10.1080/014461998372600. (n.d.).

Brunner, P. H., & Rechberger, H. (2004). Practical handbook of material flow analysis. Lewis.

Bullock, P. and Gregory, P. J. (1991) Soils: A neglected resource in urban areas. In Soils in the urban environment (P. Bullock and P. J. Gregory, eds.), pp. 1–5. Blackwell Scientific Publications, Oxford, Great Britain. (n.d.).

Cahoon, D.R., Lynch, J.C., Roman, C.T. et al. Evaluating the Relationship Among Wetland Vertical Development, Elevation Capital, Sea-Level Rise, and Tidal Marsh Sustainability. Estuaries and Coasts 42, 1–15 (2019). Https://doi-org.libproxy.berkeley.edu/10.1007/s12237-018-0448-x. (n.d.).

Cappucci, S., Bertoni, D., Cipriani, L. E., Boninsegni, G., & Sarti, G. (2020). Assessment of the Anthropogenic Sediment Budget of a Littoral Cell System (Northern Tuscany, Italy). Water, 12(11). https://doi.org/10.3390/w12113240

Cecchetti, A. R., Stiegler, A. N., Gonthier, E. A., Bandaru, S. R., Fakra, S. C., Alvarez-Cohen, L., & Sedlak, D. L. (2022). Fate of Dissolved Nitrogen in a Horizontal Levee: Seasonal Fluctuations in Nitrate Removal Processes. Environmental Science & Technology, 56(4), 2770-2782. (n.d.).

Cecchetti, A. R., Stiegler, A. N., Graham, K. E., & Sedlak, D. L. (2020). The horizontal levee: A multi-benefit nature-based treatment system that improves water quality and protects coastal levees from the effects of sea level rise. Water Research X, 7, 100052. https://doi.org/10.1016/j.wroa.2020.100052

Charlier, R. H., Chaineux, M. C. P., & Morcos, S. (2005). Panorama of the History of Coastal Protection. Journal of Coastal Research, 211, 79–111. https://doi.org/10.2112/03561.1

Chen, T. B., et al. "Assessment of trace metal distribution and contamination in surface soils of Hong Kong." Environmental pollution 96.1 (1997): 61-68. (n.d.).

Christensen, T. H., Cossu, R., & Stegmann, R. (1989). Sanitary landfilling: Process, technology and environmental impact. (Engineering TD795.7 .S266 1989). London ; San Diego : Academic Press, c1989.; cat04202a. https://libproxy.berkeley.edu/login?qurl=http%3a%2f%2fsearch.ebscohost.com%2flogin.aspx%3fdirect%3dtrue%26db%3dcat04202a%26AN%3ducb.b14571703%26site%3deds-live

Chun-Li Peng, Domenic E. Scorpio & Charles J. Kibert (1997) Strategies for successful construction and demolition waste recycling operations, Construction Management and Economics, 15:1, 49-58, DOI: 10.1080/014461997373105. (n.d.).

CLIMATE CHANGE IMPACTS, VULNERABILITIES, AND ADAPTATION IN THE SAN FRANCISCO BAY AREA. (n.d.). 67.

Cloern, J. E., Knowles, N., Brown, L. R., Cayan, D., Dettinger, M. D., Morgan, T. L., Schoellhamer, D. H., Stacey, M. T., van der Wegen, M., Wagner, R. W., & Jassby, A. D. (2011). Projected Evolution of California's San Francisco Bay-Delta-River System in a Century of Climate Change. PLOS ONE, 6(9), e24465. https://doi.org/10.1371/journal.pone.0024465

Connor, M. S., Davis, J. A., Leatherbarrow, J., Greenfield, B. K., Gunther, A., Hardin, D., Mumley, T., Oram, J. J., & Werme, C. (2007). The slow recovery of San Francisco Bay from the legacy of organochlorine pesticides. Environmental Research, 105(1), 87–100. https://doi.org/10.1016/j.envres.2006.07.001

Costanza, R., Pérez-Maqueo, O., Martinez, M. L., Sutton, P., Anderson, S. J., & Mulder, K. (2008). The Value of Coastal Wetlands for Hurricane Protection. Ambio, 37(4), 241–248. Http://www.jstor.org/stable/25547893. (n.d.).

Cox A.; Ireland P.; and Townsend M., 2006. Managing in Construction Supply Chains and Markets. Report, Thomas Telford. (n.d.).

Craul, P. J. (1992). Urban soil in landscape design. (Bioscience & Natural Resources S592.17.U73 C73 1992). New York : Wiley, c1992.; cat04202a. https://libproxy.berkeley.edu/login?qurl=http%3a%2f%2fsearch.ebscohost.com%2flogin.aspx%3fdirect%3dtrue%26db%3dcat04202a%26AN%3ducb.b15533967%26site%3deds-live

Daniella Hirschfeld & Kristina Hill. (2017). Choosing a Future Shoreline for the San Francisco Bay: Strategic Coastal Adaptation Insights from Cost Estimation. Journal of Marine Science and Engineering, 5(3), 42. https://doi.org/10.3390/jmse5030042

Davis JA, Hetzel F, Oram JJ, McKee LJ. Polychlorinated biphenyls (PCBs) in San Francisco Bay. Environ Res. 2007 Sep;105(1):67-86. Doi: 10.1016/j.envres.2007.01.013. Epub 2007 Apr 23. PMID: 17451673. (n.d.).

Dermont, G., Bergeron, M., Mercier, G., & Richer-Laflèche, M. (2008). Metal-contaminated soils: Remediation practices and treatment technologies. Practice periodical of hazardous, toxic, and radioactive waste management, 12(3), 188-209. (n.d.).

Diaz, D.B., 2016. Estimating global damages from sea level rise with the Coastal Impact and Adaptation Model (CIAM). Climatic Change, 137(1), pp.143-156. (n.d.).

D'Or, D., Demougeot-Renard, H., & Garcia, M. (2009). An Integrated Geostatistical Approach for Contaminated Site and Soil Characterisation. Mathematical Geosciences, 41(3), 307–322. https://doi.org/10.1007/s11004-009-9213-9

Du, S., Scussolini, P., Ward, P. J., Zhang, M., Wen, J., Wang, L., Koks, E., Diaz-Loaiza, A., Gao, J., Ke, Q., & Aerts, J. C. J. H. (2020). Hard or soft flood adaptation? Advantages of a hybrid strategy for Shanghai. Global Environmental Change, 61, 102037. https://doi.org/10.1016/j.gloenvcha.2020.102037

Duke, R. R., Stephens, P. D., Terrill, S., Shellhammer, H., Webb, E., Henkel, L., & Thomson, D. (2004). BAIR ISLAND RESTORATION PROJECT MONITORING PLAN. (n.d.).

Dusterhoff, S., McKnight, K., Grenier, L., and Kauffman, N. 2021. Sediment for Survival: A Strategy for the Resilience of Bay Wetlands in the Lower San Francisco Estuary. A SFEI Resilient Landscape Program. A product of the Healthy Watersheds, Resilient Baylands project, funded by the San Francisco Bay Water Quality Improvement Fund, EPA Region IX. Publication #1015, San Francisco Estuary Institute, Richmond, CA. (n.d.).

Effland, W. R., & Pouyat, R. V. (1997). The genesis, classification, and mapping of soils in urban areas. Urban Ecosystems, 1(4), 217–228. https://doi.org/10.1023/A:1018535813797

Fagherazzi, S., et al. (2012), Numerical models of salt marsh evolution: Ecological, geomorphic, and climatic factors, Rev. Geophys., 50, RG1002, doi:10.1029/2011RG000359. (n.d.).

Ferguson, L. E. (2018). A Gateway without a Port: Making and Contesting San Francisco's Early Waterfront. Journal of Urban History, 44(4), 603–624. https://doi.org/10.1177/0096144218759030

Ford, M. A., Cahoon, D. R., & Lynch, J. C. (1999). Restoring marsh elevation in a rapidly subsiding salt marsh by thin-layer deposition of dredged material. Ecological Engineering, 12(3–4), 189–205. https://doi.org/10.1016/S0925-8574(98)00061-5

Foster-Martinez, M. R., Lacy, J. R., Ferner, M. C., & Variano, E. A. (2018). Wave attenuation across a tidal marsh in San Francisco Bay. Coastal Engineering, 136, 26–40. https://doi.org/10.1016/j.coastaleng.2018.02.001

Goals Project. 2015. The Baylands and Climate Change: What We Can Do. Baylands Ecosystem Habitat Goals Science Update 2015 prepared by the San Francisco Bay Area Wetlands Ecosystem Goals Project. California State Coastal Conservancy, Oakland, CA . (n.d.).

Goovaerts, P. (2001). Geostatistical modelling of uncertainty in soil science. Estimating Uncertainty in Soil Models, 103(1), 3–26. https://doi.org/10.1016/S0016-7061(01)00067-2

Grenier, J. L., & Davis, J. A. (2010). Water quality in South San Francisco Bay, California: Current condition and potential issues for the South Bay Salt Pond Restoration Project. Reviews of environmental contamination and toxicology, 206, 115–147. Https://doi.org/10.1007/978-1-4419-6260-7_6. (n.d.).

Hale, S. E., Roque, A. J., Okkenhaug, G., Sørmo, E., Lenoir, T., Carlsson, C., Kupryianchyk, D., Flyhammar, P., & Žlender, B. (2021). The Reuse of Excavated Soils from Construction and Demolition Projects: Limitations and Possibilities. Sustainability, 13(11), 6083. https://doi.org/10.3390/su13116083

Hallegatte, S., Green, C., Nicholls, R. et al. Future flood losses in major coastal cities. Nature Clim Change 3, 802–806 (2013). Https://doi.org/10.1038/nclimate1979. (n.d.).

Hallegatte, S., Ranger, N., Mestre, O. et al. Assessing climate change impacts, sea level rise and storm surge risk in port cities: A case study on Copenhagen. Climatic Change 104, 113–137 (2011). Https://doi-org.libproxy.berkeley.edu/10.1007/s10584-010-9978-3. (n.d.).

Haltiner, J., Zedler, J. B., Boyer, K. E., Williams, G. D., & Callaway, J. C. (1996). Influence of physical processes on the design, functioning and evolution of restored tidal wetlands in California (USA). Wetlands Ecology and Management, 4(2), 73–91. https://doi.org/10.1007/BF01876230

Han, Q., Schaefer, W., & Barry, N. (2013). Land Reclamation Using Waste as Fill Material: A Case Study in Jakarta. 7(6), 10.

Hao, J. L., Hills, M. J., & Huang, T. (2007). A simulation model using system dynamic method for construction and demolition waste management in hong kong. Construction Innovation, 7(1), 7-21. Doi:https://doi.org/10.1108/14714170710721269. (n.d.).

Haycraft, W. R. (2000). Yellow steel: The story of the earthmoving equipment industry. (Institute for Research on Labor and Employment HD9715.25.U62 H39 2000). Urbana : University of Illinois Press, c2000.; cat04202a. https://libproxy.berkeley.edu/login?qurl=http%3a%2f%2fsearch.ebscohost.com%2flogin.aspx%3fdirect%3dtrue%26db%3dcat04202a%26AN%3ducb.b15816880%26site%3deds-live

Heberger, M., Cooley, H., Herrera, P., Gleick, P. H., & Moore, E. (2011). Potential impacts of increased coastal flooding in California due to sea-level rise. Climatic Change, 109(1), 229-249. (n.d.).

Hendriks, L. A. M., Leummens, H., Stein, A., & Bruijn, P. J. D. (n.d.). Use of Soft Data in a GIS to Improve Estimation of the Volume of Contaminated Soil. 18.

Hill, K. (2015). Coastal infrastructure: A typology for the next century of adaptation to sea-level rise. Frontiers in Ecology and the Environment, 13(9), 468–476. https://doi.org/10.1890/150088

Holmes, R., Burkholder, S., Holzman, J., King, J., & Suedel, B. (2022). Integrating Engineering With Nature® strategies and landscape architecture techniques into the Sabine-to-Galveston Coastal Storm Risk Management Project. Integrated Environmental Assessment and Management, 18(1), 63–73. https://doi.org/10.1002/ieam.4434

Hoover, D. J., Odigie, K. O., Swarzenski, P. W., & Barnard, P. (2017). Sea-level rise and coastal groundwater inundation and shoaling at select sites in California, USA. Journal of Hydrology: Regional Studies, 11, 234–249. https://doi.org/10.1016/j.ejrh.2015.12.055

Hu, M., Van Der Voet, E., & Huppes, G. (2010). Dynamic Material Flow Analysis for Strategic Construction and Demolition Waste Management in Beijing. Journal of Industrial Ecology, 14(3), 440–456. https://doi.org/10.1111/j.1530-9290.2010.00245.x

Hummel, M. A., Berry, M. S., & Stacey, M. T. (2018). Sea level rise impacts on wastewater treatment systems along the US coasts. Earth's Future, 6(4), 622-633. (n.d.).

Hummel Michelle A., Griffin Robert, Arkema Katie, & Guerry Anne D. (2021). Economic evaluation of sea-level rise adaptation strongly influenced by hydrodynamic feedbacks. Proceedings of the National Academy of Sciences, 118(29), e2025961118. https://doi.org/10.1073/pnas.2025961118

J. E. Neumann et al., Joint effects of storm surge and sea-level rise on US coasts: Neweconomic estimates of impacts, adaptation, and benefits of mitigation policy.ClimaticChange129, 337–349 (2014). (n.d.).

Katsumi, T. (2015). Soil excavation and reclamation in civil engineering: Environmental aspects. Soil Science and Plant Nutrition, 61(sup1), 22–29. https://doi.org/10.1080/00380768.2015.1020506

Kennedy, C., Pincetl, S., & Bunje, P. (2011). The study of urban metabolism and its applications to urban planning and design. Environmental Pollution, 159(8/9), 1965–1973. 8gh. https://libproxy.berkeley.edu/login?qurl=http%3a%2f%2fsearch.ebscohost.com%2flogin.aspx%3fdirect%3dtrue%26db%3d8gh%26AN%3d61258043%26site%3deds-live

Kirwan, M. L., & Megonigal, J. P. (2013). Tidal wetland stability in the face of human impacts and sea-level rise. Nature, 504(7478), 53–60. https://doi.org/10.1038/nature12856

Kleint, R. J. T., Nichollst, R. J., Ragoonaden, S., Capobianco, M., Astontt, J., & Buckley, E. N. (2022). Technological Options for Adaptation to Climate Change in Coastal Zones. 14.

Kondolf, G. M., Gao, Y., Annandale, G. W., Morris, G. L., Jiang, E., Zhang, J., ... & Yang, C. T. (2014). Sustainable sediment management in reservoirs and regulated rivers: Experiences from five continents. Earth's Future, 2(5), 256-280. (n.d.).

Kulp, S. A. & Strauss, B. H. New elevation data triple estimates of global vulnerability to sea-level rise and coastal flooding. Nat. Commun. 10, 4844 (2019). (n.d.).

Lawrence, J., Bell, R., Blackett, P., Stephens, S., & Allan, S. (2018). National guidance for adapting to coastal hazards and sea-level rise: Anticipating change, when and how to change pathway. Environmental Science & Policy, 82, 100–107. https://doi.org/10.1016/j.envsci.2018.01.012

Lawrence, J., Blackett, P., & Cradock-Henry, N. A. (2020). Cascading climate change impacts and implications. Climate Risk Management, 29, 100234. https://doi.org/10.1016/j.crm.2020.100234

Lin, CW. Mapping Soil Lead and Remediation Needs in Contaminated Soils. Environmental Geochemistry and Health 24, 23–33 (2002). Https://doi-org.libproxy.berkeley.edu/10.1023/A:1013949917278. (n.d.).

Liu, J., Dietz, T., Carpenter, S., Alberti, M., Folke, C., Moran, E., Pell, A., Deadman, P., Kratz, T., Lubchenco, J., Ostrom, E., Ouyang, Z., Provencher, W., Redman, C., Schneider, S., & Taylor, W. (2007). Complexity of Coupled Human and Natural Systems. Science (New York, N.Y.), 317, 1513–1516. https://doi.org/10.1126/science.1144004

Llatas, C. (2011). A model for quantifying construction waste in projects according to the European waste list. Waste Management, 31(6), 1261–1276. https://doi.org/10.1016/j.wasman.2011.01.023

Lubell, ., Stacey, M. & Hummel, M.A. Collective action problems and governance barriers to sea-level rise adaptation in San Francisco Bay. Climatic Change 167, 46 (2021). Https://doi-org.libproxy.berkeley.edu/10.1007/s10584-021-03162-5. (n.d.).

Macintosh, A. (2013). Coastal climate hazards and urban planning: How planning responses can lead to maladaptation. Mitigation and Adaptation Strategies for Global Change, 18(7), 1035–1055. https://doi.org/10.1007/s11027-012-9406-2

Mackenzie, J., Haggerty, S., Aguirre, A. C., Azumbrado, T., Bruins, J., Connolly, D., Cortese, D., Dutra-Vernaci, C., & Giacopini, D. M. (n.d.). Metropolitan Transportation Commission. 180.

Magnusson, S., Johansson, M., Frosth, S., & Lundberg, K. (2019). Coordinating soil and rock material in urban construction – Scenario analysis of material flows and greenhouse gas emissions. Journal of Cleaner Production, 241, 118236. https://doi.org/10.1016/j.jclepro.2019.118236

Magnusson, S., Lundberg, K., Svedberg, B., & Knutsson, S. (2015). Sustainable management of excavated soil and rock in urban areas – A literature review. Journal of Cleaner Production, 93, 18–25. https://doi.org/10.1016/j.jclepro.2015.01.010

Martín-Antón, M., Negro, V., del Campo, J. M., López-Gutiérrez, J. S., & Esteban, M. D. (2016). Review of coastal Land Reclamation situation in the World. Journal of Coastal Research, 75 (10075), 667–671. https://doi.org/10.2112/SI75-133.1

Matthews, E. (Ed.). (2000). The weight of nations: Material outflows from industrial economies. World Resources Institute.

McClintock, N. (2015). A critical physical geography of urban soil contamination. Geoforum, 65, 69–85. https://doi.org/10.1016/j.geoforum.2015.07.010

McGranahan, G., Balk, D., & Anderson, B. (2007). The rising tide: Assessing the risks of climate change and human settlements in low elevation coastal zones. Environment and Urbanization, 19(1), 17–37. https://doi.org/10.1177/0956247807076960

Mchergui, C., Aubert, M., Buatois, B., Akpa-Vinceslas, M., Langlois, E., Bertolone, C., Lafite, R., Samson, S., & Bureau, F. (2014). Use of dredged sediments for soil creation in the Seine estuary (France): Importance of a soil functioning survey to assess the success of wetland restoration in floodplains. Ecological Engineering, 71, 628–638. https://doi.org/10.1016/j.ecoleng.2014.07.064

Meuser, H. (2010). Contaminated Urban Soils (Vol. 18). Springer Netherlands. https://doi.org/10.1007/978-90-481-9328-8

Miles, A. K., & Ricca, M. A. (2010). Temporal and spatial distributions of sediment mercury at salt pond wetland restoration sites, San Francisco Bay, CA, USA. The Science of the total environment, 408(5), 1154–1165. Https://doi.org/10.1016/j.scitotenv.2009.10.04. (n.d.).

Milhous, R.T. (1998), Modelling of instream flow needs: The link between sediment and aquatic habitat. Regul. Rivers: Res. Mgmt., 14: 79-94. Https://doi-org.libproxy.berkeley.edu/10.1002/(SICI)1099-1646(199801/02)14:1<79::AID-RRR478>3.0.CO;2-9. (n.d.).

Milligan, B., & Holmes, R. (2017). Sediment is critical infrastructure for the future of California's Bay-Delta. 85(2), 13.

Möller, I., Kudella, M., Rupprecht, F., Spencer, T., Paul, M., Van Wesenbeeck, B.K., Wolters, G., Jensen, K., Bouma, T.J., Miranda-Lange, M. and Schimmels, S., 2014. Wave attenuation over coastal salt marshes under storm surge conditions. Nature Geoscience, 7(10), pp.727-731. (n.d.).

Morris, M. A., Spencer, K. L., Belyea, L. R., & Branfireun, B. A. (2014). Temporal and spatial distributions of sediment mercury in restored coastal saltmarshes. Estuarine Biogeochemistry, 167, 150–159. https://doi.org/10.1016/j.marchem.2014.09.010

Myers, R. J., Fishman, T., Reck, B. K., & Graedel, T. E. (2019). Unified Materials Information System (UMIS): An Integrated Material Stocks and Flows Data Structure: Unified Materials Information System. Journal of Industrial Ecology, 23(1), 222–240. https://doi.org/10.1111/jiec.12730

Narayan, S., Beck, M. W., Wilson, P., Thomas, C. J., Guerrero, A., Shepard, C. C., Reguero, B. G., Franco, G., Ingram, J. C., & Trespalacios, D. (2017). The Value of Coastal Wetlands for Flood Damage Reduction in the Northeastern USA. Scientific Reports, 7(1), 9463. https://doi.org/10.1038/s41598-017-09269-z

Nicholls, R. J. (2004). Coastal flooding and wetland loss in the 21st century: Changes under the SRES climate and socio-economic scenarios. Climate Change, 14(1), 69–86. https://doi.org/10.1016/j.gloenvcha.2003.10.007

Perry, D. C., Chaffee, C., Wigand, C., & Thornber, C. (2020). Implementing adaptive management into a climate change adaptation strategy for a drowning New England salt marsh. Journal of Environmental Management, 270, 110928. https://doi.org/10.1016/j.jenvman.2020.110928

Pitlick, J., & Wilcock, P. (2001). Relations between streamflow, sediment transport, and aquatic habitat in regulated rivers. Geomorphic processes and riverine habitat, 4, 185-198. (n.d.).

Plane, E., Hill, K., & May, C. (2019). A Rapid Assessment Method to Identify Potential Groundwater Flooding Hotspots as Sea Levels Rise in Coastal Cities. Water, 11(11), 2228. https://doi.org/10.3390/w11112228

Prem Chhetri, Jonathan Corcoran, Victor Gekara, Chris Maddox & Darryn McEvoy (2015) Seaport resilience to climate change: Mapping vulnerability to sea-level rise, Journal of Spatial Science, 60:1, 65-78, DOI: 10.1080/14498596.2014.943311. (n.d.).

Ready, M. J., & Ready, R. C. (1995). Optimal Pricing of Depletable, Replaceable Resources: The Case of Landfill Tipping Fees. Journal of Environmental Economics and Management, 28(3), 307–323. https://doi.org/10.1006/jeem.1995.1020

Rosado, L., Niza, S., & Ferrão, P. (2014). A Material Flow Accounting Case Study of the Lisbon Metropolitan Area using the Urban Metabolism Analyst Model: The Urban Metabolism Analyst Model. Journal of Industrial Ecology, 18(1), 84–101. https://doi.org/10.1111/jiec.12083

R.,V. Glasow, T.,D. Jickells, A. Baklanov, G.,R. Carmichael, T.,M. Church, L. Gallardo, et al. Megacities and large urban agglomerations in the coastal Zone: Interactions between atmosphere, land, and marine ecosystems The Rolyal Swedish Academic of Scniences, 42 (2013), pp. 13-28, 10.1007/s13280-012-0343-9. (n.d.).

S. Brown, R.J. Nicholls, C.D. Woodroffe, S. Hanson, J. Hinkel, A.S. Kebede, et al. Sea-level rise impacts and responses: A global perspective (117–149) Springer, Netherlands (2013), 10.1007/978-94-007-5234-4_5. (n.d.).

Sauerwein, M. (2011). Urban soils–characterization, pollution, and relevance in urban ecosystems. NIEMELÄ, Jari; BREUSTE, Jürgen H.; ELMQVIST, Thomas, 45-58. (n.d.).

Schoellhamer, D. H., Mumley, T. E., & Leatherbarrow, J. E. (2007). Suspended sediment and sediment-associated contaminants in San Francisco Bay. Environmental research, 105(1), 119–131. Https://doi.org/10.1016/j.envres.2007.02.002. (n.d.).

Schoellhamer, D. H., Wright, S. A., & Drexler, J. Z. (2013). Adjustment of the San Francisco estuary and watershed to decreasing sediment supply in the 20th century. Marine Geology, 345, 63–71. https://doi.org/10.1016/j.margeo.2013.04.007

Schwab, O., Laner, D., & Rechberger, H. (2017). Quantitative Evaluation of Data Quality in Regional Material Flow Analysis: Data Quality in MFA. Journal of Industrial Ecology, 21(5), 1068–1077. https://doi.org/10.1111/jiec.12490

Seasholes, N. S. (2003). Gaining ground: A history of landmaking in Boston. (Environmental Design F73.3 .S46 2003). Cambridge, Mass. : MIT Press, c2003.; cat04202a. https://libproxy.berkeley.edu/login?qurl=http%3a%2f%2fsearch.ebscohost.com%2flogin.aspx%3fdirect%3dtrue%26db%3dcat04202a%26AN%3ducb.b16014820%26site%3deds-live

SFEI and SPUR. 2019. San Francisco Bay Shoreline Adaptation Atlas: Working with Nature to Plan for Sea Level Rise Using Operational Landscape Units. Publication #915, San Francisco Estuary Institute, Richmond, CA. Version 1.0 (April 2019). (n.d.).

Shellenbarger, G. G., Wright, S. A., & Schoellhamer, D. H. (2013). A sediment budget for the southern reach in San Francisco Bay, CA: Implications for habitat restoration. Marine Geology, 345, 281–293. https://doi.org/10.1016/j.margeo.2013.05.007

Shirzaei, M., & Bürgmann, R. (2018). Global climate change and local land subsidence exacerbate inundation risk to the San Francisco Bay Area. Science Advances, 4(3), eaap9234. https://doi.org/10.1126/sciadv.aap9234

Soulsby, C., Youngson, A. F., Moir, H. J., & Malcolm, I. A. (2001). Fine sediment influence on salmonid spawning habitat in a lowland agricultural stream: A preliminary assessment. Science of the Total Environment, 265(1-3), 295-307. (n.d.).

Spencer, T., Schuerch, M., Nicholls, R. J., Hinkel, J., Lincke, D., Vafeidis, A. T., Reef, R., McFadden, L., & Brown, S. (2016). Global coastal wetland change under sea-level rise and related stresses: The DIVA Wetland Change Model. Global and Planetary Change, 139, 15–30. https://doi.org/10.1016/j.gloplacha.2015.12.018

Sprankling, J. G. (2008). Owning the Center of the Earth. UCLA LAW REVIEW, 63.

Stagg, C. L., & Mendelssohn, I. A. (2011). Controls on resilience and stability in a sediment-subsidized salt marsh. Ecological Applications, 21(5), 1731-1744. (n.d.).

Staudt, F., Gijsman, R., Ganal, C., Mielck, F., Wolbring, J., Hass, H. C., Goseberg, N., Schüttrumpf, H., Schlurmann, T., & Schimmels, S. (2021). The sustainability of beach nourishments: A review of nourishment and environmental monitoring practice. Journal of Coastal Conservation, 25(2), 34. https://doi.org/10.1007/s11852-021-00801-y

Steding, D. J., Dunlap, C. E., & Flegal, A. R. (2000). New isotopic evidence for chronic lead contamination in the San Francisco Bay estuary system: Implications for the persistence of past industrial lead emissions in the biosphere. Proceedings of the National Academy of Sciences, 97(21), 11181–11186. https://doi.org/10.1073/pnas.180125697

Sun, H., Grandstaff, D., & Shagam, R. (1999). Land subsidence due to groundwater withdrawal: Potential damage of subsidence and sea level rise in southern New Jersey, USA. Environmental Geology, 37(4), 290-296. (n.d.).

Swain, D. L. (2021). A shorter, sharper rainy season amplifies California wildfire risk. Geophysical Research Letters, 48(5), e2021GL092843. (n.d.).

Taillardat, P., Thompson, B., Garneau, M., Trottier, K., & Friess, D. (2020). Climate change mitigation potential of wetlands and the cost-effectiveness of their restoration. Interface Focus: A Theme Supplement of Journal of the Royal Society Interface, 10. https://doi.org/10.1098/rsfs.2019.0129

Tarr, J. A. (1996). The Search for the Ultimate Sink. [Electronic resource]: Urban Pollution in Historical Perspective. Akron, Ohio : University of Akron Press, 1996. (Baltimore, Md. : Project MUSE, 2015); cat04202a. https://libproxy.berkeley.edu/login?qurl=http%3a%2f%2fsearch.ebscohost.com%2flogin.aspx%3fdirect%3dtrue%26db%3dcat04202a%26AN%3ducb.b21470849%26site%3deds-live

Temmerman, S., & Kirwan, M. L. (2015). Building land with a rising sea. Science, 349(6248), 588–589. https://doi.org/10.1126/science.aac8312

Tessler, Z. D., Vörösmarty, C. J., Overeem, I., & Syvitski, J. P. M. (2018). A model of water and sediment balance as determinants of relative sea level rise in contemporary and future deltas. Geomorphology, 305, 209–220. https://doi.org/10.1016/j.geomorph.2017.09.040

Torio, D.D. and Chmura, G.L., 2013. Assessing coastal squeeze of tidal wetlands. Journal of Coastal Research, 29(5), pp.1049-1061. (n.d.).

Vähäaho, I. (2016). An introduction to the development for urban underground space in Helsinki. Tunnelling and Underground Space Technology, 55, 324–328. https://doi.org/10.1016/j.tust.2015.10.001

Valiela, I., Lloret, J., Bowyer, T., Miner, S., Remsen, D., Elmstrom, E., Cogswell, C., & Robert Thieler, E. (2018). Transient coastal landscapes: Rising sea level threatens salt marshes. Science of The Total Environment, 640–641, 1148–1156. https://doi.org/10.1016/j.scitotenv.2018.05.235

Van Meirvenne, M., & Goovaerts, P. (2001). Evaluating the probability of exceeding a site-specific soil cadmium contamination threshold. Geoderma, 102(1), 75–100. https://doi.org/10.1016/S0016-7061(00)00105-1 van Slobbe, E., de Vriend, H. J., Aarninkhof, S., Lulofs, K., de Vries, M., & Dircke, P. (2013). Building with Nature: In search of resilient storm surge protection strategies. Nat Hazards, 20.

Verhoeven, J. T. A., Soons, M. B., Janssen, R., & Omtzigt, N. (2008). An Operational Landscape Unit approach for identifying key landscape connections in wetland restoration. Journal of Applied Ecology, 45(5), 1496–1503. https://doi.org/10.1111/j.1365-2664.2008.01534.x

Vileisis, A. (1999). Discovering the unknown landscape: A history of America's wetlands. Island Press. (n.d.).

Villoria Sáez, P., & Osmani, M. (2019). A diagnosis of construction and demolition waste generation and recovery practice in the European Union. Journal of Cleaner Production, 241, 118400. https://doi.org/10.1016/j.jclepro.2019.118400

Wilby, R. L. (n.d.). A Review of Climate Change Impacts on the Built Environment. CLIMATE CHANGE AND CITIES, 33(1), 15.

Williams, P. B., & Orr, M. K. (2002). Physical Evolution of Restored Breached Levee Salt Marshes in the San Francisco Bay Estuary. Restoration Ecology, 10(3), 527–542. https://doi.org/10.1046/j.1526-100X.2002.02031.x

Wong, C. S. C., & Li, X. D. (2004). Pb contamination and isotopic composition of urban soils in Hong Kong. Science of The Total Environment, 319(1), 185–195. https://doi.org/10.1016/S0048-9697(03)00403-0

Zhao, Q., Bai, J., Huang, L., Gu, B., Lu, Q., & Gao, Z. (2016). A review of methodologies and success indicators for coastal wetland restoration. Ecological Indicators, 60, 442–452. https://doi.org/10.1016/j.ecolind.2015.07.003

Conclusion

The work undertaken for this dissertation seeks both to broadly frame and deeply examine an emergent challenge of the climate change era that will come to matter dramatically to developed shorelines in coming decades. While sea level rise is employed as the umbrella term for the climate phenomenon of interest, we can understand it as wicked in the sense that it actually entails many different interacting challenges that cut across domains. Accordingly, while certain physical realities related to the material and industrial ecologies of resources are the subject of the work here, they lead us to consider their meaning and implications in deeper ways. Some basic insights connecting the core chapters may be useful to reflect upon.

First, it is interesting to consider how general notions related to adaptation discussed in chapter one relate to the particular case study and its management of sediment resources discussed in chapters two and three. The SF Bay is grappling with a clear adaptation situation as embodied by its increasingly tenuous sediment deficit—analogous to an adaptation gap. Similarly, the region recognizes that sediment is crucial in terms of its adaptive capacity; though this resource is also limited. Barriers to adaptation exist in practically every sense imaginable: from hurdles presented by outmoded regulations to the difficulty in long-term financing of equitable approaches to the problem itself. How its various adaptive management processes might play out in the context of broader adaptation planning will depend, to no small extent, on the various ways in which organizations and institutions resist or overcome the lock-in and path dependent effects that a sediment-as-waste-product paradigm will tend to perpetuate; thus reducing adaptive capacity in the overall system and region. In turn, the industrial and development processes that connect sediment supplies (and the capacity they may confer) to the demand that instrumentalizes them (as adaptation projects) embody tensions based on private sector for-profit operations that cleave to an unsustainable resource management model (and the maladaptive outcomes it promulgates) which is, to some degree, rendered at the mutual exclusion of the broader public interest.

The mechanisms by which this happens are linked to processes explored and articulated in the second chapter: wherein processes of urban development—literally the means of production of urban space—are arranged such that a dominant classification logic for dictating the flows of excavated soil and sediment render this resource as a byproduct of urban development and metabolism—perhaps (or increasingly) even urbanism itself.

Accordingly, and in a strange kind of marriage of convenience, environmental contractors, developers and landfill operators are incentivized towards a highly wasteful resource regimen: one in which considerations of the opportunity costs associated with landfilling sediment are externalized. That is, for the broader public and future generations, we can see the makings of a vexing but predictable market failure. This, of course, is also true of and applies to the environmental justice dimensions of the interconnected problem aspects illustrated herein: in particular, starkly evident in the potential calamity of coastal squeeze and wetland drowning occurring as a function of not reusing urban sediment resources in adaptation and restoration schemes.

Insofar as the work establishes the nature of multi-year construction projects that will be involved in constructing horizontal levees and ecotones with excavated sediment in San Mateo County, and especially given the profoundly outmoded governance of these resources, major innovations are both possible and increasingly important efforts in which to invest. In no small part, there is a need for leadership to mandate and streamline basic permitting and reporting standards across broad organizational fields and more meaningful spatial scales and with the intent of aiding an overall climate adaptation paradigm that will come to dominate so many resource issues in the region—whether we actively prepare for this eventuality or not. This dissertation is proof both of the willingness of government agencies and offices to help in processes geared towards adaptation, and of the severely difficult reality of doing so as a function of byzantine record-request processes, redundancy, lack of clarity and countless dead-ends. If nothing else, the research stands as its own testament and justification for the need for advances in statistical modeling techniques that can overcome some of these barriers, which is a hallmark of much applied industrial ecology work.

These entanglements—of data and offices, leadership and the status quo, resources and governance in complex socioenvironmental settings—also emphasize another lesson of the work: the all-too-familiar hot potato cliché. In short, and because of a lack of leadership, coordination and (maybe most fundamentally) communication and awareness, various actors within the overall network connected to anthropogenic sediment management in an urban shoreline act independently, and this produces enormous shortcomings in the efficiency of work that might otherwise be possible. Perhaps this is an central lesson related to the complexity of planning processes where multiple stakeholders, procurements, and various scenarios complicate problems and tend to increase uncertainty. But the factionalizing and balkanizing effects of narrowly-defined mandates that don't generate broader platforms for cooperation and coordination are, to some extent, institutional issues: and they are, as such, possible to overcome with changes in *culture*--maybe especially as it relates to the values and priorities that come to constitute a definition and understanding of the public interest.

Yet there, also, we encounter another need for adaptation; or at least another role for it to play in this context. That is, some sense of our public interest and public good must emerge and evolve as a function of the severity, enormity and complexity of climate change and the risks and hazards it poses. In chapter one, we encountered this articulated as institutional adaptation itself. In the real world, theories about how and why institutional adaptation happen may be of limited value. What is surely of immense value, on the other hand, is the illustrative power of seeing and showing how our public interest is tied to its resources and in ways that implicate multiple levels of governance and the cross-sector actors whose mission, mandate or profit margins are linked to the management of these resources. In her pioneering work on common pool resources, Elinor Ostrom explored how collective (or collectivized) sensibilities about justice and equity were at play in adjudicating aspects of the physical world which might not, at first blush, seem to speak to higher ideals and deeper meaning in terms of societal ethics and intergenerational and interspecies justice. Ostrom's work illustrates a recognition of these realities—those at the intersections of aspirational ethics and seemingly uninteresting logistics—as a profoundly rich place, both in terms of the environmental problems they frame and the possibilities for interrogating them.

Insofar as this work may hold some insights for those engaged in the strategic adaptation of systems and places to climate change, a central tenet of strategic planning is helpful to finally reflect upon and consider in context. Strategic planning requires an articulation of the goals of some enterprise (the ends) and how the resources (means) required to realize these goals are, or can become, possessed by those engaged in the undertaking. Two things are important to note about this axiomatic principle. First, in terms of how resources are captured or collected, enormous variety and flexibility can exist: thus the techniques, technologies and tools for realizing goals may be diverse, adaptive and even unprecedented. In that sense, the "how" might be a matter of practicalities, timing or sheer will—and perhaps all of the above in some measure. In this sense, slippery concepts related to chaos, chance and the human commitment to addressing some challenge come into play, and often in unexpected ways, when plans attempting to realize some future state of affairs is attempted. This echoes the notion that adaptability is, to some extent, a process of realizing and seizing opportunities as they emerge.

The second consideration of strategic planning's implied definition concerns what happens when one's ends and means do not comport. In turn, this situation demands that one of two things happen or that, all things being equal, a third inevitably will. Namely, one must identify and adopt a new goal if the resources are insufficient to achieve the original one; or else the something about the resources—their collection, allocation, definition, status, utilization, etc.—must themselves be changed in order to reach said goal. If neither of these adaptations can be made to address the disparity between means and ends, the strategy fails. Consider this in the context of the SF Bay Area explored here. The region has identified widespread wetland restoration as a crucial climate adaptation goal. It has passed legislation and funding provisions to accomplish this end. The physical (sediment) resources to realize the goal are not assessed to emerge in the expected sequence of events or state of affairs that scientists have projected will play out without massive human intervention. Thus we see the choice starkly emerging: does the region change its stated goals, or ways in which it marshals its resources?

This dissertation does not tell us the answer, of course: it serves to frame the question. And in the ever-changing context of climate change affecting an entire, complex regional landscape, there may be any number of answers that must be conjured. What we can see in the work is that even in something as mundane as the way that our society chooses (and/or fails to change its choices about) how it "throws away dirt", a wildly rich, complex and important world of possibilities also exists: wherein there lies an adaptation pathway built on something as understated and simple as a ramp of subtly sloping soil. This microtopographic feature of the landscape is a constructed landform: one that may protect our society from flooding, and our most vulnerable the most of all; it may stave off the cataclysmic collapse of our wetlands and global flyways, and resist catastrophic losses in biodiversity; it may save our region many billions of dollars in avoided costs and through protection of existing infrastructure; it might improve water quality and reduce the throughput of contaminants into the Bay itself; it may form the backbone of extensive networks of public open spaces and natural resources; and, in these ways, it may serve as a deep investment in our region's future and the health, safety, welfare and justice of countless people.

This modest landform does any of this only if it is actually constructed, of course. And it will only ever *be* constructed if the decision makers of the region decide that new modes of public, environmental and resource stewardship can and should be realized and embraced: in short, the broad, strategic inception, and deep implementation of climate change adaptation; and the myriad efforts involved in its planning.