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Interrogating the ‘science of climate accountability’:
Allocating responsibility for climate impacts within a frame of climate justice

A dissertation submitted in partial satisfaction of the
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by

Emily Lynn Williams

Committee in charge:
Professor David Lopez-Carr, Chair
Professor Simone Pulver
Professor Leila Carvalho
Dr. Chris Funk

September 2022

The dissertation of Emily Lynn Williams is approved.

Simone Pulver

Leila Carvalho

Chris Funk

David Lopez-Carr, Committee Chair

June 2022

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VITA OF EMILY LYNN WILLIAMS
SEPTEMBER 2022

EDUCATION

- Doctor of Philosophy in Geography, University of California, Santa Barbara, June 2022
    - Interdepartmental PhD Emphasis in Climate Sciences and Climate Change
    - Interdepartmental PhD Emphasis in Environment and Society
- Bachelor of Science in Environmental Studies, University of California, Santa Barbara, June 2013

FELLOWSHIPS, GRANTS, AND AWARDS

- Recipient of the 2021-2022 Winifred and Louis Lancaster Dissertation Award in Social Sciences *(June 2022)*
- Graduate Research Fellowship Program, National Science Foundation (NSF GRFP) *(Fellowship years: 2016-2020; Tenure years: 2016-2019)*
- Central Fellowship, UC Santa Barbara *(2020-2021)*
- Leal Anne Kerry Mertes Scholarship Award for Field Research *(2021)*
- Chair's Recognition of Outstanding Service, Department of Geography *(2021)*

SELECTED ACADEMIC PUBLICATIONS

Pellow, D. N., **Williams, E.,** & Rizo-Centino, A. R. (2021). Collaborative Research and Action for Climate Justice in California. Capitalism Nature Socialism, 1-18.

Williams, E; Funk, C; Shukla, S.; McEvoy, D. (2020) Quantifying Human-Induced Temperature Impacts on the 2018 United States Four Corners Hydrologic and Agro-Pastoral Drought. Bulletin of the American Meteorological Society, 101(1), S11-S16.

Williams, E. (2019). Attributing blame?—climate accountability and the uneven landscape of impacts, emissions, and finances. Climatic Change, 1-18.

Pricope, N.; Pardo-Rodriguez, L.; Lopez-Carr, D.; **Williams, E**.; & Zorich, L. (2018). Geographic Vulnerability to Climate Change. In Oxford Bibliographies, 3, 1-30.

Brown, M.; Funk, C.; Pedreros, D.; Korecha, D.; Lemma, M.; Rowland, J.; **Williams, E.**; Verdin, J. (2017). A climate trend analysis of Ethiopia: examining subseasonal climate impacts on crops and pasture conditions. Climatic Change, 142(1-2), 169-182.

SELECTED PRESENTATIONS

- Discussant, American Geophysical Union (AGU) Annual Conference. Townhall Climate Litigation-Relevant Research: Defining a Growing Field *(2021)*
- Presenter, American Association of Geographers (AAG), Annual Meeting. Science for Loss and Damage: Overcoming the Uneven Landscapes of Impacts and Emissions. Part of Climate Finance Justice panel *(2018)*
- Side Event Moderator, Intergenerational Inquiry. 19th Annual Conference of the Parties, United Nations Framework Convention on Climate Change in Warsaw, Poland *(November 2013)*

ACADEMIC EMPLOYMENT

- Graduate Student Researcher, Climate Hazards Center, University of California, Santa Barbara *(2021-2022)*
- Teaching Assistant, University of California, Santa Barbara *(Winter & Fall 2018)*
- Graduate Student Researcher, Environmental Studies Program, University of California, Santa Barbara *(2019)*
- Lab Assistant, Climate Hazards Center, University of California, Santa Barbara *(2015-2016)*

COMMUNITY ORGANIZING, PUBLIC ENGAGEMENT, & CAMPAIGNING EMPLOYMENT

- Project Coordinator, Environmental/Climate Justice Research-Advocacy Collaborative, Santa Barbara, CA *(2019-2020)*
- Steering Committee member & campaign lead, 350 Santa Barbara *(2015-2021)*
- Increasing Media Reporting on Climate Change: Making Extreme Event Attribution Science Accessible to Journalists. *In partnership with Climate Nexus, see Climate Signals (2019-2020)*
- Campaign Director, Fossil Free, California Student Sustainability Coalition *(2013-2015)*

SELECTED MEDIA

- **Williams, E.;** LeQuesne, T. (Oct 2019). The University of California Finally Has Divested from Fossil Fuels. The Nation.
- Stokes, L.; Pellow, D.; **Williams, E.** (2019). No to New Oil Drilling. Santa Barbara Independent.
- **Williams, E.** (2020). A Global Pandemic Is Not a Climate Solution. Santa Barbara Independent.
- Radio interview on "Environmentalism's Next Generation" (Mar 2013). NPR's On Point with Tom Ashbrook.
- Radio interview on NPR member stations regarding Williams et al. 2020 *(NPR member stations KJZZ in Arizona, KNAU in Arizona, and KSJD in Colorado) (2020)*

ABSTRACT

Interrogating the 'science of climate accountability':
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by

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Communities around the world are already facing the impacts of climate change. In this 1°C warmer world, many of those who have already endured impacts have little recourse, while 'big emitters' have largely externalized costs of their activities. The field of climate accountability has emerged as a response to this uneven distribution of harms and gains. The question—who ultimately is responsible for climate impacts?—has been asked with increasing frequency over the past decade in both policy spheres and litigation as extreme events have increased in both likelihood and intensity. In this dissertation, I interrogate this broader field of climate accountability, leveraging cross-disciplinary methodologies to build evidence for—and identify gaps in—this field. The central question underpinning the dissertation is: who is responsible for climate impacts, and how can the field of climate accountability best serve impacted communities?

To do so, I build a conceptual framework to guide allocating causal responsibility (Chapter 1). Identifying causality for impacts is an insufficient and yet necessary component of all proposed climate accountability mechanisms. The bulk of this dissertation then tests this conceptual framework by conducting ‘end-to-end attribution’—or attributing climate impacts to sources of greenhouse gas (GHG) emissions—by focusing on climate change-related drought impacts in the Southwestern United States. End-to-end attribution broadly includes three components: extreme event attribution (Chapter 2), impact attribution (Chapter 3), and source attribution (Chapter 4). Chapter 2 presents two detection and attribution (D&A) analyses, quantifying the impact of increased temperatures from anthropogenic climate change on local vapor pressure deficit (VPD) and vegetation health in the Four Corners region of the Southwest. The studies find that anthropogenic forcing increased temperatures, corresponding to sizeable increases in VPD and substantial impacts on vegetation health. Chapter 3 examines climate-related drought impacts for A:shiwi—or the Zuni Tribe—in New Mexico. The chapter presents the results of ethnographic field work and archival analysis, outlining the types and extent of climate impacts faced by the tribe, conceptions of causality for those impacts, and lessons learned for appropriate approaches to responsibility. Finally, Chapter 4 conducts source attribution by tracing nation-state, industrial, and consumer-based contributions to GHG emissions and the actions, attitudes, and omissions which have accompanied those emissions. It furthermore presents a systematic analysis of climate denial, doubt, and delay messaging from the American electric utility industry. This dissertation concludes by reflecting on the challenges associated with end-to-end attribution, including where current approaches may advance versus hinder the pursuit of climate justice.

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Introduction

November 2013

In 2013, I managed to secure what I thought was a golden ticket—a front-row seat to seeing history being made. I had been accredited to join the University of California delegation to the 19th Conference of the Parties (COP) of the United Nations Framework Convention on Climate Change (UNFCCC) in Warsaw, Poland. The UNFCCC is the international climate negotiations space, where countries send policy-making delegates to negotiate agreements about how to address climate change.

On the first day of the conference, each nation's delegate delivered their opening minute-long statement. Some countries offered platitudes about the importance of the process, while others warned that the concept of "political feasibility" was getting in the way of meaningful action. Then the delegate from the Philippines took the floor. Just before the conference, Typhoon Haiyan had struck the Philippines resulting in unimaginable damages and losses. It was the most powerful typhoon to strike land to date and was likely made more intense by human-caused climate change (Takayabu et al. 2015). The Philippines negotiator Yeb Saño gave a 17-minute speech describing the "colossal devastation" of the storm, saying:

> "What my country is going through as a result of this extreme climate event is madness. The climate crisis is madness. We can stop this madness. Right here in Warsaw…[D]espite the significant gains we have had since the UNFCCC was born, 20 years hence we continue to fail in fulfilling the ultimate objective of the Convention. Now, we find ourselves in a situation where we have to ask ourselves—can we ever attain the objective set out in Article 2—which is to prevent dangerous

> anthropogenic interference with the climate system? By failing to meet the objective the Convention, we may have ratified the doom of vulnerable countries.
>
> And if we have failed to meet the objective of the Convention, we have to confront the issue of loss and damage. Loss and damage from climate change is a reality today across the world…" (Saño 2013).

I attended the next two COPs, emboldened by the global call for solidarity and the urgency needed to "stop this madness," using Yeb Saño's words. I worked with other youth to get the protection of future generations through the concept of "intergenerational equity" into the preamble of the text. But two years later, at COP21 in Paris, I began to doubt the ability of the process to deliver the meaningful change needed by so many people today and by future generations. While COP21 had pledged to limit warming to 2 degrees Celsius (2°C) and aim for 1.5°C, the current pledges added up to 3°C (Climate Action Tracker). And Global North Countries—led by the United States—fought language regarding historical responsibility, leading to the Paris Agreement stating that the loss and damage mechanism would *not* provide a basis for "liability and compensation." I went home, sobered and schooled, and with a much better understanding of just how much work needed to be done. I would work in solidarity with others, with future generations, and dig in for the long haul.

The Dissertation

Communities around the world are already facing the impacts of climate change. While negotiations are pursued at regional, national, and international scales to reduce greenhouse gas (GHG) emissions and avoid further warming, the world has already warmed on average by 1°C. While the same negotiations aim to fund projects to ease adaptation to already "locked-in" warming, this adaptation generally fails to meet the scale of needs (Schlosberg and Collins 2014). In this warmer world, many of those who have already endured impacts have little to no recourse.

The field of climate accountability seeks to address to this uneven distribution of harms (Frumhoff et al. 2015; Burger, Wentz, and Horton 2020). The question—who ultimately is responsible when disaster strikes?—has been asked with increasing frequency over the past decade as extreme events (including wildfires, hurricanes, droughts, and heatwaves) have increased in both frequency and intensity. Answers to this question have been elusive. At the international level, under the auspices of the United Nations Framework Convention on Climate Change (UNFCCC), countries have been embroiled in a debate for years about whether loss and damage (L&D) mechanisms should include a mechanism for liability and compensation. Since these negotiations have stalled, both domestic and international lawsuits have blossomed in the past 10 years in which communities, municipalities, and states have filed lawsuits against federal governments and oil, gas, coal, and electric utility companies for their role in emitting GHGs and contributing to experienced damages.

The idea of the "science of climate accountability", a phrase coined by Peter Frumhoff with the Union of Concerned Scientists, is based in leveraging scientific advancements for application to the question of responsibility and liability. Such questions emerged early as 2003, with climate scientist Myles Allen asking "[w]ill it ever be possible to sue anyone for damaging the climate?" in a review of application of scientific advancements in climate change to lawsuits (Allen 2003). Although young, the field of climate accountability has generally cohered around developing and examining methodological tools, concepts, and mechanisms that may be leveraged to address three types of injustices—distributive justice, i.e. responding to the inequitable distribution of harms; procedural justice, i.e. ensuring those most impacted are included in the decision-making process; and corrective justice, i.e. whether entities owe restation to others due to their role in creating or exacerbating harm (Scholsberg and Collins 2014; Gardiner 2011).

My dissertation interrogates this field of climate accountability, leveraging cross-disciplinary methodologies to build evidence for—and identify gaps in—this field. The central question underpinning the dissertation is: how can scientific advancements in demonstrating causation between emissions sources and sites of impacts help progress this field of climate accountability, and in doing so, how can we—scientists and practitioners—ensure that these advancements center justice and community needs?

'Safe' Climate Change: Safe for Whom?

Article 2 of the UNFCCC states the goal of the convention is to "prevent dangerous anthropogenic interference with the climate system." Yet who defines what constitutes 'dangerous interference'? Hulme (2008) describes how the Intergovernmental Panel on Climate Change (IPCC), with the publication of the First Assessment Report (FAR) in 1990, set the terms for how climate change would be approached. The IPCC FAR set the norms for discussing the science of climate change, in which "[c]limate is defined in purely physical terms" and "[w]hat is sought to be stabilised is a quantity—global temperature, or its proxy carbon dioxide concentration—a quantity wholly disembodied from its multiple and contradictory cultural meanings" (Hulme 2008:6). This frame of climate change was picked up by the UNFCCC. When the UNFCCCC was signed into treaty in 1992, its 'ultimate objective' was stated as achieving a "…stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system." Nearly a decade later, the IPCC Third Assessment Report (TAR) included a figure which identifies dangers, or levels of impact, associated with different thresholds of global mean average temperature rise, with yellow depicting lower dangers and red depicting higher dangers. In this figure, above approximately 2°C was a much higher concentration of red. While this "Burning Embers" figure provided policymakers with a quick visual of the scale of impacts from such conceptual and abstract numbers as 2°C, it still "generally overlooks the spatial geographies of climate change" (Liverman 2009:286). The "Burning Embers" figure cemented the concept of 'dangerous climate change', in which targets should be set below or at 2°C so as to avoid 'dangerous' impacts above that threshold.

At COP15 in 2009, 2°C of global average temperature rise was determined as the 'safe' level of climate change. Then, at COP21 in 2015, the Paris Agreement was negotiated and agreed to, which reified the goal of staying below 2°C above pre-industrial levels, with an intention to limit to 1.5°C in "…recognizing that this would significantly reduce the risks and impacts of climate change" (Paris Agreement, Article 2). The Paris Agreement thus recognized that significant impacts would occur even at warming below 2°C.

These targets are important—such targets offer a common framework around which nation-states can negotiate and try to prevent further climate change. Mitigation—or efforts to reduce greenhouse gas (GHG) emissions to prevent further interference with the climate—represents crucial forward-looking attempts toward justice. Thus, these targets act as a tool for nation-states to create policy for mitigation. Yet the targets for identifying 'dangerous climate change' implies that there is 'safe climate change' (Risbey 2006; Liverman 2009). Moreover, "…[c]hoosing a 'safe' level of change may also provide a false sense of comfort that the problem is solved" (Risbey 2006). While decision makers recognize that there are serious impacts that occur below these targets, using a 2°C, or even 1.5°C, threshold as separating 'safe' from 'dangerous' climate change represents a political negotiation or cost-benefit curve weighing impacts below the threshold on one hand and 'political feasibility' or economic development on the other (Jaeger and Jaeger 2011; Liverman 2009). Therefore, this concept of 'safe' warming—and the related allowable level of emissions—unintentionally classifies certain impacts that occur below the threshold, however serious and harmful, as acceptable.

As a result, these targets have contributed to climate injustices around the world. Hopkins (2020) explains that:

> "You can't have climate change without sacrifice zones, and you can't have sacrifice zones without disposable people, and you can't have disposable people without racism" (Hopkins 2020).

Coined by Robert Bullard, the phrase "sacrifice zones" identifies the places that bear the brunt of impacts—be it resource extraction, toxic dumping, or climate impacts—largely as a sacrifice for the rest of society, which benefits from the activities creating impacts but avoid their consequences (Bullard 1990; Buckley and Allen 2011; Klein 2015). In the case of climate change, sacrifice zones are the places and communities that are least responsible for causing climate change but who bear the impacts of average temperature rise deemed as 'politically necessary' by decision makers (Klein 2015; Hopkins 2020). Therefore, the communities who experience climate impacts below the 1.5°C or 2°C mark exist in such sacrifice zones and are often left with limited resources and little to no recourse. Therefore, climate justice activists and scholars are increasingly calling for addressing this inequitable distribution of harms.

The Big Questions

In responding to this call, there are two overarching questions being asked: (a) who is responsible for climate impacts and how can they be held accountable, and (b) how can the field of climate accountability best serve impacted communities?

The first question revolves around how responsibility and accountability for climate change are conceptualized, delineated, and pursued. Responsibility and accountability—two interconnected yet distinct concepts—exist for and have been thoroughly examined, critiqued, and developed for many aspects of life, particularly in ethics and philosophy. Several scholars have begun to explore the definitions of responsibility and accountability for environmental and climatic harm, including geographers (e.g. Michael Mason), political theorists (e.g. David Schlosberg), and philosophers (e.g. Henry Shue). Implicit in this question of responsibility and accountability is the need to then define causation; specifically, how can a causal link be sufficiently demonstrated to show that the harms experienced by the impacted community are at least in part due to the actions of the emitter? This is a methodological question which is couched in a normative assertion of the persuasiveness of certain types of evidence. Arising from the methodological question of defining a causal link is a theoretical and deeply geographical question. In defining a methodology for demonstrating a causal link, choices are made about scale of aggregation.

The second question focuses on the communities whom climate accountability scholars seek to serve. In delimitating responsibility and emphasizing the need of proving a causal linkage, do certain communities become prioritized by the ease with which their climate impacts may be described by current methodological tools in Western science? This potential tension—aspects of which have been identified by others (e.g. Hulme 2014; Lahsen and Ribot 2022)—is coined *attributability versus vulnerability* in this dissertation. How can climate accountability be pursued in a way that pursues justice for those most impacted communities? Does that pursuit require sacrificing attributability, or can this tension be extinguished by approaching the question of causality in another way? Yet, even if disproportionately impacted communities are prioritized, this field risks replicating past harms if climate accountability is pursued *for* them rather than *by* and *with* them. How can this field then center impacted communities—their voices, perspectives, and definitions of needs—in the pursuit of climate accountability?

Geographical Foundations to this Approach:

This dissertation pursues these two questions regarding the field of climate accountability by leveraging theories, methods, and tools from relevant disciplines. Geography, especially, is well suited to this task. Indeed, geographers Mike Hulme, Diana Liverman, and Petra Tschakert provide an understanding of how climate change occurs through complex political ecologies and impacts occur across a backdrop of vulnerability and exposure. Moreover, other geographers—such as Doreen Massey, Salley Marston, and Theodore Schatzki—provide theoretical approaches to scale and space and place to examine causality and power in physical geographical locations far from one another. Finally, geographer David Harvey provides the theory to understand how climate change has occurred through growing inequality and access to resources and power through accumulation by dispossession, and geographer Gavin Bridge takes this further to understand how states and firms leverage that power to continue privileged access to resources.

Climate change does not exist in a silo. Impacts do not occur without the pre-existing social, economic, political, and environmental context, just as emissions responsibility cannot be allocated in a vacuum. Traditional political ecology, rooted in geography, provides an understanding how such systemic drivers as capitalism, imperialism, and colonization lead to on-the-ground impacts (Liverman 2015). These processes occur across multiple scales with variable decision-makers, with climate change resulting from nation-states and firms engaged in economic considerations of profit, and then occurring against multi-scalar socio-environmental vulnerability (Liverman 2004; Bridge 2008). Geographers similarly provide theoretical approaches to understanding causality in the local-global-local causal chain that is climate change. A common approach to climate change has been through the concept of hierarchical scale, in which systemic drivers of climate change occur at the top scale, leading to impacts 'on the ground' (Blaikie and Brookfield 1987). Such approaches facilitate examining cross-scalar causality for socio-environmental processes.

Furthermore, geographers have developed theories for viewing responsibility and agency in cross-scalar relationships. In responding to such cross-scalar socio-environmental problems, certain approaches leave no room for agency (Marston et al. 2016:421). If there is no agency at the top hierarchical level, there is no possibility for responsibility, so that "… 'the global' and its discursive derivatives can underwrite situations in which victims of outsourcing have *no one* to blame…" (Marston et al. 2016:427). Yet, the drivers of events—

in this case, climate change—do not exist at a top scale, but rather are "…those proximate or even distant localities from which those events arguably emerged" (Marston et al. 2016). While climate change is a global phenomenon, climate change does not cause impacts, as the concept of climate change cannot be a responsible party. Doreen Massey offers an alternative view of scale that recognizes agency across locations. Places are "…the moments through which the global is constituted, invented, coordinated, produced" (Massey 2004:11). Places are therefore "agents", whereby places—and importantly the people in those places—through their actions produce effects in other, sometimes faraway, places (Massey 2004). In this view, causal chains—or cause-and-effect relationships linking actions to impacts—extend still across spaces, but instead from a broad global down to a local, the causal chain connects places of agency to other places with agency, through complex networks. Schatzki (2002) refers to these places as 'sites', where "things hang together as clusters of interrelated determinant stuff" and are connected to other sites (Marston et al. 2016).

Such geographical theories allow for researching and understanding "global capitalism" and "international political economy", for example, as systemic drivers of climate change and climate impacts, but also recognize these processes as results of decision making in specific sites. These patterns show up again and again in various sites because of actions at different sites and places, extending across space, and often perpetuated by the same group. Therefore, by understanding these processes as *patterns* instead of actors with agency, it allows for keeping explanatory power and deep understanding that come with these patterns, but still recognizing how those actors with agency instigate, perpetuate, maintain, resist, undermine, or challenge these patterns. For example, an impact wasn't caused by "colonialism" any more than it was by "climate change", as such language assumes that "colonialism" or "climate change" is an agent. Rather, the site experiences these patterns of climate change and colonialism, but both patterns are caused, perpetuated, and maintained by those with agency, and similarly resisted, undermined, or challenged by (generally at the site of impact) others with agency.

An example of such a pattern propagated across time and space is the process of accumulation by dispossession (Harvey 2003). As with capital and other resources, fossil fuels have been accumulated by institutional actors by the dispossession of people's lands through the intertwined processes of colonialism and imperialism (Harvey 2003; Maldonado 2018). This process looks very different in different places, with variable effects of dispossession on people and on land, enacted by different actors. Yet, this pattern of 'accumulation by dispossession' can be traced across time and space and is one of the largest systematic drivers of climate change. It is, however, propagated by actors or unique sites with agency. As will be described in Chapter 3, this has enormous implications for historical responsibility for climate change.

To examine causality between GHG emissions and climate impacts requires a set of tools and methodological approaches. Political ecology is uniquely suited to this work, with deep roots in geography. Political ecology offers critical understandings of socio-environmental vulnerability and a long history of mixed-methods across scales to understand drivers and outcomes of that vulnerability (Blaikie and Brookfield 1987; Liverman 2004; Liverman 2015; Tschackert 2012). Yet, Tschackert 2012 explains that political ecology has not engaged much "…in actually taking part in 'doing' the science…, particularly with respect to measuring and interpreting climate variability and change" (Tschakert 2012). Tschakert (2012) identifies this "analytical mistake" of political ecology researchers largely not engaging in the science of climate change and climate impacts given the unique tools, theories, and approaches held by these researchers. Indeed, many climate change assessments have assumed linear, one-way causal chains between climate and impacts, where the concept of 'vulnerability' is relegated to a singular aspect that exists on the ground that mediates climate change. Instead, political ecology research examines the political, economic, social, and other nuanced drivers of vulnerability (Tschakert 2012; Liverman 2015).

Much groundwork has been laid by these, and many other, geographers. While the field of climate accountability has not fully engaged such geographical approaches—including methods, theories, and tools—these approaches are well suited to answering the 'big questions' in the field. Therefore, my goal in this dissertation is furthermore to examine how these geographical approaches may be leveraged in answering the research question by applying them to empirical research within the 'science of climate accountability.'

I. Towards a field of climate accountability

Although young, the field of climate accountability already exists and pulls from many disciplinary traditions, including philosophy (Shue 2017, Lusk 2017, Francis 2020), history (Franta 2018a, Oreskes and Conway 2010), law (Burger, Wentz, and Horton 2020; Byers et al. 2017; Marjanac and Patton 2018), and climate science (Thompson and Otto 2015, Otto et al. 2017). Still more disciplines circle the field of climate accountability—geographers focus on how losses and damages are constructed (e.g. Wrathall et al. 2015, Hulme 2014, Huggel et al. 2016) and political scientists examine the potential for policy mechanisms (e.g. Huq et al. 2013). It may be more fairly stated, however, that scholars from these fields engage with questions regarding climate accountability, bringing with them their discipline's methods, tools, and norms. In doing so, they are rapidly defining a field that is beginning to cohere around certain assumptions, methods, and practices. Yet this field is still forming and therefore has yet to be clearly defined. Now is therefore the moment to cast a critical eye upon this area of inquiry to understand where it came from, where it is now, and what strengths and weaknesses it possesses—and how those might translate into advancing versus hindering the pursuit of justice. This critical analysis then may inform how this field may be further shaped to be the best that it can be.

In this chapter, I present this nascent field of climate accountability, exploring its history and how it has been shaped by disciplinary approaches, examining where it is today, and unpacking why certain default tendencies and assumptions occur repeatedly in the field. I begin by introducing the practitioner field of climate accountability—with roots in international negotiations, current efforts in law, and leveraging of climate research for these mechanisms—and explore what sets it apart from other efforts to address losses and damages from climate change (Section 1.1). From this review, I identify two large challenges currently facing the mechanisms from being operationalize and from being based in principles of justice (Section 1.1.3). I then explore the academic field of climate accountability and how certain advancements in research and theory may unstick or further entrench those challenges. I begin by identifying dominant theoretical frames that define most academic approaches this field (Section 1.2) and provide an overview of the advancements in relevant research areas (Section 1.3). Finally, I introduce what is required for translating this research into one of the mechanisms—civil law (Section 1.4). With this survey of the field presented, I end by introducing the structure of the dissertation and how it aims to address these challenges (Section 1.5).

1.1. Defining the Practitioner Field of Climate Accountability[1]

Communities around the world are already experiencing both damages and losses from anthropogenic climate change. "Loss and damage" is a broad umbrella concept referring to several distinct definitions. At its broadest, it can be understood to refer to the social, political, economic, or cultural impacts related to climate change. Damages are those impacts which may be repaired or restored, while losses are those which are irrevocably harmed or lost (Stabinsky and Hoffmaister 2015). Some of these losses and damages are already empirically attributable to anthropogenic—or human-caused—climate change, such as the deadly 2003 European heatwave (Mitchell et al. 2016).

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[1] Material from: 'Williams, E. (2020). Attributing blame?—climate accountability and the uneven landscape of impacts, emissions, and finances. Climatic Change, 161(2), 273-290. © (2020). [Springer Nature].' Used with permission.

The need to address loss and damage is gaining increased attention, and yet remains underdeveloped as a domain of study and practice as compared with the mitigation of, and adaptation to, climate change. Mitigation includes efforts to reduce emissions of greenhouse gases (GHGs) and halt destruction of carbon sinks, while adaptation includes efforts based in community and ecosystem adjustments in response to both current and projected impacts of anthropogenic climate change. If mitigation and adaptation are both successfully addressed, losses and damages from climate change would not exist: “avoided” loss and damage, therefore, refers to impacts that would have occurred were it not for successful mitigation of GHG atmospheric concentrations or adaptation. However, they have thus far been insufficiently addressed, and significant impacts have been observed. “Unavoided” loss and damage are impacts that could have been avoided with successful adaptation, and “unavoidable” loss and damage are those that cannot be adapted to (Verheyen 2012).

Future efforts to mitigate and adapt to climate change will likely be insufficient and continue to yield more unavoided loss and damage. At the international scale, nation-states have reached a consensus with the goal of limiting global average temperature rise to below 2°C, with efforts to stay below 1.5°C (Paris Agreement 2015). Such a temperature target is ambitious, as the 1.5 °C target requires reducing global GHG emissions by nearly 50% by 2030 (IPCC 2018), and while significant strides in reducing emissions have occurred, political will is lacking in many arenas. According to the Climate Action Tracker, current enacted policies and national pledges would amount to 3 °C of warming. However, even if global average temperature rise is limited to 1.5°C, while avoiding some of the most devastating impacts of anthropogenic climate change, the additional 0.5°C of warming (compared with current warming) will result in greater unavoided and unavoidable losses and damages than have been observed thus far.

Due to the fact that climate change-related losses and damages are now observable, and will continue to grow, different sub-definitions of, and approaches to address, “loss and damage” have been developed. While there are multiple mechanisms and domains of study and intervention in loss and damage, only a few are concerned with questions of responsibility for avoiding losses and damages, and assigning accountability when they occur.

1.1.1. Policy, Law, and Science for Loss and Damage

A brief history of loss and damage and the UNFCCC

At the broadest geographic scale, loss and damage (L&D) has its earliest history in the United Nations Framework Convention on Climate Change (UNFCCCC). The UNFCCC is the international treaty which houses efforts between nation-states to address anthropogenic climate change. All efforts within this body to address L&D specifically are based on the common-but-differentiated responsibilities (CBDR) to govern the global commons (McCarthy et al. 2014).

The first mention of L&D in the United Nations occurred before the UNFCCC entered into force. It was included in the declaration from the Rio Earth Summit (Wrathall et al. 2015), where signatories agreed that “...states shall...develop further international law regarding liability and compensation for adverse effects of environmental damage caused by activities within their jurisdiction or control to areas beyond their jurisdiction” (Principle 13, Rio Declaration 1992). In 1991, the island nation of Vanuatu, on behalf of the Alliance of Small Island States (AOSIS), proposed the inclusion of a L&D fund in the UNFCCC. Under this proposal, states would contribute financial resources to the fund on the basis of their differentiated responsibilities—50% of their contributions determined by national historical contribution of GHG emissions and 50% of the contribution based on capacity (as measured by GDP) (Annex V. Insurance Mechanism 1991).

When the UNFCCC text was solidified, however, the AOSIS proposal was not included, instead the text offered consideration to "...actions related to funding, insurance, and the transfer of technology" to address L&D (UNFCCC 1992). While AOSIS would continue to submit policy recommendations for the inclusion of L&D, L&D did not formally enter into the UNFCCC negotiations until the 13th Conference of the Parties (COP) in 2007, which laid the groundwork for what would become the Warsaw International Mechanism (WIM) on Loss and Damage, negotiated at COP 19 in Warsaw, Poland in 2013 (Warner and Zakieldeen 2011; UNFCCC 2008; UNFCCC 2014). The WIM houses all L&D considerations within the UNFCCC in three ways: risk management, coordination between stakeholders, and providing resources to address L&D.

Boyd et al. (2017) trace how, since AOSIS's earliest proposals, the consideration of L&D under the UNFCCC has progressed through several iterations: (1) adaptation and mitigation, (2) risk management, (3) limits to adaptation, and (4) existential (Boyd et al. 2017). These typologies differ in two primary ways—the relative focus on preventing future versus addressing existing L&D, and whether a consideration of responsibility for climate impacts is emphasized. The adaptation and mitigation typology focuses mostly on the prevention of L&D with no provision for responsibility, while the existential typology focuses primarily on addressing current L&D in part by establishing responsibility, and the other two fall somewhere in the middle. The WIM currently follows the risk management approach. While the WIM does provide space for finance transfer, as with all other aspects of UNFCCC-based negotiations, finance transfer in this case is voluntary and not based on required compensation.

Loss and damage in law

Over the past decade, a series of legal conversations have begun over how liability and compensation for past, actual, or future L&D might be secured. Unlike the UNFCCC, these efforts have not been bound by assigning responsibility to a single actor (e.g., nation states alone), but rather have been filed both against nation-states and companies, on behalf of municipalities, counties, states, and Non-Governmental Organizations (NGOs).

Seeking compensation for L&D through legal recourse is built upon a longer tradition of liability in legal theory and action. Legal scholars, for example, have drawn remarkable parallels between the lawsuits against tobacco companies and the potential to hold companies liable for ACC-driven L&D (Lipanovich 2005; Byers et al. 2017). In the U.S., at the end of the twentieth century, a series of lawsuits were filed by states against tobacco companies based on tort liability, which is used to address civil wrongs between two parties and provide compensation for the incurred costs of damages. Based in part on the tobacco industry's defective product, failure to warn the public about the dangers of the product, "moral depravity" related to their disinformation campaign, and active blocking of alternative, "healthier" tobacco products, the industry was made to pay $246 billion in total (Lipanovich 2005).

This approach has been adopted by those who want to secure finance for those impacted by anthropogenic climate change. In 2005, shortly after hurricane Katrina, residents of New Orleans filed suit against Murphy Oil for the emissions associated with their product (Comer

v. Murphy Oil 2007). Three years later, Kivalina, Alaska—both in its capacity as a native tribe and a city—filed a lawsuit against 24 oil, gas, electricity, and coal companies for the damages they faced from melting sea ice and related land loss (Kivalina v. ExxonMobil 2009). Both tort liability lawsuits were dismissed due to the political question doctrine (referring to the separation of powers in the U.S., generally based on a ruling in which the executive branch is determined to be better placed to make such rulings) and in part due to the difficulty in establishing causality. However, they provided a foundation on which other cases could be built. In the last few years, a new generation of anthropogenic climate change-related L&D lawsuits have been filed using a similar approach. Since 2015, citizens in the U.S., the Netherlands, France, and Canada have filed suit against their respective governments for inaction on climate change (related to mitigation) and pre-empting future unavoided L&D. Similarly, the Philippines launched a probe into the legal liability of U.S.-based oil and gas companies for climate impacts on the island nation. Meanwhile, in the U.S., cities, counties, and states have filed lawsuits against oil and gas companies due to projected L&D impacts (Sabin Center for Climate Law). Many of these legal suits are based in tort law, which includes "public nuisance" measures (in which the loss or damage is suffered by the public at large) and "product liability" measures (in which the manufacturer of a product is legally responsible for the damages caused by their product).

So far, several of the municipality-based lawsuits have been dismissed, at least in part based on the perceived inability of plaintiffs to provide sufficient evidence that L&D can be attributed to specific energy companies and nation-states (the defendants). A requirement for tort liability cases to be heard is to demonstrate "fair traceability." "Fair traceability" involves demonstrating that the "injury-in-fact" (loss or damage) sustained by the plaintiff can be attributed specifically to the actions of the defendant(s). Once “fair traceability” is demonstrated, the case can proceed to court; at this stage, there is an even higher bar of causation that needs to be established. This is true for all tort-based cases, including those based in nuisance- or negligence-based claims, and product- or strict-liability (Byers et al. 2017). Thus, to succeed in court, demonstrating causality from impacts to sources of emissions is a necessary step. In the case of climate change-related L&D, the causal chain connecting the actions of defendants in emitting GHGs to the climate impacts borne by the plaintiffs is longer and more complex than other environmental damages cases (e.g., local pollutants). Tort liability for climate change thus rests heavily on the scientific ability to demonstrate that plaintiff’s damages have likely been caused in part by anthropogenic climate change, and that those in turn can be connected to the defendants’ actions (Pfrommer et al. 2019; Marjanac and Patton 2018; Lusk 2017; Byers et al. 2017). As will be discussed in Section 1.1.3, this requirement can be a significant barrier to respond to the L&D of some of the most vulnerable communities.

Loss and damage in climate science

Climate change detection-and-attribution studies represent the third large domain generally explored in this space. Detection and attribution (D&A) encompass a set of methodologies to (1) detect an observed change in a physical hazard which would be highly unlikely with natural variability alone and then (2) attribute that change to anthropogenic climate change with a statistical measure of confidence (NAS 2016). D&A studies are conducted for different reasons—to better plan for adaptation, to examine current climate impacts, project what those impacts may be in the future, support climate damages lawsuits, or just simply for scientific curiosity (Hulme 2014). All, however, either directly or indirectly, contribute to the conversation on L&D by measuring the extent to which observed climate impacts are driven by anthropogenic climate change versus natural climatic variability (Lusk 2017).

Attributing observed L&D to anthropogenic climate change involves investigating two links—between emissions and meteorological change, and between that change and socio-environmental impacts (Otto et al. 2014). D&A studies have mostly been published over the past decade because methods had to be developed (and imported from epidemiology) to address the significant inherent spatial complexity and temporal opaqueness of the phenomenon. Most D&A studies are concerned with assessing the extent to which anthropogenic forcing influenced meteorological change; however, a select few go further. D&A studies have been published attributing change in intensity or frequency of impacts from drought, extreme precipitation, and heatwaves to anthropogenic forcing (e.g., Herring et al. 2015). Scientists have been developing methods to conduct what can be called "end-to-end attribution" (Stone and Allen 2005). "End-to-end attribution" is the process of attributing extreme events to emissions of GHGs, using probabilistic approaches such as calculating the "fraction of attributable risk" (FAR). Within this domain, yet using different methods, Ekwurzel et al. 2017 attributed slow-onset climate impacts to specific sources of emissions—specifically, global average temperature rise and sea level rise to emissions from industrial carbon producers. This was made possible by Heede (2014), who traced GHG contributions from 1750 to 2010 to industrial carbon producers. See Section 1.3.1 for more details.

1.1.2. Defining Responsibility, Accountability, Justice, and Loss and Damage

Not all approaches to L&D are based in principles of responsibility and accountability. Returning to the typology of L&D introduced by Boyd et al. (2017), the risk management and limits to adaptation approaches do not necessarily require proof of damage attributable to anthropogenic climate change and hence are somewhat easier to implement (Warner et al. 2009; Boyd et al. 2017; Huggel et al. 2015). Approaches in the risk transfer/risk sharing realm, such as insurance-based mechanisms, make automatic pay-outs based on some external measure of risk (Benami et al. 2021). These approaches generally rely on early warning systems to determine what constitutes a pay-out moment based on a climatic measure (e.g., greater than a certain amount of rainfall in a 24-hour period (flooding) or less than a certain amount of rainfall in a two-month period (drought)). Impacted people may be identified as all those who live in a certain geographic region, but also may be further split up by occupation, role as head-of-household, or by income. In this way, if the climatic measure passes the threshold, payments automatically go out to those who are identified as vulnerable. There are some ethical concerns related to how thresholds are defined, and which communities receive payments (Hulme 2014).

The risk-transfer approach transfers or shares risk among all those who participate in the insurance pool as it minimizes cost that otherwise would be too great for people to bear themselves. In some alternative approaches, payouts come from a government-funded pool. This approach has broad support—there is support for risk-reduction-based approaches that rely on funding from developed countries the international climate policy realm (Huggel et al. 2016:905-906; Warner et al. 2009) for index insurance-based approaches (Warner et al. 2009; Munich Re; Surminski et al. 2016). Notably, the earliest proposal for a loss and damage fund under the UNFCCC was that of an insurance pool and would have been based in principles of responsibility (Stabinsky and Hoffmaister 2015). If nation-states with large historical causal—and moral—responsibility were to voluntarily contribute substantially to a fund, it could act as a form of insurance pool in which the 'polluter pays' and other countries could tap into that fund to pay for addressing losses and damages from climate events. However, such a responsibility-based approach to paying into an insurance pool has not been met with the same level of support.

As risk management approaches do not require demonstrating proof in causality, they are hence to an extent easier to pursue (Huggel et al. 2015). Therefore, what rationale exists to pursue more difficult legal and policy mechanisms for addressing L&D which do require that proof? Such mechanisms—including legal liability and policy-based compensation—offer two things that may advance justice in a way that risk-based insurance mechanisms are unable to. First, the impacted community may be defined at different scales, especially in legal pursuits, and therefore communities have the option to pursue accountability for their L&D as they not pre-determined by the body who creates the insurance mechanism. Second, 'big emitters' may be brought in to be held accountable and pay out for the L&D, instead of the people paying from their own pool. For a UNFCCC-based insurance pool, to provide substantial enough funding, contributions to the fund would need to be based on a measure of historical contributions from each nation-state to climate change, and then the nation-states would need to voluntarily contribute proportionally to and substantially enough to match their historical responsibility. Who would voluntarily contribute substantially enough to such a fund to meet their accountability requirements and the on-the-ground needs? This voluntary nature of such contributions is what makes a corrective justice-based L&D mechanism so unlikely.

Instead, an accountability-based approach to climatic losses and damages centers three related concepts: distributive justice, corrective, and procedural justice, under the umbrella of climate justice.

Responsibility for climate impacts is a core value of climate justice. Climate justice is both an organizing principle and a research program which strives to address the historical economic, political, and social conditions in which climate change is rooted, and engage solutions that support communities traditionally marginalized and most impacted (Schlosberg and Collins 2014). Central to climate justice is the understanding that there are uneven distributions of both benefits and harms of GHG-emitting activities, leading to differentiated responsibilities in which those who have contributed least to GHG-emitting activities tend to bear disproportionate burdens from anthropogenic climate change (Gardiner 2011; Schlosberg 2013; Robinson and Shine 2018). Thus, there are multiple "varieties" of justice which intersect with climate change. These include distributive justice, related to the (in) equal distribution of harms or benefits, and procedural justice, ensuring that those most impacted may participate in decision-making, as their historical exclusion "enabled inequitable distribution" in the first place (Schlosberg and Collins 2014). A core pillar of climate justice is furthermore corrective justice, in "...the transfer of resources from those responsible for the injustice of climate change to those most vulnerable to it" (Schlosberg and Collins 2014), in order to address the uneven distribution of unavoided impacts (distributional justice) (Gardiner 2011).

Responsibility and accountability are therefore crucial concepts as they relate to corrective justice. Conceptualizations of, and the relationship between, responsibility, answerability, attributability, and accountability are contested, as exemplified by the many definitions presented by philosophers (e.g., Cuomo 2011; Smith 2012; Shue 2017), by those interested in global governance (e.g., Clapp 2005; Mason 2008), and by those focused on environmental and climate justice (e.g., Schlosberg and Collins 2014; Schlosberg 2013). At its simplest, responsibility can be thought of as an obligation that exists between an agent and the public or small group of people to "do no harm" (Shue 2017; Mason 2008). However, responsibility also hinges on the ability to avoid doing harm; blameworthiness may only exist if there was an alternative to causing harm, the harm was foreseen, and the agent made an evaluative judgment (or choice) regarding the potential outcomes (Cuomo 2011; Frumhoff et al. 2015; Smith 2012). Responsibility may thus be considered as a relationship between an agent and a community, the latter which may bear the impacts attributable to agent's attitudes, omissions, or actions (Smith 2012). When harm is done, and that relationship is breached, then there is a responsibility to "clean up your own mess" (Shue 2017), which leads into accountability. Answerability and redress are core elements to accountability, in which agents are "…"held to account" for their (in) actions according to set standards" (Mason 2008). In this dissertation, responsibility will refer to the obligation to do no harm within the relationship between the emitting agent and climate-impacted party; accountability will refer to answerability and redress when the obligations of that relationship are breached.

Thus, I refer to those approaches to L&D that focus on accountability for climate impacts, rooted in principles of climate justice, as "accountability-based approaches." This type of approach speaks to the pursuit of justice in two realms—(1) justice at the source of GHG emissions, by holding accountable those who have "caused" climate change, and (2) justice for the most vulnerable communities at the sites of exposure to climate impact, by addressing both the climate change-fueled L&D as well as acknowledging the historical, complex, and layered marginalization that led to them being impacted, while finding solutions that address the root causes. Thus, an accountability-based approach encourages addressing L&D in a way that strives for the two realms of justice through the act of re-establishing a relationship between them.

Non-accountability-based approaches also are based in justice, and yet are broadly confined to the second type. For instance, an approach to L&D which focuses on supporting impacted communities through development of early warning systems and investing in resilient infrastructure is based on justice at the site of impact; it however does not address the responsibility of the entity that in part caused the impacts. In certain cases, this may be insufficient to address both historical and current harms. Even if adequate financial (and non-financial) support was provided to the impacted communities, it would not address the consideration of historical injustice (outlined above).

That being said, while an accountability-based approach rooted in climate justice should include some form of resource transfer, that material transfer on its own is a necessary yet insufficient aspect for climate justice. Focusing solely on financial transfers for establishing accountability for L&D may "...suggest that environmental, personal, and cultural goods and services can be subsumed into a liberal conception of property rights..." (Wrathall et al. 2015). While certain types of impacts that can be compensated (damages), there are items, places, and concepts of qualitative importance that cannot be quantitatively valued (Wallimann-Helmer 2015). When compensation is pursued as the sole action, it can shift to what would become a restorative relationship into a transactional relationship. Beyond compensation, certain calls for accountability involve “reconciliation…including important forms of acknowledgement and recognition” (Thompson and Otto 2015). However, in many cases, when considering the material needs of paying for repairing damages, a financial transfer is necessary to strive for justice. Finance transfer is thus a partial yet core aspect. In this way, accountability-based approaches represent an imperfect justice.

Understanding L&D in these terms, therefore, has the potential to start the process of transferring finance across uneven distribution of emissions and impacts to compensate for damages and provide an opportunity for restitution. However, there is a gap between “understanding” and “realizing.” There are certain tensions that have thus far largely prevented the realization of such mechanisms.

1.1.3. Tensions in the Field

There are significant complications, including political resistance, when operationalizing an accountability-based approach to L&D. These complications in large part stem from first the process of determining who was responsible for avoiding harm (and therefore who is accountable for compensation), and second determining the impacted community.

Complications of the emitting agent: Who is responsible?

The first complication stems from determining who is in the position of the responsible agent (i.e., the GHG emitter). First, while GHG emissions are pervasive throughout society, that does not necessarily mean that responsibility is similarly distributed. The assertion that emissions are so intertwined with the global economy that they cannot be assigned to an agent maintains that both everyone and no one is responsible for the problem. Perhaps everyone—nation-states, industry, individuals, producers, and consumers, alive today and yesterday—bear some degree of responsibility, but what about significant responsibility? Identifying one "responsible agent" does not imply that other agents bear no responsibility; rather the process of choosing one agent involves indicating that specific agent bears a unique responsibility as a function of its GHG emissions and "attitudes, omissions, or actions" (Smith 2012). These "attitudes, omissions, or actions" include both relative contributions to atmospheric concentrations of GHGs and whether an evaluative judgment regarding the agent's action was made, particularly if the agent had the information as to the consequences of their action (or inaction).

Should emissions be attributed to nation-states, industrial carbon producers, or individuals? Similarly, should they be stratified by producers of emissions or consumers of the goods produced (Cuomo 2011; Bastianoni et al. 2004)? These aggregations—producers versus consumers, and scale—are adopted by different mechanisms and domains of study. The UNFCCC adopts the nation-state producer approach, while many climate liability lawsuits attribute emissions to industrial carbon producers. There are fundamental assumptions built into each approach. Aggregating to the level of the nation-state derives from an ontology of the state possessing the authority to influence emissions through command-and-control or market mechanisms, thereby bearing the responsibility for damages from emissions when they are not curbed (Rajamani 2000). Conversely, aggregating to the level of the industry stems from an ontology where firms are rational actors, possessing the self-determination to make decisions and therefore bear responsibility for those decisions when they produce harms (Frumhoff et al. 2015). Finally, aggregating emissions to the consumer assumes, accordingly, the ability to dictate changes in supply through altering demand (Bastianoni et al. 2004). These questions are explored in Chapter 4.

Discussions of accountability for L&D have been fraught with tension, as those who may be considered as responsible for the emissions are generally resistant to the accountability-based approach, mostly due to its logical conclusion—liability and compensation. Central to this resistance is the assertion that responsibility cannot be attributed to one agent. In the legal sphere, industry and related interest groups have filed countersuits against individual lawyers and those municipalities who have sued for climate related L&D. A think tank, the Competitive Enterprise Institute, filed a suit against a law professor, Ann Carlson, based on her work on climate liability suits, following a similar tactic as used against climate scientists as a method of intimidation. In response to the Californian climate lawsuits, ExxonMobil began to file countersuits against the cities and counties, claiming they failed to disclose climate risks in their bonds. Finally, company defendants have thus far been successful within the body of existing current private climate litigation; industry appeals to judges on multiple cases have resulted in dismissal based on the assertion that the emissions cannot be tied to the companies specifically. This means no lawsuit has passed the discovery stage into the trial stage. This is true for the UNFCCC as well; the WIM does not include a liability and compensation provision due to resistance of certain industrialized countries. The WIM provided an institutionalized shift from a liability and compensation approach to one of hazards and risk management (Wrathall et al. 2015). This shift occurred because "discussion of liability compensation had remained controversial for most industrialized countries," (Warner and Zakieldeen 2011), mostly due to the fact that they have contributed the bulk of historical emissions. This shift was cemented with the Paris Agreement at COP 21 in 2015.

The Agreement states that “Article 8 (for the WIM) does not involve or provide a basis for any liability or compensation” (Paris Agreement 2015), language that was included to assuage the U.S.’s concerns about over potential requirements to provide finance in the future of developing countries.

Complications at the site of impact: attributability vs vulnerability

Determining who or what constitutes a “climate-impacted community” is an important consideration related to justice at the site of impact. Climate change can lead to increased frequency or intensity in hazards (e.g. drought, fires, floods), and if a community is exposed to or vulnerable to that hazard, can be impacted (IPCC 2014). A community’s vulnerability to climate change is predicated on pre-existing factors which influence their “propensity or predisposition to be adversely affected” (IPCC 2014). These factors include socioeconomic relationships, political and cultural factors, and the broader local environmental context. Therefore, communities with the largest pre-existing vulnerabilities will generally incur more severe L&D as compared with those with low vulnerability. Climate change thus largely disproportionately impacts low-income, communities of color, and communities situated in the Global South, due to those pre-existing structural drivers of inequality and marginalization (O’Brien and Leichenko 2000; Tschakert et al. 2013).

While an anthropogenic climate change-driven hazard may contribute to significant L&D, its intensity or relative contribution may pale in comparison to other environmental or social, political, and economic factors which initially made the community vulnerable. These communities are highly climate-impacted *because of* their exposure to and vulnerability to the hazards. Conversely, when areas with lower pre-existing vulnerability experience a hazard that leads to L&D, while the community may be able to adapt more easily, that L&D is more attributable to anthropogenic climate change. These areas of lower vulnerability tend to have higher levels of wealth; for example, damages may be accrued because of the destruction of a valuable property. In other words, the less vulnerable a community is to climate impacts, the more clearly attributable those impacts are to anthropogenic climate change when they occur, and vice versa.

Therefore, when determining who is a "climate-impacted community", the following question arises—are they the communities, or societies, with the highest vulnerability, the highest damages, or places with the clearest and easiest-to-attributed climate-related L&D (Hulme 2014)? This tension between *attributability* and *vulnerability* can have significant implications for outcomes of mechanisms to address L&D.

This tension is clearly evident in legal cases. Table 1 outlines the locations of the tort-based climate liability suits that have been filed in the U.S. as of 2022, as well at the ranked poverty level of the county (or county-equivalent) in which it was filed (based on 2010 census data). The ranked poverty level shows the poverty level of the county compared to all other counties in the state, where low values correspond to lower poverty levels and high values correspond to higher poverty levels. As can be seen, most lawsuits have been filed in lower poverty counties—13 of the lawsuits were in the lowest 50th percentile, while 7 are in the lowest 25th percentile. Only 5 were filed in higher-poverty counties, above the 50th percentile. Two of those were the first such lawsuits filed in New Orleans, Louisiana (2005) and Kivalina, Alaska (2008), located in a borough and parish, respectively, with higher poverty rates than their respective states. The other three, filed in 2018 and 2020, were in the cities of Baltimore, New York, and Hoboken, a bedroom community of New York. Baltimore City is an independent municipality. It is true, however, that focusing on county-level indicators of income can blur sub-county community experiences. For instance, two of the California lawsuits were filed on behalf of cities of lower socio-economic status than the county average (Richmond in Contra Costa County and Imperial Beach in San Diego County).

However, aside from Kivalina, these places are relatively high resource urban municipalities, and while poverty rates in the cities themselves may be higher than the county or state average, there is nonetheless economic wealth concentrated in many of them. The places with the lowest vulnerability tend to have more resources—financial and social—which may yield lawsuits. Similarly, these places have some of the highest property values which, when damaged, can yield some of the highest monetary damages. While not being the most vulnerable places, they may be— from a tort liability standpoint—the most easily attributable, and therefore winnable, cases.

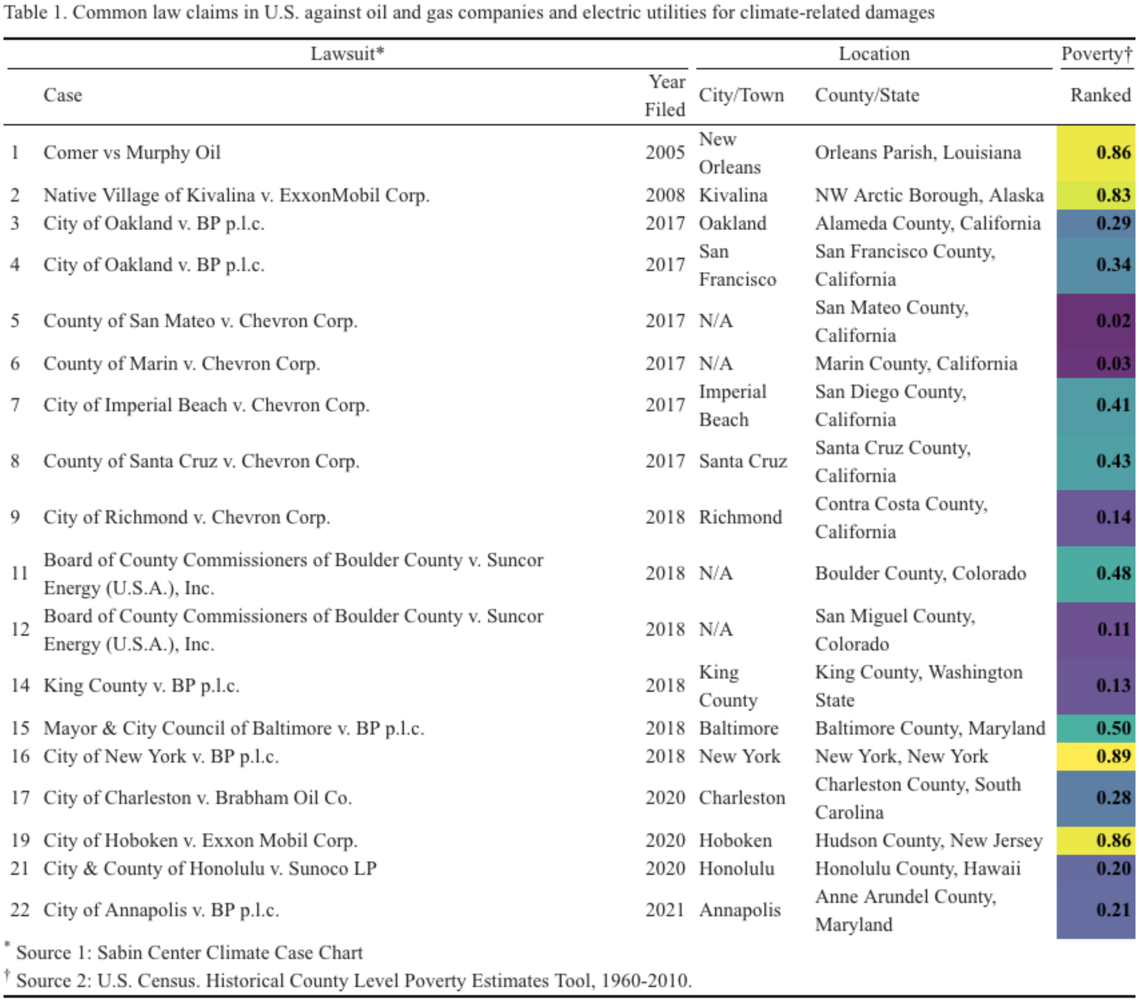


Table 1. Common law claims in U.S. against oil and gas companies and electric utilities for climate-related damages

	Lawsuit*		Location		Poverty†
	Case	Year Filed	City/Town	County/State	Ranked
1	Comer vs Murphy Oil	2005	New Orleans	Orleans Parish, Louisiana	**0.86**
2	Native Village of Kivalina v. ExxonMobil Corp.	2008	Kivalina	NW Arctic Borough, Alaska	**0.83**
3	City of Oakland v. BP p.l.c.	2017	Oakland	Alameda County, California	**0.29**
4	City of Oakland v. BP p.l.c.	2017	San Francisco	San Francisco County, California	**0.34**
5	County of San Mateo v. Chevron Corp.	2017	N/A	San Mateo County, California	**0.02**
6	County of Marin v. Chevron Corp.	2017	N/A	Marin County, California	**0.03**
7	City of Imperial Beach v. Chevron Corp.	2017	Imperial Beach	San Diego County, California	**0.41**
8	County of Santa Cruz v. Chevron Corp.	2017	Santa Cruz	Santa Cruz County, California	**0.43**
9	City of Richmond v. Chevron Corp.	2018	Richmond	Contra Costa County, California	**0.14**
11	Board of County Commissioners of Boulder County v. Suncor Energy (U.S.A.), Inc.	2018	N/A	Boulder County, Colorado	**0.48**
12	Board of County Commissioners of Boulder County v. Suncor Energy (U.S.A.), Inc.	2018	N/A	San Miguel County, Colorado	**0.11**
14	King County v. BP p.l.c.	2018	King County	King County, Washington State	**0.13**
15	Mayor & City Council of Baltimore v. BP p.l.c.	2018	Baltimore	Baltimore County, Maryland	**0.50**
16	City of New York v. BP p.l.c.	2018	New York	New York, New York	**0.89**
17	City of Charleston v. Brabham Oil Co.	2020	Charleston	Charleston County, South Carolina	**0.28**
19	City of Hoboken v. Exxon Mobil Corp.	2020	Hoboken	Hudson County, New Jersey	**0.86**
21	City & County of Honolulu v. Sunoco LP	2020	Honolulu	Honolulu County, Hawaii	**0.20**
22	City of Annapolis v. BP p.l.c.	2021	Annapolis	Anne Arundel County, Maryland	**0.21**

* Source 1: Sabin Center Climate Case Chart

† Source 2: U.S. Census. Historical County Level Poverty Estimates Tool, 1960-2010.

Table 1. Common law claims in U.S. against oil and gas companies and electric utilities for climate-related damages. Ranked poverty scores is county-level, and shows the poverty level for the county in which the claim was filed as a function of all counties in the state—a low score corresponds to the lowest poverty-level county in the state.

Similarly, scientific detection and attribution studies are most successful when the climate signal is clear. There are several necessary components to a successful D&A study—few confounding variables present, "good data", available regional expertise, and research funding. D&A studies work by identifying the human "signal", or evidence that increased radiative forcing from human activities (specifically anthropogenic forcing) led to the change in hazard. Conducting a D&A study in a place with many co- occurring processes (confounding variables) that simultaneously influence the impact being studied makes it difficult to isolate the climate signal from the noise. This can preclude D&A studies from being conducted for more complex events. Similarly, the studies require “good data”—data that has consistent temporal and spatial coverage with the appropriate resolution, and that is accurate (measured by strong agreement with other products). Good data exists overwhelmingly in more industrialized areas of the world. Finally, even when data and the “perfect” case study exist, the availability of funding and expertise are limited resources; in some cases, due to a lack in scientific regional expertise and mismatched funding cycles, some areas of the world may receive less attention. Therefore, not all cases—or even case types—of potential climate change-related L&D receive attribution research (Huggel et al. 2016). For illustrative purposes, the American Meteorological Society’s special issue on “explaining extreme events of 2014 from a climate perspective” included 33 case studies—two were conducted in South America and another two in Africa, compared with six in North America, seven in Asia, and five in Australia alone (Herring et al. 2015). This has improved, however; recent issues have included a more distributed global coverage.

Finally, this tension between attributability and vulnerability can also exist in policy-related financial mechanisms. As highlighted by Hulme 2014, focusing on easy-to-attribute communities “raises practical and ethical concerns about any subsequent investment allocation guidelines which (exclude) the victims of ‘tough-luck weather’” from funds. This critique can be extended to communities impacted by other co-occurring environmental, social, political, or economic processes. Given that the WIM does not have a provision for compensation, the extent to which this tension would be extended into the international arena is subject to conjecture. That being said, if it were based on compensation for losses, whereby developed countries would foot the bill, it is likely that there would be a relatively high standard for (a) demonstrating that the L&D suffered by a county was in some part related to anthropogenic climate change, and (b) that the damages would not have occurred were it not for climate change. Likely, there would be significant negotiation regarding adequate valuation of damages. There would likely be even more difficulty in determining adequate payment for losses—those things that cannot be recovered or mended—and whether payment is ethical.

While significant efforts are being made to level the playing field and provide resources—scientific, legal, and policy—to some of the most vulnerable and marginalized communities, there is still a disproportionate distribution of these resources.

1.2. Dominant Frames Underwriting the Field

The previous section introduced the practitioner field of climate accountability and identified two major challenges present in the field. These challenges have largely prevented the field of accountability from progressing in the two mechanisms and pose potential challenges to ensuring the mechanisms promote justice for the most impacted communities. The first challenge relates to establishing responsibility. Who—what entity, for what time period—is responsible and thus should be held accountable in these mechanisms? The second challenge revolves around how best to ensure that these mechanisms—and research conducted to support these mechanisms—best serve impacted communities instead of the easiest-to-attribute places. The rest of this chapter—in truth, the rest of this dissertation—will interrogate how advancements in research may support addressing these two challenges, and where potential pitfalls lie.

There are certain dominant frames that have underwritten much of the conversation in this field. These frames have different assumptions regarding responsibility, causality, and impacts, and each provide a somewhat different answer to these challenges. These theoretical foundations have been largely imported from the broader conversations regarding socio-environmental dimensions of climate change to the specific field of climate accountability, and now implicitly underlie the different approaches to the field. In engaging with the socio-environmental dimensions of climate change, scholars broadly approach the issue with certain normative assumptions and backgrounds. Moving beyond the demarcations of 'political scientist' or 'atmospheric scientist', we bring approaches or frames that set how we see and interpret the world and explain everything from causality to impacts of climate change. There are five such dominant approaches explored in this section. They are frames that repeatedly appear in scholarship about or tangential to the question of climate accountability. They are: (1) state sovereignty, (2) neoclassical economics, (3) political economy and ecology, (4) science and technology studies, and (5) environmental and climate justice. The first three are identified and interrogated by McCarthy et al. 2014 as defining the 'socio-cultural dimensions of climate change', while the latter two are central to this question of climate accountability.

These frames cohere around the physical aspects of anthropogenic climate change. Among them, there is consensus regarding the material drivers (emissions of greenhouse gases and reductions of carbon sinks), the mechanism by which these drivers lead to anthropogenic climate change (the enhanced greenhouse effect), and the primary impacts of anthropogenic climate change (e.g. increasing global average temperature, expanding and rising seas, and changes in precipitation patterns). Where they differ, however, is based on how they conceptualize sources of emissions, vulnerability to impacts, and the questions of causality and responsibility. They therefore differ on the social dimensions of climate change. Therefore, approaching the question of climate accountability through these various frames yields significantly different implications. The frames are explored below, including how they address or contribute to the two major challenges.

1.2.1. The Five Frames

***State Sovereignty**:* Within the 'state sovereignty' frame, greenhouse gas (GHG) emissions are a form of transboundary pollution as they do not stay confined by the administrative borders within which they were emitted, and thus affect the global commons of the atmosphere, and by extension, the global climate (Ostrom 1990; McCarthy et al. 2014). Harms thus are placed on populations beyond the borders of the emitting nation state (McCarthy et al. 2014; Bastianoni et al. 2004; Mason 2008). In this frame, the nation-state as an aggregate entity is the emitting actor. Therefore, emissions produced within a border of a nation-state are ascribed to that state. Moreover, the nation-state as a whole is also the impacted place, as this frame largely remains geographically and sociologically insensitive to heterogeneity (including inequality) between societies and individuals within those borders.

Therefore, the 'state sovereignty' frame approaches the question of climate accountability by focusing on inequities among nation-states. These inequities occur as a 'climate debt' that has resulted from the historically disproportionate rate at which countries have engaged in GHG-emitting activities, thereby having a disproportionate negative impact on the global commons (Neumayer 2000). While considering past emissions that have contributed to the climate debt, this approach is largely concerned with forward-looking considerations for how to allocate the remainder of the carbon budget between 'luxury emissions' (in nation states that have used fossil fuel energy to build their economy) and survival emissions (in nation states that are earlier along the development pathway) (Rajamani 2000). While the concept of a single ‘development pathway’ can, and should, be critiqued, nation-states that have contributed the least to GHG emissions tend to be those whose resources and people were exploited through imperialism and colonialism and thus have been halted along their respective ‘development pathways’; conversely, nation-states who have enjoyed centuries of unbridled expansion and development at the cost of others bear greater responsibility for taking action on climate change (Peet, Robbins, and Watts 2010).

As such, under this approach, the idea of “common but differenced responsibilities” (CBDR) was coined by the United Nations Framework Convention on Climate Change (UNFCCC) Earth Summit in 1992. CBDR underpins much of the consideration of responsibility. Moreover, impacts and emissions alike are to be addressed through international governance (McCarthy et al. 2014). To address this problem of the pollution of the global commons, the state sovereignty frame leverages international spaces, like the UNFCCC, to try to limit emissions and the destruction of carbon sinks. As such, backward-looking approaches focusing on climate accountability also operate through these international negotiating spaces (for example, the UNFCCC WIM).

***Neo-Classical Economics**:* The neo-classical economics-based approach views the fundamental problem of climate change as two connected failures. The first failure is that GHG emissions and associated climate change have become external to the market—as “external costs” or “externalities”—and as these costs have not been included in the market valuation of the organization’s activities, they constitute a market failure. The second failure is the failure to “internalize” these externalities (McCarthy et al. 2014; Nordhaus 2013; Stern 2008). As with the state sovereignty view, the neo-classical economics view rests, in some fashion, on the tragedy of the commons and the related externalization of the costs of profit onto another entity. This frame assumes a rational actor who, by definition, makes decisions that are the most rational for their own profit maximization. As the actor has a carbon footprint, “…the emission of greenhouse gases…is perfectly sensible for selfish, utility-maximizing rational actors, when they are allowed to do so for free and profit from it” (McCarthy et al. 2014). If they were not allowed to do so for free, anthropogenic climate change would likely still exist but at an ‘acceptable’ level, or at the point in which the marginal costs of climate-induced impacts meet the marginal abatement costs (Nordhaus 2013; Aldy et al. 2010).

To pursue responsibility and internalize externalities, most proposed solutions are based on the commodification of carbon: if a price is put on carbon—such as setting a carbon tax based on the social cost of carbon—the cost is then internalized to the emitting entity, and the entity can include the cost in cost-benefit analyses (Nordhaus 2013; Stern 2008). The challenge is in correctly estimating the social cost of carbon to lead to an efficient solution. Given the non-insignificant uncertainties in climate and economic models, impacts may be economically underestimated, reaching a suboptimal point and failing to ‘internalize’ the true costs (Heal and Millner 2014). There are similarly ethical deliberations regarding the correct ‘discount’ rate, or at what rate impacts on future generations should factor into decisions today—the largely used discount rate prioritizes costs now over costs in several generations, which is a fundamental mismatch with the timeline of climate change, in which emissions today affect the climate for several generations (Hepburn 2006). An alternative solution is a hybrid model including both a cap on emissions and allowing for trading of emitting permits (cap-and-trade), thereby ensuring enough emissions reductions but allowing for the market to determine how best to allocate emission-reducing actions. Like the state sovereignty frame, much of this frame is focused on future emissions.

***Political Economy & Ecology**:* The 'political' in political economy and political ecology recognize emissions, and therefore climate change, as a byproduct of the structural exploitation of resources and of people (Robbins 2011). Political economy theorizes climate change as rooted in "…capitalism and colonialism exploiting forest and then fossil fuels across the globe for accumulation, and to a multinational fossil fuel industry supported by states through subsidy, warfare, and special interests" (Liverman 2015:304). Such accumulation has occurred through the dispossession of land and resources. This 'accumulation by dispossession' has occurred both by and to nation-states, and, especially in the more recent historical record, by corporations to civil society (Harvey 2003; Liverman 2004) and has resulted in deep inequities (McCarthy et al. 2014). Political ecology similarly examines how colonialism-capitalism has created deeply entangled institutions (Peet, Robbins, and Watts 2010), such as Bridge's (2016) "resource/state" whereby the systematic extraction of resources has propped up the creation of the state and vice versa.

While political economy provides a larger analysis of power, structural inequalities, and exploitation, political ecology provides space for the inclusion of principles and methodology from atmospheric chemistry, ecology, and geophysics to examine the implications of human actions on the atmosphere, on the environment, and on human societies. Additionally, it both interfaces with the structural conditions surrounding the phenomenon of climate change, as well as locates the agency of individuals or smaller institutions, as it can "…counter an over-emphasis on the political economy of climate that can erase the agency of individuals and communities or fail to take science and nature seriously" (Liverman 2015). Finally, it is geographical by design and therefore sensitive to scale, so that analysis crosses scales from local sources of emissions to global ramifications of radiative forcing to regional and local impacts (Peet, Robbins, Watts 2010).

In the pursuit of climate accountability, while both political economy and political ecology accept emissions as the direct drivers of climate change, these approaches focus on the systemic drivers, or root causes, of emissions. To 'solve' climate change, therefore, one must address the underlying structural inequalities and power grabs from deeply entangled institutions that underlie emissions. Yet, while firms and the state have some power and agency to make changes, it is a much more structural approach than the governance and neo-classical economics-based approaches. While there are rational actors, they cannot make significant changes to emissions without a more robust transformation of the larger political and economic systems. Whether entities have agency to make those transformations, and who those entities are, differs across this broad approach.

***Science and Technology Studies**:* Science and Technology Studies (STS) is concerned both with the materiality of GHG emissions and the struggle over the position of the 'expert' regarding those emissions. STS interfaces with the materiality, or physical properties, of emissions and how they affect the earth's climate system. Determining however how those physical properties and their interactions in climate sciences are represented as 'correct' or 'expert' knowledge is where the STS approach provides an analysis of politics, power, and special interests. In this view, science is a political battleground, in which scientists, fields, and industry are vying for credibility and control over or ownership of ‘the expert opinion’. Science is far from neutral, but rather has entered political and socio-cultural realms (Jasanoff 2011). Therefore, this approach is concerned with what knowledge is, how it is produced, and who gets to produce that knowledge (Hess and Frickel 2014). Disinformation, or climate denial, is therefore the result of certain actors having won the title of ‘expert opinion’ and proceeding to share misinformation. This can then influence policy and culture. Furthermore, STS offers the concept of ‘sociotechnical imaginaries’: a theoretical framework to understand how certain visions and goals for a future, as made possible by science and technology, are shaped through control over the dominant narrative (Jasanoff and Kim 2013). These competing narratives and visions replicate because of larger political and economic dynamics – the role of media, industry funding of disinformation, and politics in academic and science itself. Therefore, (re)taking the position of expert is of utmost priority to be able to promote alternative society-wide visions and goals.

The battleground of climate accountability in this field then is in the battle for credibility across scientific, political, and socio-cultural communities. Countering disinformation, uncovering scientifically invalid claims, winning public acceptance, and instilling a sociotechnical imaginary in the public are key. For example, in *Merchants of Doubt*, enormous agency is ascribed to a small “handful of scientists [who] obscured the truth on issues from tobacco smoke to global warming” as they exploited uncertainties in the scientific process (Oreskes and Conway 2010). Fighting disinformation on the public stage is an answer to working toward responsibility. This includes both knowledge and rhetoric around the materiality of GHG emissions and impacts, as well as the narratives of what is possible within the sociotechnical imaginaries.

***Environmental & Climate Justice**:* Environmental justice (EJ) is ultimately concerned about how already-marginalized communities disproportionality bear the burden of toxins and other environmental hazards (Schlosberg 2013; Mohai, Pellow, and Roberts 2009; Bullard 1990). The community is central in this approach. Environmental injustices occur when communities are treated as sacrifice zones, or areas where, "…human lives are valued less than the natural resources that can be extracted from the region" (Buckley and Allen 2011:171; Klein 2015). That higher burden is differentiated along geographic lines and through matrices of domination. The 'matrix of domination' paradigm understands how the axes of race, class, and gender interact, reinforcing one another, whereby the combination of each of the three categories creates a unique position in the social hierarchy (Collins 1990). The research program of climate justice (CJ) is a more recent development with its roots in EJ (Schlosberg 2013). While EJ looks to the disproportionate burdens on communities, CJ is also concerned with power and the disproportionate sources of those burdens. Thus, while EJ may focus more on local sources of pollution, CJ crosses scales more easily from local to global and global to local. CJ is also concerned with distributive equity, or equity in sources of emissions (Schlosberg 2013). It therefore lends itself to assessing disproportionality between the largest emitting entities and the communities most impacted by climate change—whereby those most impacted by climate change often have contributed least. The core aim of EJ is to address inequities as "all people and communities are entitled to equal protection of environmental and public health laws and regulations" (Bullard 1990). The core of climate justice is to "raise the voices of those communities least responsible but most severely impacted—viz., poor people of color and indigenous peoples—and demands a climate policy that redresses existing economic and environmental inequality" (Dayaneni 2009).

Responsibility within an EJ/CJ frame, like the political economy and ecology frame, addresses disproportionate sources of emissions, while recognizing that emissions are not the primary cause. As explained by Dayeneni's concept of 'carbon fundamentalism': "the atmospheric carbon concentration levels are an indicator of the problem and must be addressed…such a narrow framing hides the larger ecological context and the inequitable economic system that got us here" (Dayaneni 2009). To strive for responsibility and accountability, rights-based and restorative justice-based approaches are centered (Scholsberg and Collins 2014; Wilder et al. 2016; Dayaneni 2009). Disproportionate historical emissions are considered to identify responsible parties. Yet techno-solutions and monetization of carbon are rejected as solutions (Scholsberg and Collins 2014; Dayaneni 2009). Compared to the political economy and ecology frames, however, in the EJ/CJ frame, the community is centered rather than the concept of climate change. Therefore, any actions toward responsibility or accountability will be dictated by the unique needs of the community, which may center around climate impacts or may not.

1.2.2. Comparing the Five Frames

Packed into each of these frames are assumptions about where the problem occurs, why climate change exists, what accountability looks like, and which entity is responsible. These assumptions are reviewed in Table 2.

	State Sovereignty	Neo-Classical Economics	Political Economy & Ecology	STS	Environmental & Climate Justice
Central Responsible Node	Nation-state	The market	The System	Knowledge brokers	Proximate polluters, made possible by the system.
What does justice look like for impacted community?	State-funded payouts / compensation	Payouts / compensation	Addressing systemic processes leading to impacts.	N/A	Community-led initiatives (one size does NOT fit all).
How injustice should be rectified	Policy instruments.	Put a price on it.	Systemic change.	Dispel disinformation & create a vision.	Other actors take direction from community.
Scale / Site	Nation-State Scale & Global Atmospheric Commons	Industry & Markets	Institutional (Political Economy); Local/Community + Institutional (Political Ecology)	Texts, debates, institutions.	Community-level
Aliases	Territorial model	Market solutions	Structural	Expert knowledge	Community activism & empowerment

Table 2: Assumptions about responsibility and justice in the five dominant frames.

As described in Section 1.1, the state-sovereignty and neo-classical economics frame have defined and shaped the plurality of mechanisms on the socio-environmental dimensions of climate change. Much of climate change-related decision-making occurs at the level of the nation-state or through market instruments. For example, the international negotiations space under the United Nations Framework Convention on Climate Change (UNFCCC) falls squarely within the state sovereignty frame. As evidenced by the failure of the UNFCCC WIM (Section 1.1.1), this frame in ascribing power to the level of the nation state is unwieldy due to the lack of an inter-state enforcement mechanism. Moreover, this frame cannot distinguish between the actions of non-state actors. It is assumed that the most relevant decision-making power exists at the level of the nation-state. But what of non-state actors? Moreover, what of impacts occurring within the borders of a nation-state, across a highly inequitable national population? This is a question I will revisit in Chapter 4. The neoclassical economics frame is also present in many of these conversations. Interestingly, this frame does not have a concept of responsibility or accountability. As climate change occurs due to market failures, all proposed actions are forward-looking to internalize the cost of carbon on the emitting actors in the market. To the best of my knowledge, this frame has only examined past emissions so as to allocate the remainder of the carbon budget, instead of for the backward-looking purpose of delineating fair distribution and recourse.

The other frames, however, emerge in actions such as grassroots campaigns responding to climate impacts (environmental and climate justice frames), and efforts to hold accountable large both state- and non-state emitters (political economy and ecology), and through lawsuits (STS).

I hypothesize there is opportunity in leaning into these frames to advance the field and address the two challenges. Political economy/ecology (PEPE) and environmental/climate justice (EJCJ) are more focused on backward-looking questions of responsibility compared to neo-classical economics. PEPE and EJCJ facilitate looking at actors at all different scales while state-sovereignty ascribes most power to the level of the nation state. Political ecology specifically is about studying socio-environmental relations, including cross-scalar causality. It also builds on STS by examining how scientific analyses are influenced by socio-political processes and power (Forsyth 2008). I therefore these three frames can help advance the field of climate accountability as:

⇒ By focusing research on climate accountability couched within an EJ/CJ frame, historically marginalized and highly impacted communities are, by definition, ‘centered’. Centering here refers to placing the voices, opinions, needs, and experiences of the community at the center of the research, whereby the research is then based on these attributes of the community. I argue therefore that the EJ/CJ is best suited to ensure that the *attributability* versus *vulnerability* tension doesn't lead to an overemphasis on attributability. Moreover, the goal of climate justice is the basis for the concept climate accountability—again, as it is concerned with distributive and corrective justice.

⇒ Leveraging PE/PE approaches allows for disentangling highly complex causal chains and entangled institutions, allowing for not immediately arriving at an answer of a 'responsible party' but rather examining agency and actions across a wide range of actors. Moreover, the political ecology approach, specifically, ensures a consideration of climate responsibility is couched in the local manifestation of impacts and the unique causal chains that exist for that site. The frame facilitates conducting quantitative environmental science-based research alongside quantitative and qualitative socio-cultural and political analyses to trace complex chains of causation.

⇒ Finally, STS allows for casting a critical eye on why emissions exist and critiquing the dominant frames that explain the justification for emissions. STS methods can also provide evidence to demarcate who is a 'responsible party'. Moreover, as described in the previous section, the very topic of climate accountability has been made highly political; the fight around climate accountability is in part a fight over knowledge. In fact, the very fact that this dissertation is political—that examining climate accountability has been questioned as a biased practice—is due to certain narratives created by those holding the 'expert' position. Engaging these questions with an STS frame can bring the politicization of the research into the subject of the research.

In sum, in this dissertation, I primarily leverage the PE/PE, the STS, and the EJ/CJ frames to interrogate climate accountability. This is in part because they have received less attention in the practitioner field of climate accountability, but also in large part as they (a) center justice and (b) offer explanatory power to the socio-cultural dimensions that have led to emissions, created impacts, and allowed for the furthering of emissions and impacts, all of which is central to the question of climate accountability.

1.3. The Academic Field

Returning to the two challenges presented in Section 1.1, key developments in four academic fields can help to address the first challenge—allocating responsibility—and elucidate current roadblocks to the second challenge—addressing attributability vs vulnerability. Academic research on the various contributions to GHG emissions and advancements in attributing the effect of increased GHGs in the atmosphere to local impacts will help address the first challenge. These advancements largely fall into source, extreme event, and impact attribution (described below). Furthermore, examining responsibility requires examining the attitudes, actions, and omissions accompanying those emissions, or engagement in some form of action that is considered morally ‘wrong’—this is explored in Chapter 4. Moreover, advancements have been made that can help to center the most impacted communities rather than the easier-to-attribute sites and scales. Certain forms of research employing mixed methods, different forms of knowledge, and accounting for multiple causal chains leading to the climate impact can help address this challenge. This is explored in Chapter 3.

In this section, I explore the key developments in relevant academic fields to conduct end-to-end attribution, and the tendency for certain methods to be employed more frequently than others. These developments, and resolving these tendencies, can help to address these two challenges.

1.3.1. Key Developments in Each Field

Key Developments in Each Field: Source Attribution

Carbon dioxide (CO_2) concentrations in the earth's atmosphere have been generally stable over the past 800,000 years, oscillating between approximately 200 and 300 parts-per-million (ppm). Humans are altering this carefully balanced system at an unprecedented rate through the increased emission of GHGs and the destruction of carbon sinks. Since the industrial revolution, concentrations of GHGs have sharply increased, particularly CO_2. CO_2 has risen from around 277 ppm in 1750 to 414 ppm in 2021 (Global Carbon Project 2022), at a rate of 2.0 ± 0.1 ppm/yr in recent decades (IPCC 2014).

Where do these emissions come from? Each year, the Global Carbon Project does an analysis of the remaining carbon budget. The carbon budget is how much carbon dioxide equivalent (CO_2e)—or the total of all GHG emissions converted to the warming potential of CO_2—may be emitted while staying below certain thresholds. The carbon budget is a function of sources (left) and sinks (right) of carbon:

$$e(ff) + e(lulucf) = G(atm) + S(ocean) + S(land) + B_{im}$$

Where *e(ff)* represents GHG emissions from the extraction and combustion of fossil fuels and cement production; *e(lulucf)* represents GHG emissions from land use and land use change and forestry (LULCCF); *G(atm)* is the growth rate in the concentration of emissions in atmosphere; *S(ocean)* is the emissions that are absorbed into the ocean (the largest carbon sink); *S(land)* is the emissions absorbed by land; and finally B_{im} is an error term (Le Quéré et al. 2018). Human-driven changes to the concentration of CO_2e in the atmosphere comes from the left side of the equation through emissions from fossil fuel combustion and cement production, and through emissions from the destruction of carbon sinks through land change.

By far, the largest source of emissions is related to the first term—fossil fuels and cement. From 1956-2016, 82% of all emissions came from fossil fuels and industry, while 18% were due to LULCCF (Le Quéré et al. 2018:423). In the 'fossil fuel and industry' category, most of the emissions comes from energy production from fossil fuels (IPCC 2014:46). Of the CO_2 from fossil fuels, about 40% is from coal, 40% from oil, and 20% from gas (Neelin 2011:66). Moreover, nearly half of all emissions have occurred since the 1980s (Heede 2014), and cumulative CO_2 emissions from fossil fuels and cement production have tripled since 1970 (IPCC 2014:45). There is high certainty in attribution of fossil fuel-related emissions to global concentrations of GHG emissions; at the global scale, the uncertainty is ± 5% (Le Quéré et al. 2018:423). While the accounting of emissions from industrial production and manufacturing is relatively straightforward with a high degree of certainty, it is less accurate for emissions from LULCCF—encompassing agriculture, deforestation, ranching activities, and conversion of rural to urban spaces—with uncertainty of ± 50% (Le Quéré et al. 2018:423). There is also a much higher year-to-year fluctuation in emissions from LULCCF compared to those from fossil fuels (Le Quéré et al. 2018:423). Part of this is due to disturbance (disrupting carbon sinks) and other processes which have been hypothesized but not yet determined that have caused a mismatch in the predicted and observed levels of net primary productivity (Chapin, Maston, and Vitousek 2012:212). Another large factor influencing global climate is aerosols—which have a cooling effect and are often but not always emitted with GHG-emitting industrial activities. There has also been poor global documentation of historical aerosol emissions (Burger, Wentz, and Horton 2020:129), and there is indication that location of emission strongly determines the climatic impact of aerosols (Persad and Caldeira 2018). Between the outsized contribution of, and the relatively low uncertainty in attribution of fossil fuels to global concentrations of CO_2e, most source attribution has focused on fossil fuels.

Source attribution analyses quantify emissions contributions from different entities to increases in atmospheric GHG concentrations. In its simplest form, it is an accounting problem in which historical (current) emissions are summed by entity and their percent of cumulative (current) emissions is calculated; as such, quantitative assessments of contributions tend to be in percentages of annual or cumulative emissions. Evidence comes from documentary sources, such as national emission inventories or corporate emissions or securities disclosures (Burger, Wentz, and Horton 2020:75). There has been thorough national-level documentation of annual emissions since 1990 as dictated by the reporting requirements from the UNFCCC and further reported by institutions such as CAIT and the World Resources Institute (Burger, Wentz, and Horton 2020:135). Documentation at the industrial scale is more patchwork and exists due to independent research projects. Heede (2014) created a database of emissions from 1750-2014 for 90 industrial carbon producers (oil, gas, and cement producers), providing a systematic view of emissions from this industry. Yet for electric utilities, national reporting of percent of territorial emissions must be used to back out emissions from this industry: in 2019, electricity generation accounted 32% of US energy-related CO_2 territorial emissions (EIA 2021a). Finally, while single analyses have compared carbon footprints of individual households (e.g. Kennedy et al. 2014), there is no documentation of emissions from individual consumers (instead, studies rely on per-capita approaches at the nation-state scale).

Source attribution has illuminated patterns, particularly disproportionality in emissions. Studies have attributed emissions to entities along three broad lines—temporal (historical versus current, and pre- vs post-development of scientific consensus), supply chain (producers vs consumers), and scale (individual, industrial, nation-state). The most fundamental difference in source attribution occurs along the third line—scale—with debates within each sub-body of literature on the first two—temporal and supply chain. These are explored in Chapter 4.

Key Developments in Each Field: Climate Change Attribution

The link between increased concentrations of GHGs in the atmosphere and a global increase in radiative forcing comes from climate science and physics. Burger, Wentz, and Horton (2020) refer to this as climate change attribution.

There is a natural greenhouse effect on Earth that has kept temperatures mild due to the presence of GHGs in the atmosphere. Each unique GHG has its own radiation absorption bands. Some of these bands are already ‘saturated’, where there are enough molecules of the gas that absorb in that band so that no radiation of that wavelength can make it through the atmosphere. However, some bands are not yet ‘saturated’; for GHGs that absorb in that band, adding more of them will increase the absorption for those bands (primarily in infrared/longwave part of the spectrum), leading to the *enhanced* greenhouse effect. When the source of those gases is anthropogenic, the additional absorption is then the *anthropogenic* greenhouse effect.

The GHG that is of primary concern to both scientists and policymakers is carbon dioxide (CO_2). CO_2 is not the most 'potent' GHG but is the most prevalent: 78% of all emissions from 1970 to 2010 were CO_2 (IPCC 2014:5). Other GHGs are more 'potent' in that they absorb more energy. For instance, methane (CH_4) is nearly 30 times more 'potent' than CO_2. However, these gases also have different average residence times, where CH_4 emissions stay in the atmosphere for much shorter time periods than CO_2. Several metrics have been devised to compare these GHGs. The global warming potential (GWP) measures the 'potency' of each as a function of how much energy they can absorb as well as their residence time in the atmosphere (IPCC 2014). However, GWP does not allow for the consideration of the net effect of all GHGs and aerosols. All emissions can be considered together to determine their net effect on how much extra energy is in the earth's system—radiative forcing (IPCC 2014:45). Radiative forcing is a measure of the capacity of the various emissions (gases and aerosols) to affect the earth's energy budget. It specifically refers to the change in the amount of energy hitting the earth's surface, and hence is measured in watts-per-meter-squared (W/m^2). As of 2014, combining the effects of all emissions, human created radiative forcing is 2.3 watts per meter squared W/m^2) (with uncertainty margins from 1.1 to 3.3) (IPCC 2014:44).

That increase in W/m^2 affects the climate system. With positive radiative forcing, the earth's surface responds by emitting that same amount of energy in long-wave radiation (heat). In a simplified, idealized earth with no other complex phenomena, it is straightforward to calculate exactly how much the earth will warm due to increases in radiative forcing: using the Stefan-Boltzmann equation, in this simplified earth, if CO_2 were doubled from pre-industrial levels, the earth would warm by 1 degree Celsius. This is an undisputed physical relationship. But the earth is not that simple; there are several sources of uncertainty in the link between increased atmospheric concentrations of GHGs, increases in radiative forcing, and resulting increases in temperature, largely due to estimates of equilibrium climate sensitivity.

Climate sensitivity is determined by the presence of feedback loops. For example, a major feedback loop is related to surface albedo in the Arctic—light colors reflect radiation while dark colors absorb it. Bright, white ice reflects radiation back to space that would otherwise contribute to the energy imbalance. However, as temperatures warm, that ice melts and turns into the dark blue of the ocean, which absorbs radiation, contributing to the energy imbalance and resulting in increased temperatures. By adding all the complexities—all the feedback loops, glacial cycles, global currents, etc.—to the warming estimated using the Stefan-Boltzmann equation, one can approximate how much the earth will warm due to an increase in radiative forcing. Climate sensitivity (λ) is the measurement of that warming (T), or of how sensitive the climate is to a change in radiative forcing (F) ($\Delta Ts = \lambda * \Delta \mathrm{F}$). The transient climate sensitivity (TCS) is the real-time response when atmospheric CO_2 is doubled; equilibrium climate sensitivity (ECS) is the increase in temperature once all the feedback loops finish looping and everything stabilizes. What is ECS for our non-simplified world? For a long time, it was estimated that ECS was between 1.4 and 4.5 degrees Celsius (National Research Council 1979). However, that estimate was refined and narrowed in 2020 to between 2.6 – 3.9 °C (Sherwood et al. 2020). This refined estimate of ECS implies that the earth will be on average 2.6-3.9 °C warmer when atmospheric concentrations of CO_2 reach 560 ppm—as of December 2021, the concentration was 417 ppm (NASA 2022).

While estimates of ECS are increasing in precision, there is still uncertainty. However, if the focus is on current climate change, rather than future projected, these uncertainties can be partially accounted for by directly measuring temperatures. As will be described later, however, these uncertainties are not completely removed by focusing on current measurements, as many experiments depend on counterfactuals—or what the climate response would have been without some or all anthropogenic GHG emissions.

Key Developments in Each Field: Trend and Extreme Event Detection and Attribution

To relate increases in anthropogenic forcing to changes in extreme events and environmental trends, detection and attribution methods are used. Detection is the "…process of demonstrating that climate or a system affected by climate has changed in some defined statistical sense without providing a reason for that change" while attribution is the "...process of evaluating the relative contributions of multiple causal factors to a change or an event with an assignment of statistical confidence" (Hergel et al. 2010). While the detection and attribution (D&A) of human influence on the climate system has been a large focus of the IPCC since its inception in the 1990s, D&A of human influence *on local or regional extreme events* has developed relatively rapidly over the past two decades. In the mid-2000s, researchers began to create methods to adequately measure two major time scales of biophysical impacts: slow-onset, long-term shifts ('trends'), versus quick-onset, extreme weather events ('extreme events'). Understanding whether anthropogenic climate change has contributed to a heatwave, flood, fire, or drought requires teasing out contributions from natural variability and anthropogenic forcing on climate variables affecting that extreme event.

Trend attribution refers to attributing the effect of radiative forcing on large scale trends in the "hydrosphere, cryosphere, lithosphere, biosphere, and the interactions between those components" (Burger, Wentz, and Horton 2020:77). This relates climate change to slow onset events, such as sea level rise, glacial melt, temperature rise, and desertification. The most direct effect of increased radiative forcing due to human activities is the increase in global surface temperatures. According to the IPCC: "Human activities are estimated to have caused approximately 1.0°C of global warming above pre-industrial levels" (IPCC 2018). This warming, however, has not occurred as uniform 'bathtub' warming. There is significant spatial variation; for instance, the Arctic is warming much faster than many other places in the world (partly due to the ice albedo feedback). Additionally, this warming has shifted the probability distribution of temperatures, producing a fatter tail for the hot end and a skinnier tail for the cold end so that more frequent hot extremes (and less frequent cold extremes) have been documented (IPCC 2014:53; NAS 2016:20). This warming has led to sea level rise, through the coupled effects of thermal expansion of the ocean due to warmer temperatures and additional water in the ocean from land ice melt (as sea ice melt does not contribute to sea level rise) (CITE); in recent decades, ice sheet and glacier melt has contributed more to sea level rise than thermal expansion (IPCC 2019).

For cases where the climate impact is related to a trend (such as sea level rise), these trends then need to be translated into local effects. It is more difficult to make broad claims about climate trends at regional scales, because "[a]s one moves from larger to smaller averaging regions, the range of the natural variability increases" (Neelin 2011:247). However, in moving to regional scales, the ability to understand and account (or control) for different local factors increases. Continuing with the example of sea level rise, coastal communities experience different rates of sea level rise due to topographic factors (is the place low-lying?), geological factors (is there vertical land movement due to subsidence or uplift), or other processes (e.g. sediment compaction due from groundwater or oil/gas extraction) (Sweet et al. 2017). These collectively determine *relative* sea level rise. These factors may add up significantly; while absolute sea level rise in the Gulf of Mexico is ~ 3mm/year, *relative* sea level rise in the Mississippi Delta is ~12mm/year (Jankowski, Törnqvist, and Fernandes 2017).

For extreme event attribution, a different set of tools is required. Such forensic anthropogenic climate fingerprinting on extreme events is done using detection and attribution science. Detection and attribution (D&A) of anthropogenic forcing on extreme events generally use methods which "…rely on the observational record to determine the change in probability or magnitude of events… [and/or] use model simulations to compare the manifestation of an event in a world with human-caused climate change to that in a world without" (NAS 2016). The first approach compares the current event—its probability of occurring or some measure of its intensity—to historical analogues to determine how these characteristics may have changed in the current record, while the second approach makes use of coupled ocean-atmospheric climate model experiments to compare model output for various variables between, for instance, an experiment with no anthropogenic forcing (no GHGs or aerosols) to one that includes all forcings. In this latter approach, a Fraction of Attributable Risk (FAR) may be calculated, comparing the probability of the event in both model experiments (as introduced by Allen 2003).

These methods are best suited to diagnosing events which are influenced by anthropogenic forcing when there is ample evidence and long-term records. Events that experience more natural variability—such as PDO, AMO, or ENSO—require long-term records to tease out long-term, low frequency internal variability from anthropogenic forcing. Moreover, the methods work best for events whose connection to anthropogenic forcing is based on sound physical principles, particularly those related to some aspect of temperature, so they are primarily thermodynamically—rather than dynamically—forced. For instance, the earliest D&A study of anthropogenic forcing on an extreme event was in 2004, in which the effect of anthropogenic forcing on the 2003 European heatwave was assessed (Stott et al. 2004). Both confidence in the findings and the strength of signals are greater when they are thermodynamically forced (NAS 2016:128). As such, heatwaves and extreme cold events are more diagnosable than convective storms or extratropical cyclones (NAS 2016:4-10).

These methods traditionally share a null hypothesis that the extreme weather event was *not* anthropogenically forced, and a conservative preference for Type II over Type I errors (in which it is preferable to erroneously fail to reject the null hypothesis than to erroneously reject it) (Trenberth 2011a; Trenberth et al. 2015; Lloyd and Oreskes 2019). As such, when an anthropogenic fingerprint is detected on the frequency or intensity of the extreme event, the findings are highly defensible. Yet, as confidence is lower for dynamically forced events, Type II errors (finding no human influence on the extreme) are more common for dynamically-climate-driven events using these methods (Trenberth et al. 2015). A separate methodological approach has been proposed to avoid Type II errors. The argument is based on the reasoning that in this hotter world, most events are in some way anthropogenically-forced, so "should not the burden of proof be on showing that there is no human influence?" (Trenberth 2011a). Therefore, "…it is not a question as to whether it is playing a role but what that role is" (Trenberth et al. 2015). Building out of this philosophical inversion, a newer methodological approach has been presented as a "storyline" approach, to be compared to the more risk-based assessments (such as FAR) (Lloyd and Oreskes 2019; Trenberth et al. 2015). This approach takes the event as given—with its unique characteristics—and interrogates how climate change may have altered some of the characteristics (Lloyd and Oreskes 2019). For an event with multiple climatic drivers—both dynamic and thermodynamic—this storyline approach proposes diagnosing how the thermodynamic aspects altered the event and attributing anthropogenic forcing on those specific aspects.

Moreover, multi-step attribution approaches may be necessary to isolate the human fingerprint on certain events. There are both 'single-step' and 'multi-step' attribution. Single-step approaches can be done for variables with "long and consistent time series of observations…that can be simulated explicitly in current models driven solely with external climate forcing…" while multi-step methods are used for variables which do not have the long observational record which are explored in a physically or statically based analysis and then linked to "the attributable change in a variable such as large-scale surface temperature" (Bindoff et al. 2013:878). For a heatwave, the single-step approach may be sufficient, while for a vegetation mortality event, the multi-step approach may be required. Many extreme event D&A studies are two-step attribution studies, in which the first attribution step is of radiative forcing to a large-scale change such as temperature rise, while the second attribution step is from that temperature rise to the extreme event, such as drought or flooding.

Two recent reviews of attribution research have shown that current methods are relatively well adept for finding the 'human' influence on long-term temperature related impacts (desertification, sea-level rice from ice melt, permafrost melt), but face challenges when examining impacts that are secondary or tertiary to temperature change (fire, hurricanes, flooding) (NAS 2016). This is reflected by the relative number of studies published. In a compilation of D&A studies on extreme weather events, of the 404 events included, 132 are on extreme heat, while 68 are on drought, 16 are on wildfires, 132 on extreme heat, and 3 are on ecosystem function (Carbon Brief 2021).

Key Developments in Each Field: Impact Attribution

The last step in the typology is impact attribution. For the purposes of end-to-end attribution, impact attribution pulls its definition from the IPCC Working Group 2 (WGII) on Impacts, Adaptation, and Vulnerability. Impact attribution, according to WGII, "…generally links responses of natural and human systems to observed climate change, regardless of its cause" (IPCC 2014:4). There are two significant components to this definition. First, this definition of impact attribution is agnostic to the cause of the climatic changes leading to impacts, meaning it does not distinguish between those impacts stemming from anthropogenic climate change versus from natural climate variability. To be used in end-to-end attribution, impact attribution must be somehow further assessed to make the distinction between which impacts would have occurred without anthropogenic climate change versus which were created (and to what intensity) by anthropogenic climate change. The second component is that the WGII definition constrains the analysis to a single causal chain—the effect of observed climate change on human and natural systems. From an attribution standpoint, impact attribution is more difficult than the other attribution fields as it needs to account for many "confounding factors" and is conducted as a multi-step attribution analysis (Burger, Wentz, and Horton 2020:110-112). While such studies may account for other changes and their effects on those systems, many will attempt to single out the climate change component.

In this definition, then, impact attribution is a tightly defined field. However, the larger field of impact and vulnerability studies demonstrates that there are opportunities for 'impact attribution' to become broader as it develops to capture to the true impacts of climate change more accurately. It can tap into this larger field to capture the impacts of climate change more accurately by leaning into those "confounding factors", and it can become integrated with detection and attribution studies by incorporating the outcome of those studies as part of the analysis. As such, these broader fields are reviewed here as key developments in the 'impact attribution' field.

From the standpoint of those who have the lived experiences of climate impacts, "cofounding factors" are the many layered processes which interact with climatic hazards to produce impacts. Put more simply, "confounding factors" are the life with which climate change interacts. In impact attribution, the overemphasis on climate change as a driver while discounting or aiming to minimize confounding factors can distract from the real amalgamation of causes of the impact (Hulme 2014; Huggel et al. 2013). To truly capture the impacts of climate change on a community, it is necessary to examine how climate change interacts with the processes, challenges, and layers of life for that community. This kind of analysis has been crafted and honed within the discipline of vulnerability studies. With the growing understanding in Western disciplines that humans could affect the environment, and be affected by the environment, in the middle of the 20th century, a group of scholar-activists were studying how local exposure to toxins led to adverse health outcomes in urban spaces. This work was the beginning of what today is largely known as vulnerability studies and would branch into the hazards and human ecology branch (Burton, Kates, and White 1968), early political ecology research on vulnerability (Liverman 2015), and the *academic* environmental justice tradition (Bullard 1990).

These three branches offer unique strengths and frames for understanding causation of impacts. The hazards branch largely can be described as studying human-environmental dynamics at various scales, by which peoples' decisions are bounded by "nature, personality, society and culture" and local histories. This branch further splits into human and cultural ecology, historical ecology, and hazards research, including writers such as Gilbert White, Ian Burton, Robert Kates (Burton, Kates, and White 1968) on human and cultural ecology, and Carl Sauer, Billie Lee Turner II, and Karl Zimmerer on historical ecology. The political ecology branch then examines the *why* of the questions raised by the hazards branch—it examines the political in driving environmental change with a focus on how marginalization, inequality, and injustice shape and are shaped by environmental change. This branch is wide, oft critiqued with, as aptly summarized by Forsyth 2008: "where is the politics, or where is the ecology, in political ecology?". To answer that critique, it further branches into those who peer closely at the ecology (Blaikie 2008, Peta Tschakert), those who delve into the political (Michael Watts, Tim Forsyth), and those who straddle the two worlds, painting how disasters have both ecological and socio-political constructions (Neil Smith and William Freudenburg), how conceptions of the environment have shaped human relationship to said environment (Paul Robbins, Piers Blaikie), and how to incorporate ecological modelling and political assessment into disaster research (Peta Tschakert, Susan Cutter, and William Freudenburg) and adaptation research (Adger 2005). The Environmental Justice branch continues straight up from the trunk, constituting the core normative and ethical commitments of the roots of the field. This branch centers the lived experiences of those experiencing environmental change where they ‘live, work, and play’, and seeks to understand the needs of those people. Moreover, its core goal is to promote justice (Schlosberg 2013; Pellow 2017). It examines the underlying reasons for disproportionate burdening largely stemming from the intersections of race, class, and gender (including the economics of impoverishment and externalities and the tendency for government and industry to seek the path of least resistance) (Pellow 2017). Referred to as the ‘father of environmental justice’, Robert Bullard has defined this field, with later scholars contributing key insights (Pulido 1996; Mohai, Pellow, and Roberts 2009; Pellow 2017), for continuing the environmental justice tradition into climate justice (Schlosberg and Collins 2014; Nagel 2012).

These three branches are relevant for impact attribution as each one aims to conceptualize vulnerability to climate change and understand how and why impacts occur when, where, and to whom. Yet each provides a different lens and naturally leads to different approaches to assessing impacts. There are three major methodological approaches within vulnerability studies relevant to this discussion: those using a more traditional scientific framing around a linear chain with the focus on the end-point of the impact (“impact assessments”); those using more complex diagrams of causality and incorporating many different factors and stressors, including both climatic and non-climatic processes (“vulnerability assessments”) (Fussel and Klein 2006); and those that seek to describe impacts for a place through ethnographic, historical, or other “people-centered” methods.

Impact assessments begin with climate change and then examine the effect of climate change on a single measure of impact. The goal is to minimize confounding factors—everything that is non-climatic is constrained into the single term, “sensitivity” (Fussel and Klein 2006). Much of the original hazards research falls into this approach, as do integrated assessment models (Fussel and Klein 2006) and studies which link climate science to a single quantitative metric of ‘human impact’. Examples of such studies range from linking climate change to risk of water shortages (Vorosmarty et al. 2014), to identifying the climate change cost of property damage (Emanuel 2011) and defining a relationship between climate and GDP (Burke 2015). Other studies that seek to identify the effect of climate change on crop yield (Lobell et al. 2014), grain prices (Davenport and Funk 2015), and global food production (Parry et al. 2004). Others link climate change to health outcomes (Grace et al. 2015; López-Carr et al. 2016; Mitchell et al. 2016), while a set links climatic changes to frequency of violence (Burke et al. 2009; Hsiang, Meng, and Cane 2011; Hsiang and Meng 2014). The core strength in the impact assessment approach is that it naturally lends itself to distinguishing between the effects anthropogenic climate change and climate variability on the impact. As there is only a single causal chain considered (climate change to impact), and everything else is held constant under ‘sensitivity’, the outcomes of detection and attribution studies may be readily applied to determine the proportion of impact attributable to anthropogenic climate change (and in some cases have, e.g. Mitchell et al. 2016).

Vulnerability assessments similarly rely on causal chains but break socio-economic and political drivers out of the ‘sensitivity’ box and include explicit considerations of these non-climatic drivers of vulnerability (Fussel and Klein 2006; Tschakert et al. 2013). The goal is to understand how climate change affects people in unique places and contexts. An example of this approach is the ‘double exposure’ framework in which the simultaneous and interacting effects of globalization and climate change are examined together as they produce outcomes (O’Brien and Leichenko, 2000). These studies bring together multiple potential causal chains and tend to use either quantitative or mixed methods approaches (e.g. Travassos et al. 2020;

Shonkoff et al. 2011). I would argue that qualitative examinations, or 'autopsies', of disasters could fit into this category (Klinenberg 2002; Freudenburg et al. 2012; Smith 2006). Detection and attribution research may fit into these types of assessments yet is rarely done. Hence, these studies tend to be agnostic to the fingerprint on climatic changes.

Finally, people-centered approaches begin with the lived-experience of the group who bears the impact, and the scope conditions for defining relevant factors, stresses, impacts, and causal links are defined in conversation with the local context, and in some cases with the people themselves. The goal of people-centered approaches is to understand the local context and then determine to what extent climate is a major factor compared to others. These studies often center qualitative input from the impacted community via interviews (Wilder et al. 2016; Shonkoff et al. 2011; Nania et al. 2014; McCubbin et al. 2015) and even participant observation (e.g. Méndez et al. 2020), though some use mixed methods (e.g. Smith and Rhiney 2016), some employing human ecology, historical ecology, political ecology, and some center and rely on a mixture of interviews, long durée history, literature review, and theory to do a deep ethnographic dive (Watts 2013; Shearer 2011; Maldonado 2018; Marino 2015). To the best of my knowledge, D&A research has never been incorporated into these types of studies.

These methodological approaches largely map onto these approaches—hazards research tends to use impact assessments or vulnerability assessments; political ecology research tends to use vulnerability assessments or people-centered methods; while environmental justice research tends to use people-centered methods, with some vulnerability assessments.

These branches and approaches offer various strengths to impact attribution. The impact assessment models fit most easily into end-to-end attribution due to their clear linkage between hazards and social outcomes, and hence are promising in their ability to demonstrate evidence of causality for mechanisms that require such. Yet they may miss key elements of the various causal processes that contribute to the impact, so are limited to what can be quantified and what can be externally identified. Instead, the vulnerability assessment and people-centered approaches are more finely attuned to understanding impacts and needs of impacted communities. This is explored in the next section.

1.3.2. End-to-End Attribution: Minimizing Uncertainty, Prioritizing Methods

As described above, significant advancements have occurred in each of these fields and in attempts to do end-to-end attribution. Yet, the two primary challenges identified in the practitioner field of climate accountability also plague the academic field. Significant advancements have occurred to conduct end-to-end attribution and attempt to minimize uncertainty yet still faces non-insignificant levels of uncertainty. Moreover, I posit that in this attempt to minimize uncertainty, attributability is being heavily prioritized over focusing on the most vulnerable places.

In considering existing work in this space, certain disciplines and methods or frames appear more frequently than others. A question I have repeatedly asked myself is: why are many studies of climate impacts based on pairing climate science with quantitative indicators of impacts? Is there an interdisciplinary bias toward this type of work, or is there something inherent about the question that makes these sets of methods most suitable to answering the question?

Much of the research on ‘human dimensions of climate change’ couples climate science with economic, epidemiological, agricultural, or demographic indicators of impacts (see “Key Developments in Each Field: Impact Attribution”). These tend to fall in the “impact assessment" bin. A certain subset of these studies—which I refer to as indicator-based *deterministic studies*, or those that seek to define some sort of deterministic relationship or rule of thumb between climatic change and human activity—have questionable roots and application. By fitting curves between climate and measures of violence or economic strength as measured by GDP, these studies contain echoes of the now-denounced approach of environmental determinism, most popularly championed by Jared Diamond's (1997) *Guns, Germs, and Steel*, and by which societies are said to be predetermined to certain attributes based on their physical environment. However, many of the other studies—which I here refer to as indicator-based *impact-based studies*—have advanced understanding of the scale and types of impacts associated with climate change. These impact-based studies can be leveraged for identifying vulnerable places due to health or food security, allocating aid, or giving an economic face to climate change which may allow for political will for climate mitigation. While they have value, they do dominate the field—these generally are the only impact attribution studies that are used for instance in the state sovereignty and neoclassical economics frames. As the indicators are dependent variables, they are limited in application as they cannot assess adaptation potential nor examine how co-occurring processes mediate climate impacts.

What do the indicator-based, impact assessment studies miss? If the goal is to understand the human impact of climate change, rather than a specific, pre-defined indicator, then the voices of the community are key to include in the analysis. To illustrate the importance of including community voice, Fernandez-Bou et al. (2021) highlight some of the pitfalls associated with such studies based on a meta-review of scholarly articles, media representation, and policy for residents of San Joaquin Valley in California coupled with interviews with those residents. They find that of all articles in Elsevier and Springer on disadvantaged communities in the San Joaquin Valley of California, none included interviews with those residents, meaning the voices of the impacted communities were not included. This resulted in a mismatch between the primary concerns of the communities and what the articles and media representation focused on (Fernandez-Bou et al. 2021). Moreover, scale can be an issue with these studies; if not carefully selected, choice of scale can miss important information. California identifies 'disadvantaged communities'—or communities that are exposed to and are highly vulnerable to toxic burdens—through the CalEnviroScreen. This identification process is done at the census-tract level; this scale, however, is sometimes too coarse in rural areas, so communities that are highly burdened by pesticides and other industrial activities are made invisible if they fall in a tract with a well-off, unburdened community (Fernandez-Bou et al. 2021).

In part responding to those pitfalls, there are some studies that are impact-based but use other approaches to examine the human impact; these tend to fall in the vulnerability assessment and people-centered approaches (see "Key Developments in Each Field: Impact Attribution"). These studies capture the unique needs of local communities by situating the analysis in the content raised by the community's voice(s). They also examine how climate change interacts with pre-existing stressors to make a unique local mosaic of risk and impact, thereby exacerbating existing inequalities. These studies can also break through the rigidity of scale, making visible otherwise invisible people and communities—for instance, in the mudslide following the Thomas fire in Montecito, California, the undocumented community living in this highly wealthy region were the worst-affected, or "the (in)visible victims behind the bougainvillea curtain" (Méndez et al. 2020:54). Yet, these studies are, by definition, hyper constrained to the local and limited in their generalizability. They also generally do not incorporate a climate change assessment as part of the study. Therefore, while these studies tend to be "downscaled", or look at local changes, to examine the climate change component of stressors they reference external literature, rely on generalized trends, and/or relying on observations from interviews. As such, they are crucial studies that paint a portrait of the true human impact of climate change, but generally are not included in end-to-end attribution.

Therefore, the quantitative indicator-based impact assessment studies tend to be most often leveraged in efforts for (partial) end-to-end attribution. There seems to be two primary reasons underlying the dominance of the first type of study and relative absence of the second type of study in end-to-end attribution. It is easier to translate quantitative indicators of human impacts of climate change to methods in climate science. Moreover, it is easier to 'upscale' such indicators to the same scale at which climate change and extreme events and trends are measured. If the goal is to minimize uncertainty and facilitate easier linkages to do end-to-end attribution, this will therefore lead to an indicator-based dominance in the field.

On translations: Uncertainty

End-to-end attribution here occurs along a causal chain. Causal chains link indicators across multiple steps when an event triggers or impacts another event indirectly through the connections of multiple events. Causal chains are commonly used to understand how certain phenomena come to be, from environmental regimes and policy outcomes (Young 2001), to determining legal liability (Leone 2015), to the relationship between greenhouse gas emissions and social pressures (Moser and Hart 2015; Adger, Arnell, and Tompkins 2005). The latter is found particularly in integrated assessments, such as the "…end-to-end connection of a causal chain from the change and spatial pattern of fossil fuel emissions or land use, through biophysical and socioeconomic impacts, to social consequences" (Gaile and Willmott 2003:247). End-to-end attribution along the causal chain will cut across disciplines and evidence types. The emitting site—located in a specific, geophysical place or in a cross-scalar, cross-local organization—makes decisions which will affect the emissions of CO_2e. Those emissions increase radiative forcing at a global scale, then biophysical changes at regional and local scales, and then the lived experiences of those at a specific site at a local scale (Figure 1). The cause and effect can be separated by large geographical distances as well as large temporal scales.

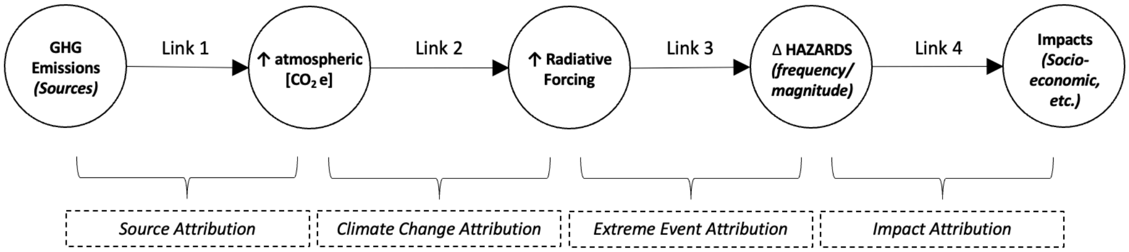


Figure 1. Causal chain. Based on Williams, E. (2020). Attributing blame?—climate accountability and the uneven landscape of impacts, emissions, and finances. Climatic Change, 161(2), 273-290. © (2020). [Springer Nature].' Used with permission.

The causal chain extends across different disciplines as described in Table 3. For example, the connection between the first two steps (emissions source and increased concentration of greenhouse gases) is generally studied in industrial ecology, organizational sociology, and global environmental governance, while the next translation (increased concentration of greenhouse gases to increase in radiative forcing) generally falls squarely in climate sciences and meteorology. Therefore, there are different types of evidence that apply to each part of the causal chain. To conduct *end-to-end attribution*, then, requires translations between each connecting node.

Table 3.

Examples of (sub-)fields	Step	Link
Industrial Ecology, Organizational Sociology, Global Environmental Governance	*Emissions sources*	*1*
Climate Science; Meteorology; Earth Sciences	*Atm [CO2], radiative forcing, extreme events*	*2,3*
Geography; Sociology; Anthropology; Economics	*Impacts*	*4*

The causal chain interrogated by end-to-end attribution is concerned with the material linkages (e.g. from GHG emissions to radiative forcing to temperature). To connect each node in the chain, sometimes the connection is as simple a process as a linguistic or empirical extension between two disciplines. However, sometimes a concept or approach may exist in one discipline but not the other, leading to difficulty in finding like parts to connect. As Blaikie (2008) emphasizes, "[m]ulti-disciplinarity while frequently recommended is also critiqued for tendencies to inconsistency, mixed metaphors and crossed interpretations." These mixed metaphors and crossed interpretations can lead to findings which are inaccurate, leading to the necessity of translations. Translations in science here refer to the methodological considerations in connecting two evidence types and/or disciplines.

Translations are required to address uncertainty in connecting nodes. This uncertainty stems both from the state of the body of research as well as the nature of the problem. Some of the uncertainty in each link is due to the lack of research, and thus presents gaps in the literature to fill. A prime example of where the development of methods and data has facilitated translations is in the detection and attribution of extreme events: as new methods are developed (e.g. probabilistic methods in detection and attribution research), new data becomes available (e.g. local measures wildfire extent), and new biophysical relationships are discovered (e.g. relationships between temperature rise and atmospheric moisture demand), these gaps become 'fillable', giving rise to a new field of research and/or an opportunity to fill in gaps. Some of the uncertainty, however, comes from the very nature of the problem, and, to the best of current knowledge, advancements in methodological approaches and additional data will not reduce that uncertainty. This part of translations is dealt with by the thoughtful handling of uncertainty and error.

Several studies have conducted parts of end-to-end attribution, particularly linking source, climate change, and extreme event attribution (Burger, Wentz, and Horton 2020:128). Examples include:

⇒ An analysis linked sea ice loss to individual, personal emissions. They determined a linear relationship of 3 square meters of September Artic Sea ice loss for every ton of CO_2 emitted; the study goes on to illustrate "the contribution of personal CO_2 emissions to the loss of Arctic sea ice" on the order of tens of square meters per year (Notz and Stroeve, 2016).

⇒ Another study attributed global mean temperature rise and sea level rise to emissions of industrial carbon producers (or the top 90 emitting oil, gas, and cement companies), finding that half of temperature and sea level rise can be attributed to those companies (Ekwurzel et al. 2017).

⇒ Another attributed contributions from 'Carbon Majors' (the 90 largest industrial emitters of CO_2) to ocean acidification (Licker et al. 2019).

⇒ Skeie et al. (2017) and Li et al. (2016) both link emissions from countries to increases in global mean surface temperature.

⇒ Otto et al. (2017) attribute the increase in global mean surface temperature (GMST) and the change in likelihood of the 2013-2014 Argentinian heatwave to emissions from countries.

Each of these studies link emissions sources to extreme events or trends by identifying a single measure of that trend or extreme event—sea ice loss, sea level rise, or surface temperature—and linking it to source emissions. To do so, these studies extend a linear relationship between the source's proportion of total global emissions and the extreme event or trend attribution in the study. There are challenges in this linear extension. Harrington and Otto (2019) explain that were the climate system a linear system, determining relative contributions from each entity would be as simple as assuming that "the climate change–related damages which can be apportioned to a specific fossil fuel producer equals to the fractional contribution towards global emissions at a given time step… multiplied by the corresponding increase in attributable damages over that same time step … taking the sum across all time steps then yields an 'attributable damage' estimate for that company…". However, if there are nonlinearities where earlier emissions lead to different levels of radiative forcing compared to later emissions, then simply adding cumulative emissions per entity and linking that to a percent of total radiative forcing and temperature increase could be a faulty assumption. Otto et al. (2017) examine the removal order of countries when examining contributions and find that "in the context of extreme events…we can conclude that early emissions matter more." They find for instance that when the US is assumed as the earliest emitter, the attribution study identifies over 100% increase in risk of such a heatwave occurring due to US emissions, while if it is the last emitter, the attributable increase in risk falls to 28% (Otto et al. 2017:759). Ekwurzel et al. 2017 test for this potential non-linearity of the system by considering the removal order of Carbon Majors (or large, industrial emitters of CO_2), and find that the errors produced by the removal order are relatively small. This suggests that removal order is a source of uncertainty—smaller for the GMTR study and larger for the heatwave study—but if removal order is done in line with the order of most emissions, this can be somewhat accounted for. In other words, removing emissions when the emissions actually occurred can largely account for this.

Moreover, there are non-linearities between increased radiative forcing—and even global mean surface temperature—and local impacts. While a general relationship can be defined between increased emissions and extreme heatwaves, the same cannot be said for extreme heatwaves and, for instance, mortality. This is because while the first link is a biophysical one, for which generalizable rules may be determined, the second relationship includes many other factors including human decision-making. The rule may be determined for generalized exposure, but other factors—such as building cooling centers, access to drinking water, and ability to temporarily relocate, which are all mediated by socio-economic and political factors—will mediate the exposure and vulnerability of people to that heatwave, and hence, risk of mortality (Huggel et al. 2016; IPCC 2014). It is for this reason that while projections of heatwaves may occur, projections of human mortality are far more complex and prone to errors. To make the link, then, upscaling or downscaling may then be used. The indicator-based studies tend to exist at a coarser scale (meso-scale, e.g. census-tract, county, state), while the ‘human voice’ studies exist at a finer scale (e.g. community- or household-level). To assess how climate change leads to impacts, the human impacts are either scaled up (in the case of the indicator-based studies), or the climate impacts are downscaled (for the ‘human voice’ studies). For impact attribution, indicator studies (described earlier in Section 1.3.1) are used frequently as the *indicator* (e.g. crop yields, GDP, or hospital visits) are linked (generally statistically) to the extreme event or long-term trend (e.g. heatwave or increasing maximum daytime temperature).

Given how many potential sources of uncertainty exist along the causal chain, and the scientific desire to minimize those uncertainties, measures of the human impact are generally chosen to minimize even further uncertainties. Harrington and Otto (2019) caution that "…if nonlinearities are found in both the impact profile and the relative emissions profile in the company, even very small ones, then the liable damage estimates can vary dramatically." The more closely related the indicator is to a biophysical property, the smaller the uncertainty. As such, the quantitative, indicator-based measures of human impact are generally used more often in linking the human impact to limit additional uncertainty.

Even when all caution is taken to minimize uncertainty, some level of uncertainty continues to exist. How they are treated comes down to a question of preference for type 1 or type 2 errors. Type 1 errors occur with a false rejection of the null hypothesis (or, thinking you found something that isn't actually there), while type 2 errors falsely fail to reject the null hypothesis (not finding something that is there). Generally, in science—including in detection and attribution science—type 1 errors are seen as more serious than type 2 (Lloyd and Oreskes 2019). This rule-of-thumb, however, is far from a scientific rule. It is the same tendency that prefers highlighting the 'conservative' estimates of an impact. A preference for type 2 over type 1 errors may make sense "when we really don't know what's going on", yet if there is already "strong, independent evidence to support a cause-and-effect relationship…" then type 1 might not be as bad (Oreskes and Conway 2010:157). If we have background knowledge that the phenomenon might exist, or if the consequences of the phenomenon existing would be severe, type 2 errors can be just as significant, if not more so, than type 1 (Angeregg et al. 2014). Holding a preference for type 1 over type 2 errors can be thought of as following the precautionary principle (Lloyd and Oreskes 2019). With that said, then, for climate change, which makes more sense—a preference toward type 2 or type 1 errors? It comes down to what constitutes *persuasive* evidence. What constitutes persuasiveness is often based on the implications of the evidence: "…the degree of scientific certainty demanded [by decision-makers] is proportional to the cost of doing something about it" (Oreskes and Conway 2010:76-77). In short, it depends on the application of the question. In cases where the precautionary principle is exercised, type 2 errors are considered as less serious than type 1 errors. An example of this would be in adaptation planning if the potential for climate impacts is catastrophic. In these cases, then, the uncertainty included in focusing on human impacts far removed from biophysical indicators is the necessary focus of these efforts, rather than a hinderance to the overall reduction in uncertainty in end-to-end attribution.

As what constitutes "persuasiveness" is highly subjective and context-dependent, this discussion of whether type 1 or 2 errors would be incomplete without considering whether there are agents pushing for one or the other to be prioritized. There is a well-documented history of those who profit from certain products targeting the "persuasiveness" of scientific evidence examining the potential harmful effects of those products. For example, in examining the link between tobacco smoke and cancer risk, faced with the problem of low exposure rates of secondhand smoke and the ethical inability to conduct an experiment, scientists turned to the weight-of-evidence approach, in which studies were examined together as evidence, rather than as individual results. Taken together, "[t]hese data were statistically significant and could not be explained away by other causes, risk factors, or chance" (Oreskes and Conway 2010:141). However, a scientist funded by the industry (Fred Singer) exploited the use of the weight-of-evidence approach and labelled it "bad science" or "junk science" (Oreskes and Conway 2010:143). The phrase of "no proof" was born as terminology to refer to the inherent uncertainties in the epidemiological links between increased risk and frequency of cancer and prevalence of smoking. The tobacco industry latched onto it in the 1990s, and since then, it "…became the mantra of nearly every campaign in the last quarter of the century to fight facts" (Oreskes and Conway 2010:34). Similar tactics have been used for climate change. Singer similarly used the range in sensitivity estimates and emissions scenarios in climate change to argue that it fell within natural variability, while another industry-funded scientist would lead an attack on the IPCC peer review process in how it structured chapters and reported on uncertainty to undermine its findings.

It is this very uncertainty inherent to climate change that has made it possible to create a popular discourse maintains that both everyone and no-one is responsible for the problem. Actors may lean into the complexity of climate change to shift blame because they understand that if climate impacts are labelled as human-caused, the door is open for responsibility to be established, closely followed by liability (Thompson and Otto 2015). In attempting to avoid liability, actors may use discursive tools to shift responsibility away from themselves and onto others: "…governments, nongovernmental organizations and corporations are selecting those data, images and reports that represent and advance their interests and, perhaps, reduce their responsibilities…" (Liverman 2015:307).

Translations: Summary

To summarize, thoughtful choices of methods and translations are required in conducting end-to-end attribution and should be chosen within the context of the attribution's application as the threshold for evidence may vary. While the indicator-based impact studies fit neatly into extreme event attribution, and therefore respond to the first large challenge facing this field (again, demonstrating causality), they don't capture the true contours of climate impacts nor emphasize the community's voices or needs and may additionally select places with clear attributable impacts rather than more complex layered impacts (the second challenge). Quantitative indicators may be more powerful in certain contexts where a single measure with small uncertainty is needed for end-to-end attribution, while qualitative measures may have more of a place when multiple impacts may be simultaneously considered together (as in law, below).

Uncertainty should be considered and minimized where possible along the causal chain but with a mindful consideration for whether limiting uncertainty is needlessly prioritized over accurately and persuasively capturing the human impacts of climate change. No matter how much methodological advancement occurs, as with any study, there will always be some amount of uncertainty. Determining what level of uncertainty is acceptable will therefore depend on the application—i.e. in what venue and for what purpose causality is being demonstrated.

Therefore, the two challenges presented in this chapter are not necessarily at odds with one another. The first challenge—demonstrating causality, and therefore responsibility—is about translations along a causal chain and across disciplines, or how to conduct end-to-end attribution. What the translations look like (and what benchmark is used to determine how rigorous the translations are) is determined by what measure of causation is required. Why is end-to-end attribution being done—is it for a specific application? This will determine what kind of evidence and, hence, what form of linking along the causal chain is sufficient. For instance, to demonstrate causation in law requires a considerably different threshold and approach than in science. Therefore, asking first *why* causation is being demonstrated—

specifically, for what mechanism—should be asked first, as depending on the type of causation required, demonstrating causation may not occur after all at the expense of centering the most impacted communities.

1.4. Leveraging Scholarship: Science-to-Law Translations

The fastest growing application for end-to-end attribution is in law. This section examines the translations required for the causal chain to be accepted as 'valid' by law, including level of acceptable uncertainty and types of evidence used.

As described in Section 1.1.1, the UNFCCC WIM currently functions within a risk-transfer approach as developed countries have largely blocked liability and compensation from inclusion in the mechanism (Warner and Zakieldeen 2011; Wrathall et al. 2015; Huq et al. 2013; James et al. 2014). Moreover, L&D conversations in this space have provided little guidance as to what criteria would be required to demonstrate causation were the mechanism to be eventually transferred to a compensation and liability approach (Huggel et al. 2016). Some studies indicate that attribution science would be relevant for this mechanism even with the current block to liability and compensation (Huggel et al. 2016; Huggel et al. 2015; Huq et al. 2013; James et al. 2014). For instance, Huggel et al. (2016) posit that a focus on recognition/acknowledgement and reconciliation within a frame of restorative justice is the most promising way forward on the international stage, and potentially require a lower threshold of demonstrating causation. They argue that use of attribution research is however still applicable here, in the recognition of responsibilities and inequities between Global North and Global South countries. That said, they also turn to the current legal sphere to shine light on what demonstrating causation would look like.

In domestic US law—as with law in many countries—both causal responsibility and the attitudes, omissions, and actions that constitute blameworthiness are considered. Translations are required between academic analyses and law. Doing so is boundary work, in that it is interfacing science with application, and requires negotiating between the confines of each. While "…science is not devoid of values prior to some politicization…", it does have its own sets of norms and practices which buffers the practices from dangerous uses (Guston 2001:399). Yet as "…the robustness of scientific concepts such as causation and representation are important components of liberal-democratic thought and practice (Ezrahi 1990), one can imagine how the flexibility of boundary work might lead to confusion or even dangerous instabilities between science and nonscience" (Guston 2001:399). This is particularly visible in law—the courts rest heavily on scientific evidence, yet the distilling, communication, and weight of that evidence is conducted in a non-scientific realm. Scientific uncertainties are debated by non-scientists and evaluated by non-scientific peers (a jury or judge). Boundary organizations have thus emerged to facilitate translations across these two spaces (e.g. Climate Science Legal Defense Fund; the Union of Concerned Scientist's Science Hub for Climate Litigation; the Climate Science Social Network; and Columbia University's Sabin Center for Climate Change Law).

While many current barriers to establishing accountability in the courtroom for climate-related damages are not due to a lack of scientific evidence but rather due to legal barriers, scientific barriers similarly must be addressed for any case to proceed successfully. For litigation holding emitters accountable for damages or adaptation costs, there are generally two points at which scientific evidence enters the courtroom—establishing standing, and as evidence in the proceedings.

Before a case enters a courtroom, it needs to overcome several threshold issues. Two thresholds issues—the Political Question Doctrine (PQD) and Displacement—are often invoked in climate litigation and have nothing to do with end-to-end attribution. PQD "prevents U.S. courts from considering cases that raise policy decisions best addressed by the legislative or executive branch of the government" (Byers et al. 2017:272). This was invoked by lower courts for *Connecticut vs American Electric Power,* but the Supreme Court did not accept PQD as a barrier, indicating that it will present less of a threshold issue in the future (Byers et al. 2017:272-273). Displacement is invoked when U.S. courts are asked to "consider cases involving issues of national concern that are statutorily regulated by the other branches of government" (Byers et al. 2017:276). The federal statute that often gets invoked in Displacement is the Clean Air Act, as occurred in *Kivalina vs ExxonMobil* (Byers et al. 2017:276). As of 2022, many of the outstanding cases in the US are fighting over jurisdiction (whether the case will be tried in state or federal court), as Displacement would likely be triggered if tried in federal court.

A third threshold requirement is standing, which is the first point of entry for science into the legal space. The injured party (the "plaintiff") must establish standing to have their case heard by the court by showing that they have experienced a measurable injury ("injury in fact"), that the defendant caused it ("causation"), and that a court ruling would bring about some redress ("redressability"). The standing threshold—specifically the "injury-in-fact" and "causation" components—is the first point where end-to-end attribution is applied in liability. "Injury-in-fact" must be particular to the party (i.e. not a "generalized grievance") and must be measured or demonstrated in some way. Demonstrating "causation" requires showing that that injury-in-fact is "fairly traceable" to the actions of the defendant. This can be demonstrated with a ‘but-for’ test: “would the plaintiff not have been injured but for the defendant’s action” (Burger, Wentz, and Horton 2020:150). This has been a barrier to cases—*Kivalina vs. Exxon* was dismissed by a lower court as the judge determined that standing was not satisfied as damages could not be traced to the defendants. Legal scholars now believe this to be less of an issue with new scientific advancements (Burger, Wentz, and Horton 2020:160). Indeed, in *Juliana v United States* nearly a decade later, the court ruled that the plaintiffs had established standing (Burger, Wentz, and Horton 2020:164). Standing requirements have been criticized as being subjective, “incoherent”, and “uncertain in application and unpredictable in result” (Byers et al. 2017:274; Burger, Wentz, and Horton 2020:153). Between scientific advancements and this incoherent nature of the standing threshold, chance seems to be just as likely as evidence to be the determining factor in satisfying the standing requirement. However, in cases involving municipalities with large demonstrable damages, standing has been more easily satisfied due to the particularization of harm.

No case has yet surpassed these threshold issues, but when they do, the real application of end-to-end attribution will occur. Once the case overcomes those threshold issues, then, the plaintiffs need to demonstrate an actual injury and show two types of causation—factual (or scientific) and proximate (or legal) causation (Byers et al. 2017:278). Like for standing, an actual, specific injury must be demonstrated (Burger, Wentz, and Horton 2020: 202). The more difficult part seems to be in demonstrating causation, though. Both types of causation aim to answer the question: but for the defendant breaching their duty of care, would the impact have occurred? A breach of care is shown if the defendant “failed to exercise reasonable care to protect others from a foreseeable risk of harm” (negligence) or if “the defendant’s interference with the plaintiff’s person, property, or public goods was “unreasonable”” (Burger, Wentz, and Horton 2020:197). Compared to scientific requirements for minimizing uncertainty, the same level of evidence is not required in law. While criminal law does require evidence of ‘beyond a reasonable doubt’, civil law requires ‘more likely than not’—civil law aims to determine who is more likely to be correct, the plaintiff or the defendant. That said, compelling evidence is still required. To use scientific evidence in demonstrating causation, it needs to satisfy the *Daubert* standard in which the scientific technique is tested, the analysis is peer reviewed, the errors are known and presented (including certainty bars), and the approach is generally accepted by the scientific community (Burger, Wentz, and Horton 2020:169). There is no specific numeric requirement for certainty in US courts; rather, the more certainty, the better, and if it’s unrefuted, better still (Burger, Wentz, and Horton 2020:171).

Demonstrating factual causation includes both showing general causation (“whether the action in question *could have* caused the alleged injury”) and specific causation (“whether the action in question “more likely than not” *actually caused* the alleged injury”) (Byers et al. 2017:279). Scientific evidence is crucial in demonstrating general causation in the case of climate change, as there are multiple actors and phenomena that may lead to an injury. Statistical or probabilistic analyses are useful here as they can indicate whether a specific actor (the defendant) could have a significant enough role in causality to be considered by the court (Burger, Wentz, and Horton 2020:2000). Based in toxic tort—specifically the use of epidemiology to show the effect of toxic exposure on cancer and other health effects—the ‘doubling of risk’ test may be used. It involves demonstrating that exposure to environmental or climatic change at least doubled the risk of developing the harm (Grossman 2003). Note that in science, a FAR of 0.1 (or a 10% increase in risk) is significant, yet FAR of >0.5 is required for tort (Stone and Allen 2005:316). The 'doubling of risk' (relative risk, RR) requirement (FAR > 0.5, or RR > 2) is now required by *Daubert,* and has been broadly accepted across jurisdictions, yet it is far from a scientific rule (Carruth and Goldstein 2001:201). This 'rule' was determined by boundary organizations as they attempted to define best practices for interfacing science (specifically epidemiology), statistics, and law, with a range of opinions being reached on what should be the threshold or whether such a 'bright line' threshold based on RR / FAR exists (Carruth and Goldstein 2001:205-206).

To demonstrate specific causation, the plaintiff needs to show that the "defendant's actions or behavior were 'a necessary element' in bringing about the injury" (Byers et al. 2017:280). Specific causation traditionally rests on the "but for" test, yet the test is notoriously difficult to satisfy in the case of environmental harms, as there are many other factors that may contribute to the injury-in-fact (Grossman 2003:23) and isolating causation between defendants can be burdensome (Byers et al. 2017; Burger, Wentz, Horton 2020). Several alternative approaches have been designed for environmental harms (Byers et al. 2017:281-283). These include:

- ⇒ The "substantial-factor"/material contribution test: while multiple different processes could have brought about the harm, the one in question is sufficient on its own to bring about the harm (Byers et al. 2017).
- ⇒ Co-mingled product approach is based in the idea that if the total effect of many different products brought about harm, then each individual product can be considered to have caused harm (Byers et al. 2017).

- ⇒ Market share approach in which the amount of liability would be a function of their total share of global emissions (Byers et al. 2017). This approach was used in tobacco and pharmaceutical suits (Stuart-Smith et al. 2021). Source attribution would be directly applicable in this case.
- ⇒ In some jurisdictions, doubling of risk has been used also in demonstrating specific causation, but there is a lack of consensus across jurisdictions on whether this may be used for specific causation, and if so, whether it is necessary or sufficient (Carruth and Goldstein 2001:204).

Furthermore, even if specific causation is demonstrated, proximate causation (aka "scope of liablity" and "legal cause") must also be demonstrated. The key component to proximate causation is foreseeability (Byers et al. 2017:278, 284; Marjanac et al. 2018:17-18). It is used to limit liability when factual causation is satisfied but the defendant shouldn't be held liable if they did nothing wrong. Research on attitudes, actions, and omissions of the defendants is the most relevant for demonstrating proximate causation (see Chapter 4).

So far, I have reviewed how this would work in theory. In practice is another story, however. Some legal scholars believe that public nuisance lawsuits for climate liability are increasingly possible, primarily due to three reasons (Carlson, 2018). First, the science is nearly "good enough" to connect emissions to damages (Marjanac and Patton 2018; Ganguly et al. 2018). Second, extractor defendants, as compared to consumers or nation-states, have contributed a large enough percentage of total global emissions to be measurable (Heede 2014; Ganguly et al. 2018). Third, there is now evidence that certain industrial carbon producers had the knowledge of climate impacts of their product, created and spread disinformation, and undermined alternatives to their product (Supran and Oreskes 2017;

Frumhoff et al. 2015). However, while the evidence is much more compelling, there remains a disconnect between scientific advancements and evidence reviewed in court. Stuart-Smith et al. (2021) find that, despite significant recent advances in attribution research, when reviewing court cases that allege defendant's GHG emissions led to plaintiff's damages, "…most cases did not quantify the extent to which alleged impacts are attributable to climate change, and fewer still provided quantitative evidence linking defendants' emissions and plaintiffs' injuries." Specifically, 73% of assessed cases failed to reference any peer-reviewed attribution studies. Stuart-Smith et al. (2021) go on to describe how many cases do not reference any studies that describe the link between the specific injury-in-fact and the emissions from the plaintiff, yet as we know from earlier, this is a key criterion to establishing causation. As the authors note, there an opportunity here, for "in most cases concerning impacts for which the causal link to climate change does exist, existing scientific methodologies could fill the evidentiary gaps identified by courts."

As seen above, far from having clearly defined rules for admissibility of evidence in climate change tort (civil law showing damages), the courts are still determining what constitutes persuasive evidence and it varies greatly among jurisdictions. Still, source, climate change and extreme event, and impact attribution are highly relevant for demonstrating specific causation (Burger, Wentz, and Horton 2020:205). Courts accept a range of impact attribution studies, from indicator-based to vulnerability-based studies. For extreme event and impact attribution, there are ways in which attribution may grow that may make it easier to be admitted in court. A lot of focus has been given to changes in probability or likelihood. Yet as described above, there is nothing unique about RR > 2 (FAR > 0.5), and this threshold could mean that climate-change exacerbated damages—that are both real and significant yet fall below that threshold—are dismissed. It may be prudent to consider other ways of identifying the size of the human fingerprint on extreme events and damages. If attribution studies instead show the change in intensity or magnitude instead of probability, it could be more easily applicable to demonstrate specific causation. Stuart-Smith et al. (2021) posit that "Attributing changes in event intensity to a defendant aligns with the logic of the 'but-for' test in law and may satisfy causation tests by showing how the magnitude of a harm was altered by an individual defendant's conduct." For example, in impact attribution, if proportion of damages can be demonstrated, this may also be used to satisfy causation. For example, if a municipality were to experience $50 million in damages related to a drought, but as that drought was made more severe by anthropogenic climate change, that municipality experienced $100 million in damages, that $50 million could be the damages considered in the lawsuit.

1.5. Summary & Organization of the Dissertation

The chapter explored how the nascent field of climate accountability has formed and grown in recent decades, and identified some of its strengths, challenges, and opportunities. It unpacked the assumptions or frames and methodological approaches that are commonly used to conceptualize, delineate, and pursue climate accountability. In doing so, several lessons stand out.

Currently, civil law is the climate accountability mechanism that is the most clearly defined and has the largest change of being realized. Accountability-based approaches to the UNFCCC WIM are currently stuck. This is not to say that civil law is the only vehicle—indeed, approaches based on recognition of responsibility (Huggel et al. 2015) and restorative and transitional justice (Klinsky and Brankovic 2018) have been alternatively explored. Yet as lawsuits are currently filed, by exploring how to develop evidence for civil lawsuits, this presents a unique opportunity to examine the intersections of scientific knowledge and praxis to explore the advancements in the climate accountability field.

Demonstrating responsibility within law and ethics is a function of both demonstrating causation and showing that there is something morally 'wrong' about that causation. Causation is demonstrating cause-and-effect along a causal chain and has to do with the material nature of GHG emissions, extreme events, and impacts. This component of responsibility in law is demonstrating that an 'injury in fact' is 'fairly traceable' to actions of the defendant. Advancements in end-to-end attribution methods—including source, extreme event, and impact attribution—are key to demonstrating this. However, for causation to lead to responsibility, there has to be a 'violation of a social principle'. This is synonymous with 'proximate causation' in law, in which concepts such as foreseeability determine whether the defendant *should* be held liable, even if causation is demonstrated. This can also include other 'attitudes, actions, and omissions', such as promoting disinformation about climate change or fighting alternatives to GHG-emitting activities (Frumhoff et al. 2015).

Regarding causation, there is a danger in overemphasizing the importance of minimizing uncertainty as this can lead to a tension between *attributability* and *vulnerability.* Traditional methods in scientific research on attribution aim to minimize confounding variables. However, it is the confounding variables that create impacts—pre-existing exposures and vulnerability differentiate whether a community will be heavily impacted by a hazard or not (Lahsen and Ribot 2022; Raju, Boyd, and Otto 2022; Smith 2006). Therefore, if accountability-based approaches to L&D are based in climate justice—including distributive, procedural, and corrective justice—then the most impacted communities should be focused on. ‘Most impacted’ then should be defined by experiencing the greatest impacts, not the impacts that are most linearly attributable to anthropogenic forcing.

Moreover, there are different requirements for demonstrating causation in science and law. Addressing these requirements head-on can help to alleviate some of that tension. While scientific evidence is leveraged in legal proceedings, for causation to be demonstrated based on that science, linear end-to-end attribution is not necessarily required. Instead, evidence may be presented in separate analyses across the full causal chain—from source to extreme event to impact attribution—as the evidence is then examined as a whole to demonstrate causation. Impact attribution may also be conceptualized in a way that is more useful in lawsuits, such as quantifying proportion of an impact attributable to anthropogenic climate change, rather than a change in likelihood or probability of that event. Yet while quantitative, indicator-based impact assessments have great value in measuring particularized harm, courts also accept non-quantitative based measures, or more complex vulnerability assessments, which can provide much more persuasive evidence of injury-in-fact. Therefore, conducting end-to-end attribution is still important, but can explore many different causal processes—especially in impact attribution—and explore how anthropogenic forcing as a causal chain interacts with other causal processes to exacerbate local impacts. Put another way, while end-to-end attribution is helpful for law, it can include non-linear processes and non-climatic causal chains, so long as the climate component is identified and measured. Researchers and practitioners in the field should therefore be thoughtful of what type of certainty is required and when and be cautious of the source of the overemphasis on issues of (un)certainty.

To do end-to-end research under a climate justice approach, conducting research within the frames of political economy can help to examine agency between actors as they contribute to emissions and, alongside STS approaches, examine how certain framings and production of knowledge is used to justify the continued emissions of GHGs. Moreover, political ecology and environmental justice frames will by definition promote distributive justice by ensure a focus on the most impacted communities, and procedural justice by ensuring the community is engaged to define the approach used. This facilitates asking first and foremost who is impacted and based on their voices, what do they need?

Organization of the Dissertation:

This dissertation aims to do just that. In this dissertation, I conduct end-to-end attribution in an empirical case study. In doing so, I examine the various challenges presented in this chapter, and test my assertion that PE/PE, STS, and EJ/CJ are well placed to address these challenges. My approach is presented in figure 2. Figure 2 includes the methodological translations for causal responsibility as well as the theoretical bounding boxes for determining whether social principles have been violated.

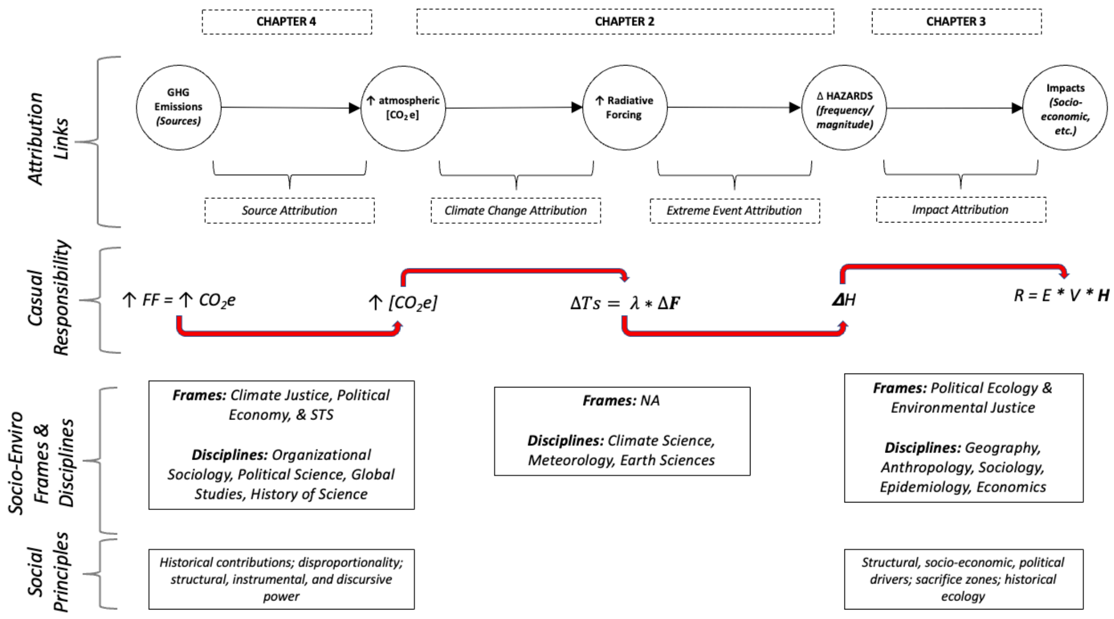


Figure 2. Conceptual framework for assessing climate responsibility and accountability and associated methods and disciplinary approaches.

I use this framework to guide three empirical chapters conducting end-to-end attribution for drought-related impacts in the Southwestern US. In these chapters, I respond to the guiding questions of this dissertation and grapple with some of the challenges raised in this chapter. The chapters do the following:

⇒ Tracing the empirical analysis along the causal chain begins first with source attribution. To determine responsible entities involves considering disproportionality in historical contributions and wielding of various forms of power to continue emitting or prevent change. Once those steps are conducted, demonstrating causal responsibility is an accounting exercise for CO_2e emissions (e.g. Heede 2014). This is found in Chapter 4.

⇒ Then the increase in concentration of CO_2e can be related to a change in global radiative forcing and the effect of that forcing on extreme events. Detection and attribution of anthropogenic forcing on drought in the Southwestern US and related impacts to vegetation is presented in Chapter 2.

⇒ Finally, impact attribution involves not only determining the effect of increased hazards at a local site, but the experiences of other drivers—structural, socio-economic, and political—in creating vulnerability in the first place and the history of the place that has rendered it as having highly particularized injuries. Moreover, within an EJ/CJ frame concerned with procedural justice, this involves focusing on the voices and needs of the community to drive this work. This is found in Chapter 3.

Ideally, this research would thus begin with the impacts for a community to center procedural justice. However, this dissertation was created iteratively, jumping between different parts of the chain as various challenges were identified and as new ideas emerged. One such challenge—the COVID19 pandemic—drastically shifted the order of research in this dissertation. Going against my own guidance of the need to begin with the community, the detection and attribution of climate change on extreme events and the examination of actions of big emitters was done before conversations with the impacted communities. The challenges from this reality will be explored throughout the dissertation as well, and particularly will be explored in the conclusion.

II. Detection and Attribution of the Effect of Human-Induced Temperature Increases on Vegetative Drought in the Greater Four Corners Region

2.1. Background

Anthropogenic climate change has left fingerprints on extreme events around the world, including wildfires, floods, heatwaves, and droughts (Climate Nexus 2020). These anthropogenically-fueled events have occurred in a world that is just 1°C warmer on average. Over the past decade, records have been frequently shattered—the 10 largest fires on record by area burned in California have all occurred since 2000, the five hottest years on record have occurred since 2015, and the Atlantic hurricane season of 2020 produced a record-breaking number of named storms. Moreover, recent years have seen an apparent increase in the number of anthropogenically-fueled extreme events. In 2020, there were a record-breaking twenty-two billion-dollar disasters in the United States (U.S.) alone (NOAA 2022). Moreover, that figure lumps together all the Western U.S. wildfires, indicating how this record-breaking figure may have underestimated impacts (Frank 2021). With continued greenhouse gases and associated warming, in the future, there is likely to be a continued increase in such events.

Since the turn of the century, the Southwestern United States (U.S.) has been in a megadrought (Williams et al. 2020; Williams, Cook, and Smerdon 2022). This drought has been associated with low water levels in the Colorado River, drying soils, and desiccating vegetation, leading to impacts on people, plants, and animals in the Southwest. Disentangling the anthropogenic drivers of this drought and its variable impacts is important for understanding the unique role that human-induced climate change has played in inducing or otherwise exacerbating the drought-related impacts. This chapter examines the desiccating effects of the drought on rangeland vegetation in the greater Four Corners region of the Southwest, covering much of the Colorado Plateau, and attributes the role of human-induced temperature increases in the intensity of that desiccation.

2.1.1. What is Drought?

Opening the U.S. Drought Monitor (USDM) map, you are struck by a play of colors across the Western U.S., ranging from yellows to dark reds. Indeed, the June 14, 2022 map indicates that nearly the entirety of the Southwestern U.S. is in some form of drought (Figure 1, USDM 2022). “S” and “L” dot the map, indicating areas of short-term and long-term impacts, while lines indicate “dominant impacts.” The classification scheme developed by the USDM incorporates estimates of precipitation, soil moisture, vegetation health, groundwater levels, pasture and range conditions, several drought indices, and local qualitative reporting of drought conditions.

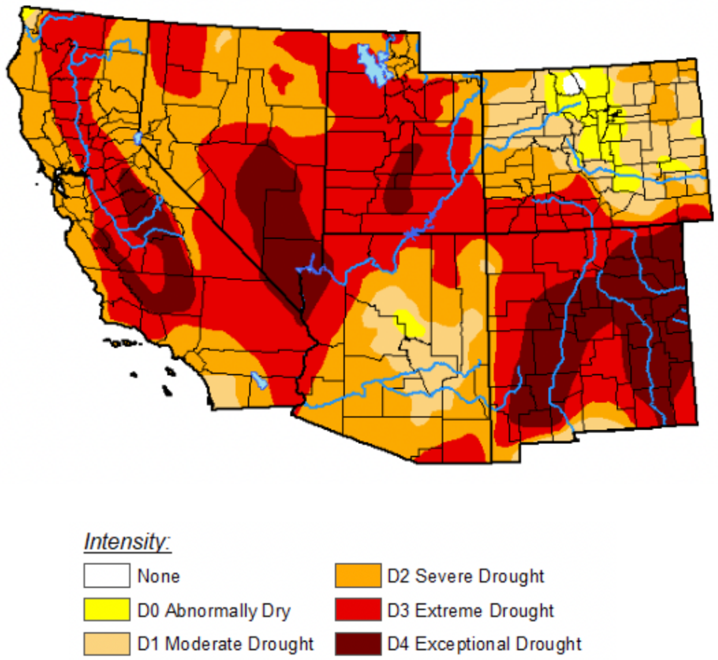


Figure 1. US Drought Monitor Map for June 14, 2022. The U.S. Drought Monitor is jointly produced by the National Drought Mitigation Center (NDMC) at the University of Nebraska-Lincoln, the United States Department of Agriculture, and the National Oceanic and Atmospheric Administration. Map courtesy of NDMC.

As aptly put by Funk and Shukla, "[d]roughts are enigmatic…creeping, and hard to define despite the fact that they are one of the most widespread and damaging types of natural disasters..." (Funk and Shukla 2020:23). Since 2000, after severe storms and hurricanes, droughts have resulted in the greatest economic losses in the U.S. at $7.2 billion/year on average (NOAA 2022). While damaging, as indicated by the numerous indicators used by USDM, droughts can also be difficult to define, yet alone quantify. What differentiates drought from a generally dry region? Is lower-than-normal precipitation sufficient to create drought? How about heatwaves? Or are droughts fully politically created, related to legislative decisions about water distribution between cities or sectors? These various questions and that "enigmatic" quality of droughts stem in part from the fact that there are many different types of droughts (Trenberth et al. 2014; NAS 2016:94-95). There are meteorological droughts, which are fully driven by reduced precipitation, and agnostic to any other meteorological, environmental, or socioeconomic contributions. Hydrologic droughts, instead, are defined by a reduced water supply, where groundwater resources, surface water bodies (e.g. lakes, ponds), or streamflow are lower than normal. Therefore, these first two drought types are defined by the change in water supply relative to reference precipitation or ground or surface water. There are then droughts which can be broadly understood as "insufficient water to meet needs" (NAS 2016:95), and hence is fundamentally an issue of supply and demand (Funk and Shukla 2020). These include agricultural drought, in which there is insufficient water for agricultural demand, and socioeconomic drought, in which the lack of water impacts people via agricultural output or domestic water availability. There is also ecological drought, which is defined as a reduction in water availability "that drives ecosystems beyond thresholds of vulnerability" (Crausbay et al. 2017). Vegetative drought—the focus of this chapter—is a type of agricultural or ecological drought and is here defined as insufficient water availability to meet local vegetative demand.

In these supply-demand droughts, the supply side is influenced by how much water is provided to the system (via localized precipitation, incoming streamflow, or anthropogenic water diversions such as aqueducts or irrigation); by how much water is removed from the system (by atmospheric evaporation, runoff, anthropogenic water diversions, or increased water use); and by how much is stored by the system (including soil moisture, snowpack, dams, water tanks, soil moisture, etc.) (Funk and Shukla 2020; Weiss et al. 2009; Yang et al. 2018; NAS 2016:94). The demand side includes water pulled from the system by anthropogenic (e.g. water pumping) or non-anthropogenic (e.g. plant growth) factors. If a system has greater demand for water than is present in the system, and insufficient storage to pull from, it will experience drought; however, if supply of water is greater than demand, or if there is plentiful storage (in a soil column, a reservoir, or snowpack), then the system will not experience drought.

As such, drought can be driven by several factors. Drought can be driven by a reduced supply of water into the system, such as less rainfall (meteorological drought), less incoming streamflow (hydrologic drought), or, theoretically, anthropogenically altered water diversions. Drought can also be driven by an increase in water being removed from the system, such as increased anthropogenic demand (e.g. more pumping of groundwater resources), or increased atmospheric evaporative demand, which will evaporate water out of the system. In certain places, direct anthropogenic drivers (such as increased water demand or damming and otherwise altering rivers and streams) have also led to or exacerbated drought.

Ultimately, this chapter focuses on the anthropogenic climate change drivers of vegetative drought in this region. In the absence of major disturbances, vegetative drought is largely controlled by two types of drivers—meteorological and plant-level physiological factors. This chapter examines both changing meteorological conditions and the vegetation responses. To do so, this chapter begins with an introduction to the Southwestern U.S. drought (Section 2.2), then reviews meteorological drivers of hydrologic drought (Section 2.3), and then reviews vegetation responses to hydrologic drought, including plant physiological responses (Section 2.4). The chapter then presents two empirical case studies which disentangle the effect of anthropogenic climate change on vegetative drought via increased temperatures (Section 2.5).

2.1.2. The Case Study: The U.S. Southwest

The U.S. Southwest has been called "…one of the most "climate-challenged" regions in North America", characterized by both variable and low precipitation and high temperatures (Overpeck et al. 2013; Wilder et al. 2016). As such, it is both semi-arid and drought prone. While droughts are short-term imbalances between supply and demand, aridity is the long-term imbalance between water supply and potential demand which defines the hydrological and biological characteristics of a region (Maliva and Missimer 2012:21-22). In such arid areas, vegetation growth tends to be water-limited instead of energy-limited and are often drought-prone (Maliva and Missimer 2012; Funk and Shukla 2020; Funk and Brown 2006; McVicar et al. 2012).

The Four Corners Region of the U.S. Southwest is where the states of Utah, Colorado, New Mexico, and Arizona intersect (Figure 2A). It lies on the Colorado Plateau, a high desert region of the intramountainous Western U.S. It has both high- and low-elevations, ranging from grasslands to shrublands to forests. While higher elevation portions of the region are cooler and wetter, the region is primarily semi-arid, with relatively low water storage and low moisture input. High elevations get > 1000mm of annual precipitation, while lowlands generally get under 500 mm. The study region for this chapter is the greater Four Corners region (34-39N, 112-105W), encompassing much of the Colorado Plateau and the spatial extent of exceptional drought in the 2018 water year (WY2018).

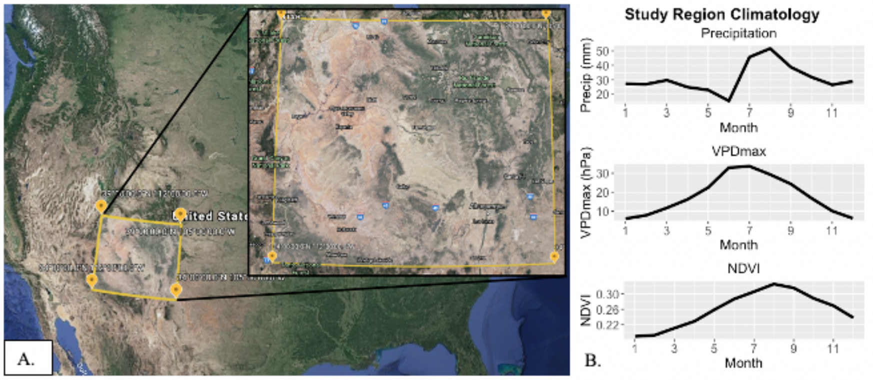


Figure 2. The study region: the greater Four Corners region of the Southwestern U.S. (A). Climatological precipitation, VPD$_{max}$, and Normalized Difference Vegetation Index (NDVI) are shown for the spatial average of the region (B). Precipitation and VPD are from the PRISM Climate Group while NDVI is from MODIS (see Section 2.3).

As shown in Figure 2B, the region receives bimodal precipitation, with snow in winter months and monsoonal rains in mid-summer (Garfin et al. 2013:3; Crimmins et al. 2013; Pascale et al. 2019). As such, water availability in the region comes in the form of winter snowpack, spring snowmelt, and summer monsoonal rains. Winter snowpack is an important hydrologic variable for the region, as water stored in the snowpack melts in spring and provides moisture during the otherwise dry spring months. This provides crucial moisture for vegetation, which begins to grow in late winter/early spring, and peaks in mid-late summer (Garfin et al. 2013). Snowmelt and associated runoff peaks in March-April, feeding both permanent and ephemeral streams and rivers. Finally, summer precipitation is brought by the North American Monsoon (NAM) arriving generally in July. The rain brought by the NAM often falls in short periods rather than extended across the full season; therefore, it can get most of its summer moisture in just a few storms. Temperature and vegetation generally follow the same cycle—temperatures are at local minima in winter associated with limited vegetation growth and reaches local maxima just before the arrival of the NAM, toward the end of the growing season. The arrival of the monsoonal rains cools the temperatures and provides moisture into the end of the growing season. Therefore, as snowmelt peaks in March-April, and the NAM generally doesn't arrive until July, the fore summer (May-early July) is both dry and warm. Therefore, it is this hot-dry fore summer (or midsummer, if the monsoon fails) that is at biggest risk for vegetative drought (Williams, Cook, Smerdon 2022; Weiss et al. 2009).

This semi-arid region is primarily covered by shrublands, forests, and grasslands, with some small areas of croplands and urban development (Theobald et al. 2013; Dewitz 2021). In terms of land-use and water use, the largest sector is the ranching sector. On the Colorado Plateau, cattle and sheep are the most common livestock (USDA 2019; Copeland et al. 2017). Cattle stocking rates have been relatively stable over the past century, while sheep stocking rates have declined (Copeland et al. 2017). Grazing density, however, has been relatively stable since 2000 (Copeland et al. 2017). The fraction of the Colorado Plateau covered by cropland has been relatively stable since 1950 at 3% (Copeland et al. 2017). Much of that cropland is for livestock feed, and most water withdrawals on the Colorado Plateau are for irrigation (Copeland et al. 2017). Simultaneously, increasing oil and gas development and population growth place additional demands on water (Copeland et al. 2017). These combined activities have placed enormous demand on already limited water supplies (Theobald et al. 2014; Copeland et al. 2017).

Against this background of high demand and high aridity, the Southwestern US has been in a megadrought since 2000 (Williams, Cook, and Smerdon 2022; Williams et al. 2020). The drought has been characterized by low precipitation, high temperature, and high VPD (Mankin et al. 2021; Williams, Cook, and Smerdon 2022). The reduced precipitation has been identified as largely due to natural variability (Williams et al. 2020; Lehner et al. 2018). Yet, elevated temperatures in the past few decades have exacerbated the moisture reductions from that low precipitation, increasing the intensity of the drought (Lehner et al. 2018; Crimmins et al. 2017; Weiss et al. 2009). This is a new ‘flavor’ of drought, in which hot conditions played a significant role in the drought’s intensity (Weiss et al. 2009; Crimmins et al. 2017). These factors combined have led to much of the Four Corners region being in drought since 2000 (Figure 3).

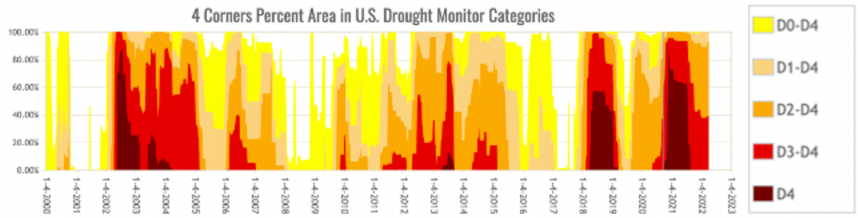


Figure 3. Timeline of Drought Conditions in Four Corners Region (from USDM 2022). This figure shows the extent of abnormally dry (D0), moderate drought (D1), severe drought (D2), extreme drought (D3), and exceptional drought (D4). Note, this time series is for the USDM-defined Four Corners region, mostly concentrated in Arizona and New Mexico. However, state-level timeseries look similar. The U.S. Drought Monitor is jointly produced by the National Drought Mitigation Center (NDMC) at the University of Nebraska-Lincoln, the United States Department of Agriculture, and the National Oceanic and Atmospheric Administration. Map courtesy of NDMC.

Direct anthropogenic factors—or disturbances—can affect both the supply and demand side of drought. Increased water diversions and industrial activities can affect water supply, while changing land use and population growth can affect demand. These are held static for the two analyses presented in this chapter. Copeland et al. 2017 reports that livestock stocking rates have been largely static over this time (demand side). And while diversions continue, most of the anthropogenic additions and removals of water to and from the region were completed before 2000. Not all disturbances may be controlled for, however—major fires have occurred in the region since 2000. However, by screening out forests (where the most intense fire activity has occurred) and focusing on rangelands (which recover quicker from fire activity than forests), fire disturbance can be partially controlled for. Therefore, this chapter focuses specifically on the meteorological and plant physiological factors of drought.

2.1.3. Meteorological Drivers of Hydrologic Drought

Meteorological changes can lead to or exacerbate hydrologic drought through multiple variables. These include reduced precipitation, changed timing or intensity of precipitation, precipitation falling as rain instead of snow, warm temperatures leading to early snowmelt, and hot temperatures leading to higher evaporative demand. As such, a region may be in ecological drought if there is insufficient water for normal ecosystem functioning (due to higher evaporative demand) but may not be in meteorological drought if the rainfall to date has been normal. Generally, however, meteorologically-driven (or exacerbated) droughts can be coarsely grouped into two categories—those that are mostly precipitation-driven or driven by a combination of low precipitation and elevated temperature.

Precipitation

The most direct contribution to hydrologic drought is reduced moisture input, and the most direct cause of reduced moisture input is reduced precipitation. While certain areas are climatologically drier (measured by total annual precipitation) than others, certain seasons and years can be anomalously dry. There are numerous sources of natural variability that can drive temporary reductions in precipitation via dynamic processes (Ahrens 1994, Goodrich et al. 2007; Pascale et al. 2019). Precipitation, however, is also influenced by thermodynamic changes, at least at large scales. As defined by the Clausius-Clapeyron relationship, as temperature increases, the atmosphere has an increased moisture-holding capacity (Ahrens

1994). This physical relationship between temperature and specific humidity has led to an indication in climate models of increased precipitation under climate change.

Recent studies have begun to identify the anthropogenic fingerprint on changing precipitation. While confidence is high for attribution of temperature-related events, it is lower for convective processes (NAS 2016). Therefore, the highest confidence results are those tied to thermodynamic drivers of precipitation. First, as precipitation in certain regions is closely tied to changing SSTs, increased SSTs have been linked to reduced precipitation in different regions (e.g. Funk et al. 2019; Carvalho 2019). Moreover, studies have also pointed to the intensification of precipitation events because of anthropogenic forcing (Trenberth et al. 2011b; Pascale et al. 2019; Swain et al. 2018). Intensification of extreme precipitation as a result from the Clausius-Clapeyron relationship (Westra et al. 2013). This intensification does not occur evenly everywhere, however; instead, evidence suggests that this relationship increases extreme precipitation in energy-limited environments, while extreme precipitation is decreasing in water-limited environments (Prein et al. 2016). However, in the Southwestern U.S., many of these studies find little indication of anthropogenic fingerprint on changed precipitation total. Conversely, one study finds that the combination of greenhouse gas emissions (warming) and aerosol emissions in North America (cooling) shifted the inter-tropical convergence zone (ITCZ), leading to increased summer precipitation in the Western U.S. With the reduction of aerosol emissions since, summer precipitation has fallen as the ITCZ is shifting north again (Bonfils et al. 2020). However, confidence is low overall for anthropogenic drivers of changing precipitation in the Southwestern U.S. (Williams et al. 2020; Lehner et al. 2018).

Temperature

Increasing temperatures also contribute to drought. In regions in which snowpack is an important hydrologic term (including large portions of the Western US), increased temperatures can lead to precipitation falling as rain instead of snow and lead to early snowmelt, reducing storage terms and hence water supply later in the season. Substantial reductions in snowpack have been observed for the Northern Hemisphere in spring (March-April) (IPCC 2013:25). Snow Water Equivalent (SWE) is commonly used to measure the storage term of snowpack—it is the amount of water that would be released if the entire snowpack melted. Studies have found that at least half of the observed reductions in SWE in the Western U.S. from 1950-1999 were due to anthropogenically-increased temperatures (Pierce et al. 2008; Barnett et al. 2008). These reductions in SWE are related to two mechanisms. Warming temperatures in spring (March-May) have led to enhanced snowmelt in these spring months (Kapnick and Hall 2011; Shukla et al. 2015). Moreover, a shift in the snow-to-rain ratio due to anthropogenic warming has also shifted runoff timing for the Sierra Nevada range (Huang et al. 2018). This combination of reduced winter snowpack with earlier snowmelt in March-May has led to earlier runoff in the Western US, leading to lower water availability in late spring and summer months (Kapnick and Hall 2011; Barnett et al. 2008; Hidalgo et al. 2009). While these changes do not affect total annual water input, they can lead to a longer dry season.

Increased temperatures also have affected streamflow. While reduced precipitation has the greatest control over streamflow in the Colorado River Basin, increased temperatures have led to measurable further reductions (McCabe et al. 2017; Weiss et al. 2009; Udall and Overpeck 2017; Woodhouse et al. 2016). For the Colorado River, one study identified that it is likely an increase in evaporation or snowmelt instead of a shift from snow to rain that has driven most of the reductions in streamflow (McCabe et al. 2017). Specifically, more than half of the reduced streamflow in the Colorado River is due to warming, with streamflow reductions of approximately 9% / 1°C increase (Xiao et al. 2018; Milly and Dunne 2020).

Warming temperatures also increase the moisture holding capacity of the atmosphere. As such, increased temperatures increase atmospheric evaporative demand. A simple physical principle underlies this process. As described by the Clausius-Clapeyron equation, the amount of water vapor required to fully saturate the air increases as an exponential function of temperature (Ahrens 1994:117,188). Therefore, as air temperature increases, the atmospheric demand for water increases exponentially. This increases evaporative demand, thereby driving an increase in evapotranspiration (ET) from surface water bodies, from soil, and from plants. ET_p is the evapotranspiration that would occur if there were sufficient surface water to meet evaporative demand (Trenberth et al. 2014). If there is enough water available, and there is no surface resistance, this then theoretically increases actual ET (ET_a) until that parcel of air is fully saturated. However, if there is insufficient surface water, or resistance to ET, the actual amount of water vapor in the parcel is less than the parcel can hold, leading to a deficit between that saturated potential value and the actual value. This can lead to or exacerbate surface water reductions.

This deficit can be measured in terms of pressure (Ahrens 1994:116; Daly et al. 2015). The amount of water vapor that can be held by the air—the Saturation Vapor Pressure (SVP)—increases exponentially as a function of temperature (Equation 1b). The Actual Vapor Pressure (AVP) is a function of how much water is available, or relative humidity (Equation

1c-d). If AVP is below SVP, there is a deficit—a Vapor Pressure Deficit (VPD) (Equation 1a).

$$[\boldsymbol{a}]\ VPD = SVP - AVP$$

$$[\boldsymbol{b}]\ SVP = 6.1094 * e^{\frac{17.625*T}{243.04+T}}$$

$$[\boldsymbol{c}]\ AVP = 6.1094 * e^{\frac{17.625*T_d}{243.04+T_d}}$$

$$[\boldsymbol{d}]\ T_d = \frac{237.3\ln\left[SVP * \left(\frac{RH}{611}\right)\right]}{7.5ln10 - \ln\left[SVP * \left(\frac{RH}{611}\right)\right]}$$

Equation 1. Vapor Pressure Deficit (VPD) series of equations (from Daly et al. 2015). (a) VPD is a function of SVP and AVP. (b) SVP is a function of temperature. (c) AVP is a function of dewpoint temperature, which is (d) a function of SVP and relative humidity.

VPD is high in arid, water-limited regions, as these areas tend to experience elevated temperatures and low moisture. Thus, high VPD can increase the risk of hydrologic (and ecological and vegetative) drought, as it places a large evaporative demand on the earth's surface (NAS 2016:98). VPD is the largest control on atmospheric evaporative demand, and hence better captures that evaporative demand than does temperature and relative humidity (Peng et al. 2018; Wang et al. 2019).

Anthropogenic climate change has increased VPD for much of the world. As SVP is an exponential function of temperature, SVP increases exponentially with warming. However, in many areas, AVP does not. For AVP to increase, there would need to ample available surface water source to evaporate. Over land-locked regions, that evaporation is constrained by multiple processes, including low available surface water (Byrne and O'Gorman 2016). This has been documented for the US—VPD has increased across the continental US

(CONUS), particularly in summer months, mostly driven by warming temperatures (Ficklin and Novik 2017). Similarly, globally, more than half of vegetated areas have experienced an increase in VPD, due mostly to rising SVP (Yuan et al. 2019).

Compound Events

Often, droughts are not due to just one variable or extreme event. Instead, if two events occur together, even if only one is extreme on its own, they can interact to produce an extreme compound event. A common compound event is the co-occurrence of anomalously low precipitation and high temperature producing 'hot droughts' (Cheng et al. 2019; Udall and Overpeck 2017). Compound events can produce extreme drought even if neither variable on its own was extreme—if precipitation is low and occurs alongside high temperatures, the high temperatures can shift what would be moderately dry conditions due to precipitation deficits alone to extreme drought (Aghakouchak et al. 2014; Zscheischler and Senevirante 2017). As such, in assessing such droughts, univariate models are often insufficient as they fail to capture the concurrent climatic variables driving the compound event (Aghakouchak et al. 2014; Zscheischler and Senevirante 2017).

The Southwestern U.S. drought is just such a compound event (Williams, Cook, and Smerdon 2022; Williams et al. 2020; Mankin et al 2021; Lehner et al. 2018; Weiss et al. 2009), as was the multi-year California drought (Diffenbaugh, Swain, and Touma 2015; Mann and Gleick 2015; Griffin et al. 2014). As shown in Figure 4, for the study region, as temperatures have increased in recent decades, compound hot-dry events are occurring more frequently.

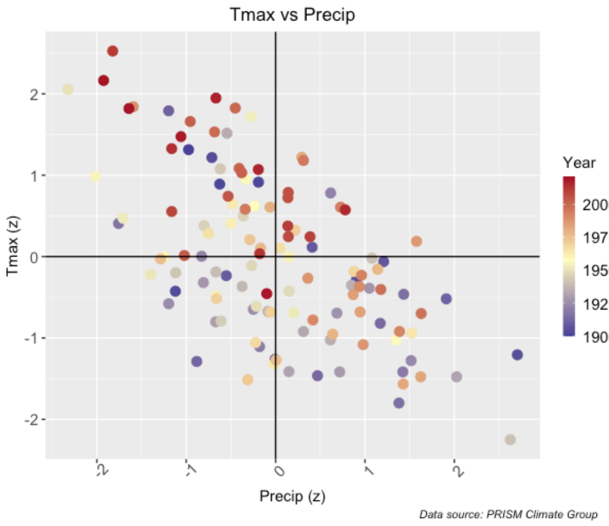


Figure 4. Standardized temperature versus precipitation for the spatial average of the study region. Data comes from the PRISM Climate Group. This figure is modelled on the figures in Diffenbaugh, Swain, and Touma 2015; Mankin et al. 2021; and Mann and Gleick 2015.

A global change in drought?

As described above, increasing temperatures and decreasing precipitation can lead to hydrologic drought. When does that translate to ecological or vegetative drought? Increasing VPD has an important effect on ET, which itself may lead to or exacerbate drought. For example, elevated temperatures and VPD have decreased soil moisture in CA and across the greater Southwest contributing to hydrologic and ecological drought (Griffin and Anchukaitis 2014; Williams et al. 2015; Shukla et al. 2015; Williams, Cook, and Smerdon 2022; Williams et al. 2020). Yet, this effect is tempered by other processes. While increasing VPD increases the atmospheric evaporative demand, actual ET (ET_a) may not rise as quickly as would be expected based solely the processes described above. To understand why, it helps to look at common methods of estimating potential ET (ET_p). There are two primary approaches to estimating ET_p—using the simpler Thornthwaite equation and the more physically-based

Penman-Monteith (PM) equation (Dai 2011). The Thornthwaite formulation is just a function of temperature, latitude, and month. The PM additionally includes net surface radiation (in lieu of latitude), wind speed, SVP, and VPD. Both formulations capture the fact that ET_p rises with increasing temperatures. However, use of PM has been broadly accepted as more accurately capturing ET_p (Dai 2011; Funk and Shukla 2020; Trenberth et al. 2014). This is illustrated by a debate about the presence of a global trend in drought.

The debate revolved around the following question: with the physical understanding that increased temperatures (and thus atmospheric evaporative demand) lead to increased ET_p, does that then translate into a global increase in ET_p and therefore hydrologic drought? Two papers found seemingly opposing results—Dai 2013 finds a significant role of temperature when modelling global drought projections and predicts widespread drought, while Sheffield et al. 2012 maintain that there will not be a risk of widespread drought in the future. What explains this discrepancy? Trenberth et al. 2014 examined the methodology of both papers and found three main differences in the papers' methods which influence results. Both papers used the Palmer Drought Severity Index (PSDI) as the drought metric, which accounts for both moisture inputs and outputs relating to the supply side of drought—namely, precipitation, runoff, and ET. ET, as explained above, increases with temperature, but is also affected by relative humidity (which will influence VPD, and hence atmospheric evaporative demand) and windiness (which will transport evaporated water away). The two papers used different formulations for ET—Dai 2013 uses Thornthwaite which excludes the effect of windiness and RH, but has lower uncertainty globally, while Sheffield et al. 2012 use PM which is more physically accurate but produces higher global uncertainties due to limited data availability. Second, they use different precipitation datasets, with the precipitation data used by Sheffield et al. 2012 having a ‘wet bias’ in recent years. Finally, they choose different baseline periods—Dai 2013 chooses a relatively wet baseline period, while Sheffield et al. 2012 choose a period that includes anthropogenic forcing, therefore likely a drier period. In sum, Sheffield et al. 2012’s (Dai 2013’s) study design resulted in a relatively drier (wetter) baseline and wetter (drier) current conditions, indicating a smaller (larger) change in drought.

These results demonstrate a few important takeaways. First, the metric to measure drought and methods employed should be carefully chosen to ensure that the drought type of interest is being measured. Second, there is a tradeoff between simplicity of measurement and precision when it comes to understanding the effect of increased atmospheric evaporative demand on ET_a. ET_a is influenced by variables captured in the PM formulation that are missed in the Thornthwaite formulation. Dai 2013 chose to accept the loss of precision by using Thornthwaite as the accuracy of data needed for PM at the global level was poor. Instead, at a more regional or local level, attribution of the effect of anthropogenic climate change on drought can be more accurate as these various data (and other local changes) may be assessed (NAS 2016:96).

2.1.4. Vegetative Drought

As described in the previous section, increased temperature exerts a significant influence on drought and can turn a moderate precipitation-driven drought into a severe hot-and-dry drought. There is evidence that increasing temperature, and therefore VPD, has increased water constraint worldwide and affected the global carbon cycle (Jiao et al. 2021; He et al. 2021; Yuan et al. 2019). However, vegetative drought is influenced not only by the hydrologic inputs, outputs, and storage terms, but also by the capacity of vegetation to mitigate these changes. While increases in VPD will lead to greater evaporative demand, surface resistance from reducing soil moisture, plant stomatal-closure, and changing water use efficiency of plants will mediate the effect of increasing VPD on vegetative drought. Such vegetation responses to increasing VPD must be considered to understand how increasing VPD contributes to vegetative drought. These vegetative responses are examined in this section, beginning with plant physiological responses, then moving from the plant-scale to ecosystem-scale rates of ET_a, to VPD impacts on ecosystem-level net primary productivity (NPP), to the differential responses of different plant species to increasing VPD.

Plant Physiological Responses to Increasing VPD and Decreasing SM

Plants photosynthesize to gain carbon for maintenance respiration and growth, requiring the intake of carbon dioxide (CO_2) through small holes in the leaf surface called stomata. Plants also transpire as part of photosynthesis: to absorb CO_2, they open their stomata and release water vapor. Transpiration is a passive process—water moves from soil to root to xylem to air due to a gradient of water potential, moving from high to low water potential and is therefore held under tension in the plant (Chapin et al. 2012:104-107). Therefore, the VPD between the leaf surface and the air (leaf-level VPD, or VPD_L) is the primary driver of transpiration (Chapin et al. 2012:106; Grossiord et al. 2020). There is almost always a vapor pressure gradient between the inside of the leaf and the outside (or VPD_L greater than 0), because the leaf is almost always fully saturated and is warmer than the bulk air, while the outside air is nearly always unsaturated (Chapin et al. 2012:106; Grossiord et al. 2020). Therefore, when stomata are open, water vapor will move from inside the leaf to the air.

However, there are two sources of resistance to water movement from the leaf to the air—boundary layer resistance and stomatal resistance (Tais and Zeiger 2004:96-98). Turbulent mixing (windiness) moves air parcels saturated with water vapor from transpiration away from the leaf, thereby facilitating continued transpiration (Chapin et al. 2012:116). Boundary layer resistance (r_b) exists when there is little turbulence so the surface air becomes saturated—when this occurs, transpiration will slow or halt. However, if there is turbulence (and hence low r_b), transpiration will occur until stomata close. This stomatal closure is referred to as decreased stomatal conductance (g_s) or increased stomatal resistance (r_s), where g_s is the amount of water vapor conducted from the plant, and r_s is the resistance to that conductance.

Plants can actively sense local environmental conditions and change the rate of transpiration (and therefore photosynthesis) through the opening and closing of stomata (Chapin et al. 2012:112-113; Grossiord et al. 2020). Stomata generally close during the night when the plant is not photosynthesizing. However, during the day, with ample moisture, a plant will photosynthesize—and therefore transpire—at its maximum rate, with water moving up the plant and out through stomata. Yet, if the plant senses low moisture conditions or high evaporative demand, it will close stomata to avoid desiccation. Therefore, plants may decrease g_s (increase r_s) in response to increased VPD_L or decreased soil moisture supply (Chapin et al. 2012:112-114; Novick et al. 2016).

When soil moisture (SM) declines, water films become thinner on soil particles and there is less accessible water for plant roots to capture. As plants can sense available SM around their root systems, they change g_s in response to the SM around the roots rather than throughout the soil column (Chapin et al. 2012:114). Therefore, plants don’t show water stress proportional to rate of SM decline. Instead, they generally don’t show water stress until ~ 75%

SM reduction, at which point they will generally decrease g_s, therefore reducing ET_a below the maximum rate (Chapin et al. 2012:117). Similarly, plants will decrease g_s (increase r_s) in response to increased VPD_L (Grossiord et al. 2020; Oren et al. 1999; Sperry et al. 2017; Ficklin and Novick 2017). While VPD and g_s are inversely related, it is not a linear relationship. Across all VPD values, the relationship is negative, but g_s declines more rapidly with increasing VPD at low VPD compared to high VPD, so $dG_s/d\mathrm{VPD}$ is steepest at lower VPD values (Grossiard et al. 2020; Oren et al. 1999; Zhang et al. 2019).

These processes reflect the tradeoff between carbon assimilation and water loss that defines the rate of photosynthesis in dry conditions (Sperry et al. 2017). The plant aims to assimilate carbon through photosynthetic activity, but as the very act of photosynthesis loses water, unconstrained photosynthesis in dry conditions could lead to catastrophic depletions in water tension leading to hydraulic failure and air bubbles in the xylem (cavitation). Therefore, under increasingly dry conditions with increasing atmospheric VPD_L, this tradeoff increasingly supports reductions in transpiration to conserve water, which also reduces the rate of carbon assimilation. Plants are required to continue some level of photosynthesis, however. Stomatal conductance will never go to zero so long as there is moisture in the plant, as living vegetation will keep stomata slightly open to perform some photosynthesis (Massmann et al. 2018). During periods of extreme or extended drought, if VPD_L remains high or soil moisture remains critically low, it can overwhelm the plants' ability to mitigate dry conditions. If the plant does not close its stomata during periods of water stress and plant water potential drops dangerously low, it risks cavitation which can be fatal to the plant (Tais and Zeiger 2004:95-96).

ET_a Responses to Increasing VPD and Decreasing SM

While plant physiological responses to increasing VPD offer insights to how increasing VPD will affect ET_a, the world is not one big leaf. Instead, at the ecosystem scale, ET has two sources—direct evaporation from the soil, and transpiration from plants. There are two key equations to understand these processes: the surface energy balance equation (equation 2) and a specific formulation of the Penman-Monteith (PM) ET_a equation (equation 3).

The surface energy balance explains the balance between incoming solar / shortwave (K) and outgoing longwave (L) radiation (equation 2a) (Chapin et al. 2012:96-97). Incoming radiation is mediated by planetary albedo (α), where the higher the albedo, the more radiation is reflected ($(1 - \alpha)K_{in}$) (equation 2b). Outgoing radiation is a governed by blackbody radiation, or emissivity * temperature^4, where the sky component of longwave radiation is influenced by cloudiness, while the surface component is influenced by how much radiation is intercepted at the surface (equation 2b). For radiation intercepted at the surface, energy is then transferred into the soil as heat (G), released into the air as sensible heat (H), or the energy is used to evaporate water (latent heat, LH) (equation 2c). Sensible heat is just heat, while latent heat is the energy used for the phase change of water from liquid to vapor.

$$(a): R_{net} = (K_{in} - K_{out}) + (L_{in} - L_{out})$$

$$(b): R_{net} = (1 - \alpha)K_{in} + \sigma\left(\varepsilon_{sky} * T_{sky}^4 - \varepsilon_{surface} * T_{surface}^4\right)$$

$$(c): R_{net} = H + LE + G$$

Equation 2: Surface energy balance equations from Chapin et al. 2012:96-97).

Increased concentrations of greenhouse gases in the atmosphere will increase L, which then must be balanced through the right side of equation 2c—through H, LE, or G. This is where soil moisture (SM) and vegetation cover come into play—with ample SM and high photosynthetic activity in vegetation (and hence transpiration), greater ET_a occurs, meaning more energy is transferred as latent heat flux. Conversely, dry soils and limited photosynthetic activity means more energy is transferred as sensible heat flux (Chapin et al. 2012:99; Wang et al. 2019). As will be described later, this increase in energy in the earth's system from anthropogenic climate change is driving differential changes in H and LE in different places.

Therefore, as ET_a drives LE, it therefore accounts for the partitioning or ratio between H and LE—with more ET_a, there is less H (meaning less heat). Yet increasing ET_a also decreases local water resources. The Penman-Monteith equation describes how ET_a is dependent on VPD, windspeed, temperature, radiation, and G_s (equation 3). The (R_n – G) term is the combination of latent and sensible heat flux (as net radiation minus soil heat flux from equation 2c). The r_a and r_s terms are aerodynamic (or boundary) and stomatal resistance, respectively. The Δ term is Clausius-Clapeyron relationship, in which SVP increases as an exponential function of temperature. Finally, the (p_a*c_p) term relates to air density and specific heat capacity, while γ is a constant. Increased VPD will increase the top term, but also affect the r_a and r_s terms.

$$ET = \frac{\Delta(R_n - G) + \ p_a \ * c_p * \frac{VPD}{r_a}}{\Delta + \ \gamma * (1 + \frac{r_s}{r_a})}$$

Equation 3: The FAO Penman-Monteith equation for ET as a function of surface and aerodynamic conductance, SVP, VPD, and latent and sensible heat flux.

These two equations offer insights into how surface ET_a will change with increasing VPD. Just as plants exert stomatal resistance (r_s), the ecosystem exerts surface resistance (R_s). Similarly, the ecosystem-scale equivalent of stomatal conductance (g_s) is surface conductance

(G_s). Over non-vegetated surfaces (i.e. bare soil), increasing VPD corresponds to a direct increase in ET_a over *moist* soil, as there is no r_s and as long as there is low r_b (Dai 2013). Yet, as surface SM decreases, there is less available moisture to evaporate, thereby increasing R_s and decreasing the rate of $dET_a /dVPD$ (Zhou et al. 2021). Moreover, while the world is not one big leaf, there are many leaves, so the r_s described in the previous section will also contribute to the decline in $dET_a /dVPD$ (Massmann et al. 2018). These two processes decrease G_s, limiting ET_a (Wang et al. 2019; Ficklin and Novick 2017; Novick et al. 2016; Massmann et al. 2018). Therefore, increasing VPD corresponds to a weaker response of ET_a than would exist without R_s (a lower $dET_a /dVPD$). Importantly, ET_a will still increase with VPD; R_s will simply make ET_a lower than it would be without R_s (Massmann et al. 2018).

What does this mean for energy fluxes? Increasing VPD will drive an increase in ET_a, leading to latent heat flux from the earth's surface. Yet, if there is not enough available surface moisture, energy will be released instead as sensible heat. Therefore, as VPD rises, and as surface moisture declines, the partitioning between latent and sensible heat flux will shift, leading to more sensible heat flux (Wang et al 2019; Zhang et al. 2008; Cheng et al. 2019). This increase in sensible heat can then further increase temperatures. This process is land-atmosphere coupling, in which reduced surface moisture further leads to temperature increases and evaporative demand (Wang et al 2019; Zhang et al. 2008; Cheng et al. 2019). This ratio of sensible to latent heat flux is called the Bowen ratio—in semi-arid environments, the Bowen ratio is high, so most energy transfer occurs as sensible heat flux (Chapin et al. 2012:99). The Southwestern U.S. has a high Bowen ratio and significant land-atmosphere coupling. Zhang et al. 2008 find that land-atmosphere coupling over CONUS explains much of the variance in maximum summer temperatures. Over the southwest, this coupling apparently explains around ~50% of interannual summer T_{max} variance.

Net Primary Productivity Responses to Increasing VPD and Decreasing SM

Plant productivity is commonly measured as Net Primary Productivity (NPP), which is the net carbon gained by plants annually (Chapin et al. 2012:161-162). It is the different between Gross Primary Productivity (GPP) and respiration. GPP and NPP track well—about half of GPP is converted to NPP (Chapin 2012:161). In non-water-limited ecosystems, NPP increases exponentially with increasing temperature while NPP increases rapidly with precipitation, but above approximately 2000 mm/yr, declines with additional precipitation (due to waterlogging of the soil and make it hard for roots to access nutrients). Conversely, in dry sites, NPP is generally water-limited (Chapin et al. 2012:169-171).

Increasing VPD can affect GPP via available SM, via the direct effect on stomatal closure, and on leaf area. Similarly, increasing atmospheric CO_2 can affect GPP. As described in the previous section, surface resistance (R_s) will constrain the rate of ET_a with increasing VPD. What does this mean for vegetation health and growth in water-limited sites? This affects plant productivity in two ways, related to that tradeoff between carbon assimilation and water loss. In the extreme, over-prioritizing water conservation can lead to carbon starvation, while over-prioritizing photosynthesis can lead to cavitation (Grossiord et al. 2020; Chapin 2012:123).

While increasing r_s can conserve water, it is at the expense of photosynthesis (Ficklin and Novick 2017). For short-term drought, this may be a worthy tradeoff, as the plant can then photosynthesize when water is available later. Therefore, in water-limited times, plants will slow their slow growth rate to match environmental supply (Chapin et al. 2012:169). There is evidence that this has been occurring: studies have found that increasing VPD has affected the global carbon cycle, where a decrease in global GPP/NDVI has been observed with the increase in VPD (He et al. 2021; Yuan et al. 2019).

Just as r_s increases with VPD_L, there is also a negative response of photosynthetic carbon assimilation to increasing VPD_L, but weaker (Grossiord et al. 2020; Zhang et al. 2019; Fu et al. 2022). In other words, GPP is less sensitive to increasing VPD than is r_s (Grossiord et al. 2020; Zhang et al. 2019; Fu et al. 2022). This is because the water-use efficiency (WUE) of plants increases with g_s. WUE is the carbon gained per unit of water lost ($WUE = A_n / T$) (Chapin et al. 2012:146). It changes with g_s because the inward flux of CO_2 experiences more resistance than the outward flux of water, so there is a larger proportional effect of r_s on water flux than on CO_2 flux (Chapin et al. 2012:146). Therefore, while stomatal closure reduces carbon assimilation, carbon assimilation is not as low as it would be without an increase in WUE (Chapin et al. 2012:123). In short, WUE increases with increasing VPD_L, tempering the effect of increasing VPD_L on carbon assimilation.

As such, WUE is very closely related to VPD. Given that relationship, researchers have dervived the intrinsic WUE (iWUE), which refers to the carbon gained per unit decrease of stomatal conductance (A_n / g_s) (Zhang et al. 2019; Fu et al. 2022; Zhou et al. 2017). Therefore, iWUE captures the unique stomatal sensitivity to VPD, while controlling for evaporative potential from high VPD (Zhang et al. 2019). Zhang et al. 2019 found that at relatively low values of VPD, as VPD increases, and g_s decreases rapidly, iWUE increases rapidly so that carbon assimilation continues at the same rate. Yet, at higher VPD levels, especially if coupled with low SM, reduced CO_2 in the plant due to lower g_s will limit photosynthesis. Therefore, this increase in iWUE with increasing VPD does not continue unabated. At high VPD in arid sites, iWUE stabilizes or even decreases (Zhang et al. 2019). Therefore, when VPD is very high, the impacts on photosynthetic activity are pronounced.

What about the effect of declining SM? Historically, most analyses have relegated the effect of increasing VPD as an indirect effect on GPP via reductions in SM (Chapin et al. 2012:169; Williams et al. 2020). Yet, as described in the plant physiology section, both soil water potential and leaf water potential relate to flux of water—plants close stomata with increasing VPD_L, while stomatal conductance is affected when SM levels fall below ~75%. So, it follows that theoretically either a change in VPD_L or SM near plant roots will affect transpiration rates. The physiological reasoning would state that, therefore, at very low SM levels, SM controls stomatal conductance, while at higher SM levels, VPD_L controls stomatal conductance. Several studies have disentangled the role of VPD and SM on plant growth and found this to be true at the canopy/ecosystem-scale. Novick et al. 2016 test the roles of declining SM and increasing VPD on declining G_s. For most sites, they find that VPD limits G_s more than SM, while SM exerts greater control on G_s only in arid sites experiencing anomalously low SM. Fu et al. 2022 find similarly that VPD contributes more than SM to limiting GPP, except when SM is <30th percentile, when SM then dominates. Conversely, GPP sensitivity to VPD remains relatively constant across SM gradients, with slightly higher sensitivity at SM > 40th percentile (Fu et al. 2022). He et al. 2022 also find that, globally, VPD remains significant in explaining net ecosystem productivity (NEP) even when controlling for SM. Finally, Massmann et al. 2018 find evidence that for most vegetation types, VPD explains most of the variation in ET over the range of observed VPD. For only a few PFTs (grasslands and savanna) is ET_a not explained by VPD, and they hypothesize this is due to exceptionally low SM. The overall takeaway is that when SM conditions are exceptionally low, SM constrains g_s, ET_a, and GPP. However, when SM conditions are low to average, VPD is the dominant control over each variable.

Finally, as WUE is the carbon gained per unit of water lost, an increase in CO_2 can also increase WUE (a "CO_2 fertilization effect"). With more CO_2 in the air, plants can have partial stomatal closure to lose less water while still fixing the same amount of carbon. In *non-water-limited* areas, Yang et al. 2018 find that increasing atmospheric CO_2 has almost entirely offset the effect of VPD on ET_a. Yet, in *water-limited areas*, Jiao et al. 2021 examine the effect of increasing CO_2 on GPP, finding a significant role of increasing atmospheric CO_2 on offsetting some, but not all, of the water constraint on vegetation growth. Moreover, 21st century projections of g_s for CONUS indicate that increases in VPD and CO_2 are projected to have the same magnitude of declining effect on g_s. Translating the effect on g_s to NPP, declines in productivity from increasing VPD may offset photosynthetic gains from CO_2 (Ficklin and Novick 2017). While this evidence points to increasing CO_2 offsetting some of the deleterious effects of increasing VPD on GPP, it indicates that it will not offset all, especially in water-limited areas. Moreover, based on plant physiology, increased atmospheric CO_2 can only act to offset reduced photosynthesis due to moisture limitation, rather than lead to even greater plant growth. Experiments show that when exposed to elevated CO_2, plants initially increase photosynthesis, but then downregulate photosynthetic capacity and partially close stomata (Chapin et al. 2012:139). In other words, this effect does not mean that long-term plants are more productive under higher concentrations of CO_2; rather, it means that plants may partially close stomata to gain the same amount of carbon, meaning there is less water loss for the same carbon gain (see box 1).

Putting together all the processes described thus far, Figure 5 presents a conceptual illustration of how G_s, iWUE, and ET_a affect GPP. At relatively low values of VPD and high enough SM, surface processes act to reduce the negative effect of increasing VPD on GPP. Yet at high VPD and low SM, negative effects begin.

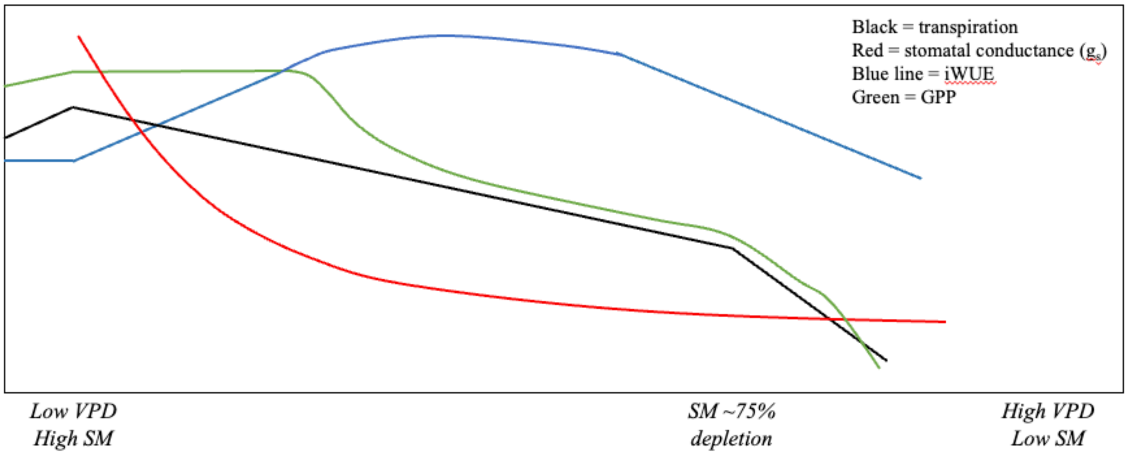


Figure 5. Conceptual illustration of combined effects of changing ET_a, G_s, and iWUE on GPP. Y-intercepts do not correspond to any specific values. This diagram may look different for different plant types and soil types.

Box 1. The CO_2 Fertilization Effect—From Scientific Phenomenon to a Tool for Climate Denial.

As described above, the CO_2 fertilization effect is real. However, it has been distorted and taken out of context as a tool for climate change denialism. For example, the American Coalition for Clean Coal Electricity (ACCCE), a trade association of American coal producers and utility companies with a long track-record of fighting climate legislation, contracted a 2014 report on climate change and coal (see Chapter 4 for more on ACCCE). The report stated that: "...largely absent from most SCC [Social Cost of Carbon] analyses is the incorporation of many important direct CO_2-induced benefits, such as improvements in human health and increases in crop production... With respect to crop production, literally thousands of laboratory and field studies have documented growth-enhancing, water-conserving, and stress-alleviating benefits of atmospheric CO_2 enrichment on plants" (Management Information Services 2014). They claim that because of uncertainty in models, "damage estimates relying on future temperature projections should be considered to be significantly inflated." Their linear projection of CO_2 fertilization laboratory experiment outcomes into the future do not include the effect of increased temperature or VPD on water availability and therefore vegetation growth.

What is Considered 'High' VPD? Differential Vegetation Response to Increasing VPD

The previous section described the pathways by which increased VPD (and CO_2) affect plant r_s, ET_a, and NPP. However, different types of plants have different traits which mediate these effects. Studies have identified how different plant functional types (PFTs) respond differently to these changes.

First, there are different productive potentials across sites—an arid grassland can never be as productive as a temperate grassland, let alone a tropical forest (Chapin et al. 2012:171). This is because different plant species take hold in different sites based on the local environmental and climatic conditions (Hirota et al. 2017). Therefore, in sites with limited water availability (water-limited sites), plant species will take hold which may not be as productive as other species but are uniquely adapted to living in water-limited sites, and therefore less likely to die during droughts compared to their more productive counterparts (Chapin et al. 2012:171). There are a few key mechanisms found in plants which may increase their drought tolerance—carbon fixation pathways, rooting depth, water potential tolerance, and prioritizing water conservation versus productivity.

Plants have different carbon fixation pathways, which are uniquely suited to different aridity conditions. The C_3 pathway for carbon fixation is present for all photosynthesis. However, some plants have certain adaptations to allow them to lose less water while photosynthesizing. C_3 plants only use the C_3 pathway and, as part of transpiration, lose around 400 molecules of water for each molecule of CO_2 gained. Two other categories exist: plants that use the C_4 pathways and CAM pathways only lose 150 and 50 molecules of water for each molecule of CO_2 gained, respectively (Taiz and Zeiger 2004). C_4 plants manage this by reducing photorespiration. As photorespiration increases exponentially with temperature, these plants can photosynthesize at higher rates in hot environments. However, they aren't necessarily more drought tolerant. Their C_4 pathway allows them to photosynthesize at higher light intensities but will still experience water loss (Chapin et al. 2012:136-137). CAM plants (e.g. cacti), conversely, transpire at night when VPD is lower and fix carbon during the day with stomata closed (Chapin et al. 2012:137). Both C_4 and CAM are energetically expensive, so result in slower growth than C_3 (Chapin et al. 2012:137). Therefore, in a cooler and wetter environment, C_3 plants have a clear advantage, while C_4 plants have the advance in a hotter environment, and CAM in a drier environment.

While decreased SM affects all plants, certain PFTs can access deeper SM while others can withstand larger reductions in SM. Root depth differentiates plants in their response to depleting SM. Deep rooting systems are found in deserts, arid shrublands, and savannas. Deeper rooting plants, or plants in the proximity of others with the ability to hydraulically lift soil water from deep to shallow depths, generally can withstand greater depletions in overall

SM. This is because these plants can access SM deep in the soil column when shallow SM is dry (Chapin et al. 2012:106-109). Shrubs for instance have deeper rooting depth than grasses; therefore, grasses will respond more immediately to reduced water availability (Bunting et al. 2019). Different PFTs moreover can withstand different levels of SM depletion without wilting. For many mesic plants (adapted to wet environments), the permeant wilting point is about -1.5MPa in terms of soil water potential. However, desert species are more drought tolerant, in part because they can withstand larger water potential drops (up to -8MPa) (Chapin et al. 2012:105). PFTs can be categorized in this sense between isohydric ('cautious') and anisohydric ('risk-taking') plants. Isohydric plants are more water sensitive and won't let water potential drop, while anisohydric will (Grossiord et al. 2020). When SM declines, isohydric plants close stomata to prevent reduction in plant-water potential; anisohydric, instead, keep photosynthesizing (Chapin et al. 2012:114). Anisohydric plants are therefore 'risk-taking', prioritizing carbon gain over water loss, and are often able to withstand greater reductions in water potential without cavitation. Yet under intense drought, they risk hydraulic failure/cavitation.

Some species also prioritize NPP over water conservation. It depends on how willing they are to trade water for productivity, as measured by their *underlying* WUE (uWUE), which is specific to a PFT (Massmann et al. 2018). This is especially visible comparing shrubs and grasses. Grasslands are more productive than shrublands but also less drought tolerant across Southwestern US deserts (Bunting et al. 2019). This is largely since grasses prioritize NPP over water conservation, and hence keep stomata open. During heatwaves, while sensible heat flux increases across all land cover types, latent heat flux decreases for shrublands but stays constant for grasslands (Wang et al. 2019). On the Colorado Plateau, with reduced precipitation and SM, C_3 grasses experience higher mortality and cover changes than C_4 grasses and C_3 shrubs. Moreover, the shrubs increase WUE to withstand moderate SM depletions (Hoover et al. 2017).

These various adaptations and traits mean that different PFTs and levels of aridity (dry versus wet sites) will respond differently to increasing VPD and decreasing SM. However, overall, above ~2kPa seems to have the greatest negative effects on GPP. Specifically, grasslands, savannas, and some croplands and shrublands seem to experience negative GPP effects at VPD above 1.5-2kPa and show high sensitivity to the lowest SM conditions. Comparing sites based on aridity, Zhang et al. 2019 find that in the wettest sites, there is an immediate quick decline in GPP with increasing VPD at around/below 1kPa, while in the driest sites, the decline begins closer to 2kPa. Moreover, in both semi-arid and arid sites, the lowest SM observations have the lowest GPP (Zhang et al. 2019). Using the same methods, comparing sites based on PFTs instead of aridity reveals that for non-irrigated crops, grasslands, savanna, and woody savanna, negative impacts seem to begin above 1kPa with almost all sites showing very low SM above 2kPa (Figures 6-7).

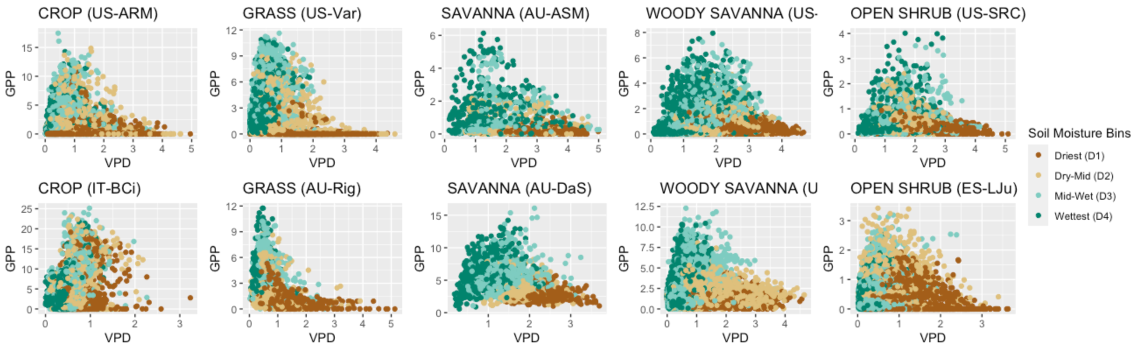
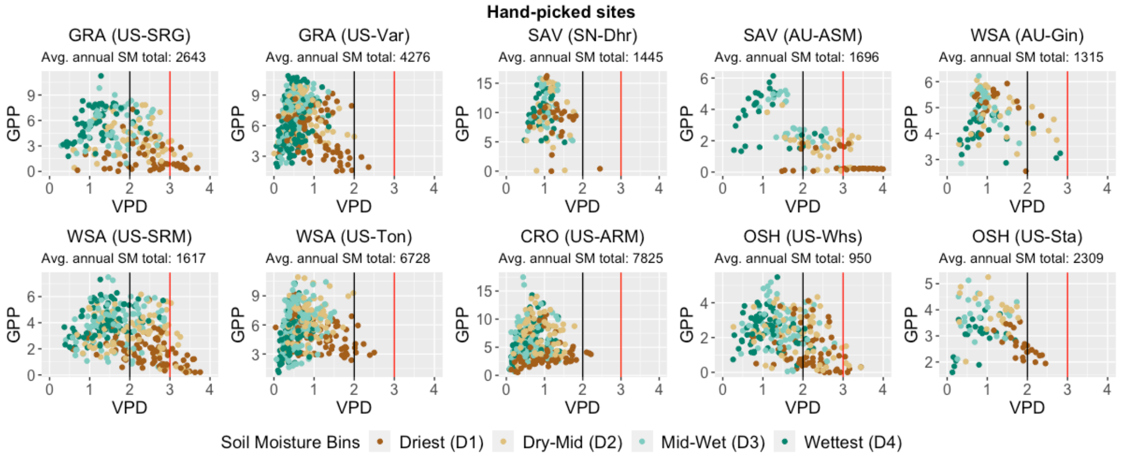


Figure 6. Across the full growing season, VPD vs GPP at different sites, binned by soil moisture content. Sites with the clearest VPD vs SM signal were chosen, as many sites have other variables which mask the effects of the two variables. Soil moisture bins are driest (< 1st quartile), dry-mid (1st quartile < x < median), wet-mid (median < x < 3rd quartile), and wettest (> 3rd quartile). Data are from FLUXNET (Pastorello et al. 2020). Methods based on Zhang et al. 2019.



Data source:
FluxNet

Figure 7. VPD vs GPP for the local peak GPP month. Grasslands (GRA), savannas (SAV), woody savanna (WSA), crop (CRO), and open shrublands (OSH) are included. The "Avg. annual SM total" is the sum of daily SM, averaged across years for each site, to facilitate comparing SM between sites. Each point represents a unique day in the peak GPP month across all years of the observations for the site. Colors represent SM bins based on local SM conditions. These 10 sites were hand-picked as they all represent some of lower SM sites for each PFT (with the exception of US-Ton). In many higher SM sites, there were confounding variables (e.g. swamps leading to water logging). By constraining this way, the interacting effects of VPD and SM as negative controls on GPP in water-limited sites come through. As with Figure 6, this figure is based on Zhang et al. 2019.

In particular, grasslands and savannas seem to have highly pronounced and early responses to low SM and to high VPD. Massmann et al. 2018 identify VPD$_{crit}$ unique to PFTs, which can be interpreted as the theoretical point at which evaporative demand is too high for plants to offset with mitigation strategies. This VPD$_{crit}$ is relatively low values for forests (~1-3kPa), ~3kPa for grasslands, ~3.5kPa for savanna, and ~5-5.5kPa for woody savanna and closed shrublands (Massmann et al. 2018). However, in practice, grasslands and savannas (woody and non-woody) seem to be constrained by SM conditions well before VPD$_{crit}$, at ~1.5 and 3kPa, respectively (Massmann et al. 2018). Another study reached similar conclusions, finding that at high VPD in arid sites, iWUE will *decrease* for some grasslands, open shrublands, savannas, and croplands, as water constraints interrupt the increase in iWUE (Zhang et al. 2019, S13). Two other studies find this effect on the GPP of savannas and grasslands. One study found that savannas and grasslands seem to be more sensitive to SM reductions than certain forest types, experiencing reduced GPP at SM reductions below ~50th percentile (Fu et al. 2022, Fig. S5). Another study found that both plant available water (PAW), which is SM accessible by roots, and VPD are the primary controls over GPP in shrublands, savannas, and woody savannas in semi-arid sites across the Sahel, with PAW important during the growing season and negative VPD effects appearing above ~2kPa (Abdi et al. 2018). The implication of these studies is that these PFTs (grasslands, savannas, non-irrigated crops, and some open shrublands) will reach deleterious depletions of SM at high VPD levels, triggering SM as the major water constraint on GPP.

Many studies comparing PFT responses to increasing VPD and decreasing SM have surprising results for crops, oftentimes due to the inclusion of both irrigated and non-irrigated crops. Several studies, however, have focused on non-irrigated crops to find VPD sensitivity levels. Zhang et al. 2017 found that maize and soybeans were sensitive to increasing VPD. For non-irrigated croplands, while negative effects are experienced at lower VPD levels, crop yields tend to decline more rapidly above 2 kPa (Lobell et al. 2014). Specifically, 2kPa is the major inflection point for soybeans (though with less significance in findings), while 2.8 kPa is the inflection point for maize (high significance) (Lobell et all. 2014).

Compared to savannas, grasslands, and non-irrigated croplands, woody savanna and closed shrublands show some more drought resilience. Woody savanna and closed shrublands prioritize water conservation over NPP. VPD_{crit} for both PFTs is significantly higher than the range of experienced VPD for both PFTs, indicating that both are well adapted to their environments to prioritize water conservation.

Finally, several light use efficiency (LUE) models have been developed to estimate GPP using satellite data. Some of these models use VPD to measure water stress, and create VPD scalars to constrain GPP, where VPD_{scalar} of 1 means no water constraint while VPD_{scalar} of 0 means no GPP occurs due to water limitations. These models have parameterized VPD values for each PFT. As can be seen in Figure 8, while two LUE models have different functions for measuring water stress, generally, savanna, grassland, and cropland experience water stress at VPD ~1-2 kPa, while shrublands experience stress at higher VPD levels.

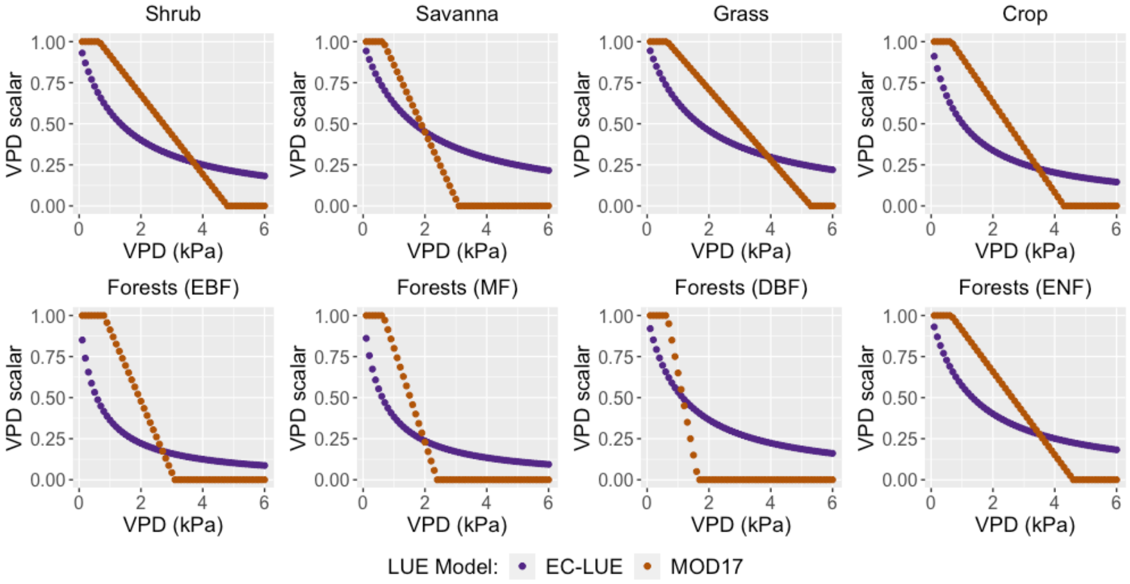


Figure 8. Functional forms of VPD scalars used in light-use efficiency (LUE) models for different PFTs. When scalar reaches 0, no GPP can occur; when scalar is at 1, GPP is not constrained by VPD.

2.2. Introduction to Analyses & Methodological Approach

The Southwestern U.S. has been in a megadrought since 2000, characterized by below-average precipitation and elevated temperatures (Williams, Cook, and Smerdon 2022; Williams et al. 2020). Since 2002, the Colorado Plateau—or the greater Four Corners region, comprising Arizona, Utah, Colorado, and New Mexico—has consistently experienced some form of drought (USDM 2022). In this time, there have been 13 "billion-dollar" drought-related events in the Southwestern U.S., many of them affecting the greater Four Corners region (NOAA 2022). In 2018 and 2020, more than half of this region was in severe or exceptional drought, associated with drying vegetation, crop and pasture loss, increased fire activity, and reduced water availability (USDM 2022; Mankin et al. 2021; Dannenberg et al. 2022).

Rangelands cover large portions of the Southwest, including 81% of federal lands in Arizona and New Mexico (USDA N.D.). They host biodiverse ecosystems as well as vegetation suitable for grazing and browsing for livestock and other animals, including grasses, forbes, and shrubs (USDA 2009; Redsteer et al. 2013). On the Colorado Plateau, cattle and sheep are the most common livestock (USDA 2019; Copeland et al. 2017). Many inhabitants in this semi-arid region, including multiple Native American tribes, engage in ranching—hence, vegetation health on rangelands has important implications for local livelihoods (Garfin et al. 2013; Redsteer et al. 2013; Ferguson et al. 2016). Most agricultural sales in New Mexico and Colorado counties are from cattle ranching, while sheep grazing has been a major cultural and subsistence activity for several counties in New Mexico and Arizona since their introduction in the 1700s (Frisvold et al. 2013; Milchunas 2006). Yet, recent drought conditions have impacted rangelands. In 2018 and 2020, 45-71% of pastureland was rated as in poor or very poor condition (USDA NASS N.D.). In desert rangelands, grazing should stay below 40% of NPP for ecosystem health, yet in drought times, grazing use can surpass that percentage, resulting in negative impacts on forage (Holecheck et al. 1999). In such drought conditions, ranchers may be forced to reduce their herd size, or livestock are forced to graze on other vegetation species, in some cases overgrazing and stressing ecosystems (Grand Canyon Trust 2022; Holecheck et al. 1999; Garfin et al. 2013).

In warm, dry environments, such as the greater Four Corners region, vegetation productivity is generally water limited rather than energy limited (Funk and Brown 2006; Jiao et al. 2021; Chapin et al. 2012:171). As rangelands are generally non-irrigated, forage conditions—and, more broadly, vegetation productivity—are sensitive to climatic changes (Frisvold et al. 2013; Poděbradská et al. 2019; Benami et al. 2021; Dannenberg et al. 2022). While most vegetation in semi-arid regions is adapted to hot and dry conditions (e.g., have higher water use efficiencies and physiological traits to resist cavitation in low soil moisture conditions), drought conditions can overwhelm these adaptations and have negative impacts on plant growth (Taiz and Zieger 2004:96-101; Jiao et al. 2021). In particular, both decreasing soil moisture and increasing atmospheric aridity can lead to or exacerbate hydraulic stress in plants (Novick et al. 2016; Dannenberg et al. 2022). In such cases, the reduction in plant water content corresponds to decreased live fuel moisture content—or the ratio of plant water to plant biomass—thereby additionally leading to increased wildfire risk (Rao et al. 2022).

As such, rangeland vegetation in this semi-arid environment is sensitive to variations in temperature and precipitation, as both affect water availability. Precipitation is a primary determinant of vegetation health in semi-arid rangelands (Liu et al. 2019; Jiao et al. 2021; Evans et al. 2010:148). With reduced precipitation, however, increased temperatures may affect vegetation health and abundance. Increased air temperatures are directly related to increases in Saturation Vapor Pressure (SVP), which, in turn, increases Vapor Pressure Deficits (VPD), yielding higher evaporative demand. As VPD increases, vegetation will experience a tradeoff between photosynthesis and water loss—plants either close stomata (halting transpiration) at the expense of photosynthesis or keep stomata open and risk cavitation due to depleted soil moisture (Chapin et al. 2012:116-117). In semi-arid regions and seasons, where and when evaporative demand is greater than available moisture, VPD—and therefore, temperature—become important determinants of vegetative health (Dannenberg et al. 2022; Weiss et al. 2009; El-Vilaly et al. 2018; Crimmins et al. 2017; Williams et al. 2020). The Four Corners region also has strong land-atmospheric coupling, in which reduced soil moisture can further increase near-surface temperature by releasing less latent heat and more sensible heat, thereby driving further increases in VPD (Zhang et al. 2008). This coupling is strongest in the summer months preceding the arrival of the monsoon, which corresponds with peak climatological temperatures (Weiss et al. 2009). This is also the season in which rangeland forage for livestock is in highest demand (Crimmins et al. 2017:92; Williams, Cook, and Smerdon 2022).

Previous studies have examined the climatic controls over semi-arid rangelands in the Southwest and their anthropogenic drivers. While significant reductions in precipitation have occurred since 2000, these have been shown to be largely due to natural variability (Lehner et al. 2018; Williams et al. 2020). Alongside reduced precipitation, temperatures and VPD have been rising for the region, which several studies have attributed to anthropogenic forcing (Seager et al. 2015; Bonfils et al. 2008; Williams et al. 2020; Zhuang et al. 2021; Mankin et al. 2021). Moreover, past studies indicate that above-normal temperatures have exacerbated droughts in the Southwest (McCabe et al. 2017; Weiss et al. 2009; Udall and Overpeck 2017; Woodhouse et al. 2016) by reducing snowpack and driving earlier snowmelt (Shukla et al. 2015; AghaKouchak et al. 2014; Cook et al. 2015). Thus, above-normal temperatures co-occurring with meteorological drought may increase the risk of severe hydrologic and agropastoral drought (NAS 2016:98; Diffenbaugh et al. 2015; Williams et al. 2015; Shukla et al. 2015; Trenberth et al. 2014). It is this combination of below-average precipitation and above-average temperatures that has reduced soil moisture, increased VPD, and plunged the region into drought (Mankin et al. 2021; Williams, Cook, and Smerdon 2022; Williams et al. 2020). However, there has been relatively little work examining the effect of warming-exacerbated drought conditions on vegetation health and resulting forage conditions.

To approximate rangeland health, a metric for vegetation health must be chosen that measures forage availability and quality. The best metric—Net Primary Productivity (NPP), or the total atmospheric carbon gained by vegetation—measures the productivity of vegetation, including forage for grazing and the productivity of non-forage vegetation (Evans et al. 2010:140; Hartman et al. 2020; Reeves et al. 2020; Jones et al. 2021). The Normalized Difference Vegetation Index (NDVI), similarly, has been identified as a useful and widely used tool. As NDVI has the quality of being globally available and is relatively easy to derive, it has been used as a proxy for forage conditions in those areas and for applications that require measurements of vegetation health while lacking the ability to measure or calculate NPP (Funk and Brown 2006; Thoma et al. 2002; Benami et al. 2021). This is in large part due to the fact that at annual timescales, NDVI and NPP have been shown to covary (Evans et al. 2010; Gaffney et al. 2018). For vegetation types with a clear growing season, such as grasslands, NDVI is a strong proxy for NPP because the leaf area is closely coupled with carbon gain, compared to other vegetation types, such as evergreen forests (Gaffney et al. 2018). Due to this close relationship between NDVI and NPP, multiple NPP products use NDVI in their algorithms. NDVI is used to approximate the fraction of photosynthetically available radiation (fPAR) absorbed by vegetation, used in some light use efficiency-based models that calculate NPP (Yuan et al. 2019). Moreover, two products that estimate NPP in grasslands in the western U.S. do so based on a statistical model relating NDVI to NPP (Hartmann et al. 2020; Reeves et al. 2020).

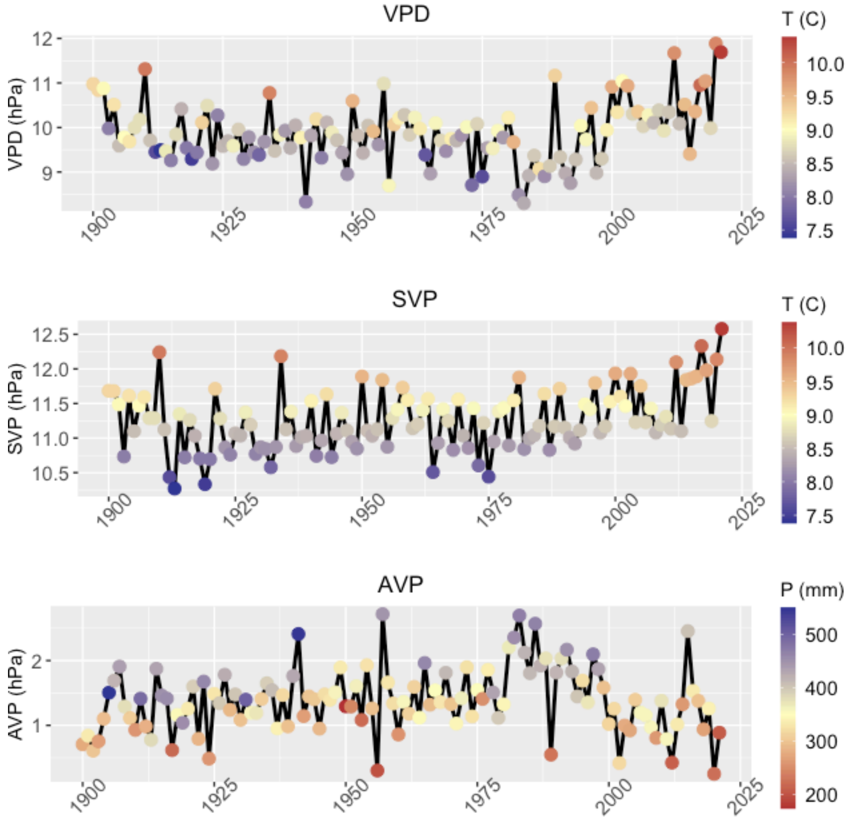
This chapter contains two empirical studies which quantify the effect of anthropogenic forcing on vegetative drought in this region. To do so, a multi-step attribution approach is used. First, the effect of anthropogenic forcing on VPD is quantified, and then the effect of that changed VPD is estimated on vegetative drought. In other words, the approach determines the sensitivity of vegetation to increasing VPD and then determines what vegetative drought would be with VPD in a counterfactual world without anthropogenic forcing. While each individual study describes its methods in detail, the studies use the following overall methodological approach.

First, to determine the effect of anthropogenic forcing on VPD, the temperature component of VPD is perturbed. As described in section 2.3.2, VPD is the difference between SVP (a function of temperature) and AVP (a function of humidity). As AVP has not changed significantly from anthropogenic forcing in this region (see below), VPD is perturbed by perturbing SVP. To perturb SVP, the change in temperature in the region attributable to anthropogenic forcing is determined using climate model output from a pre-industrial (PI) experiment and world-with-climate-change experiment.

The second step in the multi-step attribution approach is linking changes in vegetative drought to increasing VPD (the difference between VPD_{actual} and $VPD_{counterfactual}$, or ΔVPD). There are many approaches to measuring vegetation responses to ΔVPD, ranging from satellite-based indices, such as the Normalized Difference Vegetation Index (NDVI), to models which estimate GPP or NPP. Therefore, NDVI is used in the two empirical studies as a proxy for vegetation health to estimate vegetative drought. The studies link changes in NDVI to increasing VPD by developing a simple linear multiple regression model between VPD, precipitation, and NDVI. The effect of anthropogenic forcing is determined by changing the VPD values in the regression and deriving NDVI. The second study goes further to incorporate one of the NPP products to estimate rangeland productivity (Reeves et al. 2020).

There are several assumptions made in these studies. These relate to the role of anthropogenic forcing on AVP, land-atmosphere coupling, and non-linearities in *dGPP/dVPD*.

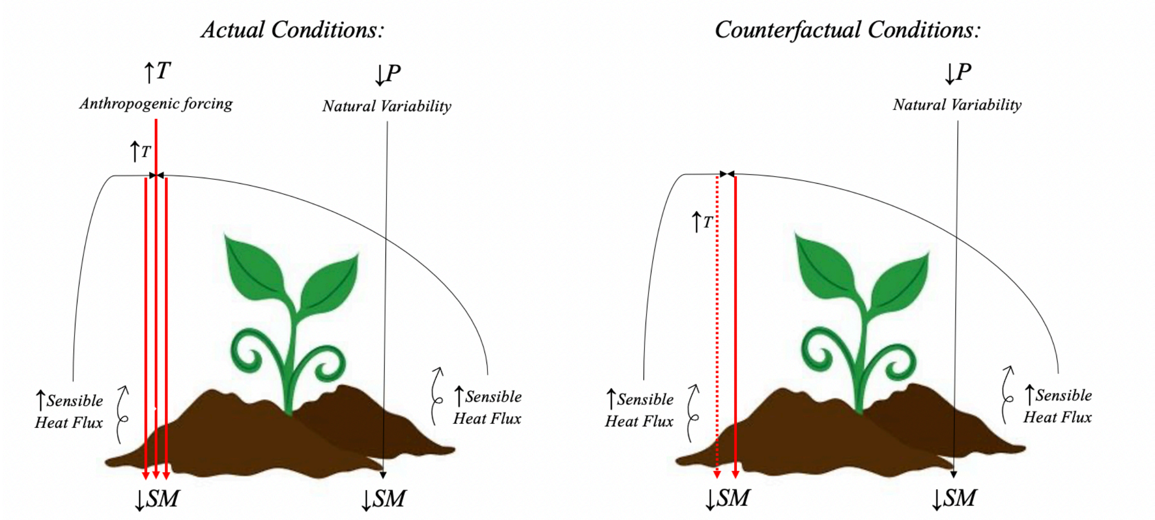
In theory, AVP should not be affected by anthropogenic forcing for this study region. As temperatures rise, the air can hold more water vapor (definition of SVP). If there is more water to evaporate—from soil, plants, or surface water bodies—it will therefore evaporate that water, increasing AVP. However, in practice, especially for land-locked regions, there is little water to evaporate and without more moisture coming into the region in the form of storm activity, there will be little increase in AVP. Again, studies have indicated in this area little sign of anthropogenic effect on precipitation in this region, meaning there has not been an increase in precipitation in the region (rather, there has been a decrease largely due to natural variability). Moreover, as described earlier, there is surface resistance to increasing actual evapotranspiration. If there is limited available surface water, there will be minimal evapotranspiration, meaning only limited increases in AVP can occur. Ficklin and Novick 2017 assess historic trends in VPD, SVP, and AVP for the U.S. In the Four Corners region, they find that while VPD and SVP have increased, AVP has decreased. They furthermore find that decreases in AVP correspond with precipitation decreases. As shown in Figure 9, for the study region for this chapter, indeed VPD and SVP have increased, while AVP has decreased, largely related to precipitation. Therefore, as the goal of this chapter is to isolate the effect of anthropogenic forcing on VPD, AVP should be held constant. What if the assumption of no anthropogenic fingerprint on AVP/RH is wrong? If it is incorrect—if there is indeed an effect of anthropogenic forcing on AVP—it is most likely that it would have decreased AVP given the trends for this area through an effect on precipitation. In that case, in a counterfactual (no anthropogenic climate change) world, AVP would have been higher, meaning the attribution results presented in this chapter would be conservative.



Data source: PRISM Climate Group

Figure 9. VPD, SVP, and AVP for the study region (34-39N, 112-105W).

As increases in SVP correspond with limited actual evapotranspiration, there is a change from latent heat flux to sensible heat flux—land-atmosphere coupling. Land-atmosphere coupling is important to consider as both reduced precipitation and increased VPD will lead to lower soil moisture, which will drive less latent heat flux and more sensible heat flux, leading to warmer air temperatures, further increasing VPD. The multi-step attribution methodology involves perturbing the temperature component to remove the background warming due to anthropogenic forcing. Doing so, however, will not remove the increase in sensible heat from the intensification of land-atmosphere coupling from that background warming, meaning the counterfactual T_{max} estimate will be higher than it would be without the anthropogenic warming. This would underestimate $NDVI_{cf}$. However, this assumes that perturbing the temperature component only removes warming from anthropogenic forcing and not any of the warming from sensible heat feedbacks. However, it seems many models include land-atmosphere coupling in the study design (Ukkola et al. 2018), which would mean that the temperature difference (ΔT_{max}) would include both the background warming as well as the sensible heat flux from that warming. Therefore, the study design should account for this feedback loop (Figure 10).



There are 3 temperature contributions to depleting soil moisture (red arrows): (1) from anthropogenically-increased temperatures (middle arrow), (2) from the sensible heat flux feedback from those temperatures (left arrow), and (3) from the sensible heat flux feedback from decreased precip (right arrow).

In the counterfactual study design, there are 2 temperature contributions to depleting soil moisture (red arrows): (1) from the sensible heat flux feedback from decreased precip (right arrow), and (2) a sensible heat flux feedback from anthropogenically-increased temperatures, an artifact of the actual conditions. But if models include land-atmosphere feedback, then left dotted arrow removed.

Figure 10. Conceptual diagram showing both anthropogenic temperature contributions and reduced precipitation contributions to land-atmosphere coupling (left) and land-atmosphere coupling with anthropogenic temperature contributions removed (right). Temperature contributions to increased

temperature inputs from land-atmosphere coupling shown as red arrows. In right-hand figure, dotted red arrow is removed when climate models incorporate sensible heat flux.

Finally, as described in previous sections, there are non-linearities in the response of vegetation productivity (and NDVI) and VPD (or *dNDVI*/*dVPD*). If significant non-linearities in *dNDVI*/*dVPD* exist across the range of VPD from $\text{VPD}_{\text{actual}}$ to $\text{VPD}_{\text{counterfactual}}$, then the estimates of the change in NDVI will be underestimated (Figure 11). While the first study does not account for such non-linearities, the second study does.

Accounting for Non-Linearity in *dNDVI/dVPD*

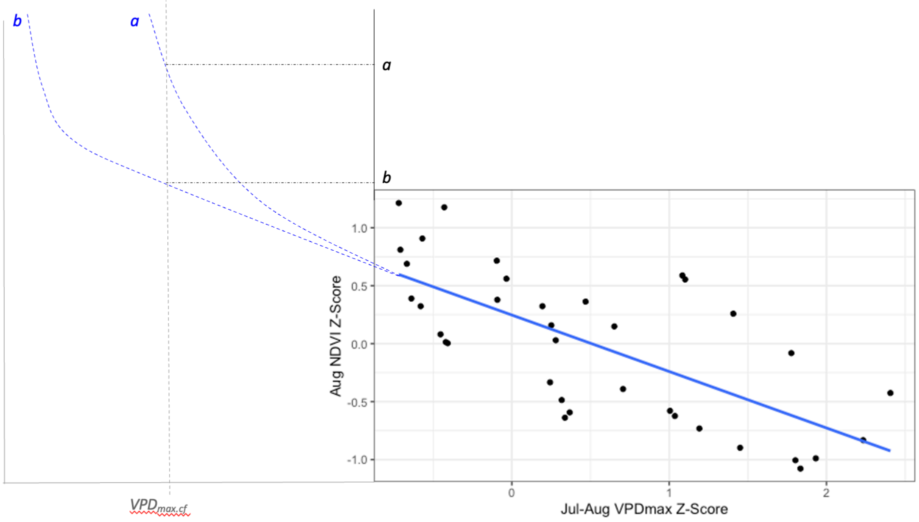


Figure 11. If the difference between $VPD_{max,actual}$ *and* $VPD_{max,counterfactual}$ *(∆VPD) occurs along a portion of the dVPD/dNDVI curve that is non-linear, then* $NDVI_{counterfactual}$ *will be underestimated, where is* $NDVI_{counterfactual}$ *(a) but is estimated as (b). Instead, if ∆VPD occurs along a linear portion of the dVPD/dNDVI curve, then this will not affect estimates of* $NDVI_{counterfactual}$*.*

2.3. Analysis #1

Quantifying human-induced temperature impacts on the 2018 United States four corners hydrologic and agro-pastoral drought[2]

In water year (WY) 2018 (October 2017 to September 2018), temperatures in the Four Corners region of the western United States (Figure 12a) were the warmest on record. These high temperatures occurred during a severe meteorological drought (West Wide Drought Tracker; Abatzoglou et al. 2017). According to the U.S. Drought Monitor (USDM), nearly 95% of the region was in severe drought in February 2018, and 56% of the region was in exceptional drought in September 2018. The Navajo Nation issued a drought declaration, finding that "drought conditions…created a critical shortage of water and range feed for livestock" (Navajo Nation 2018). Widespread agricultural and ranching losses contributed to an estimated three billion U.S. dollars in losses (NOAA NCEI 2019). The drought was characterized by significant hydrologic (limited surface water) and agropastoral (poor soil and vegetation conditions) impacts; thus, this study examines the influence of elevated temperature on hydrologic and agropastoral drought.

Given high probabilities that the twenty-first century will bring continued warming and the relatively uncertain influence of human-induced (HI) warming on precipitation in the Four Corners (Garfin et al. 2013), it is important to explore how temperature alone may contribute to enhancing hydrologic and agropastoral droughts. In this study, we estimate the potential

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[2] This research was published by the Bulletin of the American Meteorological Society. The publication is: Williams, E., Funk, C., Shukla, S., & McEvoy, D. (2020). Quantifying human-induced temperature impacts on the 2018 United States four corners hydrologic and agro-pastoral drought. Bulletin of the American Meteorological Society, 101(1), S11-S16. © American Meteorological Society. Used with permission. The article was in collaboration with Dr. Chris Funk (Climate Hazards Center, University of California, Santa Barbara), Dr. Shraddhanand Shukla (ibid), and Dr. Dan McEvoy (Desert Research Institute).

temperature increase due to HI warming and subsequently examine the impacts of elevated temperature (i) on VPD using a statistical model, (ii) on agropastoral drought using a statistical model relating VPD and the Normalized Difference Vegetation Index (NDVI), and (iii) on hydrologic drought using a hydrologic model.

Data and Methods

The study region (34°–39°N, 112°–105°W) encompasses the spatial extent of exceptional drought in WY2018 as defined by the USDM (Figure 12a). Observationally based gridded monthly means of daily minimum and maximum temperature (T_{min}, T_{max}), minimum and maximum vapor pressure deficit (VPD_{min}, VPD_{max}), and precipitation data from 1895 to 2018 for the region were obtained from the PRISM Climate Group (www. prism.oregonstate.edu/; 4 km × 4 km resolution) and, alongside snow water equivalent (SWE) measurements from SNOTEL were examined to place the WY2018 drought in historical context.

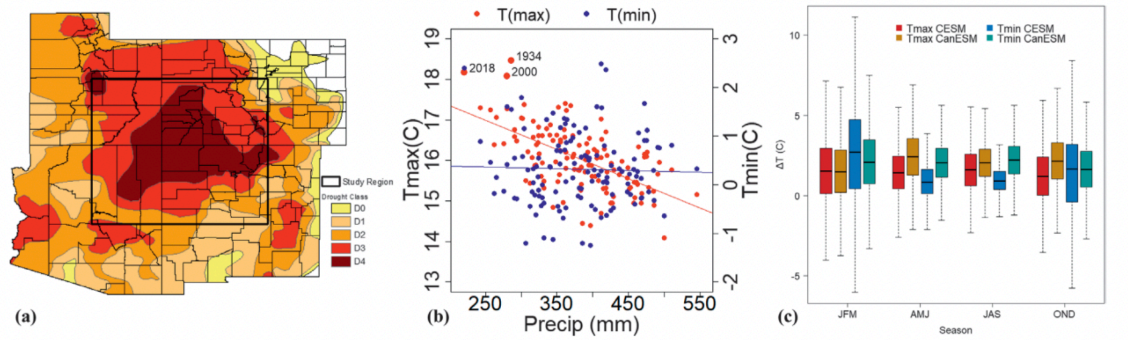

*Figure 12. Context for the WY2018 drought. (a) Study region bounding box, encompassing large portions of New Mexico, Arizona, Utah, and Colorado, overlaid on USDM 9 Oct 2018 drought extent. (b) Scatterplot demonstrating observed annual precipitation and mean T_{min} and T_{max} for each water year. Blue and red lines show T_{min} and T_{max} regression lines, respectively. (c) Human-induced temperature increases for WY2018 spatially averaged over the study region. Each boxplot displays the distribution of spatially averaged differences between the seasonal RCP8.5 and PI simulations over the 2013–23 time period. The lower and upper extent of the boxes depict the 25th and 75th percentiles of the distribution of differences. The center bar represents the median and the whiskers represent the less extreme of the maximum/minimum value or the 3rd/1st quartile + 1.5 * (interquartile range).*

To attribute the role of HI forcing on the temperature anomaly, factual and counterfactual estimates of T_{min} and T_{max} were derived. To derive factual T_{min} / T_{max} estimates, representative concentration pathway 8.5 (RCP8.5) simulations from two large ensembles (LENS) were chosen: the Canadian Earth System Model version 2 (CanESM2) (Kirchmeier-Young et al. 2017) (50-member ensemble, 1950–2100) and the Community Earth System Model version 1 (CESM1) (Kay et al. 2015) (40-member large ensemble; 1920– 2100). We selected the two models with the largest ensembles to account for the internal variability in the climate system. Counterfactual estimates were based on pre-industrial (PI) CMIP5 simulations for the same models, obtained from the Climate Explorer (https://climexp.knmi.nl/). A bias correction (described in online supplemental material) was used to align the CESM1 PI (CMIP5) simulations (Taylor et al. 2012) with the 40 CESM1 LENS simulations (Kay et al. 2015). As WY2018 experienced a weak La Niña, only model simulations with similar Niño3.4 SST anomalies (with ±0.4°C buffer) were used. HI influence on temperature was determined by comparing monthly Tmin and Tmax averages from RCP8.5 simulations for 2013–23 (sample sizes: $N_{CESM1} = 1439$; $N_{CanESM2} = 2012$) with those from the PI simulations ($N_{CESM1} = 760$; $N_{CanESM2} = 1103$).

To estimate counterfactual VPD (minimum and maximum), we calculated counterfactual SVP (SVP_{cf}) and combined these values with actual vapor pressure (AVP) to calculate VPD_{cf}. Since we focus on temperature dependencies in this set of experiments, and since 1895–2018 AVP shows no significant linear trend, we assume that human-induced warming did not change AVP. Actual SVP was first calculated using PRISM temperatures, then AVP was calculated using actual SVP and VPD. Then, the warming anomaly (from the counterfactual temperature experiment) was subtracted from PRISM temperature and used to calculate SVP_{cf}, based on the equation for VPD from Daly et al. (2015). Finally, SVP_{cf} and actual AVP were used to derive VPD_{cf}.

To estimate the effects of VPD on the NDVI (Normalized Difference Vegetation Index; a measure of greenness and vegetative stress), counterfactual NDVI was derived using counterfactual SVP and observed precipitation. NDVI observations were obtained from MODIS Terra 16-day (Spruce et al. 2016). Seasonal 2000–18 June–August mean SVP and precipitation were regressed onto the spatially aggregated magnitude of change from April to August NDVI (DNDVI). Various SVP, AVP, and precipitation lags and combinations were tested to find the optimal regression (i.e., the best predicting months and variables). June–August SVP and precipitation proved to be the best for April–August ΔNDVI (the "greenup" phase) ($\Delta NDVI = 0.17 + -0.00558 \times SVP + 0.00073 \times precip$; $r^2 = 0.766$). These regression coefficients were then used with SVP_{cf} and actual precipitation means to calculate ΔNDVIcf.

Finally, the effect of elevated temperature on hydrologic drought (specifically SWE and runoff) was estimated by using the variable infiltration capacity (VIC) hydrologic model (Liang et al. 1994) which has been used in similar attribution studies (such as Shukla et al. 2015; Xiao et al. 2018). The VIC is a physically based hydrologic model that uses atmospheric forcings including precipitation, temperature, and wind speed to compute SWE, soil moisture (SM), evapotranspiration (ET), and runoff. The VIC was run using PRISM precipitation, T_{min} and T_{max} data, and climatological wind speed [as in Livneh et al. (2013)] (upscaled from 4 km × 4 km to 6 km × 6 km). After a long-term spinup period, the VIC was run first to simulate the water budget given the observed WY2018 conditions, and then twice using counterfactual WY2018 temperatures obtained by adjusting the observed WY2018 temperatures using the difference between factual and counterfactual temperatures derived from CESM and CanESM while keeping precipitation the same.

Results

WY2018 precipitation was the lowest on record (~220 mm) averaged over the study area. There is no significant correlation between precipitation and annual T_{min} (cor = −0.03; p value = 0.73); however, a significant negative correlation exists between precipitation and annual T_{max} (cor = −0.60; p value = 0.16e-12) (Figure 12b). WY2018 T_{max} and T_{min} values were both among the warmest on record (Figure 12b). Estimates of the human-induced temperature increases from the counterfactual experiment indicate substantial warming (Figure 12c). The mean annual difference in temperature between RCP8.5 and PI ensemble runs is ~ +2°C for CanESM2 (+2.0°C T_{max}, +2.0°C Tmin) and ~1.3°C for CESM1 (+1.3°C T_{max}, +1.4°C T_{min}) for the 2013–23 decade. PRISM suggests a temperature increase of ~1.9°C (T_{max}) and ~0.9°C (T_{min}) from 1895–1929 to 2013–18.

Figure 13a shows the climatological (1895–1980) VPD (black line), actual WY2018 VPD (red line), and "alternative" WY2018 VPD (blue line, CESM1- adjusted; green line, CanESM2-adjusted) estimated using the counterfactual T_{min} and T_{max}. In June– August, actual VPD_{max} (VPD_{min}) was on average 6.6 hPa (3.1 hPa) greater than the climatology. Counterfactual estimates (blue and green lines in Figure 13a) suggest that the HI-induced temperature anomalies could account for 3.7–4.9 hPa (VPD_{max}) and 0.7–2.2 hPa (VPD_{min}), or 59%–80% (VPD_{max}) and 26%–74% (VPD_{min}), of the difference between the climatological VPD and 2018 actual June–August VPD. Average 2000–18 DNDVI (greenup) was 0.088—the region experienced severe drought during the first decade. April–August modeled 2018

DNDVI (representing greenup) was 0.067; under counterfactual temperature conditions, DNDVI was estimated to have been 0.080–0.088 based on CESM1- and CanESM2-estimated VPD_{cf}, respectively (Figure 13b).

VIC estimates of SWE (for elevations > 2,000 m) and runoff are summarized in Figures 13c and 13d. Climatologically, peak SWE months are February–April, whereas peak runoff months are May–June. The simulated 2018 March SWE peak (annual WY runoff) was ~71% (~57%) less than the climatological average. Comparing VIC simulations—those driven with adjusted temperature forcings versus those driven with WY 2018 actual temperature—reveals that March SWE would have been ~24% (CanESM) or ~19% (CESM) higher than WY 2018 observation-based SWE. Likewise, annual WY runoff would have been ~1.3% (CanESM) or ~1.43% (CESM) higher than WY 2018 observed temperature-based simulated annual runoff. These results indicate that human-induced temperature increases had a measurable impact on SWE, but little discernable impacts on runoff; the SWE effects, however, were secondary to the influence of record-low precipitation during WY 2018 (Figure 12b).

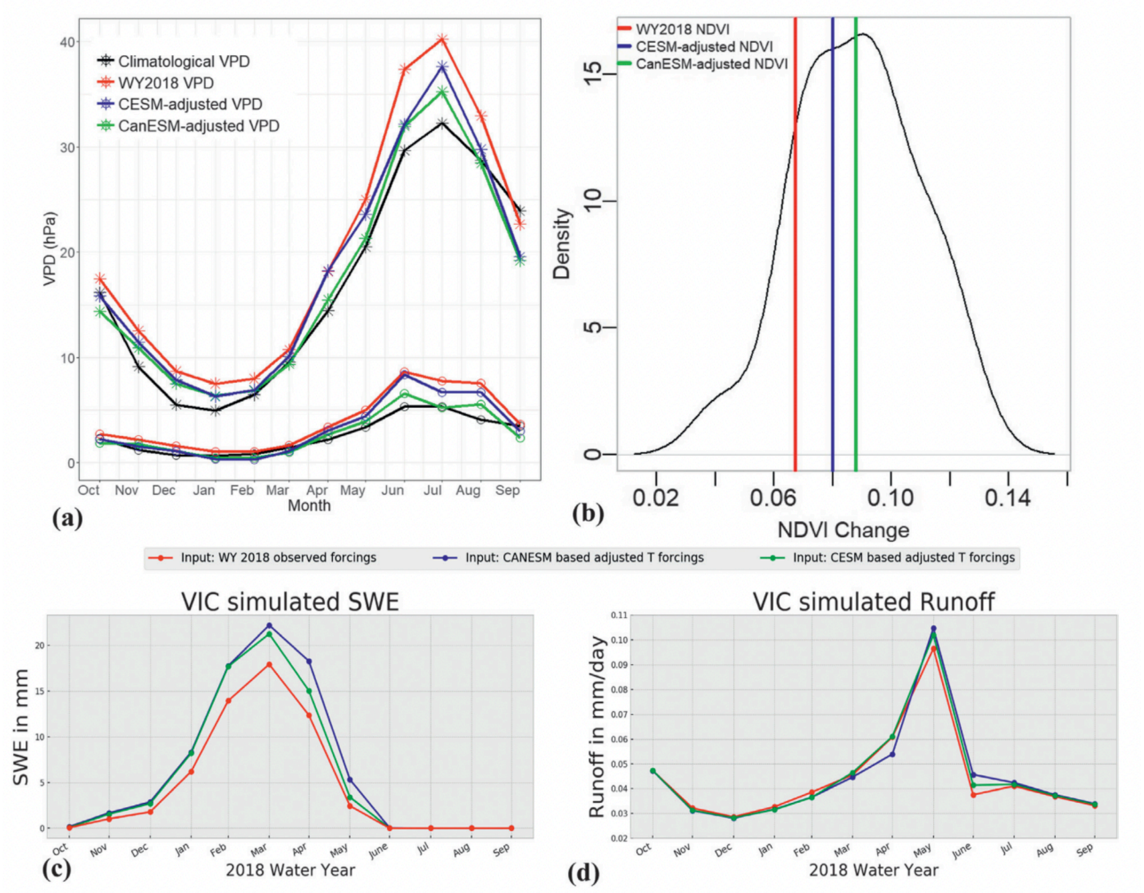

Figure 13. Hydrologic and agropastoral effects of HI-forced temperature anomalies. Climatology of each variable is shown in black [in (a) and (b) only], WY2018 actual ("observed"/factual) conditions in red, and counterfactual estimates in blue (CESM1-adjusted) and green (CanESM2-adjusted). (a) Comparison between climatological VPD, WY2018 VPD, and estimated counterfactual WY2018 VPD, estimated using the difference between counterfactual and factual temperatures as shown in Figure 12c. VPD_{max} is shown using an asterisk (*) and VPD_{min} using an open circle (o). (b) PDF of spatially aggregated actual NDVI greenup (or magnitude of change in NDVI from April to August) in black for 2000–18, modeled 2018 NDVI greenup (red), and counterfactual estimates of greenup without HI temperature increases (blue and green). Also shown are VIC model-based estimates of (c) SWE and (d) runoff derived from CanESM2- and CESM1-adjusted (counterfactual) temperatures, and actual ("observed"/ factual) temperatures for WY2018. SWE is aggregated over only those grid cells at >2,000-m mean elevation.

Discussion & Conclusion

WY2018 was exceptionally warm and dry (Figures 12a,b), and an assessment of the CESM1 and CanESM2 simulations suggested that HI warming increased air temperatures by ~1.3° to ~2°C, respectively (Figure 12c). Relatively small changes in temperature can result in large changes in VPD; thus, if AVP remains constant, human-induced warming, alone, could explain ~60%–80% of the observed WY2018 VPD_{max} anomalies (Figure 13a). WY2018 experienced low NDVI values as reflected in the poor rangeland conditions reported by the USDM for much of New Mexico, Utah, and Arizona during the same period. HI increases in SVP values likely contributed to reduced August NDVI; the magnitude of greenup was smaller in actual 2018 NDVI compared to the counterfactuals (Figure 13b). VIC simulations suggest that without the HI warming March SWE would have been ~24% (CanESM) or ~19% (CESM) higher and annual WY runoff would have been ~1.3% (CanESM) or ~1.43% (CESM) higher (Figures 13c,d).

This study did not assess the potential effect of positive land–atmosphere feedbacks under drought conditions, in which HI temperature anomalies can yield even greater observed anomalies as energy is released as sensible heat instead of latent heat (as suggested by the negative correlation between precipitation and annual average T_{max}). Therefore, our estimates of climate change–induced temperature increase on hydrology (particularly SWE) and VPD (and its influence on NDVI) may be conservative estimates. Future research will expand this analysis to cover the full time series (1900–present), allowing us to assess potential temperature impacts under less extreme precipitation deficits.

2.4. Analysis #2

Anthropogenic Climate Change is Negatively Impacting Vegetation and Forage Conditions in the Greater Four Corners Region[3]

The previous analysis was based on a spatial aggregation of the full region for a single year (2018), and hence did not account for variation in the climate-vegetation relationship across the range of elevations, land cover types, and precipitation regimes that characterize the region. In this study, we expanded on that work, exploring the links between temperature, precipitation, VPD, and vegetation health (as indicated by NDVI and NPP) across the variable topography and climates of the region for the past two decades, since the onset of the megadrought. By accounting for spatial and temporal variation, we can more accurately account for local conditions (e.g., land cover types, elevations, local climate), which may increase or attenuate local sensitivity to increasing VPD. In this study, we quantified the increase in VPD, and decrease in NDVI, attributable to anthropogenic increases in temperature/SVP, and, furthermore, estimated the corresponding reduction in NPP. Thus, we linked estimates of human-induced warming to a metric (NPP) strongly related to forage availability, relevant for both ranchers and more broadly ecosystem health.

Materials and Methods

Study Region & Data: The study region was defined as the greater Four Corners (34-39°N, 112-105°W), covering the extent of exceptional drought in 2018 (as defined as the study region for the previous analysis), and much of the extent of exceptional drought in late 2020.

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[3] This work was conducted in collaboration with Dr. Chris Funk and Dr. Shraddhanand Shukla.

For this region, maximum near-surface air temperature for 1895-2020 was accessed from CMIP6 Pre-Industrial (PI), historical, and Shared Socioeconomic Pathway 245 (SSP245) experiments, using 154 simulations across 26 models (Table 1). Monthly precipitation, maximum and minimum temperature (T_{max}, T_{min}), and maximum and minimum VPD (VPD_{max}, VPD_{min}) were retrieved for 1895-2020 from the PRISM Climate Group at Oregon State University. Monthly NDVI data were retrieved from the Moderate Resolution Imaging Spectroradiometer (MODIS) on the USGS Earth Data platform for 2003-2020 (Didan 2015). Land cover data were retrieved from the Multi-Resolution Land Characteristics (MRLC) Consortium, including the National Land Cover Database (NLCD) classification scheme used for primary land cover types (e.g., shrubland), and rangeland fractional components to determine percent cover of different land cover types on rangelands (e.g., percent bare). Elevation was retrieved using the R package, elevatr, from AWS Terrain Tiles. Soil color and characteristics were retrieved from the Soil Survey from the USDA Natural Resources Conservation Service. All data were processed to be the same spatial resolution, extent, and projection as the MODIS NDVI data.

Fitting Regressions: To determine regional climatic drivers of NDVI change, first, relationships were explored between the spatial averages over the full study region of NDVI and precipitation (P), temperature (T), and VPD. Peak NDVI values are strongly associated with annually integrated NDVI and NPP (Reeves et al. 2020). In this region, vegetation greenness typically reaches a maximum in tandem with air temperatures, during boreal summer. August was identified as the predominant peak NDVI month (Figure 14d), and hence was chosen as our predictand.

Thereafter, numerous regression models were explored between standardized, spatially averaged climatic variables and August NDVI to determine the “best fit” model in predicting peak annual NDVI from 2003-2020. All potential linear models (with one or two dependent variables) using T_{max}, VPD_{max}, or precipitation were run. Numerous seasonal aggregates were created for all variables, and then seasonal aggregates were converted to z-scores. Models were retained if they had a strong fit ($r^2 > 0.6$), a significant p-value for the temperature variable (T_{max} or VPD_{max}) (<0.05), and low collinearity between predictor variables (<0.5) and low variable inflation factor (VIF). Further, multiple regression models were retained only if they included different explanatory variables (e.g., JFM precip + Jul-Aug precip would be rejected).

After the best fit model was identified for the spatially-averaged data, substantial care was made to identify homogeneous climate and vegetation regimes within which to fit models. The best fit model was used to calculate a spatial, pixel-wise ordinary least squares (OLS) regression, in which linear models were fit for each pixel using the standardized local time series of data in the best fit model. While the pixel-wise OLS does not account for spatial relationships between pixels (compared to approaches such as Geographically Weighted Regression), the approach still allows for a crude estimation of spatial variation that affects model performance. To ascertain the drivers of spatial variation in the pixel-wise OLS, we extracted the r^2 and VPD_{max} coefficient for each pixel along with 12 potential explanatory variables related to land cover (land cover classification, % herbaceous, % shrub, % bare), to phenology and climate (peak NDVI month, SD NDVI, total annual precipitation, SD annual precipitation), and topography (slope, elevation, soil color, and proximity to major rivers).

A series of statistical tests were run relating each potential explanatory variable to the pixel-wise model r^2. Variables were transformed (using square root and log transformations where applicable) to reach normal distributions, and a multiple linear model was run with all 12 potential variables with r^2 as the dependent variable. Of the variables that were identified as significant (p-value < 0.05), variables were assessed for multicollinearity and the variables which had low collinearity (< 0.5) and together explained the most variance in model fit ($r^2 > 0.9$) were retained as the variables that best describe the spatial variation in NDVI sensitivity to climatic drivers.

Calculating Counterfactual T_{max}: Counterfactual T_{max} ($T_{max,cf}$) was calculated by subtracting the monthly increase in T_{max} attributable to anthropogenic forcing ($T_{max,att}$) from PRISM T_{max}, following the same approach as the previous analysis. CMIP6 model ensemble means were taken across 26 models (table 1), and a multi-model ensemble mean was derived from the individual model means. The multi-model ensemble mean was compared to PRISM to determine whether a bias correction was needed. Biases in the climatology for CMIP6 remained constant throughout the time period, so no bias correction was required. Two methods were used to determine the attributable increase in warming ($T_{max,att}$). The first method used the early record as the preindustrial (PI) counterfactual. For each of the 26 models, mean monthly temperatures from 1850-1880 were derived as the PI T_{max}. These T_{max} PI values were subtracted from 10 year rolling means of each model ensemble, to derive $T_{max,att}$. The second method used the PI CMIP6 experiments: for each model, the monthly mean across the last 200 years of the PI experiments was subtracted from the ensemble members in 10-year moving windows. Both methods were compared and yielded similar results for $T_{max,att}$. The first method was used to derive $T_{max,cf}$. The range of $T_{max,att}$ were subtracted from PRISM T_{max} to derive $T_{max,cf}$.

Table 1. Models used from CMIP6.

Model	Spatial Resolution	# sims (historical & SSP245)	Model	Spatial Resolution	# sims (historical & SSP245)
ACCESS-CM2	250 km	3	FIO-ESM-2-0	100 km	3
ACCESS-ESM1-5	250 km	11	GFDL-ESM4	100 km	3
CMCC-ESM2	100 km	1	GISS-E2-1-G	250 km	10
CNRM-CM6-1	250 km	6	HadGEM3-GC31-LL	250 km	1
CNRM-CM6-1-HR	50 km	1	INM-CM4-8	100 km	1
CNRM-ESM2-1	250 km	9	INM-CM5-0	100 km	1
CanESM5	500 km	25	IPSL-CM6A-LR	250 km	11
CanESM5-CanOE	500 km	3	MIROC-ES2L	500 km	30
EC-Earth3	100 km	2	MIROC6	250 km	3
EC-Earth3-CC	100 km	1	MPI-ESM1-2-HR	100 km	2
EC-Earth3-Veg	100 km	5	MPI-ESM1-2-LR	250 km	9
EC-Earth3-Veg-LR	100 km	3	MRI-ESM2-0	100 km	1
FGOALS-g3	250 km	4	UKESM1-0-LL	250 km	5

Calculating Counterfactual VPD_{max}: For each zone, counterfactual VPD_{max} ($VPD_{max,cf}$) was calculated. VPD_{max} is the difference between saturation vapor pressure (SVP_{max}) and actual vapor pressure (AVP_{max}), and SVP is a function of temperature (Equation 1). Actual SVP_{max} was calculated from actual T_{max} and was used with VPD_{max} to derive AVP_{max}. $SVP_{max,cf}$ was calculated from the estimates of $T_{max,cf}$. To isolate the effect of anthropogenically increased temperatures (and hold precipitation constant), we assume that AVP_{max} does not change in the counterfactual as there is limited available water to evaporate over this region--indeed, observed trends in AVP for this region are small compared to SVP

(Ficklin and Novik 2017; verified with our data, not shown). AVP_{max} was subtracted from the $SVP_{max,cf}$ estimates to derive estimates of $VPD_{max,cf}$. $VPD_{max,cf}$ was calculated for 1950-2020 in order to identify Time Of Emergence (TOE), or when anthropogenic forcing first significantly increased VPD_{max}. TOE was calculated as when actual (PRISM) VPD_{max} is consistently above the upper bound of the confidence interval of $VPD_{max,cf}$.

Calculating Counterfactual NDVI—Accounting for Potential Non-Linearity: Before estimating counterfactual NDVI ($NDVI_{cf}$), the potential for non-linearity between NDVI and VPD_{max} was considered. It has been shown that, across large gradients of VPD, the relationship between VPD and plant productivity is non-linear (Grossiard et al. 2020; McDowell and Allen 2015; Novick et al. 2016; Zhang et al. 2019). Yet, across a small gradient of VPD_{max}--such as the difference between actual and counterfactual VPD_{max} experienced by the study region--the relationship between measures of plant productivity and VPD_{max} may be fairly represented with a linear regression. To test for non-linearities, we explored several approaches. First, we fit a non-linear model, using a self-starting function which guesses its own coefficients. The model fit was comparable between the non-linear model and the best fit linear model (correlation between NDVI and $NDVI_{est}$ = 0.91/0.92 (linear/non-linear)). We then tested for potential nonlinearity by substituting space for time. Leveraging the fact that the study region includes a range of temperatures, we compared model fits in cooler areas to warmer areas, effectively having the cooler pixels represent the relationship between NDVI and VPD in the counterfactual. We split each zone into cooler and warmer zones, ensuring that the mean difference in VPD_{max} between cool and warm zones was at least as large as the maximum (2020) difference between actual VPD_{max} and $VPD_{max,cf}$. We fit models for each zone and took the difference between the VPD_{max} model coefficient.

Calculating Counterfactual NDVI and NPP: To calculate the decrease in NDVI attributable to human-induced warming, NDVI was first reconstructed using the model fit for each zone ($NDVI_{est}$). Then, using the same model intercept, precipitation value, and precipitation coefficient, and VPD_{max} coefficient, with the range of $VPD_{max,cf}$ z-scores, counterfactual $NDVI_{cf}$ was calculated.

Counterfactual annual net primary productivity ($ANPP_{cf}$) was estimated for each zone by fitting models which relate NDVI to NPP. Two ANPP products were considered—from the Rangeland Management Production Service (RPMS) and from GrassCast (Reeves et al. 2020; Hartmann et al. 2020). RPMS includes all primary production while GrassCast is a function of solely herbaceous production (Jones et al. 2021; Reeves et al. 2020; Hartmann et al. 2020). As certain livestock only eat herbaceous vegetation (e.g., catte), while other livestock will graze on shrubs (i.e., goats), so both products provide valuable information. Both products agree for low (<0.5 Aug) NDVI, while GrassCast estimates were higher than RPMS estimates for high NDVI values. Therefore, as the study region includes many non-herbaceous pixels, and given the relatively strong agreement between both products at lower NDVI values (which includes all except high-precipitation zones in our study region), the RPMS equations were used to estimate changing ANPP. RPMS estimates ANPP (kg/ha) using two models: a quadratic and a log-based regression for high and low NDVI, respectively (Equation 4, Reeves et al. 2020). 2003-2020 $NDVI_{est}$ was first used to estimate $ANPP_{est}$, then $NDVI_{cf}$ was substituted into the models to estimate $ANPP_{cf}$.

$$For\ NDVI\ <\ 0.46: ANPP\ =\ 971.1\ *\ ln(NDVI) +\ 1976$$

$$For\ NDVI\ \geq\ 0.46: ANPP\ =\ 240.31\ *\ e^{3.6684*NDVI}$$

Equation 4. ANPP equations as a function of NDVI, from RPMS (Reeves et al. 2020).

Results

<u>*Modeling NDVI*</u>*:* Of all the regressions, after screening for collinearity (removing predictors correlated beyond ±0.5), the model using summer maximum VPD (VPD_{max}) and winter-summer precipitation as predictors was identified as the top model in predicting August NDVI (r^2 0.87) (Equation 5). The correlation between the two predictor variables was 0.48, and the variable inflation factor was 1.3, indicating low collinearity. The model indicates that NDVI responds strongly to winter moisture supply (Jan-Aug precipitation), modulated by summer evaporative demand (July-Aug VPD_{max}).

Equation 5. $\text{August NDVI} = -0.5 * \text{Jul-Aug } VPD_{max} + 0.6 * \text{Jan-Aug Precip}$

<u>*Examining Spatial Variations Across the Region*</u>*:* While Equation 5 best describes August NDVI for the spatial aggregate of the region, the sensitivity of NDVI to climate variables will vary across the study region due to the influences of topography, climate, land cover type, and other variables (Figure 14). As such, there may be areas that are more sensitive to increasing VPD than others. The study region encompasses much of the Colorado Plateau, and is climatically and topographically heterogeneous, ranging from grasslands to forests (Figure 14b), across elevations (Figure 14c), and very variable temperature (and by extension VPD) and precipitation regimes (Figure 14e-f). The region also includes major river basins, including the Colorado River and Rio Grande (Figure 14, shown in blue).

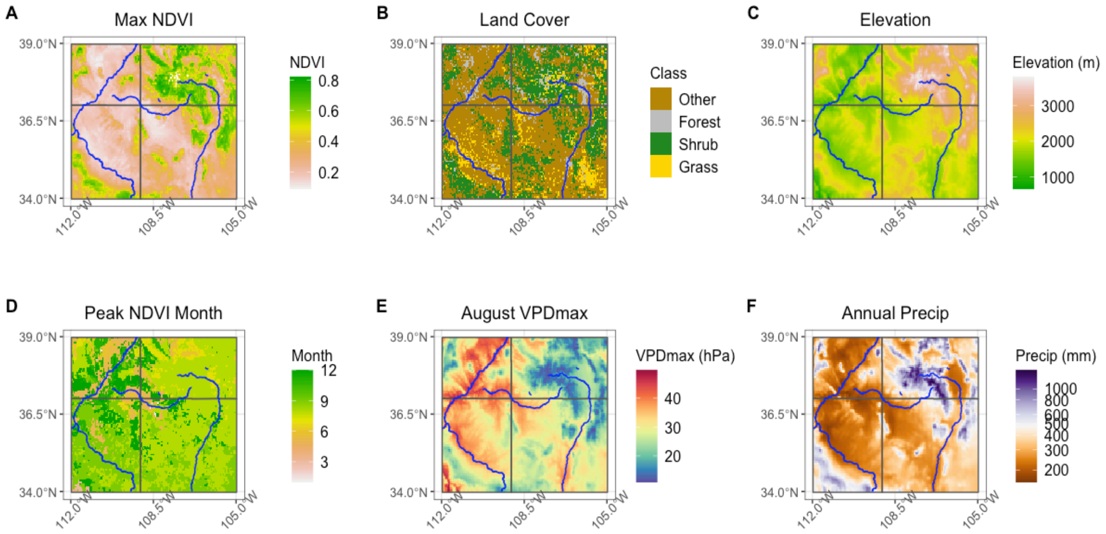


Figure 14. The study region, including (a) maximum NDVI value, (b) land cover types, (c) elevation, (d) the month of peak NDVI, (e) August VPD$_{max}$, and (f) total annual precipitation.

Figure 15 shows the spatial patterns from the pixel-wise OLS using Equation 5: the r^2, VPD$_{max}$ p-values, and VPD$_{max}$ and precipitation coefficients. The model fit is strongest in the middle (centered on the Four Corners) and southeast (in New Mexico) of the study region (Figure 14a). These areas are mostly shrublands and grasslands and receive relatively low annual precipitation and experience mid-to-high VPD (Figure 14b,e,f). Conversely, the model fit is weakest in the northeastern, eastern, and far southwestern parts of the region, corresponding with largely high precipitation, forested areas.

Examining areas with the strongest r^2 values, two sub-regions emerge. Significant VPD$_{max}$ p-values (Figure 15b) accompanied by strong r^2 values (>0.5, Figure 15a) are mostly located in the southeastern region, concentrated in New Mexico. These areas are also characterized by highly negative VPD$_{max}$ coefficients (Figure 15d), indicating that in these areas, VPD$_{max}$ has a strong negative control on August NDVI. In other words, the highest-risk areas for increases in summer VPD$_{max}$ are concentrated in the southeast of the region. Interestingly, these tend to be relatively cooler, mid-elevation areas (Figure 15c,e) covered with shrublands (Figure 14b). While we also find numerous significant VPD_{max} p-values in the forested areas of Colorado (upper-right) and Arizona (bottom-left), these areas have lower r^2 values. Conversely, VPD_{max} is not a significant predictor for the northwestern and central parts of the region, concentrated in the Colorado River Basin and along the San Juan River. These are the hottest and driest areas of the study region (Figure 14e-f), in major river basins, and with low climatological NDVI values (Figure 14a). Moreover, these regions have the largest precipitation coefficients, demonstrating the outsized importance of precipitation on NDVI. This indicates that for the center of the study region, relatively low precipitation may mask any effect of VPD on NDVI. Moreover, at very low values of NDVI (Figure 14a), satellite retrievals of NDVI are also likely to be influenced by bare soil emissions, especially in areas with red soils, which is not uncommon in the Four Corners area.

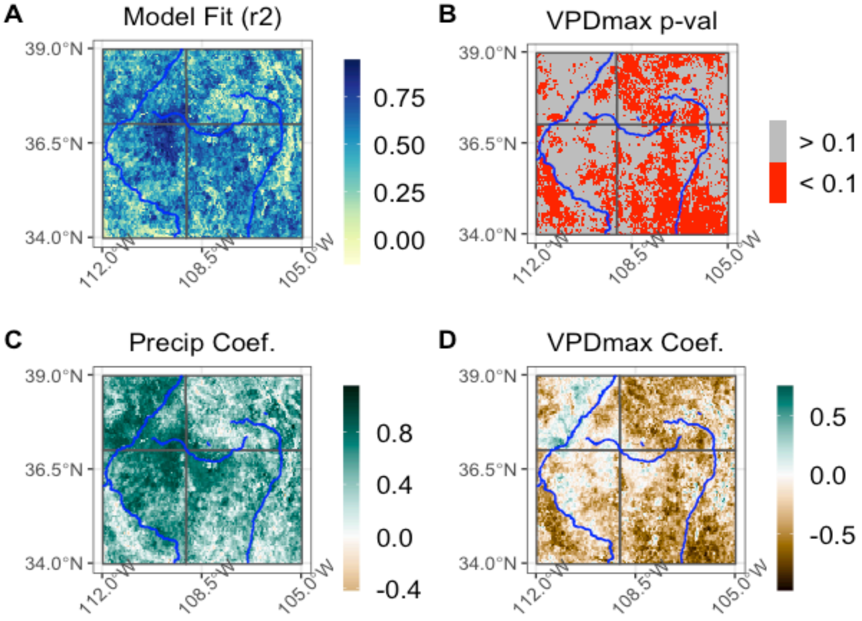


Figure 15. Results from pixel-wise OLS regression: (a) adjusted r^2, (b) VPD_{max} p-value, and standardized (c) precipitation and (d) VPD_{max} coefficients. Large rivers are shown in blue, while state administrative boundaries are shown in gray.

Examining Controls of Spatial Variations: In examining the spatial variation in model fit (r^2) and potential explanatory variables, the spatial variation appears to be primarily linked to three related variables: the phenology of vegetation (the seasonality of "greenup" or peak NDVI month), total annual precipitation, and land cover type. While NDVI peaks in August for most of the region, in the northwest NDVI peaks in winter or spring months (Figure 14d). In this region, we find frequent non-significant VPD_{max} coefficient p-values. These areas are also close to major rivers, including the Colorado River. Hence, the differences in phenology may be explained by other moisture inputs to the region, such as snowmelt and rainfall runoff from the tributaries to the Colorado River. The model fit also varies between land cover types. Forests have significantly lower r^2 values than shrublands and grasslands, while inclusion of grasslands versus shrublands in the model explains much of the variance in the spatial distribution of r^2 values. Finally, total annual precipitation is also related to model fit. High r^2 values are concentrated in areas with precipitation < 500 mm/yr (Figure 14f), while summary statistics indicate a secondary break near 250mm/yr. The highest r^2 values tend to arise when annual total precipitation falls between 250-500mm/yr.

In further analysis, since we do not account for runoff and snowfall, all non-summer peak NDVI pixels were excluded from this study. Additionally, we exclude non-shrubland and non-grassland areas, given both the relatively poor model fit for forested areas, and because we are primarily interested in impacts on rangelands and on those communities who use rangeland resources. In rangelands with NDVI peaking in summer, land cover type (grassland vs shrubland) and precipitation regime were identified as the primary controls on variation in model fit. These results indicate that, as expected, sensitivity to rising VPD varies between different vegetation types and with increasing moisture inputs (Grossiord et al. 2020; Novick et al. 2016; Rao et al. 2022).

These results were used to stratify the region into six zones: all summer peak-NDVI rangeland pixels stratified by land cover type (grasslands versus shrublands) and total annual precipitation (< 250, 250-500, and > 500 mm total annual precipitation) (Figure 16). For each zone, time-series of spatially-averaged Jul-Aug VPD_{max}, Jan-Aug Precip and NDVI were calculated. Then the "best fit" model identified earlier (Equation 5) was fit to all six sets of time-series. All six models performed very well, with r^2 values ranging from 0.71 to 0.91, and significant VPD_{max} and precipitation slope coefficients. This evaluation has established precipitation-plant regimes as unique zones with robust relationships to January-August precipitation and July-August VPD_{max}.

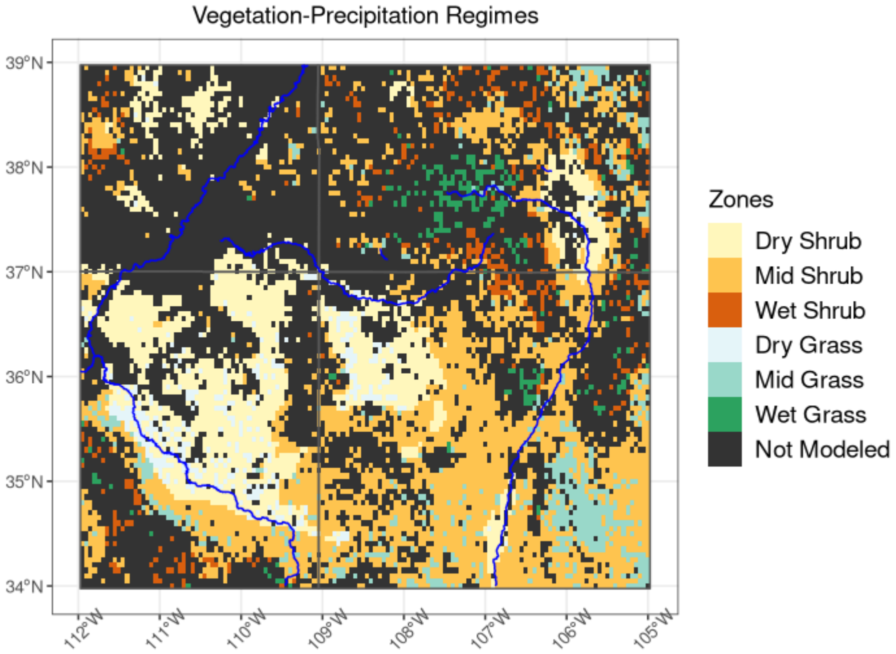


Figure 16. Map of the vegetation-precipitation regimes or unique zones for summer peak NDVI rangelands.

<u>*Counterfactual Temperature and Vapor Pressure Deficits*</u>*:* For each zone depicted in Figure 16, counterfactual T_{max} ($T_{max,cf}$) were estimated (Figure 17). The counterfactual values represent estimates of what T_{max} would have been without human-induced warming. The calculated ensemble average attributable increase for Jul-Aug T_{max} for 2010-2020 was ~1.5°C, comparable to the results of Williams et al. 2020 for this region.

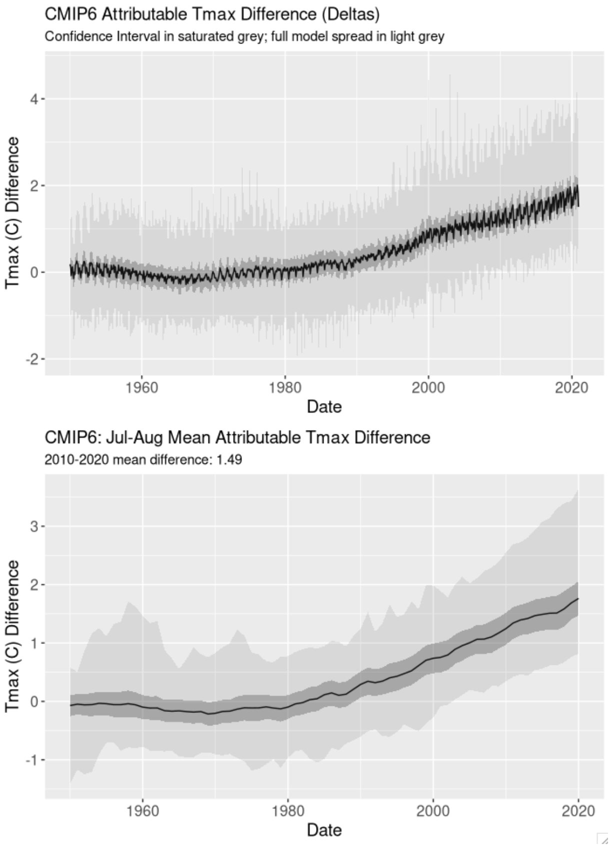


Figure 17. Attributable anthropogenic warming. Top panel (a) shows the full time series, while bottom panel (b) shows attributable warming for Jul-Aug. The 95% confidence interval is shown in dark gray, while the full model spread is shown in light gray.

Using $T_{max,cf}$, counterfactual VPD_{max} ($VPD_{max,cf}$) for 1950-2020 was derived (Figure 18). Moreover, Time Of Emergence (TOE)—or when PRISM VPD_{max} is consistently above the upper bound of the confidence interval of $VPD_{max,cf}$—was estimated as 1990. These results imply that due to human-induced warming, since 1990, VPD_{max} has been significantly higher than it would have been without that warming. Therefore, for the full study period (2003-2020), $VPD_{max,cf}$ was consistently lower than actual VPD_{max}, including uncertainty from model fit (confidence interval shown in ribbons). At the end of the study period, the largest differences between actual VPD_{max} and $VPD_{max,cf}$ are ~ 5hPa in the low precipitation zones, as these zones are warmer and the relationship between temperature and SVP is non-linear/exponential, while attributable differences for high precipitation zones are ~ 3hPa. The attributable VPD_{max} increases for all zones are large in comparison with the interannual pre-1980 standard deviations of VPD_{max} in these areas (shown in blue in Figure 18).

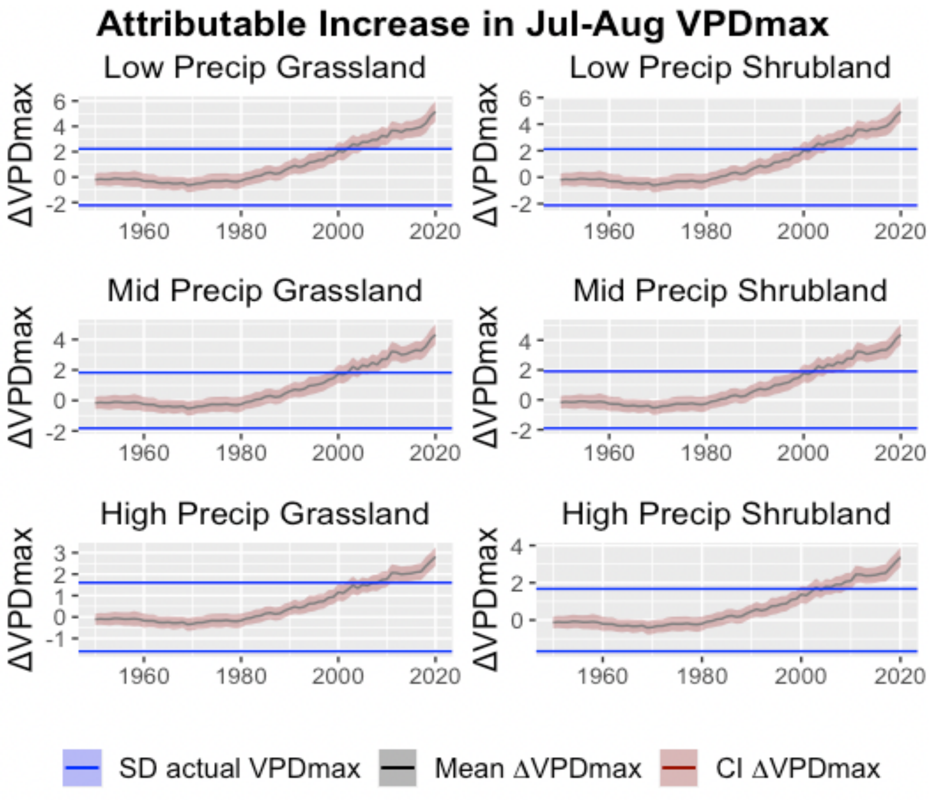


Figure 18. Estimated increase in VPD_{max} attributable to human-induced warming for each zone. Model-averaged attributable increase is shown in black ("Mean ΔVPD_{max}"). Ribbons (orange) indicate confidence interval for $VPD_{max,cf}$ calculations based on range of CMIP6-derived $T_{max,cf}$. The standard deviation of actual VPD_{max} from PRISM data for each zone from 1895-1980 is shown in blue.

Estimating Attributable Reductions in NDVI and NPP: First, to test for potential non-linearity, we examined the confidence interval of the coefficients. Table 2 presents the VPD_{max} coefficients for each zone, along with the 80% confidence intervals (CI) for the coefficients, and mean VPD_{max} for cooler and warmer pixels in each zone. The increase in VPD_{max} from cooler to warmer pixels ranges from 7-8 hPa, slightly larger than the attributable increase in VPD_{max} from human-induced warming. The largest coefficients are found for the middle precipitation zones, indicating that NDVI in these zones is most sensitive to increasing VPD_{max}. For the middle precipitation zones, the VPD_{max} coefficients are nearly identical between cooler and warmer pixels. In dry zones, warmer pixels show somewhat lower sensitivity to rising VPD than cooler pixels, while the inverse is true for wet zones. However, the CI intervals overlap for cooler and warmer pixels in each zone, indicating that the difference in coefficients is marginal. These results indicate that, for the purposes of this analysis (for the range of changing VPD_{max} considered), any non-linearity within unique zones with changing VPD is negligible. Instead, the strongest differences in VPD_{max} coefficients are found between zones, across the large precipitation and VPD_{max} gradients. Notably, each zone corresponds to a different range of VPD, with an 18-19 hPa difference in average VPD between the wet and dry zones. Therefore, by design, the $NDVI_{cf}$ analysis will capture this type of nonlinearity by comparing zones. While other factors may drive the range in VPD_{max} coefficients, including different species compositions or plant-level acclimations, these VPD_{max} coefficient ranges may be used as a coarse proxy to account for uncertainty in the magnitude and linearity of the relationship between VPD_{max} and NDVI.

	Coefficients						***VPDmax Mean***	
	Cool Pixels			Warm Pixles				
	Coef	Lower CI	Upper CI	Coef	Lower CI	Upper CI	Cool Pixels	Warm Pixels
Dry (<300mm) Shrub	-0.25	-0.33	-0.17	-0.17	-0.26	-0.07	33	41
Dry (<300mm) Grass	-0.25	-0.34	-0.17	-0.22	-0.33	-0.10	35	41
Mid (300-500mm) Shrub	-0.42	-0.53	-0.32	-0.43	-0.54	-0.32	27	34
Mid (300-500mm) Grass	-0.46	-0.57	-0.34	-0.45	-0.56	-0.34	26	33
Wet (>500mm) Shrub	-0.30	-0.43	-0.17	-0.38	-0.51	-0.25	18	26
Wet (>500mm) Grass	-0.23	-0.42	-0.05	-0.24	-0.36	-0.12	15	22

Table 2. VPD_{max} coefficients for cool and warm pixels in each zone, 80% confidence interval for coefficients, and the average VPD_{max} values for each zone.

To calculate the decrease in NDVI attributable to human-induced warming, counterfactual NDVI ($NDVI_{cf}$) was derived for each zone using Equation 5. For low and mid-precipitation zones, the model fit was strong (r^2 0.84-0.90), yet was lower for high precipitation zones (r^2 0.71-0.77). Note the sample sizes for high precipitation zones are relatively small (number of pixels: n=222 grassland; n=418 shrubland). Moreover, the middle precipitation zones (n=3294 grassland; n=652 shrubland) have the strongest VPD_{max} coefficients (-0.43/-0.47), indicating an important temperature control over NDVI. Conversely, the low and high precipitation zones have the strongest precipitation coefficients. This indicates different climatic controls over NDVI for each precipitation regime.

$NDVI_{cf}$ estimates for each zone are shown in Figure 19. Notably, the attributable reductions in NDVI increase during the study period, particularly during the first decade and after 2018, when there was both observed substantially elevated VPD and low precipitation. The mean estimated attributable reduction in NDVI in 2020 ranges from 0.35 to 0.85 standard deviations of the interannual variability in NDVI. There are patterns in $NDVI_{cf}$ across precipitation regimes—the strongest reductions in NDVI corresponding with increases in VDP are in mid precipitation shrublands and grasslands, with 0.78-0.85 SD reductions in shrublands and grasslands, respectively. These areas with the strongest responses correspond to pixels with the greatest VPD_{max} coefficients (Figure 15d).

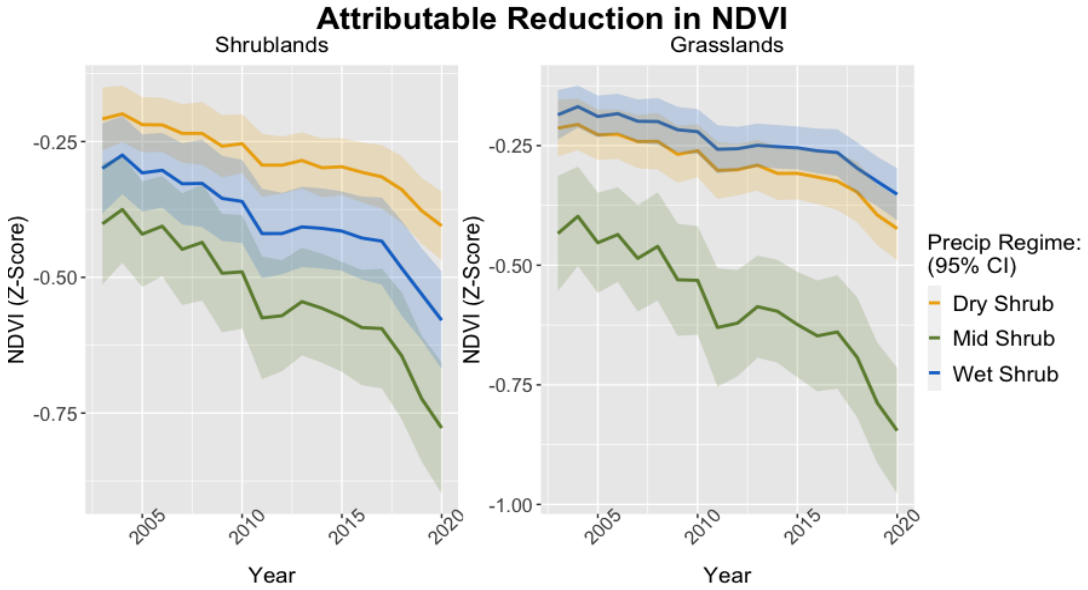


Figure 19. Estimate of decrease in NDVI attributable to anthropogenic forcing. Ribbons show 95% confidence interval (CI) across CMIP6 models. For dry pixels, the estimated decrease is relatively small (< 0.5 SD). For mid-precipitation zones (250-500mm), the decrease is greater than 0.75 SD.

While NDVI is a useful proxy for vegetation health, annual NPP (ANPP) is a more direct measure of forage abundance and overall plant productivity. As with the attributable reductions in NDVI, the largest standardized reductions in ANPP are found for mid-precipitation shrublands and grasslands (Table 3). In these regions, the attributable reductions in ANPP approach 1SD at the end of the study period, or around 50% of the observed anomaly (Table 3). Across the full study period, for these mid precipitation regimes, these reductions range from 25-60 lbs/acre of ANPP in shrublands and 40-100 lbs/acre of ANPP in grasslands.

2020 ANPP: Estimated Values and Attributable Decreases

	2020 Values		Attributable Decreases		
Zone	Actual (lbs/acre)	Anomaly (lbs/acre)	Raw (lbs/acre)	% of anomaly	Standard Deviations
Grass Dry	40	-142	30	-21	0.3
Shrub Dry	180	-110	15	-13	0.2
Grass Mid	608	-168	99	-59	1.1
Shrub Mid	568	-131	62	-47	0.9
Grass Wet	1547	-284	44	-15	0.3
Shrub Wet	1346	-275	86	-31	0.6

Table 3. 2020 ANPP and corresponding attributable reductions. ANPP for each zone for 2020 are depicted, including anomalies (from 2003-2020 mean). ANPP decreases attributable to human-induced warming ("Attributable Decreases") are shown in terms of raw reductions, as a percent of the observed anomaly, and in standard deviations of ANPP.

These reductions were further estimated at the census tract-level to depict the spatial distribution of ANPP reductions (Figure 20). Figure 20 depicts reductions attributable to human-induced warming as a fraction of the standard deviation of ANPP for that census tract. The largest attributable reductions in ANPP are mostly found in New Mexico, with some census tracts reaching greater than 1 SD of reductions in ANPP.

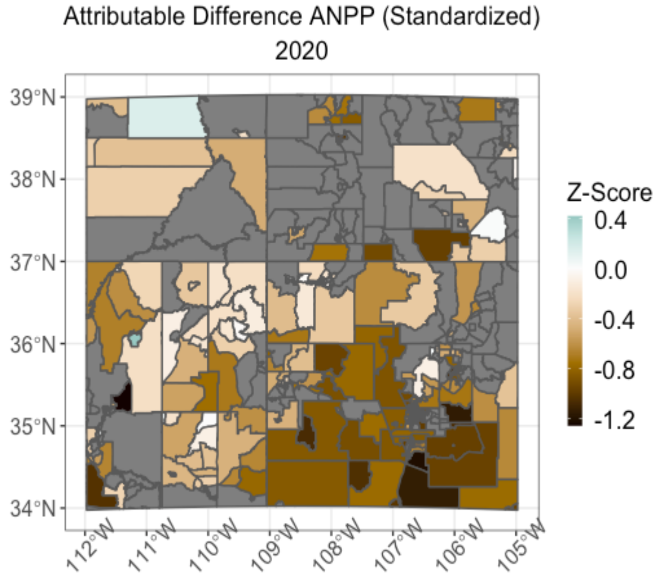


Figure 20. Standardized reductions in ANPP attributable to anthropogenic warming per census tract. Gray tracts either experience peak NDVI in non-summer months or are mostly covered by non-shrub or grass land cover types.

Discussion and Conclusions

In monsoonal areas, including the greater Four Corners region, vegetation greenness typically peaks during the hottest months just before the arrival of monsoonal rains. Therefore, it is during this hot-dry foresummer before the arrival of the monsoon in which there is high potential sensitivity to extremely high VPD values (Williams, Cook, Smerdon 2022; Weiss et al. 2009). From year-to-year, summer T_{max} and precipitation also covary—therefore, low precipitation years can further increase temperatures due to land-atmospheric coupling and surface energy balances. As such, the combined influences from failed monsoonal rains and high temperatures can significantly reduce vegetation health on rangelands. The decades of our study period have experienced low precipitation—average annual precipitation from 2003-2020 was -0.3 standard deviations below the long-term mean. Even in this lower precipitation era, the results presented here indicate that increased temperatures have produced substantial and detectable reductions in NDVI and NPP. These results indicate that while interannual variability in NDVI is primarily driven by precipitation, increased VPD levels are having a persistent and damaging influence. This finding corresponds with recent studies that have identified temperature and VPD as significant drivers of vegetation health in the Southwest (e.g., Dannenberg et al. 2022; Rao et al. 2022; Jiao et al. 2021).

Significant attributable reductions in NDVI are identified for all regions and years in the study. While there is substantial variation in the magnitude of the impacts across zones, the overall trend from 2003-2020 indicates a sizable increase in attributable reductions over the past two decades. Comparing zones, the driest areas in the study region—largely found in Arizona—have the smallest decrease in NDVI attributable to human-induced warming. These are also the areas with the hottest temperatures and lowest climatological NDVI: the average peak NDVI for these zones is ~0.22, while peak NDVI for bare ground can be ~0.1 (Huete 2002). These zones are highly water limited. It is likely that for these zones, precipitation, and therefore soil moisture, is low enough that, barring increases in precipitation, increased temperatures only have a marginal effect. Indeed, studies indicate that in the lowest soil moisture areas, soil moisture is the dominant control over vegetation growth, while VPD is the strongest control in higher soil moisture areas (Novick et al. 2016). The areas with the largest attributable decrease in NDVI are concentrated in New Mexico, at low-to-mid elevations, which exhibit slightly cooler temperatures and higher precipitation than the driest zones. These areas may receive enough precipitation to have a more pronounced sensitivity to increased VPD, and are thus the highest-risk areas to increasing VPD. These findings correspond with Novick et al. 2016, in which VPD was found to have a stronger control over stomatal conductance in wetter sites than in drier sites. These areas have also been identified as having high plant-water sensitivity due to both plant and soil traits, in which increasing VPD corresponds with decreased live fuel moisture content and higher wildfire risk (Rao et al. 2022).

In the mid-precipitation regions, these attributable reductions in NDVI roughly correspond to -25-60 lbs/acre reduction of NPP in shrublands and -40-100 lbs/acre of NPP in grasslands. To put this estimate in context, in 2018, exceptional drought covered much of the greater Four Corners region and soil moisture conditions were “very poor” (USDM 2018). The average NPP in 2018 for the mid-precipitation zones was ~-75 lbs/acre below the 2003-2020 mean, while our counterfactual NPP analysis suggests that without human-induced warming, NPP might have been ~+52 lbs/acre greater in these regions for 2018. In other words, human-induced warming contributed to approximately two-thirds of the observed 2018 NPP reductions in 2018. Throughout this study, we find temperature to have substantial influences: on VPD_{max} (Figure 4), NDVI (Figure 5), and ANPP (Figure 6). In mid-precipitation areas, we find that human-induced warming accounted for ~50% of 2020 ANPP deficits. This corresponds to the findings of Dannenberg et al. 2022, who showed that while half of the 2020 GPP anomaly was due to observed reduced soil moisture, nearly half was due to increased VPD. Our results indicate that increased VPD due to anthropogenic forcing in the mid-precipitation areas corresponds with significant reductions in forage availability. The reductions in both grasslands and shrublands are significant in terms of fodder—while cattle primarily consume grasses, sheep will eat forbes, some shrubs, and broad-leaved plants (Milchunas 2006). In particular, where these large reductions in NDVI/NPP coincide with high density livestock areas that may be areas experiencing high impacts on livestock health (Figure 21).

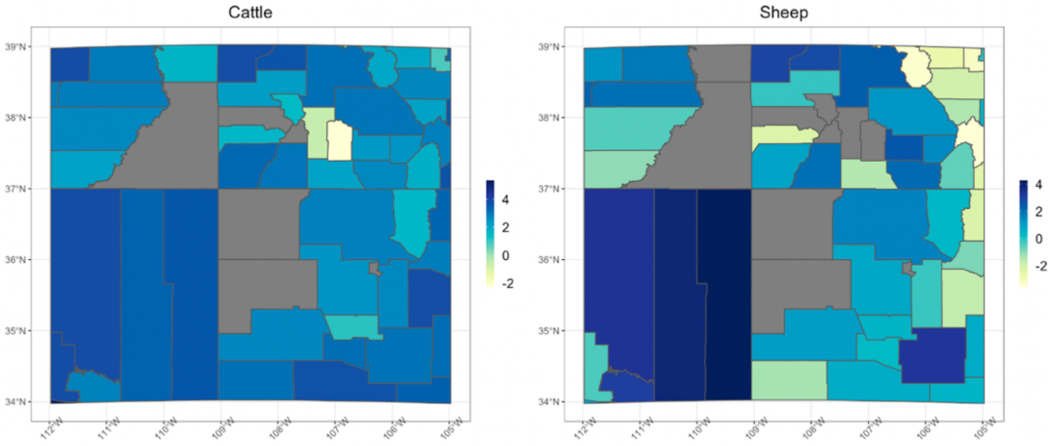


Figure 21. Concentration of cattle (left) and sheep (right) per county from USDA Census. Livestock counts are normalized: log(x/1000). The counties with the highest sheep counts are in Arizona, followed by a single county in New Mexico and one in Colorado. The counties with the highest cattle counts are in Arizona and southeastern New Mexico.

Moreover, since we do not attribute further increases in temperature due to land-atmospheric coupling, our study may yield conservative estimates of attributable increases in

VPD_{max}. While the experiments in many land surface models in CMIP experiments account for land-atmospheric coupling, some studies have indicated that the coupling in the models is too weak or the latent heat flux is too high (Yuan et al. 2022; Mueller and Seneviratne 2014). This would provide conservative estimates of heating, contributing to a conservative estimate of attributable increases in VPD_{max}. The strong VPD sensitivity indicated by our results--namely the model fit between actual NDVI, VPD, and precipitation--supports the possibility that there could be stronger-than-modeled positive feedbacks between drought, heat, and latent heat flux/evapotranspiration from the land surface.

Finally, there are many other semi-arid regions of the world with similar climates. Some areas, such as East Africa and Madagascar, have experienced similar repetitive droughts, extreme temperatures, and anomalously low NDVI. Since this study only requires precipitation, VPD, and NDVI, this methodology may be applicable to other semi-arid regions dominated by grasslands and shrublands with more limited data availability, and could also be leveraged in forecasting applications. Moreover, by identifying areas particularly sensitive to increases in VPD, the results of this study may help identify areas at greatest risk for further desiccation due to increasing temperatures.

2.5. Key Takeaways

The two studies found that while vegetative drought is due to multiple processes, particularly reductions in precipitation, increasing VPD from anthropogenic climate change is having a measurable damaging effect on vegetation. Furthermore, the fact that summer VPD and winter-summer precipitation are best predictors aligns with understanding that the hot-dry foresummer (before the arrival of the monsoonal rains) is a time in which the region is particularly susceptible to drought due to hot temperatures. Moreover, as much of the area is covered by shrublands, vegetation may have a longer memory here compared to areas that are primarily grasslands, so precipitation in the preceding eight months will affect vegetation productivity.

Peak snowpack occurs between February-April, while peak runoff occurs May-June. The first study found that temperatures measurably decreased peak snowpack SWE. However, the effect on runoff was small (~1%). If any changes in timing, it could have led to earlier runoff, though the change is also small. As the literature shows, temperature is more likely to change the timing of runoff rather than decrease runoff. Therefore, low precipitation was the largest driver of low SWE and runoff, with temperature likely leading to more rain than snow days or leading to early snowmelt, but not changing overall runoff.

Finally, the results from the second study indicate that VPD especially is constraining vegetation growth in water-limited areas where soil moisture has not yet constrained that growth. The driest (lowest annual precipitation) areas in the study region likely have very low SM. These places therefore likely are more constrained by low SM than by high VPD.

Acknowledgements & Author Contribution Statements

Study #1: The research presented in Section 2.3 was conducted in collaboration with Dr. Chris Funk, Dr. Shraddhanand Shukla, and Dr. Dan McEvoy. Author contributions: E.W.: Conceptualization (equal), data curation, formal analysis, investigation, methodology, project administration, software, validation, visualization, writing (lead) ; C.F.: Conceptualization (equal), investigation, methodology, validation, writing ; S.S.: Data curation, formal analysis, investigation, visualization, writing (edits) ; D.M.: Data curation, formal analysis, investigation, visualization, writing (edits). Thank you to Andy Hoell with NCAR for help with accessing climate model output.

Study #2: The research presented in Section 2.4 was conducted in collaboration with Dr. Chris Funk and Dr. Shraddhanand Shukla. Author contributions: E.W.: Conceptualization (lead), data curation, formal analysis, investigation, methodology, project administration, software, validation, visualization, writing (lead) ; C.F.: Conceptualization (support), methodology, validation, writing ; S.S.: Validation, writing (edits). Thank you to Anna Trugman and Joe McFadden for feedback on plant physiological responses to meteorological change and to the GrassCast and RPMS teams for input on NPP models.

III. Redefining Responsibility: Zuni Worldviews, Climate Change, Causality, and Socio-Environmental Obligations

3.1. Introduction

The Southwestern United States ('Southwest') is a largely semi-arid region, with highly variable topography—spanning from lowlands to mountain ranges—and complex seasonal cycles. This place has always been relatively dry (or semi-arid), and water has always been sacred to the *A:shiwi*—the people also known by their Spanish colonial name, Zuni. *A:shiwi* traditional history tells that they have lived in this area since time immemorial. Indeed, archeological evidence indicates the presence of the people here for at least the past 3000 years (Damp et al. 2002). Their ancestral lands encompass over 15 million acres across the Colorado Plateau in modern-day New Mexico and Arizona (Wemytewa and Peters 2010; Cleveland et al. 1995; Committee on Interior and Insular Affairs 1976:3). The Zuni reservation (or the Zuni Pueblo), while but a small fraction of the extent of ancestral lands, lies within these lands and has been considered home to *A:shiwi* for generations. This place is called *I'diwan'a*—or "the Middle Place" (Dongoske et al. 2015).

Drought is nothing new for *A:shiwi*—they were born into, have learned from, and have created practices to live in balance with this semi-arid landscape. Yet, after centuries of largely Western society-driven infrastructure development, increased demand for water from population growth, industrial activity, and introduction of Western farming and ranching methods—compounded by the more recent effects of human-caused climate change—the traditional cycles of drought have fundamentally shifted, bringing the people, plants, and animals of this region into a new era of drought. While these processes have affected nearly everyone in the Southwest, the changes are particularly pronounced and nuanced for *A:shiwi* and *A:shiwi* ancestral lands and waters.

This chapter will refer to the people, the land, the Pueblo, and culture and lifeways—which, as explained later, are entwined—together as a whole as *Zuni*. This chapter aims to understand the climate impacts that have been endured by Zuni—again, the people, lands, waters, and lifeways—and to explore what form of recourse for these impacts would fit with Zuni sensibilities, values, and worldviews. The first part—the climate impacts—relates to conceptions of causality. It requires understanding both what the impacts are and how the impacts were and are created. The second part seeks to understand what accountability and corrective actions for climate impacts would be appropriate from Zuni perspectives. These themes are explored with the understanding that there is much that Western society can learn by listening to the people, including their perspectives, lessons, voices, and needs regarding lands, waters, and lifeways.

At the beginning of one of the interviews, I was asked by the interview participant: "why Zuni?" The interviewee described how many tribes in the U.S. and across the Southwest similarly respect Mother Earth—her waters, forests, and creatures—and have an environmental ethic (Representative 5). Moreover, in many ways, the story of how Zunis relate to the environment and the impacts that have occurred due to Euro-American settler-colonialism followed by climate change is the same story that ripples across tribal communities throughout North America. What is it specifically about *Zuni* that made me want to focus this work here? In truth, what led me to learn about Zuni was first and foremost by chance (see Methods). That chance, however, led me to learning about the worldviews of the people, the history of the lands and waters, and the unique relationship to water and environment. The knowledge systems and ethics held by *A:shiwi* stayed with me and led me to pursue this work, for I felt these knowledge systems hold much nuance and wisdom in thinking about responsibility to the earth, much that Western science is largely failing to understand.

Understanding Climate Risk

This chapter pulls from conceptual frameworks and theories of climate risk, vulnerability, and impacts, and the conditions that have created those. The climate risk framework adopted by many institutions was created by the Intergovernmental Panel on Climate Change (IPCC), the international organization of Western scientists who work on understanding the causes of and physical and social impacts of climate change (Figure 1). The IPCC conception of 'risk' refers to the "…potential for [negative] consequences where something of value is at stake and where the outcome is uncertain" and occurs from the interaction of hazards, vulnerability, and exposure (IPCC 2014:5). Hazards, synonymous with 'physical impacts', are environmental changes stemming from climatic changes, such as droughts, floods, or fires. Climate change shifts such hazards, making them more likely to occur or more intense when they do. A hazard on its own will not lead to social impacts. People have adapted to living with hazards by developing local responses which reduce their exposure to hazards and make them overall less vulnerable and more resilient. Exposure here refers to "the presence of people, livelihoods…or economic, social, or cultural assets in places and settings that could be adversely affected," while vulnerability refers to the "propensity or predisposition to be adversely affected." Vulnerability can be related to many processes, including income inequality, losing access to land or water for farming practices, or interruptions in cultural and spiritual lifeways (Wilder et al. 2016; O'Brien and Leichenko 2000; Liverman 1990; Smith 2006).

All three factors—hazards, exposure, and vulnerability—have existed throughout human history. However, when conditions change, such as living in a different place (exposure), losing access to land or resources to practice traditional farming practices (vulnerability), and if droughts become intensified from industrial climate change (hazards), the risk of impacts will increase. This framework has been commonly used to understand how climatic changes translate to risk of climatic impacts.

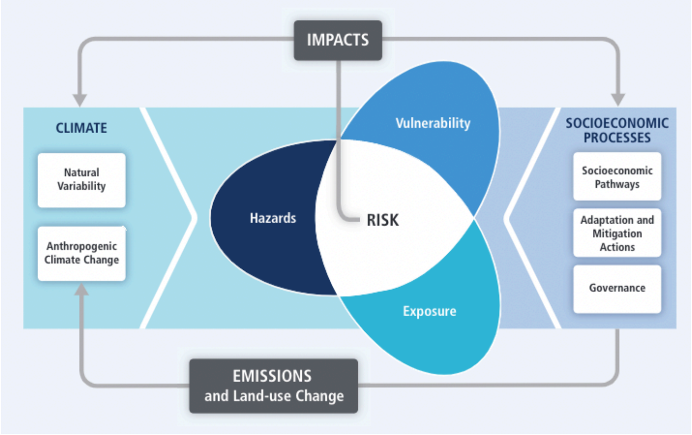


Figure 1. IPCC Working Group 2 (WGII) conceptual framework of how climate risk and social impacts are created. Figure is reproduced from: IPCC 2014:3, figure SPM.1.

There are certain aspects and experiences of indigenous peoples and cultures, however, that have led to unique exposures and vulnerability to hazards, and unique resilience to changes. While the experiences of climate change and colonialism among indigenous peoples across North America are unique, there are certain themes that connect many of these experiences. These themes include (from STACCWG 2021:7; Cozetto et al. 2013; Chief et al. 2014):

- For many tribes, lifeways—spiritual, cultural, and physical—are deeply connected to the land, waters, plants, and animals.
- Settler colonialism has dispossessed indigenous peoples of much of their ancestral lands and waters and sovereignty. Continuing settler colonialism contributes to ongoing political and economic marginalization and lack of funding, infrastructure, and other resources.
- The unique place-based ancestral knowledge held by indigenous peoples is often the best guide for living with and responding to hazards.
- The fight for regaining sovereignty, practicing and teaching language and ancestral knowledge, and protecting lands and waters is central to any climate change adaptation.

Therefore, alterative frameworks for understanding climate change impacts have been created to account for the unique needs of and impacts on indigenous peoples (Cozetto et al. 2013). These were created specifically in response to the fact that indigenous peoples have both experienced many hardships from settler colonialism and because many tribes are innovative and resilient due to that deep land-based ancestral knowledge (STACCWG 2021:7).

In addition to these frameworks, two theories provide tools to understand the ways in which climate risk has been created. The intertwined theories of *accumulation by dispossession* and *sacrifice zones* explains how settler colonialism and extractivism have jointly created climate risk through shaping vulnerability, exposure, and hazards. David Harvey introduces the concept of "accumulation by dispossession" to describe how wealth, power, and resources are disproportionately accumulated or centralized by a small group of entities through the dispossession of other groups of those attributes (Harvey 2003). This enclosure, privatization, and commodification of nature was necessary to accumulate lands on which to extract fossil fuels, the primary contributor to human-induced climate change (Liverman 2004; Liverman 2015; Harvey 2003; Watts 2012; Klein 2015). In North America, this accumulation occurred specifically via the dispossession of indigenous lands and waters (Maldonado 2018; Farrell et al. 2021). Sacrifice zones are created through this accumulation by dispossession (Maldonado 2018:74). Sacrifice zones are the places and communities which bear the brunt of toxic extraction, dumping, or otherwise undesirable land use largely for the benefit of those who do not live there (Bullard 1993). Put another way, sacrifice zones are "…where human lives are valued less than the natural resources that can be extracted from the region" (Buckley and Allen 2011:171). The extraction and combustion of fossil fuels, and fossil-powered economic development, has largely occurred in such sacrifice zones, and furthermore are the sites of some of the highest climate risk (Klein 2015). These theories provide the basis to understand that climate risk and vulnerability do not just happen but are rather created, at least in part, by people.

3.2. Methodological Approach

This chapter presents a political-historical ecology account of climate change for the Zuni people, lands, and waters. This chapter intends to be outward facing by "studying up" (Nader 1972). The concept of "studying up" is based in the understanding that impacts, processes, or other phenomena happening at a site—for a community—are related to the power relations at play at locations higher 'up' (Nader 1972:5). As an extension of this idea of studying up, this chapter aims to examine the power relations, knowledge systems, and history of two different entities in relationship with one another—colonization does not exist without a colonizer, poverty does not exist without affluence, power does not exist without marginalization (Nader 1972). Therefore, this chapter aims to trace these relationships through accumulation and dispossession (Harvey 2003).

The methodology is based on a sequential mixed methods procedure. There are three primary data sources used for this chapter—semi-structured interviews, Western science-based meteorological and environmental data, and a literature review and archival analysis. These data sources include both Zuni knowledge systems and Western science. In this chapter, I aim to center the qualitative, interview-based data and use quantitative data to provide context, in attempting to invert the common approach to mixed methods. As critiqued by Cheong et al. (2012), mixed methods procedures still largely use qualitative data as complementary to or accompanying quantitative data, including providing "context, validity and explanations to documented patterns" (Cheong et al. 2012). Qualitative data is, however, uniquely suited to understanding *why* certain patterns or processes have occurred (Cheong et al. 2012). As this chapter examines the *what* question (describing the climate impacts) so as to then examine the *why* questions (causation and appropriate accountability approaches), qualitative methods are centered here, using quantitative methods to provide context, measurement, and further describe processes in the chain of causation. Moreover, Cheong et al. (2012) explain that "[s]tories tend to emphasise social and institutional change, whereas diagnostic models tend to focus on biophysical and economic change", yet as Zuni knowledge understands the social and biophysical as integrated, the knowledge from qualitative interviews helps elucidate both types of change. Finally, this chapter is based on a sequential or iterative approach, in which multiple analyses have been conducted and the questions and a priori knowledge are informed by the results of the previous analysis (Creswell 2003).

Prior Stages of Research

I had the opportunity to participate in a previous project with the Zuni, which led to the development of the 2020 draft *Extreme Events and Harmful Environmental Trends: Zuni Lessons in Adaptation* report (Curti et al. 2020). In this project, I participated in holding workshops and semi-structured interviews with key vested parties. Based on the intensive workshops and semi-structured interviews, coupled with an extensive literature review, the project traced the climate impacts experienced by the tribe. The report highlighted the climate impacts to water, rangelands, and agriculture. The report furthermore highlighted Zuni worldviews of water as living and of 'extreme events' as manifestations of consequences of human disrespect of the earth. Coupled with the two detection and attribution (D&A) studies in Chapter 2—which identified how increasing temperatures from human-induced climate change are contributing to drought—these prior stages of research provided the groundwork to shape the questions guiding this chapter. Together, these findings prompted me to consider whether there are Zuni lessons for Western science to learn regarding causality for temperature-related drought impacts as a function of human activities.

The key guiding questions revolve around identifying climate impacts, how different knowledge systems conceptualize *causality* for those impacts, and what form of corrective or accountability-based mechanism would be appropriate to hold responsible those who have led to the impacts experienced by Zuni. The first two questions were largely explored in the original report and two D&A studies; however, while the last question is explored in Chapter

4 from a largely Western science perspective, before embarking on the analysis in this chapter, I held no understanding of Zuni perspectives and knowledge on this issue. Therefore, the research presented in this chapter is informed by these prior stages of research. The data however is based first and foremost on semi-structured interviews with eight key informants, and then used archival analysis and Western science-based descriptive analyses for meaning-making from the interviews.

Methods

Following the guidelines for considering indigenous knowledge systems in climate change initiatives, this research was conducted under the principles of free, prior, and informed consent (Chief et al. 2014). Free refers to the ability of each participant and the tribe to decide whether or not to participate; prior ensures that all information regarding the research and intended publication is given prior to the research; informed ensures that the information shared with the tribe and each participant includes the purpose of the project, the interview, and how the information will be used; while consent affirms the rights of participants and leadership to opt into or out of the research with no consequences (Chief et al. 2014). Therefore, I first approached the Zuni Tribal Council with a project description ask for feedback and seek consent for the research

Upon gaining consent in a written research agreement, I invited 18 key knowledge holders, or ‘key informants’, to participate in an interview, including all members of the Zuni Cultural Resources Advisory Team (ZCRAT) and the Tribal Council, and those members of the Zuni Division of Natural Resources (DNR) and *A:shiwi* College who were interviewed for the original report. These knowledge holders were invited based on the unique knowledge they hold related to, and their day-to-day engagement with, the questions in this research. Of the 18, a total of eight people were ultimately interviewed; while significantly fewer than the group invited, the eight interview participants span each of the groups listed above.

Given the ongoing COVID-19 pandemic, all interviews were held virtually via Zoom or over the phone. Interviewees were provided a consent form in advance which included the project description and information on the interview recording. Interviews were designed to last 60 minutes but, in practice, lasted for the duration determined by the interviewee (in some cases up to two hours). Interviews were semi-structured, based on a series of guiding questions. For interviews in which the interviewee consented to recording, interviews were recorded and then transcribed. For those for which recording was not available, notes were taken by hand. After the interview was completed, the interviewee was provided a copy of notes for them to review, edit if necessary, and consent to before the notes were used for analysis.

To accompany the interviews, further data were collected. Quantitative meteorological and environmental data were accessed from the PRISM Climate Group at Oregon State University, the USDA SNOwpack TELemetry Network (SNOTEL) station at Rice Park, NM, and the USGS streamflow gauge at Blackrock Reservoir.

Upon the completion of all interviews, interviews were analyzed as a collective whole. First, all text—including transcriptions and notes—were re-read to allow for ideas to emerge from the interviews. Then the interviews were collected and organized by theme in two rounds. The first round was based in grounded analysis, or letting themes emerge from the data rather than fitting the data into pre-set themes. The second stage then reorganized the themes from the interviews based on my a priori questions and theory guiding this chapter. In this stage, I examined whether themes that emerged from the interviews upheld my pre-existing ideas, or whether they critiqued, nuanced, or rejected those ideas. Moreover, I made space for the inclusion of new/previously unexamined concepts in my research. The themes that emerged from these two rounds of organizing interviews created the structure for the chapter. In this way, the chapter is written to be organized around and prioritize Zuni observations and worldviews.

I then conducted further Western science-based descriptive analyses, and secondary and archival analyses, to build upon or further interrogate the concepts presented by the interviews and previous stages of analysis. Using the quantitative meteorological and environmental data, I created climatologies (average monthly conditions) for the early period (before 1980) and current period (since 2000) to visually examine changes in temperature, precipitation, snowpack, streamflow, and vapor pressure deficit (VPD). Furthermore, the results from the original report and the interviews often highlighted historical events which altered the landscape and waterways and contributed to enclosure. Therefore, I engaged in secondary analysis to examine the history around the key events identified in the report and interviews. When relevant events were mentioned in the secondary analysis, I then conducted further secondary analysis on those events. When events were related to treaties, acts, or other forms of policy, I conducted archival analysis on relevant texts to examine references to rights of indigenous peoples and lands.

The results from this analysis are interwoven throughout the rest of the chapter and presented in narrative form. Quotes, knowledge, and perspectives from interviewees are anonymized and attributed to “representatives.”

Methodological Considerations and Use Terms

This chapter does not aim to prescribe adaptive strategies or recommendations for actions for Zuni, nor does it seek to examine power relations or decision-making within the Zuni community. Such pursuits can, and should, only come from the people themselves. Instead, this chapter examines inter-community and inter-worldview relationships—and how those relationships shaped impacts for the people and the lands and waters.

As much of the chapter is organized around Zuni worldviews and knowledge, the ideas and knowledge presented in this chapter belong to those who are quoted and cited. They are the experts here. They hold the collective wisdom of their ancestors, the lived experience as indigenous peoples of these lands, and years of study and place-based wisdom. There is a long history of indigenous knowledge being taken and exploited in academia, without consent of the people and without reciprocal benefits for the people (Chief et al. 2014). Importantly, traditional knowledge belongs to the tribe, and it is important to respect the sovereignty of tribal nations and indigenous people in determining which knowledge is meant to be shared with Western society. Therefore, the consent of the Zuni Tribal Council was gained before the beginning of the project, each interviewee had the opportunity to review, edit, and redact their comments, and the Tribal Council was provided the opportunity to review the chapter before its inclusion in the dissertation.

Hence, the knowledge included in this chapter is that which is explicitly meant for non-Zuni people—ranging from Western climate scientists to policy makers. I enter this space as ally as I am not indigenous to these lands. It is with this positionality, and drawing from these multiple sources of wisdom, that I embark on this description of climate change at Zuni. Moreover, within the goal of reciprocity, this chapter also questions how Western society may be more accountable to Zuni—the people, the ancestral lands, and the living water. I am grateful to the Tribal Council and all interview participants for sharing the wisdom and knowledge meant to be shared with Western society, in that it might teach us other ways of thinking about and interacting with this world.

3.3. Zuni Worldview and History

A:shiwi have lived in the Southwest since time immemorial. With ancestral lands encompassing over 15 million acres across present-day Arizona and New Mexico, they have lived in and developed with a highly variable yet largely semi-arid landscape. Their story begins in the Grand Canyon where their ancestors emerged, and then crossed the landscape until they found *I'diwan'a* (Curti et al. 2020). Their emergence story tells how the *A:shiwi* language was born from the land and the waters:

> "The Ancestors traveled great distances of space and consciousness, and their relationships with the water, land, and collective spirit, evolved with them as they journeyed across the body of Mother Earth. Expressing primal responses in rhythm with the land and waters, *Shiwi'ma bena:we*, the language of the people, was born" (Wemytewa and Peters 2010:16).

A:shiwi practices have developed out of the relationship to their ancestral lands (Enote 1995). These practices and relationships, therefore, specifically fit these semi-arid lands, changing with and adapting to the cycles of drought and wet years, and existing in reciprocity with Earth Mother and all her creatures (Curti et al. 2020). *A:shiwi* knowledge systems know the people to be embedded in and inseparable from an animate environment—land, water, and creatures are all animate and a relation to people (Wemytewa and Peters 2010:18). The people thus hold as deep a respect for the environment as they do for family (Dongoske et al. 2015:39). Water particularly is sacred, alive, and animate. As such, ceremonies and cultural stories exist around water itself, and for specific streams, ponds, and lakes (Young 1988). As explained by a traditional knowledge holder:

> "We do believe that water is a living entity, and that our ancestors thrive in the water, and rivers, ponds, springs. And so when we come upon springs...if we have a container, we try and collect some spring water to use in our ceremonies. And then we do our offering in a spring or a river. And we bless ourselves with the moisture. And we splash the water up into the air, telling the ancestors to 'hurry, go to the middle place', which is here in our village...Water is very important to us. Water is life. I've always said water is life, and that we treat it as a living spiritual entity and we treat it with respect…" (Representative 6).

As lands, waters, and creatures are kin relations, the Zuni environmental ethic is based on responsibility one has to one's familial relations. In other words, caring for the environment is as natural as caring for family, rather than based on some abstract or scientific notion of 'conservation', 'managing resources', or 'sustainability' (Dongoske et al. 2015:39; Curti et al. 2020). To put it simply, *A:shiwi* have lived with 'sustainability' guiding their practices before the contemporary Western term and concept was created. Therefore, like many indigenous cultures, especially across North America, land is not to be owned—rather than viewing lands as a ‘bundle of rights’ as common in Western cultures, it is a ‘bundle of responsibilities’ that people have to the land (Kimmerer 2013:28). As such:

> “Zunis do not own the land, they belong to the land and are part of the land. They are dependent upon it and the landscape is dependent upon them…” (Dongoske et al. 2015:39).

As a relation, land and people actively shape one another. Knowledge, culture, practice, and language emerged from this relationship with the environment, and Zuni language is expressive of people as active participants in this intimate relationship of shared responsibilities towards lands, waters, and creatures as they are all living and alive. Zunis perform and observe their responsibility toward the earth through socio-religious practices. Zuni prayers do not just ask for blessings for the peoples’ own benefit, but for all creatures and land (Representative 4). In this way, the religion is based on the understanding that the people are in a relationship with all other components of the environment:

> “By being in the same place for such a long time Zunis have developed a perception and understanding of the universe which accounts for dimensions not normally considered in modern thinking. Much of this knowledge has been gained through experience and has become a religion of reverence and respect of how nature affects our lives and how it can be lived with. Through thousands of years of sensing the conditions that make life difficult or wonderful, Zunis have become participants in the cosmological process” (Enote 1995:3).

As all participants in the environment are animate, have purpose, and exist in relationships to one another, the earth will respond in kind to the actions or inactions of others. Just as responsibility exists in these relationships, when that responsibility is breached, there are consequences. As such, appropriate and proper conducting of ceremony and ritual may bring about blessings of water, for clouds and rain are manifestations of ancestors and will bring their gift of moisture out of reciprocity to the gifts of ritual and ceremony (Fullbright 1992). However, failure to practice rituals or acts of disrespect toward Earth Mother may bring about harms (Grugel 2012; Fullbright 1992; Ford 1999). As such, when droughts or flooding occur, when water diversions for agriculture fail, or when crops do not produce, it is due to a failure on the peoples' part, be it "ritual failure or individual deviation from Zuni traditions" (Ford 1999:92). When this is your perspective, the proverbial world shifts in terms of what is a conscionable action, what to do to avoid disrespect, and what needs to be done if disrespect has been done.

This worldview is dramatically different from dominant Western worldviews. When you are in relationship with an animate earth—rather than stewarding or managing an inanimate earth—your actions are different. Yet in dominant Western worldviews, especially stemming from Christian theologians in early medieval Europe, this view of an inanimate earth justifies the exceptionalism of humans, in which humans are hierarchically ranked above animals, plants, and then minerals (Parrish 2021; White 1967). This medieval European worldview allowed for the creation of the "man versus nature" dichotomy, in which humans may impact nature or need to alternatively protect themselves from nature, but this nature is inanimate, and therefore decisions about how to 'manage' nature is based on humancentric value systems, often leading to damages to lands, waters, and creatures. This principle is also the basis for 'resource' management approaches such as conservation, premised on the concept of stewarding an inanimate wilderness—devoid of any form of relationship to or dependence on people—which led to the formation of the National Parks in the U.S. to 'protect' these lands from people, thereby often dispossessing indigenous peoples of their lands to do so (Spence 1999; Jacoby 2014). Only in recent decades has the idea of people as part of nature begun to take hold in dominant Western thought, and in its infancy, it has much yet to learn.

Traditional Agriculture

Zuni lifeways and culture are deeply interconnected with agriculture. Long known for their agriculture techniques, for generations the people have nurtured 12,000 acres of agricultural lands with little to no land, soil, or water degradation (Wemytewa and Peters 2010:17; Pawluk 1995; Folger 2020; Cleveland et al. 1995). As such, Zuni traditional farming practices are especially productive, bountiful, and sustainable (Wemytewa and Peters 2010; Cleveland et al. 1995; Ford 1985; Folger 2020). Cleveland et al. 1995 introduce a holistic definition of sustainable agriculture as whether it produces a 'good return', it nurtures the land, water, and soils for future generations, the local community is in control, it is done within cultural values, and there is equitable access to food within the community. Prioritizing these aspects has made farming successful in this arid environment (Cleveland et al. 1995).

The sustainability of these agricultural practices is guided by Zuni cosmology. Corn is a particularly important plant—there are unique folk varieties of corn specific to Zuni, and protecting these folk varieties are important from intertwined enviro-religious perspectives. The religious and agricultural calendars are intertwined, so that sowing and harvesting occurs with ceremony and prayer (Cleveland et al. 1995; Ford 1985:20). Zuni corn seeds have unique traits allowing them to be planted deeper so that the seeds may access deeper soil moisture (Cleveland et al. 1995). While the seeds would experience dry times, between their unique adaptations and the knowledge of the ancestors for how to plant, at least prior to socio-environmental harms wrought by European settler colonialism (see section 3.3.1), the seeds often produced (Representative 5).

Emerging from the enviro-religious practices developed in relationship to this landscape, the deep and expansive knowledge held by *A:shiwi* of the soils and watersheds has facilitated bountiful harvests (Pawluk 1995; Representative 5). In this landscape with limited water flows, fields were planted in areas to intercept water in its natural flows across large areas of the ancestral lands (Figure 1) (Cleveland et al. 1995; Representative 5). Numerous practices were developed in this vein, including dryland farming, or planting wide, flat fields so that when rain falls on the field, there is no runoff and it instead is absorbed by the soil; runoff farming, or directing channels of runoff to crops; irrigation and canal farming, by creating small diversions to direct water flows toward crops; and waffle gardens, or small, water-intensive gardens that were hand-watered with water from the river (Ford 1999:76-80). Fields were planted in optimal locations, such as in alluvial plains where runoff happens and soil is rich with nutrients (Cleveland et al. 1995; Ford 1999:76-79).

This view does not equate ‘sustainability’ with leaving the land unchanged. Traditional Zuni agricultural practices actively modify the landscape, in balance with and responding to changing local ecological systems (Curti et al. 2020). While small diversions and canals were created to funnel water toward fields, fields were also moved based on changes in river and streamflow. Archaeological evidence indicates that such irrigation has been used for thousands of years, without harming other plant or animal habitats or diminishing waterway capacities, or depleting soils, therefore flourishing not at the expense of but in tandem with the other lifeforms in this area (Cleveland et al. 1995; Ford 1985; Damp et al. 2002; Pawluk 1995). As further evidence of the sustainability of these practices, traditional agriculture was so bountiful that the Zuni maintained storage areas for surplus food to store for bad harvest years (Cleveland et al. 1995). As part of this lifeway system that grew up together with the lands and waters of the Southwest, food was provided to those community members in need as part of the responsibility ethic to one-another (Ford 1985:93).

Drought is nothing new but is a manifestation of disrespect

Drought is nothing new for *A:shiwi*. Climatic variability has always been present in ancestral Zuni lands, and practices were developed in concert with these changes. Western paleo-drought records indicate that severe, long-duration "megadroughts" have occurred over the past 2000 years (Garfin et al. 2013). Some droughts have been severe enough to push the people to temporarily move across their ancestral lands—in the eighteenth century, a drought led the Zuni people to temporarily migrate to the Rio Grande pueblos (Bemis 2014). Yet through prayer and ceremony, and continuing with 'sustainable' practices, the people have survived through drought.

This history indicates that *A:shiwi* have what Western science would term a strong 'adaptive capacity' in responding to drought. Yet, while adaptation generally involves planning from a Western science perspective, for the *A:shiwi* people, it is considered inappropriate—and potentially dangerous—to do planning in the same way (Grugel 2012). The Western, linear approach to planning generally uses forecasts or projections to guide adaptive actions. Yet, from Zuni perspectives, if you forecast to look for potential perils, that act may make those perils come true. Instead, Zuni perspectives are tied to cyclical, rather than linear, time (Curti et al. 2020). Therefore, in times of drought, instead of forecasting, the people turn to lessons from ancestors as they had already lived through these times and know what to do to arrive back in balance with Earth Mother. For example, as evidenced by storing food for dry years, being prepared for dry times is a long-term practice of the people. What makes it different from Western planning, however, is that it was done in a holistic way, in living in balance with the current environment, based on lessons from the ancestors (Representative 4). Indeed, many indigenous cultures are organized around a response-relationship to changing environmental conditions (Whyte 2016:89-90). Therefore, Zuni adaptive capacity is a culture, religion, and set of beliefs and values born from a relationship to a variable environment and always returning to and learning from the lessons of this relationship. Put another way, adaptation for Zuni occurs by turning to traditional wisdom and practices that have emerged out of this cycling (Curti et al. 2020).

What then may happen if those deep-time lessons are ignored, or people fall out of their relationship of responsibility with the earth? While Zuni worldviews and traditional practices have prioritized respecting Earth Mother, certain prophecies were made about times in which this respect would break down:

> “There’s a certain set of prophecies that was set saying that if we don't do certain things, or if certain things happen, this is what was predicted… most of those prophecies pretty much became true. And a lot of these came…before the establishment of actual human beings within the area. So within those timeframes

> these prophecies were given and I guess it was at that point in time we were forewarned to change our ways and habits, and if we failed, then these are what's going to happen… these were brought up to us but we just failed to realize it and follow through with what our responsibilities are… until now where we're at with, with the heavy droughts, the inability to actually do farming…" (Representative 1).

The prophecies are warnings of what will come to pass if proper practices are not upheld, and disrespect occurs. They offer a foresight to the intertwined impacts that have brought about climate risk.

3.4. Creating Climate Risk

The arrival of Europeans, and particularly Anglos and their specific project of settler-colonialism—brought many changes and damages which interfered with Zuni ways of life. Drawing on the IPCC framework for climate risk, these changes first increased both exposure and vulnerability, and then hazards, for Zuni people and lands. It is impossible to understand climate risk for Zuni without first understanding the reverberating and cumulative effects of the history of dispossession and degradation of lands and waters.

First, however, it is necessary to differentiate between changes wrought by settler-colonialism versus the changes through the consensual adoption of tools, foods, and knowledge through interaction with other people or cultures. Zuni was an exchange center for centuries before European settlement, with many trail and travel routes which other people used to come trade at Hawikuu (just south of the Zuni Pueblo) and later Halona:wa (the Zuni Pueblo) (Hart 1995:72-73). The people traded turquoise, salt, and food surplus in the years when the Zuni community's food needs were met (Cleveland et al. 1995; Ford 1985; Wemytewa and Peters 2010:16). They also traded knowledge and stories with other communities (Wemytewa and Peters 2010:16). Through this extensive exchange network, certain foods, materials, and knowledge were adopted by the people and incorporated into the concept of "traditional." Therefore, defining what is "traditional" can be complicated. It is, however, linked to how the incorporation of different foods, materials, or practices has occurred:

> "It is hard to separate the postcolonial history of living and responding to things from the traditional, because a lot of them blend together… Sheep and cattle and that whole lifestyle is all post-colonial. Yet Zuni has embraced it now as if it's traditional... If you want to be really traditional, we didn't even have that, we were just farmers. Then you get into the debate as: What does traditional really mean, does traditional mean from the very beginning, before any influence by any other people? Because even before Europeans came…Zuni was the result of a combination of different cultures that came together and resulted in something very unique…So, if Zuni—what we think of Zuni today, pre-European—was really the result of a blending of cultures, then it makes sense, that Zunis now could embrace anything European culture had to give and was beneficial and then use it and call it their own, and then still call it traditional…" (Representative 3).

What differentiates changes that might be absorbed into *Zuni* and become subsumed into the concept of "traditional", versus that which is certainly not Zuni and clashes with "traditional"? This question can only be answered by the people themselves. One interviewee offered that it may fall to the difference between technology and practices on the one hand, and mindsets, beliefs, and values on the other:

> "…practices and tools, technologies, Zunis would readily embrace anything that's new—that they discover or are introduced to—that helps them…as long as there's no detriment, or they can't think of any reason why it would go against their values and beliefs... that may become traditional Zuni as well. So traditional technologies can change and evolve and adapt and embrace other technologies from other cultures. But it's really the mindset, values, and beliefs that may stay uniquely Zuni that then helps them decide how to use new technologies and adapt them or not… I guarantee people, especially individuals, land users on a day-to-day basis, they do that all the time. Even if it's not conscious that they're actively making decisions about how to incorporate new things and new tools, and how it compares to traditional old tools, but always with a Zuni mindset of…how does it fit into our beliefs and value systems?" (Representative 3).

It is within this important distinction that the years since the mid-1500s should be interpreted. What settler colonialism did was force many changes upon Zuni—the people, the waters, and the lands—and many of these changes disrupted lifeways and cultures. As will be described in the following sections, this brought many harmful changes, most of which were imposed. Therefore, the sovereignty of and choice of the people whether to adopt changes was not respected. It is necessary to thus be mindful here how, as observed by Kyle Powys Whyte:

> “Colonialism, such as U.S. settler colonialism, can be understood as a system of domination that concerns how one society inflicts burdensome anthropogenic environmental change on another society…Settler colonialism…involves settler society seeking to fully establish itself in that territory according to its own cultural and political systems, which requires erasing the Indigenous population” (Whyte 2016:91).

The next section will trace out how both types of changes have occurred and functioned in differential and nuanced ways to shape Zuni vulnerability and exposure to climatic hazards.

3.4.1. Settler Colonialism: A History of (Largely) Dispossession

The Spanish and Mexican Administrations:

In the mid-1500s, the Spanish invaded Zuni lands (Eggan 1995). The conquistador Coronado had come searching for the fabled “Seven Golden Cities of Cibola” based on prior reports of a city of gold and riches (Committee on Interior and Insular Affairs 1976). Failing to find gold, and dismissing the agricultural wealth and knowledge of the people and land, the Spanish proceeded to bring violence (Wemytewa and Peters 2010):

> “Peace was severed when the conquistadores Coronado and Oñate invaded Pueblo territories… Taking slaves, burning crops, all in search of gold when the real wealth was

> in corn, the power of the River, and in harmony found with the Natural World" (Wemytewa and Peters 2010:17).

The Spanish destroyed religious Zuni items (and religious items of many other Pueblo tribes), and people were subjected to incredible violence and oppression at the hands of the Spanish (Roberts 2008). In 1680, the Pueblos together revolted against the Spanish and drove them out in the successful Pueblo Revolt (Roberts 2008). During the Pueblo Revolt, *A:Shiwi* left their six distributed villages and converged on the sacred Corn Mountain—*Dowa Yalanne*. They faced hardships, including drought, but remained organized amongst Puebloan communities and managed to keep the Spanish out of the area for 12 years (Roberts 2008; Eggan 1995:23).

During this time, the Spanish began issuing land grants. These grants were "designed to colonize and develop unoccupied lands" to hold them for Spanish interests, such as farming and grazing lands (Williams 1986; Minge 1995:43). In 1689, the Spanish Governor of the Province of New Mexico, in issuing a land grant, acknowledged the Zuni as a land-holding people (Committee on Interior and Insular Affairs 1976:2). However, the Spanish practice for issuing indigenous land grants was at one league in each of the cardinal directions from the "central church", or four leagues total, just a fraction of ancestral lands (Cohen 1942). This practice has been attributed as a response to the Pueblo Revolt whereby the Spanish were punishing those who actively engaged in the Revolt (Minge 1995:43). For Zuni, the land grant amounted to just at 17,636 acres—just under 28 square miles—around Halona:wa, today the Zuni Pueblo (Williams 1986). This was the first step of enclosure (Curti et al. 2020).

In 1692, the Spanish reoccupied New Mexico. With their return, several villages were abandoned and *A:Shiwi* concentrated settlement in Halona:wa, becoming the first centralized tribal organization in the Puebloan Southwest (Eggan 1995:23). Puebloan communities were considered 'wards' or protected and yet part of the Spanish crown (Cohen 1942; Minge 1995:36-37). Spanish administration and policy would continue until 1821, followed by Mexican administration from 1821-1848 (Cleveland et al. 1995). In the transition from Spanish to Mexican administration, relatively little changed for Puebloan communities, and while granted 'citizenship' under Mexican administration, that did not necessarily translate to equality (Cohen 1942:384).

While *A:Shiwi* and other Puebloan communities experienced severe religious suppression, violence, and economic hardship at the hands of the Spanish, the Spanish colonists and subsequent Mexican administrations largely did not restrict Zuni movement across and activities on ancestral lands (Minge 1995:43). *A:shiwi* had largely retained recognition of their ancestral and familial boundaries, sovereignty and control over Zuni lands, and water rights to all water bodies on their lands by both colonial entities (Minge 1995:34; Cohen 1942:383; Hart 1995:73). Moreover, Zuni farming practices largely continued undisturbed. Undisturbed does not necessarily equate with unchanged. The Spanish introduced certain crops (including cilantro, watermelon, and peaches) that were incorporated into Zuni farming practices and livestock (burros, horses, and sheep) (Cleveland et al. 1995; Ford 1985:24-26). As the people now largely lived at Halona:wa (or the Zuni Pueblo), farming became focused around this area while livestock were grazed farther from the village across ancestral lands (Cleveland et al. 1995).

The American Project:

Then came the era of the American project (Curti et al. 2020). Here, the American project is defined as the assumed ‘goodness’ of the newly fledged American socio-cultural, political, and economic systems, which rationalized the expansion westward, underwriting the supposed Manifest Destiny and justifying the taking of indigenous lands for a shared vision or dream of nationhood based on the values of Anglo settlers and governance. While the Spanish and Mexican governments had largely not restricted Zuni lands, the act of land grants and enclosures laid the groundwork for the American project to restrict access to ancestral lands. This groundwork also provided a base for the American project to drastically alter the waterways.

In 1848, Mexico ceded New Mexico to the U.S. Government with the signing of the Treaty of Guadalupe Hidalgo. This included all Zuni lands—as well as other Puebloan lands—with an explicit recognition of the land rights of Puebloan communities (Cleveland et al. 1995; Committee on Interior and Insular Affairs 1976:2). The Treaty guaranteed citizenship and property rights—which were to be “inviolably respected”—of Mexicans in the lands taken by the U.S. Government, with the understanding that Puebloan communities had been recognized as citizens under the Mexican administration (Cohen 1942). Moreover, while the Treaty continued to treat indigenous people as “under the exclusive control of the government”, the Treaty also explicitly protected the land rights of Native Americans as “special care shall then be taken not to place its Indian occupants under the necessity of seeking new homes, by committing those invasions which the United States have solemnly obliged themselves to restrain…” (Treaty of Guadalupe Hidalgo, Article XI, 1848). As such, the text of the Treaty indicated that the U.S. government would continue much as the Spanish and then Mexican governments had with regards to Native Americans, and specifically Puebloan communities. Yet, this did not come to pass.

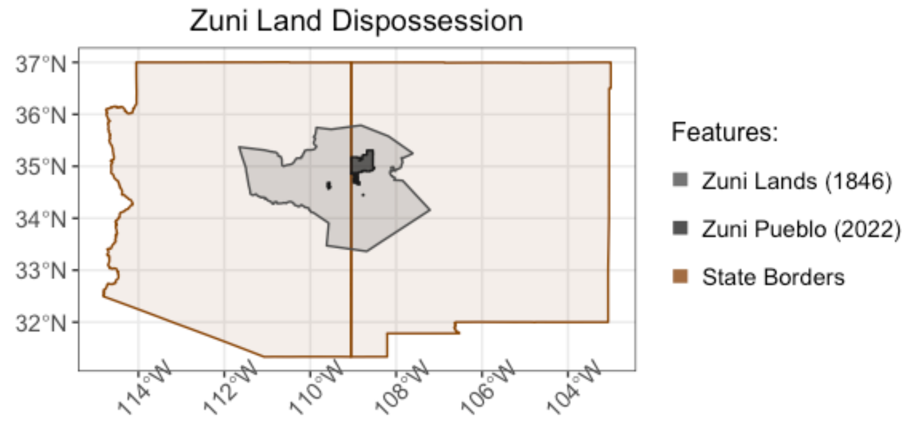
A:shiwi signed treaties with the newly arrived U.S. government in which they were guaranteed rights of self-governance and freedom of religion (Hart 1995:73-74). However, the U.S. failed to follow through on this guarantee and protect indigenous sovereignty. While the Treaty of Guadalupe Hidalgo had protected land rights, the Spanish land grant was far smaller than the generally acknowledged extent of Zuni lands and no official recognition by the Spanish government had been made of the tribe's rights to use of the lands (Jenkins 1995:55). That lack of official recognition and documentation from the Spanish period, coupled with the U.S. government's tendency to renege on treaties and spoken promises, meant that the U.S. began to take Zuni lands (Tyler 1995:69). In the years that followed, "bit by bit the U.S. government began to encroach on Zuni territory and to encourage others to do the same" (Hart 1995:74).

The Homestead Act of 1862 brought about the first round of this state-sanctioned enclosure. The Homestead Act granted Anglo settlers 160-acre homesteads, with the agreement that the homesteaders would live on and farm the land for at least five years (Cobourn et al. 2014; Powell 1879:25). Ironically, the principle of the Act was "to provide homes for poor men" and to "keep the plow in the hands of the owner" (Powell 1879:27; U.S. House of Representatives 2022). To provide these homes, lands were needed. Therefore, indigenous lands were taken to provide the homesteads, dispossessing indigenous people of lands for which they had no state-sanctioned title. The Homestead Act ultimately resulted in much of Zuni ancestral lands being titled to Anglo settlers (Cobourn et al. 2014).

The Zuni Reservation was finally established by Executive Order (E.O.) in 1877 (Cobourn et al. 2014). That same year, the Desert Land Act was passed, amending the Homestead Act to "promote the reclamation of arid and semi-arid public lands by making them available for privately-managed irrigation developments" (Landstrom 1954). As with the Homestead Act, any "citizen" could pay $1.25 for access to and use of the land, so long as they irrigate it (Landstrom 1954). Between the Homestead Act and Desert Land Act, encroachment of Anglo settlers into Zuni lands would prevent enlargement of the reservation. In 1883, an E.O. increased the boundaries of the reservation. However, the 1883 E.O. had included "the improper entry of lands within the Zuni Indian reservation in New Mexico, under the homestead laws and 'desert-land' act…", leading to an additional 1885 E.O. amending the 1883 E.O. to 'except and exclude from the addition made to said reservation… any and all lands which were at the date of said order settled upon and occupied in good faith under the public land laws of the United States' (U.S. President 1902; H.R. 1884:3). This cemented the state-sanctioned dispossession of Zuni lands for the benefit of Anglo settlers on which to live and farm.

To reiterate, Zuni ancestral territory encompassed over 15 million acres. Under Spanish and Mexican administration, the *A:shiwi* people largely retained access to these lands. However, with the American project, it was drastically restricted. From 1860-1876, with the passage of the Homestead Act and before the establishment of the reservation, Zuni lost 9 million acres, or 60% of their lands (Cobourn et al. 2014; Cleveland et al. 1995). From 1877 to 1918, the U.S. Government issued six E.O.s changing the area of the Zuni reservation, partly in response to growing Anglo settlement under the Homestead and Desert Land Acts. In 1918, the passage of an act prohibited any further changes in the size of reservations

(Committee on Interior and Insular Affairs 1976:2). This locked in the recognized extent of Zuni lands—as shown in Figure 2, the reservation was set at 340,000 acres, or just under 3% of the extent of ancestral lands (Cleveland et al. 1995). A similar history rippled across North America—on average, of tribes that have a state-recognized land base, tribal lands today are an estimated 2.6% of the extent of their ancestral lands (Farrell et al. 2021).



Data source:
Hart 1995; BIA; TIGER

Figure 2. Depiction of extent of Zuni lands dispossessed under the American Project.

In addition to the severe enclosures imposed by the American project, damage also occurred to Zuni agricultural practices and lifeways. Based in the American Project, U.S. policy was undergirded by the goal of "assimilation of Native Americans into the dominant European-American society" (Cleveland et al. 1995:2). So much of the American project was (and often continues to be) based on the idea that Anglo society, culture, technology, and land and water management is superior, so therefore they should teach indigenous people, and make them adopt, these 'better' ways (Cleveland et al. 1995). This idea and arrogance of Western practices as being 'better' prevented settlers and government agents "…from recognizing the benefits and productivity of Zuni agriculture and the importance that religious ceremonies had for stock control on fragile rangeland" (Ford 1985:149).

This was used to justify taking lands, damming rivers, and forcing changes in practices to make the lands more 'productive' (Cleveland et al. 1995). Ignoring warnings of Zuni and other Puebloan communities, the U.S. promoted an agricultural model to push on tribes based on Anglo agriculture—particularly cash crops and large-scale irrigation and damming. This included the suppression of cultural practices, many of which again are central to the Zuni relationship to the land, waters, creatures of the earth, and Earth Mother herself. One such colonial imposition was the creation of a school at Black Rock designed to persuade compliance of the Zuni people into Western cultural 'norms' coupled with the rejection of Zuni practices and traditional knowledge. At the school, Western methods of irrigation and cattle ranching were encouraged (Ford 1985:144-152; Ford 1985:152). As part of the effort to have Puebloan farmers adopt "more productive" agricultural practices, the General Allotment Act of 1887 was passed, under which communal lands on which Zunis had been farming were broken up into individual allotments or parcels. Each Zuni adult was granted 80 acres and heads of household 160 acres (later reduced to 5-10 acres) (Cobourn et al. 2014). The General Allotment Act broke up communal farming practices which were the basis of much of Zuni farming sustainability, bringing severe damages to the lands (Enote 1995; Ford 1985).

Among the most damaging impacts from U.S. agricultural policy were the changes—some permanent—to waterways. In 1882, the U.S. government sanctioned the building of the Atlantic and Pacific Railroad Company railroad, cutting across the head of the Zuni watershed (Cleveland et al. 1995). This area feeds the rivers and streams that supplied Zuni farming areas with water and rich alluvial soil (Ford 1985). The railroad facilitated rapid Anglo settlement on Zuni lands, implicitly encouraged by the U.S. government (Hart 1995:75). In addition to bringing settlers, the railroad also brought cattle and facilitated a booming timber industry by transporting lumber harvested in the Zuni Mountains (Cleveland et al. 1995). Tremendous deforestation occurred from the timber industry, leading to erosion (Cleveland et al. 1995; Ford 1985). In 1886, officers at Fort Wingate bought 40,000 acres of the newly deforested land next to the railroad for grazing cattle, rapidly overgrazing the land (Hart 1995:93,124; Cleveland et al. 1995). This combination of deforestation and overgrazing along the headwaters of the Zuni watershed led to erosion and silting of the waterways (Cleveland et al. 1995; Ford 1999:83).

Also in the Zuni Mountains, just a little south from the railroad, the Mormon colony of Ramah was settled in the 1870s to try to convert both the Zuni and Navajo peoples to their religion. Rio Pescado, a tributary to the Zuni River, was dammed by the Ramah Cattle Company for the missionary settlers in late 1890s (Wemytewa and Peters 2010; Zuni Land Claims 1990:107). This damaged the waterway, for after the dam was built, the Zuni River flow decreased (Wemytewa and Peters 2010:19):

> “That's another part of the blockage area where there used to be a stream right through Ramah on towards Pescado. Pescado had a lot of water… and that's where I used to go fishing with my son. But now, nothing… hardly any water coming through there unless it rains and it rains hard, which we haven't had for quite some time” (Representative 8).

The turn of the century brought a rapid increase in the damming and diversion of waterways. To reiterate, the Homestead Act of 1862 gave Anglo farmers indigenous lands (Cleveland et al. 1995). Yet, the homesteads acquired under the Act in these semi-arid lands kept failing under Anglo farming practices. Instead of questioning their farming methods, the U.S. Government only questioned how to better provide irrigation (Cobourn et al. 2014). John Wesley Powell, former director of the USGS and first Anglo explorer of the Colorado River through the Grand Canyon, wrote a report for Congress on the state of the lands that "are to be redeemed from excessive aridity" (Powell 1879: viii). He shared the vision that "the arid lands, so far as they can be redeemed by irrigation, will perennially yield bountiful crops, as the means for their redemption involves their constant fertilization" (Powell 1879: viii). These lands of which Powell spoke are some of the same lands on which Zuni, and other Puebloan, agriculture had flourished for generations upon generations. Powell obviously failed to witness the bountiful crops already in place on these lands, that still produced even in the late 1800s. Instead, the ontology that he espoused—this worldview of large-scale irrigation and fertilizer as necessary to transform the landscape into a fertile region—was largely accepted by Congress, leading ultimately to the Reclamation Act of 1902.

The Reclamation Act secured federal support for construction and maintenance of irrigation infrastructure including dams and reservoirs (Cobourn et al. 2014). Under this Act, the U.S. built irrigation districts in Zuni territory in the early 1900s, dramatically changing what was possible for Zuni farming practices (Figure 3) (Cleveland et al. 1995). These dams were built without consent or consultation of the Zuni people, with the paternalistic sense of 'improving' agricultural conditions (Curti et al. 2020). Rather than improving irrigation, the dams caused massive amounts of erosion, became heavily silted from deforestation in the Zuni

Mountains and overgrazing, diverted water from traditionally farmed fields, and rerouted water to soils not suited for growing crops (Ford 1985:2; Ford 1999:74). These dams have scarred the water and agricultural landscape (Ford 1985:150). As stated by an interviewee:

> “A lot of our rivers have been dammed, like Black Rock Dam and Ramah and Ojo Caliente...they were built back in the day in the 1920s, 1930s without any consultation. About 20-some years ago, they had drained the dam up here in Blackrock and they… made it a little deeper and then that's when the rain stopped coming… Our grandfathers always said not to block the waterways... But now…everything everywhere, it's all dry.” (Representative 6).

Black Rock Dam may be the most consequential and detrimental of them all. The Black Rock Irrigation Project—including Black Rock Dam and irrigation canals—was constructed as part of the Reclamation Act and authorized by Congress in 1903 (Cobourn et al. 2014; Ford 1999:82-83). The dam failed to meet the goal of improving farming conditions for multiple reasons. First, the project aimed to irrigate an area of land north of the dam (Ford 1985:102). This area—the Zuni Irrigation Project—was broken up into individual allotments that had been created under the General Allotment Act and was to be the main center of farming for Zuni (Ford 1999:82; Ford 1985:102). However, the Zuni Irrigation Project farmland is largely composed of compact clay soils. The Zuni people have always known which soils are needed for each crop (Pawluk 1995). Sand and loam soils are the best—sand is good for beans and squash, while loam found on alluvial fans or bottoms of drainages is highly fertile and good for corn. While clay soils will work for alfalfa or wheat, the soil is not suitable for corn (Ford

1999). Zuni corn has an elongated mesocotyl—i.e., the first shoot out of a seed that emerges aboveground—and a deep radical—or primary root. The corn seeds may be planted more deeply while still managing to emerge above the soil, therefore accessing deeper soil moisture, and the root system will tap into deeper water tables (Cleveland et al. 1995; Ford 1985). The clay soils of the Zuni Irrigation Project farmland are so compact that the mesocotyl cannot reach the surface (Ford 1985:102). In other words, this farmland is not suitable for traditional Zuni crops.

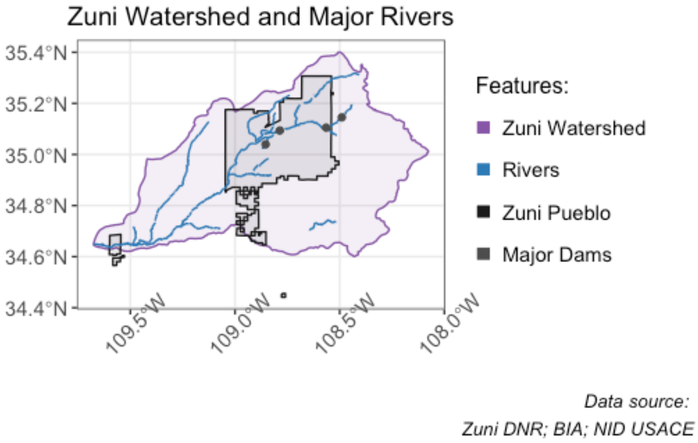


Figure 3. Zuni River watershed, rivers, and dams (Ramah, Trapped Rock, Black Rock, and Pescado).

Additionally, the dam harmed the waterways. Once the dam was in place, erosion began, and silt build up behind the dam from the deforestation in the head of the watershed (Cobourn et al. 2014; Cleveland et al. 1995; Ford 1999:83). As the dam was constructed without the consultation or consideration of the Zuni people, it was built on top of a sacred spring, the site of the Salt Mother. The workers desecrated the spring, burying it beneath layers of silt. These actions led to Salt Mother leaving for her new home at Zuni Salt Lake (Cobourn et al. 2014; Ford 1999:82-84). Furthermore, with the new farmland created by irrigation from the dam, that water was diverted from elsewhere. Therefore, water supply to the previous farming districts had begun to dry up. Zuni farmers were thus encouraged to farm this new land and abandon the other fields. Without Zuni cultivation and without the supply of water from the undammed waterways, these other fields became eroded (Ford 1999:84). In sum:

> "The man-made features that were supposed to help reserve water and all these other good things, were counterproductive because they have done the opposite since then. Now we have silt…the rich alluvial soils that have been known in this watershed area are slowly being covered over by silt…So I think we're the biggest—meaning humankind—the biggest challenge to water" (Representative 7).

As with impacts to agriculture, there were also significant impacts to livestock rearing, leading to overgrazing. Before the American project, sheep grazing had happened south and west of the reservation (Ford 1999:85). In 1935 a fence was built around the reservation that prevented Zuni herders from accessing previously utilized grazing lands (Cleveland et al. 1995; Hart 1995:77). Furthermore, grazing units were assigned to individuals (Cleveland et al. 1995). The U.S. also encouraged a shift into the cattle industry as source of income (Ford 1985:26). Before this time, Zunis had largely reared sheep. However, cattle-derived income quadrupled from 1944-1947. With more cattle grazing, and grazing activities now confined to much smaller areas, overgrazing became an issue and feed was needed (Ford 1999:85). Alfalfa had been introduced and encouraged following the completion of Black Rock Dam to "relieve pressure on Zuni grazing lands" that had been created with the enclosure of the lands (Cleveland et al. 1995; Ford 1985:27). Given that at alfalfa would grow in those clay soils of the Zuni Irrigation Project farmland, there was a shift from farming for crops for people to feed for livestock (Cleveland et al. 1995). Notably, the enclosure of lands has led not only to overgrazing but also the contamination of water, which also harms ceremonies and ceremonial practices:

> “I don't try and get [water] out of a dirt tank because there's cattle out there…you don't want to be using contaminated water. So we try to get the good water that's not contaminated, or hope it's not contaminated. Most of the water that we bring back… it's not for consumption. Not unless we know that it's from a spring and then we can drink it… most of the water that we bring back is used to wet down our pigments that we use in our ceremonies” (Representative 6).

In this way, both water scarcity and erosion and the degradation of lands at Zuni have been created through changes wrought by settler colonialism and governance (Curti et al. 2020). As Zuni is downstream of other water users, as Zuni lands have undergone multiple rounds of enclosure through dispossession, and as different land uses have been pushed upon the people, there have been enormous damages to agricultural practices and waterways.

3.4.2. The Flip Side of Dispossession: Accumulation

As described in Section 3.2 and 3.3.1, the dispossession of indigenous lands was intended to facilitate the possession and accumulation of those lands and resources for the settler-colonial project. Across North America, indigenous peoples through the violence and alienation imposed by colonial governance have been dispossessed of 99% of their ancestral lands (Farrell et al. 2021). As all extraction of coal, oil, and gas in North America was and is done on colonized lands, all emissions from these fossil fuels—which intensively contribute to global climate change—were only made possible by accumulation through Native land dispossession. Moreover, comparing the lands that were taken versus the small areas that were placed in reserve for indigenous peoples (reservations, in the U.S.), much oil and gas extraction has occurred on taken lands. For instance, a recent quantitative analysis found that reservations in North America are less likely to be situated over oil and gas reserves, whereby tribes were moved to or situated upon lands with less sub-surface oil and gas (Farrell et al. 2021). This indicates that, generally, the act of enclosure and taking of lands was necessary for access to much of the oil and gas that is extracted. In this way:

> "…the settler institutions such as those of containment, that inflicted environmental change in the past, are the same institutions that fostered carbon-intensive economic activities on Indigenous territories. That is, containment strategies, such as removal of Indigenous peoples to reservations or the forced adoption of corporate government structures, all facilitated extractive industries, deforestation and large-scale agriculture" (Whyte 2016:94).

A:shiwi are and have always been against extractive activities, including of fossil fuels (Ford 1985:84; Curti et al. 2020). Protecting the land from such activities has been a challenge in the face of enclosure and dispossession. For example, the U.S. government supported coal mining on the Zuni reservation without consent from 1908-1946 (Hart 1995:97). Labor for the mines, and transportation of the coal, was facilitated by the railroad industry (Telling 1953;

Ford 1999:74). Once the Zuni people were granted control over their lands, they blocked any form of mining (coal, oil, gas, and uranium):

> "We don't have any oil or natural gas extractions here. We did have exploratory uranium mines that happened back in the day… but our great grandfathers said no, you cannot harm Mother Earth. So they moved on. They went up towards Gallup and Church Rock, they found uranium, and then near Mount Taylor and then in the Grants area, or Laguna...now they're having huge number of cancer fatalities and patients now..." (Representative 6).

While Zuni has rejected extractive activities on lands recognized as theirs by the U.S. government, it has been more difficult to reject activities on ancestral lands which were accumulated and privatized through settler-colonialism. While there are no active oil and gas wells, coal or uranium mining, or other related infrastructure on Zuni reservation or trust lands, these industries and activities do occur directly outside of these lands. This has led to fights against extractive industries such as a proposed coal mine at Zuni Salt Lake (see Section 3.5). Today, there are many active oil and gas wells throughout Zuni ancestral lands, particularly in Arizona, and numerous plugged wells on Zuni ancestral lands in New Mexico (Arizona Oil and Gas Conservation Commission; NM OCD). Moreover, there are nearby generating stations including the Coronado Generating Station, just upriver of Zuni Heaven. The Zuni Pueblo is surrounded by, and exposed to, these polluting industrial activities, which have led to a host of health impacts:

> “Unfortunately, we have the [Coronado] Generating Station, which is east of St. John's, and it's in direct line here to Zuni, and all the emissions that go up in the air, once it rains, all that stuff falls: it falls here, and into the mesas, and we collect a lot of our medicine and other plants that we use in the mesas…
>
> A lot of the airborne pollutants have come here into the village, especially with the uranium mining that was going on in Gallup… We didn't know what cancer was, we'd never heard about cancer…and then the 80s-90s, the numbers started going up... and then we started having maybe 20 to 30 deaths a year…. when I was a kid, there was only like three or four deaths, and these were elders that had passed on. But now there's young people that are dying from cancer… Our village has been stricken with this cancer illness… It's just all that stuff that's in the air—air pollutants—I blame for the sickness that's here in our village and elsewhere…” (Representative 6).

Just as extractivism is possible because of the accumulation of lands, waters, and minerals through the dispossession of indigenous peoples’ territories, extraction can be performed here because the people and lands are able to be considered as ‘sacrifice zones’ under the U.S. colonial government which permits and privileges a siphoning of resources by developers and in the name of ‘progress’ and ‘development’ (Representative 4; Curti et al. 2020). Tribal communities have borne the brunt of energy development for a long time (Representative 5; Maldonado 2018; Whyte 2016). These places experiencing extraction are still part of Zuni ancestral lands, intimately tied to Zuni lifeways and identities, and this extraction threatens sacred sites (Representatives 1, 5, and 6). Zuni has joined other tribal communities in laboring to protect Bears Ears and Chaco Canyon from mining and drilling (Thompson 2015; Native American Rights Fund). One interviewee explains:

> “[These companies see this area] as sacrifice zones because they don't live here… The ancestral sites that are around us, surrounding these areas, are important to us still, today. They're not ruins. Archaeology will call them ruins, but we know them as the homes of our ancestors, and they're still there spiritually… For us, we've always been disenfranchised. We've always been taken advantage of because we have to live here.... for the companies that are out there, for workers that are out there, they can relocate to anywhere in the world without any remorse or any regret at most times. But for us, this is home. This will always be home for Zuni. And we can't move, even if we wanted to. Even though in our history, our ancestors have kind of moved on because of drought or other conditions. We always came back because this is where home is” (Representative 7).

Many interviewees brought up the extractivism being done by companies on lands around the reservation (Representatives 1, 2, 5, 6, and 7). Why does this happen? When I asked why this is, three interviewees in separate interviews answered with the single word: “greed” (Representatives 2, 5, and 6). They further explained they want the companies to:

> “…stop drilling or stop mining, but they won't. It’s all because of the mighty dollar… They don't really care about what's going on, they only care about how much revenue they're going to get from extracting oil and natural gas and coal…We can eliminate all

> that [the impacts] by proposing "no" on all these mines that's going on. But they won't do that… They just want that money…" (Representative 6).

> "Unfortunately, the old mighty dollar has prevented most corporations from being held accountable" (Representative 5).

> "I can come up with only one word…greed…By a corporation, by the Anglo society…it's just greed. Different corporations want to make so much money and not really caring…not realizing what they're doing to Mother Earth…" (Representative 2).

While the U.S. government may be tasked with regulating such activities, politicians are often beholden to corporate interests through lobbying, ideology, or a combination of both. Corporate accountability is then either not enforced according to laws and regulations, or laws and regulations themselves are changed to work for extractive industry interests. While politicians are tasked with listening to their constituents about climate impacts, "money talks" (Representative 5). And while "money talks", these actions are leading to and exacerbating climate change. What these companies, and much of dominant Western society, fail to understand is that:

> "…it kind of goes back to those prophecies of we're hurting Mother Earth… Mother Earth is crying, because we are abusing her. And she'll eventually come around and punish us all" (Representative 1).

It is this extraction through accumulation—these harms to Mother Earth—that has led to current states and intensities of climate change and changing hazards.

3.4.3. Changing Hazards: Climate Change at Zuni

If you ask a Western climate scientist "why is the Southwestern U.S. in drought?", they will likely talk about hotter temperatures and physical changes in circulation in the atmosphere. However, they generally will not talk about the actions or inactions of people that may have led to that dryness. It is rare that a Western scientist will immediately relate the ongoing effects of disrespect and exploitation of the earth—as described above—to that dryness, until pressed to explain the causes of those climatic changes. Once they do, Western science and Zuni perspectives seem to converge—understanding that the extraction of fossil fuels has led to changes in climate. However, from Western perspectives, it is due to the carbon dioxide (CO_2) stored in the fossil fuels, which then trap heat in the atmosphere, raising global temperatures in an *inanimate* climate. From Zuni perspectives, it is the disrespect by humans that has occurred through their extractive activities that is leading to punishment by an *animate* climate.

This worldview may hold lessons for Western science—and society more broadly—about cause and effect and respect. Core to Zuni practices and beliefs is the importance of praying for rain. As water is animate and embodied by ancestors, the prayers are a request for a blessing of moisture. While Zuni continues these rituals, however, there are other, external factors that are blocking that moisture from coming through. Given that humans are embedded in the larger animate environment, there is an inherent responsibility among all beings. When that responsibility is breached—such as between humans and the earth—then there are harms that come in turn. Just as drought can occur as a response to ritualistic failures, it can also occur to other inappropriate actions from society at large:

> "Our culture, we are devout in it, and we believe there is a connection to it and our prayers are being said. But because of what you said—the thirst in the atmosphere—the clouds aren't coming in as much as we would like them to be because of the carbon emissions. We're doing our part, but a lot of other factors that is preventing and prohibiting that presence of clouds, of moisture in this area, because of the carbon…" (Representative 7).

These other factors include extractivism. When asked about those other factors, the interviewee described what is happening at Chaco Canyon:

> "Ancestral sites have a life—they're not ruins—and they built those places because of something significant. One of the Chaco conversations that we had… the fracking, extraction of CO_2... when you're extracting, you're creating a void within Mother Earth. That void could collapse, it could make it unstable, and our ancestors knew of monsters… underneath our Mother Earth. And at times of us disrespecting the earth, they could come out. And you could interpret monsters as Godzilla or King Kong. However, it could be something as simple as CO_2, it could be carbon, it could be all these fossil fuels that are out there… It is prophesized that things that we have—our possessions—could come back and eat at us in a way if we're not respectful towards it… They [the ancestors] protected those areas, like Chaco, and they were the

> gatekeepers of keeping the bad things down. Keeping things in check, to make it almost…inert, in a way, to where it's not affecting us" (Representative 7).

These other factors amount to the disrespect of and exploitation of 'resources' of the earth. As described in the previous section, that accumulation of lands and mineral resources facilitated extraction of large quantities of oil, gas, and coal. As this occurred through the privatization of land—which, again, goes against both Zuni and many other indigenous worldviews—that privatization also aimed to dispossess Earth Mother of her own lands, waters, and minerals. It is the large-scale extraction and combustion of coal, oil, and gas and deforestation that has led to climate change. This extraction moreover has largely occurred through Western institutions. Turning again to Kyle Powys Whyte's definition of settler colonialism, it may be understood as how "one society inflicts burdensome anthropogenic environmental change on another society…" (Whyte 2016:91). As climate change is created by the dispossession of lands and burning of fossil fuels extracted from those lands, whereby the impacts of climate change are felt by all, especially those who have been affected by dispossession, then climate change presents as a "colonial déjà vu" (Whyte 2016:91). Therefore, Whyte 2016 offers:

> "…'Anthropogenic climate change' or 'the Anthropocene'… are not precise enough terms for many Indigenous peoples, because they sound like all humans are implicated in and affected by colonialism, capitalism and industrialization in the same ways" (Whyte 2017b:159).

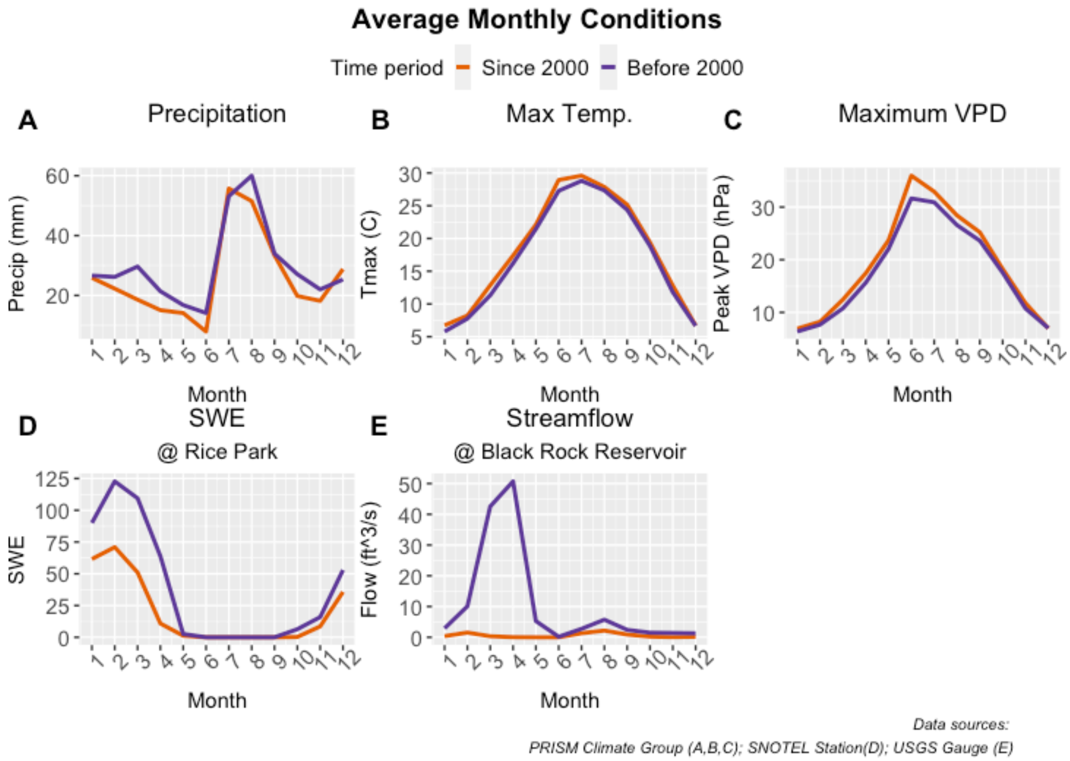
For these reasons, these extractive and exploitive actions cannot be separated from the climatic changes that have since occurred, and thus 'anthropogenic climate change' may be better referred to as 'colonial and industrial climate change' (Curti et al. 2020). Significant changes have occurred. Climate change from the extractive activities has led to drought conditions. Drought has been the predominant challenge because it has affected almost everything else, including many aspects of the climatological cycles of these lands (Representative 3; Curti et al. 2020). The broader Southwestern U.S., encompassing much of Zuni ancestral lands, is a semi-arid environment, with cold winters bringing snow and hot summers bringing rain (Garfin et al. 2013:3; Crimmins et al. 2013). Winter snowpack is an important hydrologic variable for the region, as water stored in the snowpack melts in spring and provides moisture during the otherwise dry spring months. Snowmelt feeds the streams and rivers throughout the region—this snowmelt and associated runoff peaks in March-April. This provides crucial moisture for vegetation, which begins to grow in late winter/early spring, and peaks in mid-late summer (Garfin et al. 2013). Snowmelt seeps into the soils, nourishing the plants which then provide feed for animals (Representative 6). Early summer, from May to early July, is generally hot and dry but interrupted by the arrival of the North American Monsoon (NAM). The rains from the NAM cool the region and can deliver most of its summer moisture in just a few storms (BIA 2012:5).

Zuni—and the larger Southwestern U.S.—has been in a megadrought since 2000 as defined by soil moisture anomalies in Western science analyses (Williams, Cook, and Smerdon 2022; Williams et al. 2020). This megadrought is characterized by reduced precipitation and hot temperatures which, together, have reduced water availability. These drought conditions have been observed by interviewees—including both traditional knowledge holders and practitioners of Western science. Furthermore, Western scientific data can provide context to these observations (Figure 4). Since 2001, most of the years have been dry (Representative 3; figure 4a).

The winter season has notably changed, with less snow, higher temperatures, leading to less spring runoff. Most interviewees spoke about having less snow (Representatives 2, 3, 4, 5, and 8). Decades ago, there was much deeper snow (3-6 feet deep), so deep that moving around the village or driving was difficult (Representatives 4, 5, and 8). Now, there is much less snow, particularly since 2000 (figure 4d; Representatives 2 and 3). This is linked in part to reduced winter precipitation (Representative 3; Figure 4a). Winters also have been much warmer—and more variable in temperature—in recent years, reducing the snowpack (Figure 4b; Representative 6). As runoff from snowmelt feeds streams and rivers, a reduced snowpack leads to a change in streamflow. There used to be a lot of snow until March or April, and then the river would flow from the runoff (Representatives 2 and 6). Having a smaller winter snowpack leads to less spring runoff from the Zuni Mountains (Representative 3). As this runoff feeds the streams, river, and lakes, these surface water bodies are drier (figure 4e; Representative 3).

Summer rains again cool the landscape and bring much needed moisture. The monsoonal season used to bring a lot of rain—it would rain almost every day (Representative 5). But in recent years, the monsoonal rains have reduced and shifted in timing (Figure 4a; Representative 4). Several interviewees reported that the rains are now falling in a shorter period of time, so that when it rains, it is a lot of rain all at once (Representatives 1, 3, and 5). The soil is unable to absorb the rain when it falls in a deluge, exacerbating drought conditions while simultaneously leading to flooding risk, as experienced in 2021 (Representative 3).

This combination of fewer rain days and increased temperatures has led to high evaporative demand in the air (Vapor Pressure Deficit, or VPD) (figure 4c), so there is less moisture in the ground for vegetation to grow (Representatives 3 and 6). While soil moisture varies across the Pueblo, overall, the soils have been drier (Representative 3). With hotter temperatures and lower soil moisture—especially extending to earlier in spring and into fall—there is less of a defined fire season, where fire season can now extend year-round (Representative 1). This has also impacted vegetation across the landscape. Various plants and seeds are harvested across the landscape for use in ceremony and as traditional foods (Ford 1999:82; Representatives 2 and 5). Yet, various plants that used to be found—such as the yucca plant and certain cacti that produced fruits, and plants used for religious ceremonies and medicine—aren't being found (Representatives 2 and 5).



Data sources:
PRISM Climate Group (A,B,C); SNOTEL Station(D); USGS Gauge (E)

Figure 4. Changes in key meteorological and hydrologic variables. Change in average monthly conditions, comparing average conditions before 1980 (purple) and after 2000 (orange) for (a) precipitation, (b) maximum monthly temperature, (c) maximum monthly VPD, (d) snow water equivalent, and (e) streamflow.

3.5. Zuni today

The compounding effects of colonial and industrial-caused climate change have resulted in significant impacts for Zuni (Figure 5). To put this in terms of the IPCC's framework for climate risk, settler colonialism largely ballooned two of those components—exposure and vulnerability (Section 3.4.1). Human-caused climate change, a direct consequence of that colonialism, then increased the frequency and intensity of the hazards (Sections 3.4.2 and 3.4.3). Zuni today is therefore faced with increased climate risk—due to increased exposure, vulnerability, and hazards—due to these compounding changes.

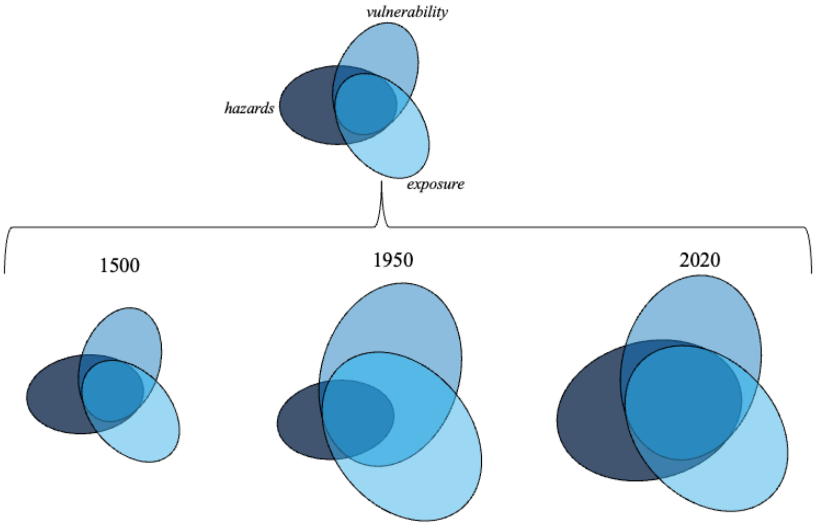


Figure 5: Climate risk for Zuni. Top figure represents the IPCC WGII AR5 conceptual framework for climate risk (IPCC 2014). The bottom row represents changing components of climate risk—exposure, vulnerability, and hazards—for Zuni over time. Circles at the center of the Venn diagram represent the total climate risk.

The ongoing Southwestern megadrought is occurring against the backdrop of dispossession and enclosure, altering of waterways, and adoption of certain technologies and practices, such as livestock rearing and water piping infrastructure. Climate impacts today are particularly outsized for the Zuni people because of the exposure and vulnerability created by this history. Yet, the adoption of certain specific technologies and infrastructures have simultaneously lessened that vulnerability. This paints a complicated picture—different aspects of the modern context have differentially shaped Zuni vulnerability to drought, both exacerbating and tempering impacts from the megadrought. One interviewee explained this nuance in responding to the megadrought study:

> "If you just look at the availability of water moisture, and then try to compare that to other times and historical data, that's one way that you could characterize the drought and say, Yeah, this is the driest it's ever been… But that doesn't speak to how big the effects are on people or other organisms and ecosystems. So for me, how bad a drought is, that's the main test: what are the effects, and how are those effects felt and trigger human responses and changes that they may or may not have ever dealt with before? …Here at Zuni, it can't be anywhere near the worst we've ever had. Because in history, Zunis have experienced droughts so bad that they've had to leave these lands and they've had to go to other places where there was more water, enough to survive… Even if it has been characterized as a megadrought from a supply side, here at Zuni, we're not experiencing that from an effect side. A lot of that does have to do with just the modern infrastructure…that can at least get you through a drought…" (Representative 3).

> "For us, droughts and floods weren't really that new in a historical context… but definitely in a modern context of living with new systems and lifestyles and urbanization and growth…Because even though we have some traditions and perspectives that can help influence those, and maybe mitigate some of those, effects, that still doesn't take away

> from all the modern ways that Zuni is still dealing with that present new challenges to try to balance along with the traditional historical context" (Representative 3).

This nuance acknowledges that certain infrastructure adopted by the tribe have lessened their vulnerability in terms of access to drinking water, for instance. Moreover, it represents a complicated picture of adoption of technologies, with varying degrees of consent by the people. Yet, core aspects of Zuni practices—including holistic measures of health and intergenerational knowledge transfer linked to agriculture and the presence of flowing water—have become more vulnerable and exposed. These have occurred via imposed changes by Western institutions which negatively affects Zuni. These changes threaten the values and beliefs, damage the lands and waters, harm the ability to conduct important socio-cultural practices. Throughout the interviews, several threads emerged as negative impacts that carry into today—less water, impacts on agriculture, impacts on livestock, loss of intergenerational knowledge and language, and economic disinvestment.

Surface water—streams, rivers, and lakes—are drying or already dry due to the compounding effects of increased diversions, increased groundwater demand which feeds the springs and lakes, a smaller snowpack and associated smaller spring runoff, and hotter temperatures leading to increased evaporation (Representative 3). Lakes are largely supplied by springs and snowmelt, while the rivers are largely fed by snowmelt, so if there is increased groundwater pumping or a decreased snowpack, those combined factors will lead to less water. In recent years, the Zuni River has been a dry riverbed (Representatives 5 and 6). Moreover, for the past few decades, the reservoirs which are used for irrigation and recreation have been largely dry (Representatives 3 and 4). While scattered summer storms have temporarily supplied water to the river and lakes, when this water evaporates, it is uncertain when they will be recharged again (Representative 3).

Water scarcity has thus become a problem for Zuni. This has largely been created from contested water rights with communities outside of the Zuni reservation, recently exacerbated by climate change. As Zuni is downstream from other communities, increased diversions upstream have limited water availability in the Zuni Pueblo (Representative 4). Moreover, the municipal water supply originally was from wells in an aquifer also used by other communities. With ongoing adjudication over water rights, and depleting water supply in the aquifer, the tribe began to source water for the municipal supply from another aquifer (Representative 3). Due to these ongoing challenges, around the same time as the onset of the megadrought, in 2000, the tribe made the decision to get water for the municipal water supply from the aquifer that feeds Ojo Caliente lake:

> "The tribe knew that going in, they didn't have much choice but to develop that source as a water supply for the community…that was the most reliable source of water... They didn't have any idea that climate change or drought might compound those effects. So, Ojo Caliente has been dry most of the past few years… Ojo Caliente lake going dry, is probably the single piece, among all the lakes and other drying effects, that people would point to and say, Yeah, this is something new in our lifetime that we've never seen" (Representative 3).

These surface water features—streams, lakes, and ponds—hold significant religious and cultural importance for the Zuni. They are sacred, and water is one of the most revered aspects of the landscape (Representatives 5 and 6). As Zuni culture, language, and knowledge is entangled in waterways, agriculture, and the lands, maintaining one is necessary for maintaining the other. Language is tied to the waterways—when the river does not flow, the language and storytelling of the river keeps it alive (Wemytewa and Peters 2010:20). Prayers and songs asking for blessings of moisture are in the *A:shiwi* language, as are prophecies and oral histories. If language is forgotten, asked one interviewee, how can you continue your prayers (Representative 5)? As such, threats to the *A:shiwi* language are entwined with the climate impacts. Across North American, many indigenous languages are at risk: linguists estimate that between 300-500 indigenous languages were spoken before Anglo settler-colonialism, and while 200 of those languages are still alive today, just over 30 are children's first language (McCarty et al. 2006). This is similarly a concern for Zuni. However, while fewer people speak it today, it is still actively used by *A:shiwi* people. In 2000, 73% of people at the Zuni Pueblo used their language at home (from Cobourn et al. 2014). However, in 2018, in the Head Start program at Zuni—which provides educational and developmental support for children of low incomes families—they had noted a decline in the *A:shiwi* language being spoken both by students and parents (Representative 7; Head Start 2018).

Other forms of intergenerational loss—tied to language and waters—are similarly at risk. Water has become commoditized: when it comes out of a faucet, when you pay for it, it is harder to see it as animate (Representatives 2, 6, and 7). As youth today do not see the Zuni River flowing, and because it is language that keeps the river alive spiritually, there is a growing disconnect or an intergenerational gap in the understanding of water as animate:

> “The experience of water can only be experienced when water is there. Since our kids have never seen a river flowing...that's something that I think is really disturbing… Spiritually, it's flowing. But I think for some of our community members, they really need to see that river flowing, [to] really understand that relationship” (Representative 7).

> “Our kids, now, they go in and turn on the faucet and that's where water comes out. That wasn't so... we had underground wells, and around the village where our grandmothers would go and collect water and carry a pot of water on their heads...and bring it back to the house. And you know that's when they treated the water with respect. Now they turn on the faucet and then it's like an endless commodity. Which it ain't, you know. If our watershed goes dry, that's the end of us, we go thirsty. And see, our kids don't really understand that...” (Representative 6).

The impacts to water have also led to challenges for different water use sectors. Zuni uses both groundwater for domestic and municipal use and surface water for farming and ranching (Zuni Division of Natural Resources 2001). Drought risk is classified as highest for the water use sectors that depend on surface water as it is the first to dry up in times of drought (Zuni Division of Natural Resources 2001). As there are many sectors that depend on water, when a drought occurs, impacts are assessed for each sector and decisions may have to be made based on water use priorities (Zuni Division of Natural Resources 2001; Representatives 3 and 5).

This has further impacted agriculture. While damages to waterways and enclosure of lands means that fewer people today practice Zuni agricultural techniques, for those who do, they rely on snowmelt from the winter snowpack and arrival of the monsoonal rains. If the snowpack is low or the monsoonal rains do not arrive, without that moisture, “you’re on the losing end” because if you plant and that moisture does not come, “there goes your seeds” (Representative 5). Having less moisture therefore has changed how people approach farming as it changes what can be grown (Representative 4). Moreover, because of drought conditions, there is less forage and water available in the Zuni Mountains for deer and elk to feed on, so they come into the village and feed on what crops people do grow (Representative 5). Moreover, when knowledge isn’t transferred across generations, this impacts agriculture. While efforts are ongoing to revitalize traditional agriculture, in these efforts, people:

> “…want to mimic…they want to do it the way their great-grandparents used to do but they don't really have the knowledge of how they did it to where it will last… it's not the actual experience. It's something that somebody remembered them telling them how to do it…” (Representative 2).

The compounding effects of drought conditions, land enclosures, damming of waterways, and loss of intergenerational knowledge has affected Zuni agriculture. Because of this, many people have largely moved away from eating what you grow to eating what you buy (Representatives 3, 5, and 7):

> “We're considered a food desert by USDA. And it's not supposed to be. This is why we're here, because this is a food paradise, an oasis, from our ancestors. And that table was shifted. Now…you can purchase Hot Cheetos with an EBT card. And I've seen that with kids, how they treat food... It's like, I saw this one group of kids come in, toss their Hot Cheetos on the counter... tossing down their EBT card, scanned it, and knew the code... Like that was just a normal day for them, and then I'll say, wait a minute, isn't that supposed to be for more like actual food-food—not Hot Cheetos—for natural, nutritious food?” (Representative 7).

As described in Section 3.3.2, because of the changes to agricultural practices through altering waterways, Zuni have largely moved from agriculture to livestock rearing. Today, livestock rearing—primarily sheep and cattle—occurs on most of Zuni reservation lands (BIA IRMP 2012:43). There have been significant impacts to livestock and rangelands through the compounding effects of land enclosure leading to overgrazing, the Western push for rearing cattle in a cash economy, and increased temperatures with less moisture leading to higher evaporation, thereby drying or desiccating rangeland forage. This means that between overgrazing and drought conditions, there is less forage (Representatives 1 and 5). These combined effects may lead to needing to change the grazing capacity of each range unit. As a livestock owner, you therefore face a choice between “either overgraze and damage Mother Earth, or you sell off your livestock” (Representative 5).

Again, while livestock rearing—particularly cattle—is not per-se traditionally Zuni, it has become an important part of the Zuni economy. In 2017, $1.23 million worth of livestock products were sold at Pueblo of Zuni (USDA 2019:46). Faced with the decision to overgraze or sell livestock, selling livestock may not be easy for some people due to economic constraints. Moreover, with less available forage, livestock owners increasingly have to grow feed or purchase feed, which is expensive (Representative 5). The Four Corners region has some of the highest poverty rates in Arizona and New Mexico; specifically, Native Americans are largely concentrated in the highest poverty counties (Wilder et al. 2016). Moreover, while the median income in 2020 in the U.S. was ~$65,000 and in New Mexico was ~$51,000, in McKinley and Cibola Counties, median household income was ~$36,000 and ~$45,000, respectively (U.S. Census 2020). Poverty—both individual and institutional—reverberates through communities, seen in terms of finances, infrastructure, water rights, and political power, and tribal communities especially have experienced this (Representative 3). Therefore, there are difficulties in being 'environmentally friendly' or practicing agriculture because the systems are now set up in a way that you need funds to do so (Representatives 3 and 5). Therefore, economic disinvestment presents a major challenge when it comes to practicing traditional relationship to environment.

While much has changed for Zuni, the mindsets, values, and beliefs that are core to Zuni have largely remained constant (Representative 3; Folger 2020). As explained in Section 3.1, rather than forecasting hazards to inform adaptation strategies, the Zuni approach to adaptation looks to lessons from the past. The people recognize that climate change will bring more of the same—while droughts or flooding may be more intense, they are still phenomenon that their ancestors have experienced (Representative 3). Faced with these challenges, despite threats to language and intergenerational knowledge transfer, the Zuni people have remained steadfast in listening to lessons from their ancestors to guide actions today and have facilitated continued knowledge transfer. This includes treating water with respect and not wasting it, continuing to use drought-tolerant Zuni seeds, and continuing prayers and ceremonies (Representatives 3, 5, and 7). Zuni religious leaders and traditional knowledge holders fulfill the role of 'facilitator' to understand these relationships and to keep important cultural practices alive across generations (Representative 7). It is this continued strength of values and prayers—and the work being done by knowledge holders who have them—that have allowed the people resilience in working through the harms that have been created and resisting new harms. These are the actions that protect.

3.6. Knowledge & Actions That Protect

In recognizing their responsibility to Earth Mother, *A:shiwi* have actively fought to protect the land and waterways. This includes reclaiming lands, securing water rights, and fighting mining and drilling.

From the establishment of the reservation in 1877, it took around 100 years before any efforts would be made by the U.S. Government to address dispossession (Hart 1995:76; Tyler 1995:69). With the recognition that significant land dispossession occurred under the American project, in 1946, the U.S. Government created the Indian Claims Commission to address outstanding land claims that indigenous people had against the federal government due to the taking of land in the preceding century (Committee on Interior and Insular Affairs 1976:3). However, tribes were given just five years to file claims. To notify tribal communities of the Commission and the five-year window, letters were sent to the U.S. government-recognized heads of tribes. As such, a single letter was sent to the Zuni Governor in English, and no other outreach was done. As the BIA did much of the administrative work at Zuni at the time, as there was no constitutional government formed yet, BIA facilitated the response to the letter. It has been documented that they drafted a letter which stated that Zunis had no claims to make to the Commission and had the Governor sign it without his understanding what the letter stated (Committee on Interior and Insular Affairs 1976:3-4; Hart 1995:80-81).

Following this failure by the federal government to rectify past harms, the Zuni tribe went through a lengthy process of recording land claims and damage to trust lands to pursue litigation. The litigation ultimately went to settlement, and through the settlement itself and through funds won through settlement, the Zuni reclaimed two sacred sites outside of the borders of the reservation—Zuni Salt Lake and Zuni Heaven. This led to a congressional act that was passed in 1978 allowing for Zuni to pursue land claims (Hart 1995:82). There were two parts to the act—the U.S. government would purchase Salt Lake and hold it in trust for the Zuni tribe, and the act provided an avenue for further suits for compensation for lands taken without payment from 1846-1946 (Hart 1995:83). The tribe had also been pursuing a land claim for *Kolhu/wala:wa*, or Zuni Heaven. In 1984, an Act was passed which granted some of the lands outright, thereby establishing the Zuni Heaven reservation, and provided an avenue for the tribe to purchase additional lands (Hart 1995:202; Zuni Indian Tribe Water Rights Settlement Act 2003). Following this, the tribe also reached settlement for damage to trust lands. In 1990, settling a suit against the U.S. government in the Court of Claims, compensation was agreed to at $25 million, or $1.69 per acre (Hart 1995:87)[4]. This figure was "lowballing" as compensation had been made based on the estimated "worth" of the land at the time that it was taken by the U.S. government (Hart 1995; Representative 7). But they

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[4] Note that $6 million of this went to attorney fees and paying for expert witnesses (Hart 1995:87).

made do with it. This settlement also led to the Zuni Conservation Act of 1990. Funds were used to purchase lands near Zuni Heaven and to set up a sustainable development plan, which would lead to their conservation program (Hart 1995:100). All lands returned to the people in trust status and funds won through the settlements were used to protect the land, allow for Zuni religious practices to proceed, purchase additional lands to protect, and set up programs to restore ecosystem health.

The tribe additionally has pursued water rights. The tribe sought to restore streamflow through Zuni Heaven as well as land just upstream along the Little Colorado River (Hart 1995). Zuni Heaven exists at the confluence of Little Colorado River and Zuni River. In the early 1900s the springs feeding this area were drying up with increased diversions and drought (Wemytewa and Peters 2010; Bemis 2014). By 1984, when the tribe had acquired Zuni Heaven, water rights in the basin were under adjudication. Therefore, Zunis entered the adjudication process which was ultimately settled under the Zuni Indian Tribe Water Rights Settlement Act of 2003. The Settlement included actions to resolve the water rights claim at Zuni Heaven and assist in acquiring surface water rights and access to groundwater to allow for wetland restoration. It additionally provided the ability for the federal government to take additional lands along the river into trust status for the tribe as required for the wetland restoration (Water Rights Settlement Act 2003). Part of what the Settlement won was getting groundwater pumping restrictions on two generating stations operated by Arizona-based utilities—Salt River Project's Coronado Generating Station[5] and Tucson Electric Power Company's Springerville Generating Station— upstream of Zuni Heaven to restore

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[5] The Coronado Generating Station, likely named after the Spanish Conquistador Coronado (see Section 3.4.1), is owned by the Salt River Project.

streamflow in the Little Colorado River through Zuni Heaven. They also won a “trust corridor” along the river which allows for restoration activities (Bemis 2014).

In addition to securing ancestral lands and restoring waterways, the Zuni people and government have been interfacing with corporations that aim to extract fossil fuels on or near tribal lands (Representative 5). The proposed Fence Lake Coal mine is the most recent of such fights. Salt River Project wanted to mine for coal just east of Zuni Salt Lake as the company was searching for a new source of coal for the Coronado Generating Station (Shively 2003; BLM Draft EIS 1990). The coal would have been shipped via railroad to the generating station, which would have crossed Zuni pilgrimage routes, sacred sites, and graves (LaDuke 2002; BLM Draft EIS 1990). The company purchased lands in the area, did test mines, and then, determining it would work for their generating station, submitted a proposal and secured a permit from the State of New Mexico in 1986 for a test mine to feed a test burn (Rodgers 1994; BLM Draft EIS 1990). They acquired the full permit to operate the mine a decade later, in 1996 (LaDuke 2002). The project would have generated 52 million tons of coal over its lifespan (BLM Draft EIS 1990). It should be noted that Richard Hart—the anthropologist who had worked with *A:shiwi* on the land claims in previous years—acted as an expert witness for Salt River Project (Hart 2011).

The tribe fought this mine. The mine threatened the groundwater feeding the Zuni Salt Lake, as it required large quantities of water to settle coal ash. By extracting water at the mine, ten miles east of the lake, it threatened the springs from the same groundwater system that feed the lake. These activities occurred against the backdrop of the damages that had occurred due to the Black Rock Dam which had led to the Salt Mother leaving the Pueblo for Salt Lake.

Salt Mother was yet again threatened by human activities. As Edward Wemytewa shared in a press release:

> "That should be a message as to why we should protect the water resources…When Zuni Salt Woman got angry and left, she taught us a lesson. We should learn from that. We can't afford to lose any of the water. When it's gone, it's gone" (Edward Wemytewa, in LaDuke 2002).

While Salt River Project attempted to buy off the tribe, Zuni led efforts to stop the mining proposal, enacting their responsibility to protect the lake and the ancestral sites (Representatives 3 and 4; LaDuke 2002). They worked in a coalition with other Southwestern Tribes and environmental groups, and resisted the project in court, through legislation, and through ceremony and ritual (LaDuke 2002; Bemis 2014). Zuni representatives testified in front of the U.S. Senate to argue for protection of Salt Lake and lobbied decision-makers and ultimately persuaded two senators and three congressional representatives to write to the Department of the Interior to block the mine, even though one of the senators was pro-fossil energy (LaDuke 2002; Indianz 2003; Representative 5). The pressure placed on the company by the Zuni tribe and their allies ultimately led to Salt River Project withdrawing the mine plan in 2003 (Bemis 2014). Instead, the company then pursued a contract with an existing low-sulfur coal mine in Wyoming (Shively 2003).

It was an impressive feat preventing the coal mine. People wondered "how could a small tribe do that to a big corporation?" (Representative 5). It was by returning to Zuni prayers, to make it so that no harm would come to Salt Mother (Shively 2003; Representative 5). Since then, the Zuni people have fought other proposals for leasing just outside of the Salt Lake area, proposed groundwater diversions for industrial agriculture, and have been successful in defeating these proposals on land outside of the trust area because of potential damages to water in trust lands (Bemis 2014). This ongoing commitment has protected Salt Lake and the surrounding area and can only be improved by opportunities to acquire more surrounding lands (Bemis 2014).

The land claims, water rights claims, and resistance against coal mining were done within Western institutions. While litigation can be a useful tool, it is insufficient on its own. These actions were guided by, pursued within, and made possible by Zuni knowledge that protects. The deep-time and deep-space knowledge held by the Zuni people, entwined in their prayers and prophecies, centers the long view of lessons from past harms and need to prioritize responsibility in relationships to the earth over any sort of quick monetary gain. This was seen with the fight against the Fence Lake Coal mine—there had already been irreversible harms from the Black Rock Dam when Salt Mother left for Salt Lake. Having lived through such harms guided the people to ensure that no such disrespect would happen again. That set the stage for the fight against the coal mine:

> “Salt Mother moved away from Zuni to its current home at Salt Lake because of the Zuni's actions or non-actions with respect to her and the environment… Zunis have that mythological, historical perspective of knowing that humans and Zunis are not perfect, that they can make mistakes and do things that have consequences on the world around them, that then could come back and affect them, as well. And to atone

> for that, or make up for that, there's always the religion and praying and sacrificing…to help make up for that, help balance things out” (Representative 3).

> “How can you clean up what humans have messed up as far as Mother Earth? … Once you mess with the Earth, you can't really clean it up, unless you implement something that's derived from Mother Earth...” (Representative 2).

This understanding that you cannot undo harms against the earth once they have occurred leads to a commitment to stopping them from occurring again. The act of practicing cultural beliefs as resistance against such extractive projects is a form of activism, as it continues Zuni knowledge and perspectives and keeps centered the responsibility or obligation humans have to the earth (Representative 7).

Layered Protections—Knowledge and Actions that Protect

In doing the interviews, I struggled to wrap my mind around how engaging with Western institutions such as the U.S. Court of Claims or filing lawsuits can occur alongside practicing Zuni traditional knowledge. Much of my thought process it turns out was overly pedantic, as I attempted to ascribe some great meaning to it, when in fact engaging with Western institutions has become necessary to protect Zuni lands, waters, and lifeways. As explained to me:

> “We live in two worlds. We live in our cultural world and then we live in the non-cultural world—meaning the white man's world, and then the Indian world. And we have to find

> that equal balance one way or another… if we're heavily weighing on one side, one culture is more heavier than the other. And we tend to not balance that equally. And a lot of it, it just involves that misunderstanding, or that lack of proper communications to understand these various changes that are happening" (Representative 1).

What does this balance look like in practice? An interviewee offered a way to think about the balance between socio-religious practices and Western policy and law—as engaging in layered protections. The laws and policies in the U.S. are generally written to favor extractive industries—particularly when it comes to fossil fuel reserves and occupied lands (Representative 4). Therefore, when extractivism threatens lands and waterways outside of reservations—which are still ancestral indigenous lands—the lands and waters must be protected. Leveraging different tools to protect against these actions is sometimes necessary. These tools are used as a supplementary layer of protection. This provides space for religious leaders and knowledge holders to continue their prayers and ceremonies unencumbered by engaging in such institutions, while others engage in the Western institutions.

In this view, there are three layers: spiritual/religious, policy and research, advocacy (Representative 4). The first and most important layer is socio-religious and based in the traditional Zuni practices, including prayers, ceremonies, and songs. It is this layer that has existed for countless generations and developed and evolved along with the ancestral lands and waters, and it is this layer that will long outlive any Western institutions. The second layer is based in research and knowledge, including conducting or otherwise engaging with Western science and participating in testimony. This layer is fraught, particularly as it is where Zuni knowledge systems and Western science are brought together, and sometimes clash as Zuni knowledge is subjected to validation or approval from Western science (Tsosie 2017). There is tension particularly regarding who is considered as an ‘expert witness’ in testimony—the person with many publications attributed to their name, or the person who holds the knowledge of countless generations of the land (Representative 7)? While there should be parity between these forms of knowledge, there are still outstanding efforts striving to reach such parity (Representatives 4 and 7). The third is advocacy through the legislative processes, fighting extractive projects through the legislative realm to protect the lands and waters. This includes the use of strategic litigation to acquire water rights for wetland restoration or resist coal mining, such as described in this section (Representative 3).

Within these layered approaches, there are large tensions. Engaging in strategic litigation, legislative processes, and policy and research may only be done when it is in line with Zuni sensibilities, knowledge, and perspectives—when it is done to protect and uphold that relationship of responsibility with the earth. These last two layers are only useful insofar as they support or provide space for the first to exist—the prayers and ceremonies. Thus, any potential future litigation would have to satisfy that core consideration.

3.7. Appropriateness of Climate Litigation

What could recourse look like for the harms experienced by Zuni, particularly with regard to climate change? Is there a way to hold accountable those who have most disrespected and harmed Earth Mother that fits within Zuni sensibilities and worldviews? As described in the previous section, litigation can sometimes be leveraged in a way to support the aims of the Zuni. Indeed, other tribal communities have pursued strategic litigation to protect ecological health or pursue water rights (Whyte 2016:92; Shearer 2011).

One such type of litigation that has increasingly been pursued is climate litigation. Climate litigation is based in principles of climate justice, specifically distributional and corrective justice, as it is concerned with the "the transfer of resources from those responsible for the injustice of climate change to those most vulnerable to it" (Schlosberg and Collins 2014). One of the first climate lawsuits was from the Native Village of Kivalina in Alaska against oil, gas, and electric utility companies for the harms they have experienced due to climate change. While the case was ultimately dismissed, the lawyer for the case described the rationale as:

> "No one asked the people of Kivalina, y'know, 'Would you like to have your environment ruined?' A lawsuit is the only way they have of expressing themselves in the environmental justice process. It's late in the day, it's inadequate, it's a blunt tool, it's the only tool they have left" (Luke Cole, 2008, quoted in Shearer 2011:115).

Since then, numerous cities, counties, and states have filed climate lawsuits that aim to both stop the companies from doing more extraction and seek monetary compensation (payments) for the impacts. None have yet been successful, but a number are currently outstanding (Sabin Center; Merner 2022). A different set of lawsuits has focused preventing harm without a damage payment component. One such climate litigation case was successful, as a Dutch court ordered Royal Dutch Shell to reduce emissions (Clarkson et al. 2021). Another was unsuccessful, as a group of 21 children and young people filed a suit against the U.S. government for failure to protect the public trust for a livable climate (Youth V Gov).

Based on the interviews, there is merit in certain aspects of these approaches, though certain aspects are not appropriate from Zuni perspectives. First, in traditional Zuni perspectives, there is not a concept of inter-personal accountability in terms of something being owed; instead, it is an accountability to the earth (Representative 6). Therefore, across the board, interviewees responded that it is inappropriate to seek direct monetary compensation for climate damages, if the money is sought after in a purely compensatory manner (Representatives 1, 2, 6, 7, and 8). The interviewees referred to teachings from the ancestors that one should not charge another for an impact, or believe you are owed anything, for no one owns anything. Getting payment for something then means treating that thing as something that may be monetarily valued, and the act of doing so will bring harm to that which you have now put a price on:

> “I was raised to understand that you cannot place a price on a person, a land, livestock, or anything, because they're there for a purpose and a reason…My late grandfather always told me that a lot of these things that happens has adverse actions, meaning if you're putting a price on land, you're putting a price on a family member that will perish unexpectedly because you paid that price on it…We don't own anything. It literally belongs to everyone. So it's kind of a hard thing for me to really swallow and digest to say that, ‘what do they owe us’? I feel that they really don't owe us anything...” (Representative 1).

> “It's inappropriate trying to get money that way…it'll have an adverse effect on our people, and it usually impacts the ones we love the most… you'll turn against your family… because it's just like being greedy, just trying to get money… To us *A:shiwi,* we don't have that concept of gaining monetary value in anything like that, like such a lawsuit. You might win, but then again, you might lose one of your loved ones. That's just how our

> ancestors have taught us of respecting Mother Earth…live and let live… So suing these companies, to me, it's not good—it's going to have an adverse effect on all your family or the people here in the village, and especially the religious leaders…" (Representative 6).

Moreover, if someone is pursuing actions or inactions which harm Earth Mother, punishment or consequences will come to that person, but those consequences are not to be doled out by another person (Representatives 1, 2, and 8). For instance, as companies are:

> "…getting money from what minerals they're collecting, eventually, our ancestors used to say it'll come back to them, come back to the company... It's just not right for what they're doing as far as the oil, gas, and all that… In the long run, it'll come back to the big companies that are earning" (Representative 8).

> "So I can't answer that question, if the government owes us …It has been done… And we learned from it… Let the burden be on their end… They've learned, I hope they've learned a lesson" (Representative 2).

What instead may be appropriate is the use of strategic litigation to stop harms from happening again, particularly if it is used to remind people of their responsibilities toward Earth Mother (Representative 4). If such litigation is used to stop companies or other entities from conducting extractive activities, and if by filing a lawsuit it is being done as an action to protect the earth, it is more in line with Zuni values (Representative 6). Some interviewees emphasized the need to center the voices of the people through any such efforts, ensuring the efforts are guided by the people themselves (Representatives 5 and 7). Decision-makers need to hear the voices of the Zuni people and truly understand the impacts of extractive activities and climate change (Representative 5). A potential approach is centering the youth's voice:

> "…maybe take an approach of the youth doing it…Because I think that's where we're going to put all our chips into the future, no matter what…for this culture to continue, these kids have to understand why it's important…[We need to be] supporting and giving the people... a voice to where it's on a level playing field…What we want to try to get across is to recapture the voice... we've been spoken for for a long time. And now we have this opportunity, but we're speaking for ourselves… I think all that collective experience, if we can gift that to our children, so they're more educated from a cultural perspective and a science perspective… I think that youth approach towards people will definitely create attention..." (Representative 7).

While direct compensatory payments through climate litigation does not align with Zuni perspectives, this does not necessarily mean that some form of funding cannot be included in these efforts. For example, in past actions—such as the Water Rights Settlement—funding has been acquired. Yet that money was used to fund restoration activities, acquire more lands to protect, and set up sustainability and conservation programs. In short, this money was used for addressing harms to the earth, not for direct compensation to or 'buy outs' of the people. Indeed, even when Zuni received funds from the settlements over land claims, they "found it difficult to accept payment in lieu of lost lands" (Minge 1995:39). If funding is pursued in such a settlement, the challenge is how to best use the funds to help mitigate the damages and invest in solutions (Representative 3).

To summarize, there is a place for pursuing strategic litigation for upholding responsibility to the earth and her waters and creatures. However, the role for accountability is more nuanced—it is appropriate to pursue measures that uphold accountability toward the earth, but these should not be purely compensatory, as it means putting a price on the invaluable. That act of valuing the invaluable will lead to harms in its own right. The danger of putting a price on and quantifying damages in such efforts for climate accountability is explained by Wrathall et al. 2015, as "[c]ounting and compensation also normatively suggest that environmental, personal and cultural goods and services can be subsumed into a liberal conception of property rights, with rights of exclusivity and alienability" (Wrathall et al. 2015:282). Instead, where this approach may be appropriate is when it aims to build more accountability between society and the environment. Zuni knowledge teaches us that those who engage in such extractive activities will at some point be held accountable by Earth Mother. In the meantime, however, pursuing actions to try to increase responsibility in relationships to the earth is not only appropriate but necessary. While Western institutions have largely laid the groundwork on which climate change was created, leveraging such institutions may be helpful as a layer of protection for the earth.

3.8. The Way Forward

This chapter has aimed to understand the ways in which the collision of Western society and science with Zuni knowledge and practices—as a function of the interconnected processes of settler colonialism and industrial climate change—has led to socio-cultural-environmental impacts, and moreover what Western science might learn if it paused to engage and begin to grasp Zuni knowledge, worldviews, and practices.

Just as impacts have not occurred solely from industrial climate change, nor will any solutions stem just from addressing that climate change. There is a real danger in looking at and treating climate change as a siloed issue, in trying to address it without addressing all the co-occurring factors that led to it, and all the pre-existing issues that it exacerbates. By just focusing efforts today on climate change risks distracting from the reason that Native Americans—and other marginalized groups—are particularly impacted by climate change:

> In "…the 70s, and in the environmental movement, with the Clean Water Act, Clean Air… 'clean' became the buzz thing. And then it was 'conservation' and then 'sustainability'… And every time something new like that comes along, it seems to create its own momentum, which can be good to bring attention to issues if it creates new things that weren't there before. But if they suck up a lot of energy and resources, just because it's a new thing, and they don't result in a lot of new solutions, it then can create a problem on its own. For natives, especially, where before all the non-natives started realizing these trends, they sit there through these years saying, 'Oh, yeah, so you just now get environmentally friendly. You're just now getting conservation. You're just now getting sustainability. Now, you're just now getting climate change'. Okay, every time you just now get something, you redirect resources and take it away from us to now fuel this new idea and approach…" (Representative 3).

Instead, these interconnected drivers and impacts must be considered in finding solutions. As uplifted by numerous scholars and communities, this involves both decarbonization and decolonization (e.g. Droz and NoiseCat 2019; IEN 2022; Eaton 2021). For Westerners, this includes addressing or mitigating that which has been impacted and holding space for Zuni to lead these efforts, promoting efforts to listen to and value non-Western science worldviews, and to stop doing further harms and disrespect to the earth.

The people have largely articulated their vision for moving forward, based on lessons from the past and living in the modern world. The way forward involves acquiring water rights, for people and ecosystems to have access to clean water, and to restore waterways, especially the river (Representatives 5 and 7). The way forward also means revitalizing agriculture, centering community in the decision-making process, protecting the drought-tolerant, Zuni folk variety seeds, and ensuring agriculture is based in the socio-religious perspectives that allowed it to flourish for generations (Representative 5). Moreover, the way forward must be guided by protecting and encouraging intergenerational knowledge transfer and determining and revitalizing what 'traditional' looks like in the modern world. In the K-12 schools, the ancestral journey, relationship to environment, and Zuni worldviews were never taught (Representatives 2 and 4). Therefore, sharing this knowledge across generations is key, including the transfer of stories, practices, and language (Representatives 2, 3, 4, and 7). This includes finding confluence between Western science and traditional knowledge:

> "There's unfortunately no way to go back on some of those things [damages]. But you can mitigate a little bit and be part of a conversation to say, how can we best learn from this? Is it teaching our kids about…[the Western science]? We really could have

> the next Doctoral student coming from Zuni… I think it's just a matter of time, I think we need that… Sometimes it is challenging to try to incorporate that within the culture… it's just like oil and water, sometimes. If you get that right conversation going it really is helpful because we're going in a direction. We can't go back. But we can slow things down. And that's just through education" (Representative 7).

A lot of this work is already being pursued by A:shiwi College. The College is currently going through the process of accreditation. With regard to Indigenous History programs, they will ask Zuni cultural representatives for advice on programming to ensure it is done in concordance with Zuni traditional knowledge. They are developing programming for Zuni Indigenous Studies. This programming will focus on topics such as emergence, Zuni pre-history, and exploring Zuni relationships with the greater region, relationships with other tribes, relationships with the environment. The programming also will teach traditional agriculture practices and culinary arts (Representative 4). Moreover, the programming will explore how traditional worldviews can be continued into the modern day. The cultural advisor will advise on "how to adapt ancient knowledge to today's situation", as these "ancient messages resonate for today" and show how we should live (Representative 4). In understanding that the university is a Western institution, A:shiwi College staff are currently exploring how to integrate traditional teaching in the confines of the university, exploring how traditional teaching and practices—including oral histories—can be central to the programming (Representative 4). This act of centering the Zuni perspectives and ancestral knowledge promotes self-determination. At A:shiwi College, teaching these perspectives and knowledges as core to the curriculum is "part of the process of decolonization" (Representative 4).

Within this context, there are lessons and actions for Western society moving forward. Some of the efforts articulated by Zuni require access to funding, water rights, and lands. For instance, the current work done by the tribe to address impacts requires more capacity and funding (Representative 3). Moreover, while acquiring water right is a lengthy process, it is key to restoring water ways. The tribe is currently under a lengthy adjudication process for rights to water for the Zuni Pueblo[6]. Additionally, as evidenced by the threat of the Fence Lake Coal Mine to Salt Lake, acquiring more of the ancestral lands to keep in trust and protect can only improve their ability to protect against extractivism (Bemis 2014).

The way forward also requires listening to and respecting place-based knowledge systems, such as that of Zuni. This includes both examining the dominant Western knowledge system and respecting and learning from other knowledge systems. If Western society is truly committed to putting these ideas into practice, examining the dominant worldview and how the damages today are a function of that worldview is necessary. For a worldview—an ontology—shapes beliefs and values, and therefore relationships, practices, and actions. Part of this is then learning from Zuni knowledge systems:

> "One of the projects that came about recently is providing [traditional knowledge holders and religious leaders]… and other leaders from Zuni and other places, this equivalency to scholars, because that's how I see them for sure. They no doubt have

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[6] Fighting for water rights for the Zuni Pueblo: Zuni River Basin Adjudication, United States vs. A&R Productions. Ongoing. http://www.zunibasin.com/new/overview.php

> the doctorate degree in Zuni traditional wisdom…I think it's time to change a little bit of that understanding. You don't have to hold a doctorate to understand what it is to be human…" (Representative 7).

One such lesson Western society could learn from Zuni knowledge systems is looking to lessons from the past. As Zuni knowledge teaches to look to lessons from the past, from our ancestors, this practice is encouraged for non-Zuni people—it is considering what Donna Haraway terms "positionality" (Haraway 1998). As activists, scholars, or policy-makers—especially those of us not indigenous to these lands, like myself—who want to support *A:shiwi* and practice our own responsibility towards the earth and each other, considering this positionality is a first step toward moving forward:

> "I understand where they're coming from. But at the same time, thoroughly take a look at the past of how things happened… Some of these activists, these groups that are pushing a lot, there could be a timeline in the past where their own family contributed to what's happening… Take a look at the past, even their own family lines to say was my forefathers part of this issue? And if it is, it's: 'Okay, yeah, it was my great, great, great, great grandfather was part of this whole issue, but I'm trying to make that correction of what has happened.' But understanding why it was done in the past, why was this occurring? Because there's always a reason to that "why" question…The first step is understanding the past of why this happened… we can't fix it, we can only mitigate it and adjust to these changes" (Representative 1).

Answering that ‘why’ question also involves taking responsibility for your own actions or inactions and, if you find you are at part responsible for harms, then changing the actions to arrive back in balance. As such, the core task that Western society can do to support the way forward is to stop the harms and disrespect and move towards a relationship of respect with the earth. Put simply, it is to stop extractivism. Today, Western society continues many of the colonial and extractive processes. One of the lessons from Zuni knowledge is that addressing climate change is not a matter of parts-per-million of CO_2 in the atmosphere which can be manipulated through carbon capture and storage (CCS) or offsets. It is fundamentally an issue about disrespect of and harm toward the earth. This lesson relates to moving away from climate change as a siloed issue to a symptom of a culture of extractivism. Indeed, this is mirrored in environmental justice discourse, which highlights that “while carbon concentration levels are an indicator of the problem and must be addressed…such a narrow framing hides the larger ecological context and inequitable economic system that got us here” (Dayaneni 2009:9). Indeed, a climate-centric framing that ignores socio-economic and political processes that create vulnerabilities can distract from the true impacts of climate change (Lahsen and Ribot 2022; Smith 2006). As seen with the Fence Lake Coal mine, while Zuni protected Salt Lake, the company pursued mining practices elsewhere. What Western society can learn is that:

> “We do have to take the responsibility to try and prevent impacts of our one and only mother earth. If we all understand our responsibility, we shouldn’t be contaminating the lands...” (Representative 5).

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IV. Allocating Responsibility for Climate Impacts:

The (Re)Politicization and (Re)Anthropomorphizing of the Causes of Climate Change

4.1. Introduction

> As "…there are "innumerable sources" of emissions… [and] the harm from global warming involves a series of events disconnected from the discharge itself"… the court could not "reach a resolution of this case in any "reasoned" manner… The Court concludes that Plaintiffs' federal claim for nuisance is barred by the political question doctrine and for lack of standing under Article III." - *Decision on Kivalina v. ExxonMobil (Armstrong 2009)*

In 2009, the 9th circuit court of appeals dismissed the case brought by the city and native village of Kivalina against ExxonMobil and other major oil, gas, and electric companies for the climate-related damages the people were, and are, facing. Part of the decision was due to technical legal issues, but a not-so-small part was based on the *perceived* inability to demonstrate causality and attribute these industrial carbon producers' emissions as a driver of the climate impacts Kivalina faces. As reviewed in Chapter 1, in law, you must demonstrate that you have 'standing' to have a civil case proceed to court, which involves three components: (1) that an injury-in-fact has occurred, (2) that the injury-in-fact is fairly traceable to the actions of the defendant, and (3) that the injury-in-fact may be redressed by a favorable decision of the court (Byers et al. 2017; Ganguly et al. 2018). The second component of standing—demonstrating that an injury-in-fact is 'fairly traceable to the actions of the defendant'—is the subject of this chapter.

In 2009, when the court dismissed *Kivalina v ExxonMobil*, there was little in the academic literature which provided a conceptual framework for climate responsibility, nor which provided empirical evidence for key components contributing to that responsibility. However, as outlined in Chapter 1, much has changed over the past decade. Just as detection and attribution science matured rapidly, *source* attribution has blossomed as a field, providing researchers with the tools to tease out contributions to anthropogenic climate change and attribute relative responsibility.

So, who is responsible for climate impacts? Buried in this question are further questions—who ultimately has contributed most to climate change, who should be held accountable for contributions to climate change, and can these relationships of responsibility and accountability be demonstrated and pursued? Is it the nation-state who contributes the most currently to annual greenhouse gas (GHGs) emissions? Is it the frequent flying consumer whose individual carbon footprint is at the tail end of a disproportionate distribution of per-capita emissions? Is it the vertically integrated corporation who extracts and combusts fossil fuels, or that which distributes electricity, plastics, or cement products? Or is it the inventor who created the internal combustion engine, the nation-state who has cumulatively emitted the most GHGs, or is it the Wall Street stock traders who keep an increasingly uncoupled from GHG emissions—yet still related—GDP afloat?

Much of dominant discourse, policy-making, and scientific analyses avoid answering the question of responsibility, and instead ascribe causal power to anthropogenic forcing itself in lieu of human actors (Raju et al. 2022). For example, discursively, the causal power is often referenced as: “climate change is largely caused by human activity” and “this impact was exacerbated by climate change”, but less often is the causal relationship referred to as “this impact was exacerbated by specific human activities that led to climatic changes…” Extreme event attribution will often identify how an extreme event was exacerbated by “human-induced climate change” or “anthropogenic climate change”, yet doesn’t distinguish between who ‘human activity’ or ‘anthropogenic’ implicates. For instance, Stone and Allen 2005 present an approach to the “end-to-end attribution problem.” Drawing from epidemiology, their approach vastly improved methodological frameworks to attribute localized hazards to anthropogenic forcing, yet the first “end” in their “end-to-end” attribution refers not to a source of emissions but rather to anthropogenic forcing itself. Climate change impacts are thus largely divorced from the actions that have led to climate change (Hulme 2008; Raju et al. 2022). While in a scientific sense, anthropogenic forcing has causal power, it does not have agency. Anthropogenic forcing is not a person nor a vested party. While it may function as a *driver* of impacts in scientific analyses, it is not the reason for those impacts nor is it responsible for those impacts. To be responsible, you must have agency, and to have agency, you must be animate.

Can climate change be animate? Drawing from the lessons learned in Chapter 3, Zuni traditional knowledge and science provides uniquely powerful insights on this question. Rooted in the recognition of people as part of the earth and inseparable from nature, Zuni knowledge teaches that actions which disrespect the earth will lead to her retribution in the form of a lack of rain, failed crops, or other events that Western scientists might define as extreme weather events and climate impacts. Within the Zuni worldview, the Earth and all her beings are animate, to be respected and to live with in a reciprocal relationship. As such, the rains and the winds are animate. Yet, still within this perspective, it is not the weather that is responsible for a lack of rain or failed crops. Rather, within the Zuni worldview, people who have disrespected the earth are responsible for climate impacts when they occur, and that impact will continue, or others like it, until people learn to respect and to live in balance with her again. Thus, within Zuni traditional knowledge and science, climate change is still not responsible. Importantly, this perspective offers us a tool—that until peoples' actions that are driving this imbalance are addressed, the impacts will continue.

Then what are the actions? Who is the 'anthropogenic' in 'anthropogenic climate change'? As discussed in Chapter 3, the usefulness of the very term "anthropogenic climate change" has been questioned. "Anthropogenic", referring to outcomes originating in human activity, does not differentiate between groups of humans and moreover keeps humans as a category distinct from the environment (Whyte 2017). The anthropogenic frame has been useful: the ability to take the cumulative historical emissions from all human activity and feed them into models has allowed for elucidating how large-scale emissions from human activity have changed the climate. This frame has allowed for a succinct and tangible way to delineate emissions, radiative forcing, macro- and meso-scale patterns and trends, and regional trends and extreme events. Yet within this frame, the question of *who is responsible* is answered with "human activity." That human activity may then be delineated between fossil fuels and land use and land cover change (Le Quéré et al. 2018), but generally is not further nuanced between groups or entities.

The lack of further specification in terms of *who* is responsibility dos not only exist due to the complexity of the causal chain. There is similarly a highly political reason that climate change is given an animate power rather than talking about it as an outcome of human behavior—the specter of climate accountability. When the question of *who is responsible* is answered with specific names, questions of accountability follow, including liability and compensation (Thompson and Otto 2015; Liverman 2015). Accordingly, a common narrative in the case of climate responsibility is that ‘everyone and no one is to blame.’ This was the view of the judge presiding over the Kivalina vs ExxonMobil case, as introduced by the opening quote in this chapter. This view focuses on the fact that climate change occurs through complex supply chains, with multiple layers of regulatory systems and diverse consumer bases, thereby spreading responsibility among a wide array of sectors and groups. Yet there is a long history in addressing environmental harms of focusing on specific sectors or entities. For example, tobacco companies have been held legally liable for lung cancer, while state governments have been required to reduce chlorofluorocarbons (CFCs) that contribute to ozone depletion (Oreskes and Conway 2010; Lipanovich 2005). It follows that certain entities or actors may hold unique responsibilities based on their contributions and actions. Rather than absolving other sectors or entities of their unique responsibilities, identifying the unique, outsized responsibilities of certain actors allows for addressing and seeking redress for actions leading to the harm.

That is the goal of this chapter—in responding to the tendency to separate climate change from the specific contours of human agency that has led to it, this chapter aims to examine the sources of emissions, the wielding of power, and the attitudes, actions, and omissions from various actors to interrogate *who* has driven, and is driving, climate change (Smith 2012; Frumhoff et al. 2015)? In moving from climate change as a *what* to a *who*, and in interrogating the deeply political context in which emissions occur, this chapter aims to contribute to a re-politicizing and re-anthropomorphizing of the causes of climate change.

4.2. Breaking Down Responsibility

Chapter 1 presented Shue's (2017) framework for understanding climate responsibility. Contributions to climate change—vis-à-vis emissions—can be sliced and diced any number of ways, thereby identifying the causal responsibility of an agent for contributing to climate change. "But causal responsibility does not entail moral responsibility," Shue reminds us. Instead, "[c]ausal responsibility must be blameworthy to become the basis for moral responsibility, and causation—or "contribution"—is blameworthy only if it is a violation of a socially accepted principle" (Shue 2017).

Shue (2017) is not the first to suggest such an approach. Freudenburg (2005) presented his theory of 'privileged access, privileged accounts' in which certain actors who have privileged access to the environment are the same who create and control privileged accounts. Privileged access entails the disproportionate access to and use of certain resources, control over the local environment, and subsequent contribution to outsized pollution. Under this theory, "toxic emissions tend *not* to be even roughly proportionate to economic activity, but instead, to be characterized by striking disproportionalities" (Freudenburg 2005:100). Building on his work, such disproportionalities have since been identified as occurring from 'egregious' polluters (e.g. Collins et al. 2020). These actors then create, uphold, and perpetuate accounts which argue for the (continued) necessity of that outsized pollution. These accounts include that pollution is economically necessary, necessary as it produces a good required by society, or that regulations will be too expensive or regulated firms will flee to places with fewer environmental regulations. These accounts are stories and explanations that are wholly accepted or 'taken-for-granted' by larger society and are (or were) thus rarely critiqued (Box 1). It is with these theories in mind—with Freudenburg's (2005) unified theory of how both access and accounts operate together, and with Shue 2017's approach to assigning responsibility based on the interaction of these terrains—that we may turn to examining actors' actions with regards to climate accountability.

To approach this task, in this chapter, I begin with assessing causal responsibility (or privileged access) and then, for those actors with substantial causal responsibility, assess the actions, omissions, and attitudes (or privileged accounts). The goal is to identify certain sectors or actors who are disproportionately responsible, as measured by outsized or egregious emissions contributions and actions that are considered violations of social principles. The goal, however, is not to unilaterally dictate a comprehensive list of those responsible versus not responsible. Therefore, this approach will not center those entities who have violated social principles but whose contributions are relatively small.

Box 1:

In 2005, Freudenburg reflected that the "privileged accounts…are rarely questioned, even in leftist critique." Since his 2005 paper, and perhaps in part due to his work, such privileged accounts have increasingly been questioned. This can be seen in the international fossil fuel divestment campaign, which largely targeted (and continues to target) the 'necessity' accounts of the industry, by questioning the social legitimacy of large oil, gas, and coal companies to continue operating in the same manner.

4.2.1. Causal Responsibility

Emissions can be broadly allocated along three main axes—scale of aggregation, site in the supply chain, and time of emission. Table 1 demonstrates how the first two axes interact.

There are various scales of aggregation for allocating contributions—for example, are emissions assigned to a nation-state, a company, or an individual? The UNFCCC negotiations regarding loss and damage (see Chapter 1) focus on the contributions from emitting nation-states; civil lawsuits in the U.S. are pursuing compensation from companies for climate adaptation costs; while individuals are largely encouraged to reduce their carbon footprint. Nuancing the scales of aggregation above, the supply chain dimension refers to whether contributions should be allocated to the site of extraction (i.e. the extractor), the emissions source (i.e. the producer of the emitting product), or to the end-user of the emitting product (i.e. the consumer).

Along both of those axes, emissions can be further allocated along the temporal dimension. This distinguishes between cumulative historical emissions, which considers who has benefitted most from the emissions which have led to current observed climate change, versus current emissions, which accounts for the trajectory of growth in emissions. As current climate change is due to historical emissions, allocating by cumulative emissions has been argued as the 'fairest' approach (Neumeyer 2000; Frumhoff et al. 2015). Instead, focusing on current emissions (i.e. the most recently emissions data for an entity) is useful in assessing the entity's current attitudes and actions. The temporal dimension also accounts for when climate change was understood as real and largely due to the combustion of fossil carbon. If foreseeability is necessary for responsibility, emissions before that knowledge existed and was accessible would be considered differently from emissions after that knowledge was accessible by the emitting actor (Heede 2014). By the late 1980s, climate change was generally accepted as real and primarily due to human activity by the scientific community, and this understanding had been communicated to Congress by James Hansen's testimony in

1988 and to the public in the first IPCC report in 1990. This cutoff would mean that all post-1988 emissions should be assessed, even though there is evidence that the scientific links were known by certain state and industrial actors as early as the 1950s (Franta 2018b). This is still a significant proportion of emissions—approximately 65% of global emissions have occurred since 1980, or in the period where climate change was publicly understood to be real, human-caused, and serious.

Along the first two axes, the most common approaches in the literature and in public discourse are the territorial (producer) nation-state approach (cell 1b), the industrial carbon producer approach (cells 2a and 2b), and the individual consumer approach (cells 2c and 3c). A somewhat more recent focus, due to current lawsuits related to wildfire damages, has been on electric utility producers (3b). These material contributions from these actors to GHG emissions are examined below.

Table 1—Scale of aggregation vs. site along supply chain. Each bin may be further split along a temporal axis.

	Extractor (a)	*Producer (b)*	*Consumer (c)*
Nation-State (1)	Where the oil, gas, or coal is extracted, regardless of destination.	Territorial emissions, i.e. emissions produced within the borders of a nation-state are attributed to that nation-state.	Emissions produced for the production of goods consumed by a nation-state are attributed to the consuming nation-state.
Industrial Carbon Producer (2)	The extractor company (i.e. the coal mining company, the oil and gas drilling company).	The coal, oil, or gas refining company, and cement companies.	Consumers may be individuals (e.g. who use gasoline) or companies (e.g. who use the products in their manufacturing).
Electric Utilities (3)	N/A *(from cell above)*	Electric utility companies, who may both generate electricity from fuels and distribute that electricity.	Individuals or large building managers (i.e. whoever owns and uses the electricity produced).

Nation States

Much of the conversation surrounding responsibility for past emissions has focused on the level of nation-states, within the state sovereignty view (Neumayer 2000, Liverman 2009).

Disproportionate, privileged access is highly visible at this level. Regardless of how emissions are sliced-and-diced along the other two axes (temporal and site along supply chain), when focusing on nation-states, significant disproportionality emerges between the Global North and Global South. For example, temporally, the entire African continent has contributed only 2.8% of cumulative global emissions and 4% of 2019 global emissions (Ritchie and Roser 2020). This clear Global North-South divide drives many international debates regarding climate change (Neumayer 2000).

Yet, different accounting approaches based on the supply chain axis results in different estimates of 'top emitter' when focusing largely on Global North countries. Erickson and Lazarus (2013) present three common accounting methods for allocating emissions to nation-states: the extraction-based method, the territorial or producer method, and the consumption-based method (columns a, b, and c in Table 1). Steininger et al. (2016) compare these accounting approaches for 2011 per capita emissions. Extraction-based approaches attribute emissions to the extracting/producing country of any exported fuels, because "countries that are large net exporters of fossil fuels can thus greatly increase their fossil fuel extraction activities with limited impact on their own GHG emissions." For 2011, extraction-based accounting demonstrates Canada, Russia, Saudi Arabia, Norway, and Australia as the largest per capita emitters. The territorial or producer approach assigns emissions to nation-states when the emissions are produced within its borders. For 2011, the production-based accounting approach identifies Canada, the U.S., Saudi Arabia, Australia, Mongolia, and Kazakhstan as the largest per capita emitters. Finally, the consumption approach assigns emissions to the nation-states where the goods are ultimately consumed. Consumption-based accounting for 2011 result in the U.S., Canada, Australia, Norway, and Finland as the largest per capita emitters.

Fairness arguments debate whether it is the emissions source (as the extractor or producer) or the consumer who should bear responsibility at this scale. While this debate is important for examining how to address current emissions, there is less data to draw distinctions for historical, cumulative emissions. Turning to the U.S., the country was a top emitter in 2011 for the production and consumption-based methods. For the extraction-based accounting method, the country only became a net exporter in 2019 (Cohen 2019); since the mid-1990s, most U.S. oil imports have been from Canada (EIA 2017). However, as will be examined later in this chapter, the U.S. has engaged in actions which have continued the extraction of fossil fuels abroad.

When turning to the temporal axis, the effect is most visible when comparing production-based emissions between the U.S. and China. When only considering current emissions, since 2005, China has been the largest annual emitter, followed by the U.S. (Richie and Roser 2020). However, when considering cumulative emissions from fossil fuels, land use, and forestry, the United States has contributed 20-25% of all cumulative emissions since 1750, with China at just over 11-13% (Ritchie and Roser 2020; Evans 2021). The U.S. and China are nearly tied for largest post-1980 cumulative emissions, at 20% and 19%, respectively (calculated, based on data from Ritchie and Roser 2020).

These various estimates indicate how choosing an axis along which to allocate emissions contributions can drastically affect the answer to ‘who has emitted the most?’ Axes must therefore be chosen with care, by considering actions, attitudes, and omissions (as described in Section 4.3).

Industrial Extractors and Producers

Emissions may also be allocated to industrial extractors and producers (cells 2a-b in Table 1). These are companies—state-owned (or integrated with the state), investor-owned, or cooperative—that extract (mine or drill), refine, and/or burn fossil fuels. One approach has been to allocate emissions to large oil, gas, coal, and cement[7] companies, commonly referred to as industrial carbon producers or the 'Carbon Majors'. These 'industrial carbon producers' are the actors that have "extracted, refined, and marketed the preponderance of the historic carbon fuels" (Heede 2014:231). Specifically, they include coal extractors and oil and gas extractors and refiners (producers). Compared to coal, many oil companies are vertically integrated, both extracting and refining their product. Heede (2014) calculates the historical CO_2e emissions from these entities, finding that 63% of all industrial fossil fuel and cement emissions from 1751 to 2010 can be traced to the Carbon Majors. Moreover, half of those emissions were emitted after 1984. There are, of course, uncertainties related to this approach, yet the total estimates are comparable to the Carbon Dioxide Information Analysis Center's (CDIAC) accounts, and, if anything, are conservative due to under-reporting by companies. Chevron and ExxonMobil are the top cumulative emitters, at 3.5 and 3.2% of global cumulative emissions, with Saudi Amarco as the third; however Saudi Aramco was the largest annual emitter in 2010. Ekwurzel et al. 2017 use this dataset to quantify the relative contribution of the industrial carbon producers to total stock of CO_2, global mean surface temperature (GMST) rise, and global sea level (GSL) rise. They find that emissions from the Carbon Majors from 1980 to 2010 contributed to over a third of the total global mean surface

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[7] Cement manufacturing produces CO_2 from the calcining of limestone: $CaCO_3 \rightarrow CaO + CO_2$ (Heede 2014).

warming from 1880-2010. Turning to the temporal axis, a shift occurred between investor-owned industrial extractors to state-owned: while in the 1950s, just seven investor-owned corporations held over 90% of all oil reserves, in 2015, the ten largest state-owned national oil companies held ~75% of all oi reserves (Appel, Mason, and Watts 2015:20).

Another approach has been to focus on a subset of carbon producers. Just as the Carbon Majors extract and combust fossil fuels and produce cement, electric utilities burn fossil fuels for electricity generation, and hence emissions can be attributed to these utilities (cell 3b in Table 1). Notably, the coal producers in the Carbon Majors are implicated in this approach (cells 2-3a in Table 1), as a sizable proportion of the coal produced by Carbon Majors is then burned by electric utilities. Focusing on the American electric utility industry, in 2019, electricity generation accounted for 25% of U.S. territorial emissions (EPA 2021), or 32% of U.S. energy-related CO_2 territorial emissions (EIA 2021a). Cumulatively, from 1973-2019, electricity generation accounted for 36% of total U.S. energy-related CO_2 territorial emissions (calculated from EIA 2021b). Notably, electricity generation made up the largest percent of U.S. territorial emissions in 2008; emissions from electricity generation steadily rose from 1973 to 2008. Yet, after 2008, emissions from the sector have generally declined (ibid) while total electricity generation (KWH) has remained relatively steady since 2008 (EIA 2021c). This indicates the beginning of a decoupling between electricity generation and emissions since 2008, or a reduction in emissions intensity. Yet comparing individual electricity utilities allows for understanding how emissions intensity varies among producers, highlighting certain actors within the same industry who contributed outsized emissions. A recent analysis found that this pattern of disproportionality both between and within industrial sectors is the rule rather than the exception (Collins et al. 2020). Jorgenson et al. (2016) examine disproportionately in power plant carbon dioxide emissions for electricity sector across 161 countries, finding that there is significant disproportionality in emissions between facilities within countries. Galli Robertson and Collins 2019 do the same for the American electric utility industry, focusing specifically on coal generation. They find significant disproportionality in both raw and standardized emissions (CO_2/MWH) between parent companies of facilities. The highest standardized emitters include Southern Company, AEP, and Duke, among others[8]. They are the highest standardized emitters because they own/operate the most inefficient/high polluting coal-fired electricity generation plants in the U.S. (Galli Robertson and Collins 2019).

Individual Consumers

Ultimately, emissions may also be attributed to individuals. Just as electric utilities use coal extracted by Carbon Majors, individuals use oil extracted and refined by Carbon Majors (e.g. tailpipe emissions from vehicles, cell 2c) and coal extracted by Carbon Majors and burned by electric utilities (e.g. residential energy, cell 3c).

Individual consumption-based allocation of emissions is infeasible, as percent contribution from each individual person—both currently alive and historic—is exceptionally small (Box 4.2) and the large number of individuals would make such an analysis intractable. Instead, most approaches average across populations, assuming equal consumption within the

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[8] A separate report conducted a similarly analysis, identifying a series of electric co-ops as the most emissions intensive (MJ Bradley & Associates 2017). However, these co-ops are small producers compared to AEP, Southern, and Duke. Moreover, the report also lumps together coal and gas generation, so the large producers that use gas (e.g. AEP) will have an overall lower emissions intensity compared to those that only use coal. It should be noted that the authors of this report include Bank of America and electric utility company, Entergy.

population, thereby deriving ‘per capita’ emissions. At the largest scale, a study averaged across the global population and calculated that for every metric ton of carbon dioxide a person emits, three square meters of Arctic Sea ice is lost (Notz and Stroeve 2016). Another similar study found that individuals, accounting for age, are responsible for between 0.5-18 yuan for costs associated with the 2018 heatwave in eastern China (Lott et al. 2021). Yet not all people emit equally; if that were the case, the process of attribution would be easy. Differentiating among groups is generally done at the nation-state level; for example, U.S. per capita emissions have consistently been significantly larger than those of China (Ritchie and Roser 2020). However, averaging across the population at the nation-state scale does not account for the highly uneven social landscapes that have resulted in very different per capita emissions between groups at all scales. A recent analysis found that the richest 10% of the global population contributed to ~50% of emissions growth from 1990-2015 (Kartha 2020). Räty and Carlsson-Kanyama (2010) found that emissions are stratified by gender in certain European countries. Kennedy et al. (2014) found that there is disproportionality in household carbon footprints, both across types of energy consumption (household energy being the highest) and across incomes (where higher incomes corresponded with higher household emissions). Goldstein et al. (2020) examine patterns in GHG-intensity for residential buildings in the U.S. and find that higher income households (largely correlated with higher floor space) are often more energy and GHG emissions intensive than lower-income homes, and homes in hotter climates are more energy and GHG emissions intensive (as household heating and cooling are the largest residential uses of energy). They find moreover that the carbon intensity of the power grid is one of the strongest determinants, so that more energy-intensive homes can also be less GHG-intensive if drawing on a largely renewable grid. While individual behavioral changes may be able to rectify some of the disproportionality in emissions, many of these stratifications are due to structural barriers. Therefore (and as further explained in Box 2), in this chapter, individuals are not considered further in terms of causal responsibility.

Box 2. What About Our Carbon Footprints?

From an emissions perspective, individuals do not qualify as contributing substantially because relative contributions from individuals are too small. For example, given that per capita emissions in the U.S. were 16 tons CO_2 in 2019, and global emissions were 36.4 billion tons CO2 in 2019 (Ritchie and Roser 2020), the average American contributed to 0.00000004% of global emissions in 2019. While emissions from all individuals summed up are significant, even the summation of individual activities do not have a significant effect on global emissions, as evidenced by the COVID-19 pandemic.

COVID-19 provided a natural experiment indicating this. In May 2020, a Santa Barbara County Supervisor wrote an op-ed with the tag line: "The Pandemic Proves We Can Change Our Habits" (Williams 2020). In the op-ed, the supervisor celebrates the fact that limiting travel due to the stay-at-home orders had reduced demand for oil and cut GHG emissions. He congratulated his constituents, saying: "You are successfully demolishing a significant part of the fossil fuel industry as global demand for oil tanks. Keep it up!" (Williams 2020). The implication here was that since people were staying home and not driving—which, in California, is the largest emitting sector—individuals were making big steps towards the behavioral changes needed to curb emissions. If this were true, we would have seen emissions reductions during shelter-in-place that should have been enough to meet emissions targets. After all, the behavioral changes were more drastic from an emissions-cutting perspective than one could reasonably expect.

Yet, the shelter-in-place order illustrated the emissions reductions that could be achieved through significant behavioral change: a reduction in emissions of 5.5%, compared to the necessary 7.5% reduction needed to limit warming to below 1.5°C. This gap exists because most of the emissions reductions have occurred due to reductions in transportation, while emissions in other sectors of the economy have remained largely unaffected. In 2021, International Energy Agency released a press release with the sub-heading stating, “Global energy-related CO_2 emissions were 2% higher in December 2020 than in the same month a year earlier, according to IEA data, driven by economic recovery and a lack of clean energy policies” (IEA 2021a). Carbon Brief similarly reported that CO_2 emissions from fossil fuels and cement were up 4.9% post-COVID (Hausfather 2021). If the drastic individual behavioral changes during the COVID-19 pandemic did not amount in sufficient emissions reductions, what level of individual change could?

With so many ways to allocate causal responsibility, this question of allocating full moral responsibility for emissions must include some examination of wrongness. Assessing attitudes, omissions, or actions can turn a simple carbon accounting exercise into an assessment of responsibility, or accountability. Therefore, to answer the question of “who is responsible”, it is necessary to examine the activities of people and organizations within a larger political economy and ecology to identify agency.

4.2.2. From Causal to Moral Responsibility

There is a long-standing debate in the environmental movement and environmental policy spaces surrounding how to allocate responsibility for environmental problems. Much of this debate has focused on producers versus consumers. From acid rain to the ozone hole to secondhand smoke to climate change, the question of responsibility for curbing polluting activities has been central to environmental issues since at least the 1960s (Oreskes and Conway 2010). The earlier environmental challenges—acid rain and ozone depletion—were largely uplifted by an environmental movement which focused on producers, or the industrial or large-scale actors who create the compounds leading to the environmental problems. The relevant industries largely resisted acting on the issues by doubting the science or the policy mechanisms, but not their role in producing the compounds (Oreskes and Conway 2010). In the 1980s, however, with the fight around tobacco and second-hand smoke, the framing of the issue began to shift—tobacco companies' public relations campaigns sowed doubt on the science, as with earlier environmental challenges, but also increasingly promoted messaging to focus on the responsibility of the consumer: the smoker (Oreskes and Conway 2010). With climate change, this rhetorical tactic of focusing on responsibilities of consumers is widely deployed (e.g. Supran and Oreskes 2021). This has come to define much of the policy conversation around climate change mitigation (e.g. Bastianoni 2004; Lenzen et al. 2007). This shift is also apparent in many social movements. From the 1960s to today, there have been shifts in discourse away from collective action toward individual, consumer-based approaches (Petovic 2009).

As described in Chapter 1, certain theoretical foundations underlie a focus on production versus on consumption—political economy / ecology and environmental justice generally focus on production, while economics and state sovereignty frames more readily lend themselves to a focus on consumption. In this chapter, I place an emphasis on the organizational extractor and producer and mid-stream consumer approaches, and less on the individual consumer approach. This is in part due to the overemphasis on individual consumption prevalent in much of common discourse (Box 4, later), in part due to the evidence of organizational activities to entrench fossil fuel use (Section 4.3), and in large part due to the highly embedded nature of fossil fuels in the global political economy. Emissions do not occur within a silo but are instead mediated by greater political, economic, social, and environmental factors. Yet certain entities within this larger context hold a combination of structural power and agency, meaning they hold agency themselves to make substantial changes to emissions. Again, while not absolving individual consumers of their unique responsibilities, beyond the fact that most individual consumers bear exceptionally small causal responsibility, individual consumers do not have structural power and agency to make substantial changes to emissions, outside of their collective role in civil society pushing for other actors to make changes. As explained by Gould, Pellow, and Schnaiberg 2004:

> "Although consumers may be the ultimate purchasers of some of the products of the new technologies, decisions about the allocation of technologies is in the realm of production managers and owners… Although consumers can accept or reject these products, they have no influence over the allocation of capital to productive technologies. Thus, it is within the production process where the initial interaction of social systems with ecosystems occurs" (Gould, Pellow, and Schnaiberg 2004:300).

Within this context, then, how can the unique responsibilities of actors embedded in that greater political economy be identified? Again, to be responsible, you must have agency. Structurally, one of the largest contentions in political economy is related to agency in the state and the firm, which boils down to the following question—is it the failure of the state to regulate (or even the desire to *not* regulate) emissions from the firm, or is it the wielding of forms of power by the firm to escape regulation from the state?

There are three main theories of how the state exists and operates—pluralism, state-centered or elitist, and Marxist—which describe the general approaches to this question. The pluralist view contends that the state is neutral in nature and is the mediating force among equivalent players (Jenkins 1994). It recognizes multiple actors with agency outside of the state, including the capitalist class and labor through unions. In this pluralist view, the state has no self-interests, nor does it exert class control. It therefore only has agency insomuch that it fails to regulate or prevent another organization from doing harm. As opposed to the pluralist view, the elitist and Marxist views of the state recognize significant agency of the state in making decisions. The elitist or state-centered theory views the state as an actor with singular agency. It is viewed as having legitimate control over the nation-state, and generally has the consent of the governed to do so as it provides order and bureaucracy as a public good. Yet, as the state is *not* neutral, it actively promotes those interests which advance its own. It will align with those who serve their agenda and fight against those who attempt to weaken their interests, both domestically and internationally. It has capacities to promote those interests including repression of opposition, mobilization of labor and resources, and through rulemaking (Jenkins 1994:23). Compared to the elitist or state-centered theory, the Marxist and neo-Marxist view, while still viewing the state as a site of agency as it wields forms of power to protect interests, views those interests as belonging to the ruling class. Instead of acting with a singular agency, the state is an instrument of the ruling class rather than its own agent. Here, the state is an executive committee of the 'haves', in which the capitalist class has the monopoly on power over the working class (Jenkins 1994). This view puts the state and proletariat at odds. Neo-Marxist theories allow for state making concessions to the proletariat to keep legitimacy and maintain consent.

In both the elitist and neo-Marxist views, the state has agency to both do harm and to fail to clean up its own mess; therefore, emissions have occurred due to the active interests of the state. The state may make concessions to non-state actors if they align with its own interests. However, under a pluralist view, emissions have occurred due to a state's failure to regulate, while agency largely exists in the organizations the state failed to regulate.

In the case of fossil fuels, there are large dependencies between the state and firm. Rather than acting in silos, these entities have worked in coordination to advance shared interests (Mitchell 2011; Bridge 2008; Watts 2015). Bridge 2008 examines oil production through a global production network approach, which focuses on the relationship between the state and firm related to resource access and between the producer and consumer related to value. Interactions and decisions may be understood through three imperatives of the oil production network: the imperative of accessing oil reserves for production, the imperative of reducing costs to stay market competitive, and the imperative of using the environment as a sink for pollutants, thereby externalizing costs (Bridge 2008). The last two, however, rely on the first imperative, as "...much competitive strategy in the oil industry…relates to control over resource access and the capture (and allocation) of rents from low-cost, high quality reserves" (Bridge 2008:402). Oil is unique in this regard as there is great value to be had just by access to and control of the resource (Bridge 2008:402). This may manifest in a "tension between resource-holding states and resource-seeking firms" as both the firm and state work to claim profit based on access to the resource (Bridge 2008:402). Similarly, in "Subterranean Estates", a wide range of scholars come together to trace how the global production network of oil extends across many actors and institutions (Appel, Mason, and Watts 2015:19). Much of the power is related to the access to these 'estates'—including the oil reserves, but also the social, political, and institutional spaces of power. In these readings of the oil assemblage, there is a coordination found between the state and industry, in which relations of power change from place-to-place and over time. For coal, similarly, power is largely related to access, yet is far more centralized than oil, in large part due to its materiality—produced from centralized seams and transported by railways and ship to be largely used in manufacturing generation, the concentration of coal (compared to the expansiveness of oil) has resulted in a more centralized network (Mitchell 2011:19). Turning back to Freudenberg's (2005) theory, power and competitiveness then are a function of the *privileged access* to these reserves. These texts identify the structural dependencies and the coordination that exists among these entities—particularly the state and the firm.

In what can be read as an extension of this material entanglement into the cultural world, industries and state actors have coordinated in campaigns and coalitions to win consent for their fossil fuel-related activities, largely based on the creation and wielding of *privileged accounts*. Brulle (2019) introduces the concept of the Climate Change Countermovement (CCCM), which he explains is an "amalgam of loosely coordinated groups", including "corporations with strong ties to the production and use of fossil fuels, acting in coordination with allied trade associations, conservative think tanks, philanthropic foundations, and public relations firms, [who] mounted a series of efforts opposed to action to mitigate carbon emissions" (Brulle 2019:1). Although comprised of many actors with different stakes, CCCM organizations share a common goal of avoiding restrictions on carbon emissions (Dunlap and McCright 2011). As such, the CCCM created front groups and campaigns to undermine climate science and resist carbon regulations. Notably, no documented campaigns, front groups, or coalitions existed before the late 1980s to challenge climate action. Individual companies or small groups of companies launched attack campaigns before that point (Oreskes and Conway 2010). The CCCM, instead, emerged in response to the growing scientific consensus and the emergence of climate change into the national public eye, following the formation of the IPCC (Brulle 2019; Dunlap and Brulle 2020). Organizational involvement peaked in the CCCM in 2003 with nearly 250 participating organizations (Brulle 2019:15).

This strategy has not been unique to climate change. Anti-environmental countermovements existed before the late 1980s, as actors with economic interests threatened by environmental regulation as well as those with ideologies opposed to regulation coordinated to resist that regulation and win the public framing contest (McCright and Dunlap 2000; Dunlap and Brulle 2020). Many of these tactics used by the CCCM have come out of a playbook used by these countermovements for multiple environmental problems, from ozone depletion to second-hand smoke to acid rain (Oreskes and Conway, 2010; Michaels 2008). While the human fingerprint has been identified on each of these—generally linked to the product of a small number of actors—these actors have deployed and refined tactics to deny the human cause or seriousness of the impacts of each. This playbook has been referred to as "the denial playbook" (Namboodri 2021), "the disinformation playbook" (Reed et al. 2021), and “the science of spin” (Goldberg and Vandanberg 2021), and largely focuses on politicizing science. STS highlights how this tactic is made possible through certain ‘knowledge brokers’—or those with access to and control over privileged forms of knowledge are regarded as experts and as such create the bounds of arguments or the playing field (Oreskes and Conway 2010).

The leading sectors in the CCCM (as defined by frequency of involvement in participating coalitions) are the coal, rail, and steel industry, oil and gas industry, the electric utility industry, and the conservative movement. Two industries within the CCCM will be examined here—the fossil fuel industry and the electric utility industry. The oil and gas sector comprised 10% of the CCCM, although only 5% of the CCCM’s leadership, while the electric utility industry comprised only 7% of the CCCM but 18% of the leadership (Brulle 2019:11-14). This suggests that while the oil and gas industry participated in the CCCM, most of its anti-climate action efforts were done internally in its organizations, while the electric utility industry conducted most of its efforts collectively as a more unified industry. While the State itself has not engaged in the CCCM, political actors have (McCright and Dunlap 2000:505; Dunlap and Brulle 2020). The Republican party has engaged in the CCCM as “the characterization of global warming as a major problem… are seen as a direct threat to sustained economic growth, the free market, national sovereignty, and the continued abolition of governmental regulations…” (McCright and Dunlap 2000:505).

4.3. Examining Attitudes, Actions, and Omissions

The attitudes, actions, and omissions of the major emitting entities (described in the previous section) are examined here. Attitudes, actions, and omissions include forward general, negative norms (aka “do no harm), and backward, special, positive norms (aka “clean up your own mess”) (Smith 2012; Shue 2017). These “are the two sides of the same coin: those who fail to fulfill the first responsibility ordinarily incur the second responsibility” (Shue 2017). These forward- and backward-looking norms include agency (who has the ability to avoid emitting), foreseeability (did the emitter know about the climate consequences of emissions), alternatives (were there non-emitting alternatives the emitter chose to not adopt), social care (was your emitting action done for normatively good or bad reasons, such as for building your own personal wealth vs developing a nation?), avoiding the need to clean up your mess (did you seek to hide climate science?), and avoiding cleaning up your mess (once you knew your actions lead to climate change, did you try to change them?).

While this section is not necessarily constrained to the U.S., there is a U.S. focus given the outsized cumulative emissions traceable to the U.S. and the fact that many Carbon Majors are headquartered in the U.S. This is furthermore made easier to analyze given the level of data availability in the U.S.

4.3.1. The State

There is an argument to be made for allocating agency to nation-states in emitting, given that much of the development of the nation-state was done through the exploitation of fossil fuels. Historical GHG emissions track well with political and economic power and exploitation: “The leading industrialized countries are also oil states. Without the energy they derive from oil their current forms of political and economic life would not exist” (Mitchell 2011:6). This is visible in the economic power of nation-states: GNP is closely related to historical and current emissions (Neumayer 2020). Industrialization of Global North countries was powered by fossil fuels, primarily coal, and then later by oil and gas. As such, fossil fuels have been extracted and used to promote the strength or hegemony of the development of Global North nation states for the past four centuries. For example, the earliest use of industrial-level fossil fuels for energy production comes from England in the 17th century (Freese 2003). Coal powered the industrial revolution in England, speeding along the country's rise to a major world power. The country's process of industrialization was on the backs of its poor, rural classes who were pushed from their lands to work in the mines (Freese 2003). This model of development would be implemented in the development of the U.S. As described in the *causal responsibility* section, the U.S. is the largest cumulative, having contributed around a quarter of global emissions since 1790. The development of the power of the U.S. as a nation-state is linked to those emissions. Fossil fuel extraction inextricably tied to colonialism and dispossession of indigenous peoples of their land (Mitchell 2011:17). First based on coal, and then in the mid-1800s with the discovery of oil reserves, on oil, the GDP of the U.S. has been built on fossil fuels (CFR 2022; Frumhoff et al 2015; Neumeyer 2000).

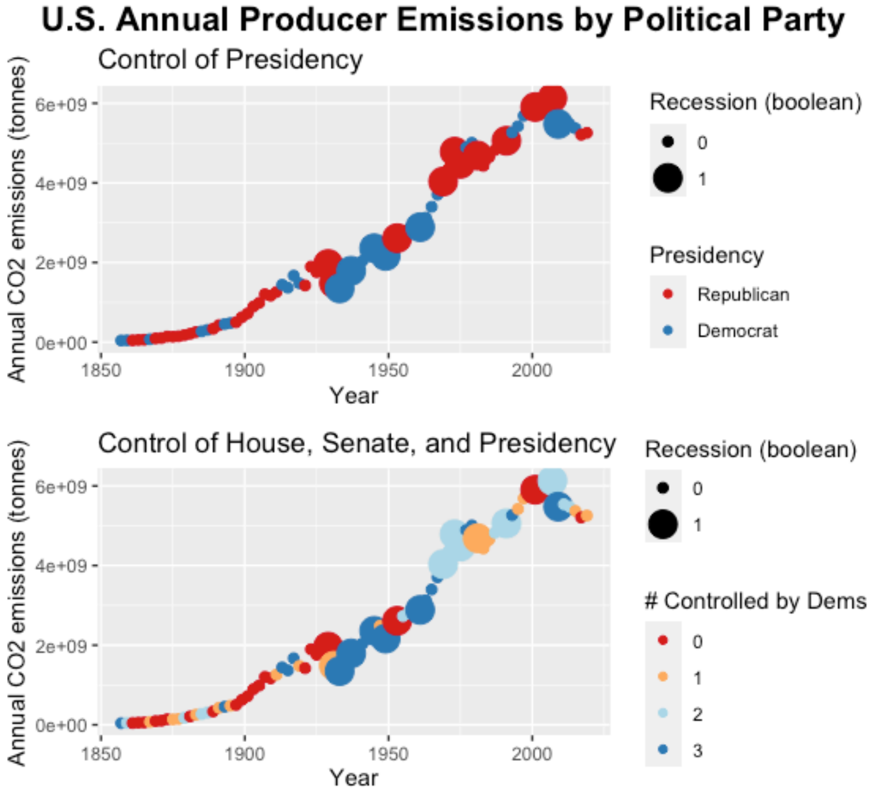
In many high-emitting extractor nation-states (Table 1, cell 1a), much of the fossil fuel extraction occurs within the nation-state as the companies are state-owned: as of 2021, around half of global oil, gas, and coal production is controlled by national government-owned companies (SEI 2021:29). Many of these are petro-states, in which the state's economy is heavily reliant on fossil fuel extraction (Watts 2017). As oil companies seek access to oil resources, for non-state-owned companies, a 50:50 approach to splitting profit has been pursued in most large extractor states (Bridge 2008:403-405). The fossil fuel extraction—generally oil—is then largely exported to high producing and consuming nations. These producing and consuming states are another form of petro-state (LeQuesne 2019a; Mitchell 2011). These international flows of oil and capital results in international carbon debt. Some countries have benefited from profit from extraction (e.g. Saudi Arabia), some from industrialization from imported fossil fuels (e.g. Spain and France), and some from both the profit from oil extraction and the development afforded by industrialization (e.g. Canada and the U.S.) (Bridge 2008). Certain countries have "…benefited disproportionately from the industrialization process that led to the accumulation of greenhouse gases in the atmosphere, yet since the damage is universal, the costs are borne by everyone", a component of the principle of common-but-differentiated-responsibilities (CBDR) (Rajamani 2000).

To respond to that harm, or to 'clean up your own mess', historical accountability has been proposed. Given that climate change today is due to past emissions, the polluter-pays-principle is presented as the fair approach as it affirms the goal of equal opportunity to use the global commons of the atmosphere, limiting not only future emissions for Global North countries but also allowing for 'survival' emissions from Global South countries (Francis 2020; Neumayer 2000; Liverman 2015). That hasn't occurred, however. Global North countries continue to emit, laying claim to larger-than-fair-shares of future emissions within the remaining carbon budget; seek to justify continued emissions through frames and rhetoric; and resist efforts for international climate accountability and compensation.

To examine 'wrongness' at the level of the state, this section will focus on the U.S. as the largest cumulative production- and consumption-based emitter; extraction-based accounting methods will also be revisited. This state has violated both norms of 'do no harm' and 'clean up your own mess.'

The U.S. has leveraged force, both domestically and internationally, to protect oil development. Exploring the decades of militarism, international relations, and international capital flows related to Middle Eastern oil production is beyond the scope of this chapter, but for decades, the U.S. has used its military force to ensure continued access to oil in extractor countries, or rather that extractor countries continue to export to the U.S. (Mitchell 2011:30; Cohen 2019; Watts 2015). Turning to the U.S., due to the Posse Comitatus Act, the military is generally not to be deployed domestically. However, the U.S. government has several times invoked acts to deploy the military domestically or rely on National Guard or police forces to pursue domestic goals. For example, in the mid-1900s, in response to refinery labor strikes, the federal government used the War Powers Act to crush the strike by placing refineries under military control (Mitchell 2011:27-28). Moreover, "the government forced the Standard Oil companies and other large refiners to concede the right of national unions to represent a collective workforce, while limiting their role to bargaining over remuneration and working conditions…" (Mitchell 2011:28). Several decades later, in response to indigenous-led resistance against the Dakota Access Pipeline (DAPL), which now crosses the Standing Rock Sioux reservation and waterways, a combination of private security forces (TigerSwan, see Section 4.3.2), the National Guard, and local police were deployed, armed with army surplus gear, and used military-style tactics of forceful oppression (LeQuesne 2019a).

The U.S. has also continued supporting extractive activities. The U.S. has largely consented to many of the demands of the oil industry, particularly under Republican leadership (Carter 2021; Dunlap and Brulle 2020; Faber et al. 2017). Some elected policy makers have also profited from blocking regulations on industry (Dunlap and Brulle 2020). However, the political party in charge of the presidency, House, or Senate has relatively little effect on U.S. annual producer emissions, which have been steadily increasing over the past century, interrupted with occasional recessions (Figure 1). All this amounts to a remaining, sizeable ‘production gap’ between emissions targets and current state-regulated activities (SEI 2021).



Data source:
History, Art & Archives, U.S. House of Representatives,
Ritchie and Roser 2020

Figure 1. U.S. Annual Producer Emissions, Political Parties, and Recessions. Top panel shows emissions as a function of the political party of the presidency, while the bottom panel shows the number of branches of government controlled by the Democratic party. Years with recessions are shown as large circles.

Actors within the state have engaged in climate denial—specifically individual politicians in the Republican Party and the party itself (Demeritt 2006; Dunlap and Brulle 2020). This constitutes a violation of a combination of social principles related to foreseeability and actions—or what was known (about the link between fossil fuels and climate change) versus what was said. The Republican party has grown increasingly right-wing, in response to progressivism in the 1960s, and fueled by Reaganism in the 1980s which solidified an "embrace of free-market, anti-regulatory ideology" (Dunlap and Brulle 2020). This has become coupled with climate denialism. From Regan, across the Bush eras, to Trump, "…Republican Administrations have worked to minimize the risks posed by climate change, block amelioration efforts, cut climate science programs and funding, and hinder agency oversight by installing deniers in important posts…" (Dunlap and Brulle 2020). As such, the party has amplified much of the climate denial messaging created by the CCCM (Dunlap and Brulle 2020). While conservative foundations and think tanks have helped to create some of the climate denial messages, politicians alongside media and blogs propagate the messages in an echo chamber (Dunlap and McCright 2011).

Finally, the U.S. has firmly resisted efforts for international climate accountability and compensation (Chemnick 2021). In the words of Todd Stern, the leader of the U.S. negotiating team for the UNFCCC Conference of the Parties: "The notion that there's actual liability—and from liability flows compensation—is something that we didn't agree with..." (Chemnick 2021).

The state has demonstrated agency and an agenda related to advancing and protecting fossil fuel development. Engaging the military to protect oil interests is evidence of the utility of the elitist view in describing the State's relationship to emissions and climate change, in which the State pursues advancing its own interests or interests of others that align with its own through its "monopoly on legitimate violence" (Jenkins 1994:22). Similarly, the continued U.S. opposition to various iterations of loss and damage mechanisms in the UNFCCC negotiations, spanning multiple administrations from different parties, fits with an elitist view of the State. Yet, the changing domestic policies and rhetoric stemming from state actors under different parties may be best explained by a Marxist view of the state, in which the interests and agency of the state stems from those in charge, and the power to enact that agency is a function of how whole the capture is of the state.

4.3.2. The Oil & Gas Industry

As with the state, the oil and gas industry has failed both ‘do no harm’ and ‘clean up your own mess.’ An argument exists for allocating emissions to the fossil fuel industry given the vast wealth that has been accumulated by corporations within the industry due to the extraction of the product. Moreover, as described in the *causal responsibility* section, half of emissions can be tied to just 90 companies (the ‘Carbon Majors’), while more than half of emissions from the Carbon Majors occurred post-1980, well after when they knew about the link between its products and climate change. Beginning in the 1800s, but certainly by the 1900s with the consolidation of assets into major corporations, the oil and gas industry has operated with great autonomy. In the late 1800s, Standard Oil owned 90% of oil refineries and pipelines, and was then broken up in the early 1900s into the Oil Majors (including Chevron, Mobil, Conoco, and Exxon) (CFR 2022). Since then, the Oil Majors have come to negotiate on the international stage, operating beyond the borders of the nation state. Due to the increasing flows of capital and corporate activity beyond the confines of nation-states, increasing attention has been given to how companies drive and shape extractive and emissions-producing activities (e.g. Bridge 2008).

Contrary to the principle of “do no harm”, the oil and gas industry knew about the harms of its products (foreseeability) while continuing to emit. The oil and gas industry had knowledge of the existence and causes of climate change as early as the 1950s. In 1959, the

American Petroleum Institute (API) listened to a lecture by the renowned theoretical physicist, Edward Teller, in which Teller explained:

> "I would [...] like to mention another reason why we probably have to look for additional fuel supplies… Whenever you burn conventional fuel, you create carbon dioxide... Its presence in the atmosphere causes a greenhouse effect [....] It has been calculated that a temperature rise corresponding to a 10 per cent increase in carbon dioxide will be sufficient to melt the icecap and submerge New York…I think that this chemical contamination is more serious than most people tend to believe" (Teller 1959, cited in Franta 2018b).

Significant documentation over the past decade has developed a timeline detailing how many firms in the oil and gas industry knew early on about the link between their product, CO_2 emissions, and climate change. A rediscovered film created by Shell in 1991 demonstrates that Shell knew about the links between fossil fuel combustion and climate change (Mommers and Carrington 2017), while peer-reviewed archival research shows that oil companies Total and ExxonMobil knew about climate change before publicly communicating doubt about its existence (Bonneuil et al. 2021; Supran and Oreskes 2021).

LeQuesne 2019a presents a re-reading of Gramscian hegemony to examine how the fossil fuel industry, acting as a cohesive whole, has leveraged various forms of power to entrench fossil fuel reliance. Gramscian hegemony traditionally includes coercion (use of force or violence) and consent (on cultural and discursive terrains). The hegemon therefore works to maintain consent, using the threat of or enactment of coercion when consent falters. LeQuesne

2019a proposes that there is a third component to hegemony which was alluded to by Gramsci—compliance—whereby the "…hegemon may establish compliance by structuring economic conditions such that a community's choice to actively consent or dissent is circumscribed by dependency upon those economic conditions" (LeQuesne 2019b:192). These three components of hegemony are seen in the industry as:

> "Through petro-hegemony, the fossil fuel industry produces conditions of consent to its operations by disseminating and reinforcing favorable narratives and public discourse that shape "common sense." Where it loses consent, it represses or circumvents dissent through its access to the coercive resources of the state, such as legislation, regulatory agencies, or militarized police forces. And finally, by blurring the distinction between consent and coercion, the industry manufactures compliance by structuring economic dependency upon its product, tax revenue, and jobs" (LeQuesne 2019b:18).

LeQuesne 2019b asserts that these strategic interventions are wielded by fossil fuel companies as they "advance their interests in purportedly democratic governance systems that have been captured by fossil fueled interests" (LeQuesne 2019b:18). In this view, therefore, the companies wield enormous power in their ability to 'capture' or interject in policy making.

Moreover, as evidence of the use of coercion—and against the State having a full monopoly on violence—the oil and gas industry has similarly leveraged violence to protect its interests, sometimes in coordination with the state. The oil industry has often coordinated with the state to secure its ventures at 'oil frontiers' (Watts 2015). For example, at Standing

Rock, Energy Transfer Partners, operator of the Dakota Access Pipeline, hired a security firm (TigerSwan) to protect its interests. TigerSwan infiltrated the camp and used force to suppress protest (LeQuesne 2019a). Turning to Nigeria, Shell has been extracting oil for decades in Ogoniland in the Niger Delta. The Shell Petroleum Development Company of Nigeria (SPDC) "…maintains what is colloquially referred to as the 'Shell police'…a special detachment of the Nigeria Police Force 'who are on attachment to Shell Nigeria and guard the company's residential, office and industrial areas and…provide escort duties in areas of high risk.'" SPDC has imported firearms on behalf of the Shell police and "Shell helicopters and boats have transported members of the Nigerian security forces. In 1987, for example, the company transported members of the Mobil Police Force (MPF) to a demonstration at Iko in Akwa Ibom State…the MPF killed two people and destroyed 40 houses" (Pegg 1999:475). While the state may in name have the only legitimate hold on violence, it has largely been allowed to be wielded by such firms.

These firms have also wielded certain forms of power to avoid the second moral norm: 'clean up your own mess.' Levy and Egan 1998 present three forms of power—structural, discursive, and instrumental—which reinforce one another (Levy and Egan 1998:342). Structural power includes the state dependence on the firm that is created, including jobs, taxes, and votes. Therefore, it is "structurally dependent on private sector profitability" (Levy and Egan 1998:342). To create or reinforce that dependence, firms may wield instrumental power, such as via lobbying through trade associations or creating PACs to finance campaigns, as well as creating campaigns or astroturf groups (organizations that appear to be 'grassroots' groups but are in fact sponsored by a larger entity) to gain social legitimacy (Walker and Rea 2014). Finally, using discursive and cultural tactics, firms can reinforce narratives and frames that gain social legitimacy for structural reliance (Wright and Nyberg 2014; Levy and Egan 1998). Discursive power can work on the same medium as instrumental, such as in schools or the media (Levy and Egan 1998:342). These forms of power reinforce one another—turning back to Freudenburg's (2005) 'privileged accounts', such an account of the firm providing an economically necessary service in providing jobs is wielding discursive power to entrench structural power. Firms could wield these forms of power to avoid emissions and pursue action to address existing harms. Instead, ample evidence has indicated they have used such forms of power to avoid those ethical norms.

Petro-hegemony and the wielding of these forms of power is well-documented in the literature (Mulvey et al. 2012; Frumhoff et al. 2015). Most evidence points to the discursive and instrumental power wielded by companies; Box 3 demonstrates this for ExxonMobil. Fossil fuel companies have wielded discursive power to cast doubt on the science of climate change, contributing to the 'politicization of science' (Bonneuil et al. 2021; Supran and Oreskes 2017; Oreskes and Conway 2010; Frumhoff et al. 2015). Discursive power has also been wielded as privileged accounts to set the realm of possibility for climate action, paving the way for instrumental power (Frumhoff et al. 2015; Lamb et al. 2020; Supran and Oreskes 2021). These include discourses which frame fossil fuels as necessary for advancing social justice and economic development, which cast responsibility for emissions onto individual consumers, or which advance 'solutions' that allow for the continued extraction of fossil fuels or that are politically, physically, or economically impossible. Firms then wield instrumental power, by which much of this discursive power has been amplified through creating front groups, by lobbying, and by contributing financially to electoral campaigns (McBeath 2016; Brulle 2019; Mulvey et al. 2016). Finally, firms have used structural power to maintain widespread use of their product, while states have allowed it. As compared to other sources of CO_2 emissions, there are alternatives available for energy production. However, through controlling available technological alternatives, multiple fossil fuel corporations have worked to fight those alternatives (Frumhoff et al. 2015).

Box 3: The Exxon Example

Greenpeace ran a sting operation in 2021 where they hoodwinked Keith McCoy (a lobbyist for Exon) and Dan Easley (ex-senior director for federal relations at Exxon) into talking about various strategies implemented at ExxonMobil (Carter 2021):

I. McCoy admitted that Exxon fought some of the science, "Did we aggressively fight against some of the science? Yes. Did we hide our science? Absolutely not. Did we join some of these shadow groups to work against some of the early efforts? Yes, that's true. But there's nothing illegal about that. You know, we were looking out for our investments, we were looking out for our shareholders."

II. McCoy discussed the use of carbon pricing as a rhetorical tool to delay climate action: "Nobody is going to propose a tax on all Americans and the cynical side of me says, yeah, we kind of know that but it gives us a talking point that we can say, well what is ExxonMobil for? Well, we're for a carbon tax…" They have pushed for this while knowing: "Yeah. No, it's not. Carbon tax is not going to happen."

III. McCoy then described the strategy for lobby lawmakers, saying "On the Democrat side, we look for the moderates on these issues. So it's the Manchins. It's the Sinemas. It's the Testers."

IV. Dan Easley highlighted the wins under Trump, explaining how “Tax has to be the biggest one, right. The reduction of the corporate rate was, you know, it was probably worth billions to Exxon.”

These quotes highlighted how the company wielded instrumental power (through lobbying and participating in shadow/front groups), discursive power through promoting climate doubt and delay messages (fighting some of the science discursively and pushing for carbon pricing), and structural power (through the federal administration granting tax breaks).

Exxon’s wielding of discursive power through promoting climate denial, doubt, and delay is well documented (Supran and Oreskes 2017; Supran and Oreskes 2021). In particular, the frame employed by Exxon which tries to individualize responsibility is a well-known tactic, as “a policy focus on consumption is almost always the easy path: It generally absolves industry and the state of responsibility for a host of problems” (Gould, Pellow, and Schnaiberg 2004:303). In Santa Barbara County, in California, Exxon has funded large advertising campaigns targeting voters (MacDonald 2020) and aimed to sponsor the local university’s alumni reunion (UCSB 2019) to promote its agenda. Exxon meanwhile continues to plan to produce more oil (Storrow 2020), including in Santa Barbara County (Welsh 2022).

4.3.3. The American Electric Utility Industry

A less often studied yet important industry to consider is the electric utility industry. Unlike nation-states and the oil and gas industry, the electric utility industry is only a producer, and not an extractor. The industry instead coordinates with extractors and suppliers. The coal, rail, and utility industries are so deeply interconnected that the first two are referred to as the coal-rail-steel industry, and that coal-rail-steel and electric utilities are uniquely intertwined in the CCCM (Brulle 2019). For example, Western Fuels Association (WFA) exists to serve coal providers, transportation services, and coal-fired utilities. In the modern context, this interestingly places coal companies more closely to the electric utility industry than to the oil and gas industry. While the fossil fuel industry in the U.S. is comprised mostly of autonomous organizations, the electric utility industry seemingly coordinates more frequently among its members. This is evidenced by dues-paying membership in the trade association, Edison Electric Institute, and the lobbying organization, the Utility Air Resources Group (UARG).

Has the electric utility industry failed the norms of 'do no harm' and 'clean up your own mess'? As described in the contributions section, compared to the U.S. as a producer and consumer and the oil and gas industry, the electric utility industry has contributed a significant, albeit smaller, amount to global emissions. The industry has also generally become less emissions-intensive over time yet continues to rely significantly on fossil fuels. Approximately half the sector is either subject to state laws or executive orders for 100% carbon-free electricity or has individually pledged to go carbon-free by 2050 (LBL 2021), while emissions intensity in electricity production has generally fallen (Freedman and Jaggi 2004). Yet, the industry is not on track to meet these targets, with some of the largest electricity producers continuing to have high emissions intensity in generation (Romankiewicz, Bottorff and Stokes 2020; Galli Robertson and Collins 2019).

Did the industry know about the climate effects of fossil fuel-powered electricity generation? If so, what did it do with that knowledge? While this has been studied extensively for the oil and gas industry in academic literature and investigative reporting, and while it is known the electric utility industry has been a central part of the CCCM, less attention has been given to the American electric utility industry. Two reports, however, have indicated that like the oil and gas industry, the electric utility industry knew of the link between its actions and climate change and sought to sow doubt and entrench its reliance on fossil fuels (Anderson et al. 2017; Triedman et al. 2019).

Here, I present a co-authored analysis of the American electric utility industry's role in creating a public debate regarding climate change[9]. While the two reports examined what certain organizations within the industry knew about climate change, when, and what they did with that knowledge (Anderson et al. 2017; Triedman et al. 2019), there are few systematic academic analyses on the industry's activities with regards to climate denial (Stokes 2020). Yet, one of the largest climate disinformation coalitions in the CCCM, the Global Climate Coalition (GCC), derived over a quarter of their members from electric utility industry organizations. The Information Council on the Environment (ICE), a short-lived climate denial campaign whose primary goal was to "reposition global warming as theory (not fact)," was composed solely of electric utility organizations (Brulle 2019; Informed Citizens for the Environment 1991). The Greening Earth Society (GES), a somewhat longer-lived climate denial campaign, was founded by WFA.

For the purposes of this paper, participation in the public discourse on climate change includes both statements regarding the existence, causes, and impacts of climate change, as well as the solvability of the problem. A well-documented strategy to undermine climate

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[9] This research was conducted in collaboration with Dr. Leah Stokes, Emma Swanson, and Sydney Bartone.

science and action is to deny or sow doubt regarding the scientific consensus on climate change (Oreskes and Conway 2010; Franta 2021; Supran and Oreskes 2017). Another pervasive strategy is to use messaging to justify delaying, or avoiding, action on climate change, including framing climate action as antithetical to social justice, placing responsibility for climate action on individual consumers, and framing the continued use of fossil fuels as necessary, inevitable, or unavoidable (Lamb et al. 2020; Supran and Oreskes 2021; Freudenburg 2005). Collectively, rhetorical strategies which cast doubt on the existence, causes, or impacts, or that wield privileged accounts to cast doubt on the solvability of climate change, affect media coverage, public opinion, and the likelihood of political action (Stokes 2020; Freudenburg and Muselli 2010). Moreover, messaging or information that is not in-line with the scientific consensus is misinformation, yet if that misinformation is knowingly shared, it is disinformation (Lewandowsky 2020).

To determine whether the American electric utility industry promoted messaging that was in-line with the scientific consensus on climate change, or whether they played a role in spreading climate misinformation or disinformation, we undertook a systematic analysis of messaging in public-facing industry documents. We analyzed utility industry documents which were authored by individual electric utilities, trade associations, affiliated research groups, and front groups. Electric utilities are the individual companies, nonprofits, or cooperatives who produce and distribute electricity. Trade associations represent the interests of their constituent electric utilities in matters of public policy. Finally, front groups include both campaigns and coalitions that are generally short-lived organizations designed to advance certain messaging.

Methods

We undertook an analysis of 188 primary documents authored by 26 organizations within or involving the American electric utility industry published between 1968 and 2019 (Figure 2). All documents in the sample reference climate change and are either authored by, or use direct quotes from, electric utility industry companies, research groups, trade associations, or other organizations in which electric utilities held, or currently hold, membership or provided funding.

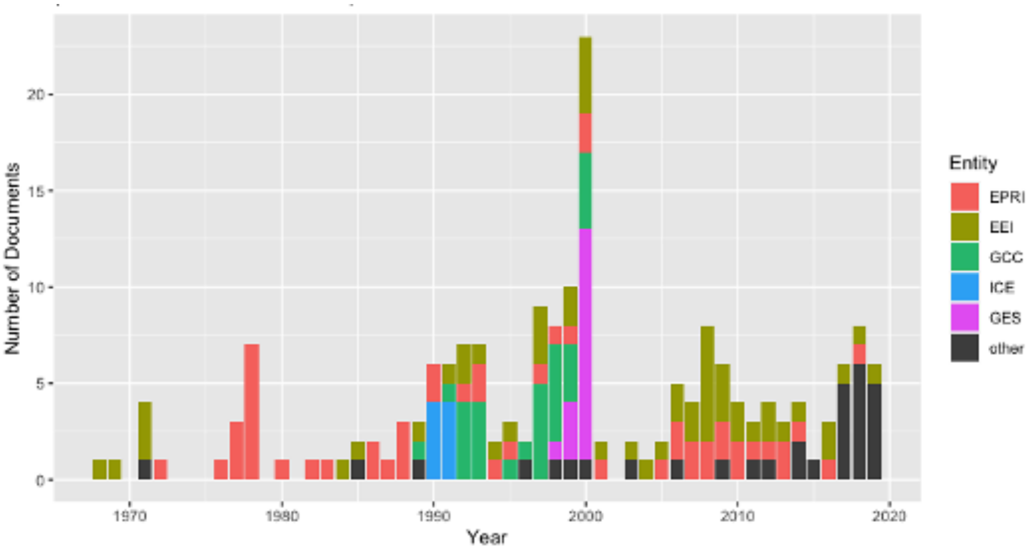


Figure 2. Bar chart of the temporal coverage of the coded document sample. Temporal spread of each of the main five entities are depicted.

Primary documents, authored by the electric utility industry, were retrieved from two online repositories—the Climate Investigation Center and Climate Files—and a report compiled by the Energy and Policy Institute (Anderson et al. 2017). After gathering this initial sample, we assessed the temporal coverage of the documents for each organization. For the relatively short-lived campaigns and coalitions—GCC, ICE, and GES—we built a temporally representative sample, or all available documents were included in the analysis. However, we identified temporal gaps in the sample for the Edison Electric Institute (EEI) and Electric

Power Research Institute (EPRI). EEI is the trade association for the investor-owned electric utility industry, in which most individual utilities hold membership. EPRI, as the research arm of the industry, conducts and publishes analyses, including on climate science and its implications for the industry. To build a temporally representative sample of external communications from these two organizations, we drew a random sample of articles from their periodicals, *Electric Perspectives* and *EPRI Journal*, that mentioned the terms “climate change”, “global warming”, “carbon dioxide”, “greenhouse gas”, or their acronyms. After adding this final set of documents, a temporally representative sample size was reached for five organizations: EPRI, EEI, GCC, ICE, and GES.

Documents were analyzed using Atlas.TI, a qualitative analysis software. All documents were classified by “author” (the organization who authored the document), “type” (whether the document is internal, external, public-facing, or compliance-based), and year of publication. A coding scheme (Table 2) was developed, modelled on the approach introduced in Supran and Oreskes (2017) and incorporating discourses of climate delay introduced by Lamb et al. (2020). The coding scheme was used to classify statements in the documents regarding the existence (Endorsement Points, EP), cause (Human-caused Points, HP), and impacts (Impact Points, IP) of climate change, as well as the solvability of climate change (Solvable Points, SP) and whether legislation was supported or not (Lobbying Points, LP). Each code category was designed to contain mutually exclusive levels (i.e. a document could only receive one code from each category).

Table 2. Coding Scheme

Code Category	Code	Description
Endorsement Points (EP): Is the climate changing or will it change in the near future?	EP1	The climate is significantly changing - or will significantly change.
	EP2	The climate may be currently changing or may change in the future.
	EP3	The climate is not changing and will not change.
Human-Caused Points (HP): Is human activity, primarily via the burning of fossil fuels, causing the climate to change?	HP1	Human activity (specifically fossil fuels) is the primary cause of current or projected climate change.
	HP2	Human activity may cause current or projected climate change.
	HP3	Human activity is not causing current or projected climate change.
Impact Points (IP): On the whole, are the current or projected impacts of climate change serious and negative?	IP1	The impacts of climate change are, or will be, primarily bad.
	IP2	The impacts of climate change may be bad, but we don't know yet.
	IP3	The impacts do not or will not exist, are or will be overstated, or the benefits will outweigh the costs.
Solvable Points (SP): Is climate change solvable?	SP1	Climate change is solvable. If responsibility is mentioned, it is specified that it is the (partial) responsibility of utility companies to solve.
	SP2	Climate change may be solvable, but it should be addressed when more is known, it is the (primary) responsibility of another entity, or fossil fuels are necessary, so solutions include technological innovation to capture carbon.
	SP3	Climate change is not solvable.
Lobbying Points (LP): What type of climate action is supported?	LP1	Argues in favor of legislation, regulations, or treaties designed to act on climate change, primarily by reducing emissions.
	LP2	Argues in favor of voluntary action on climate change only (can be in conjunction with lobbying against climate regulations).
	LP3	Argues against climate legislation, regulations, or treaties.

Coding was conducted in two rounds; in each round, each document was coded independently by two separate coders (double coding) to test for intercoder agreement (ICA). The first round of coding identified the relevant passages and the relevant code categories for each document. In the second round, each passage was coded, and then document-level codes were assigned based on the frequency of passage-level codes used. For the document-level codes that did not achieve ICA, a third coder independently coded the document, and the most often applied code was ultimately assigned to the document. An ICA of 92% was reached for the EP, HP, and IP codes on the document-level codes; an ICA of 88% was reached for the SP codes, while the LP code category was excluded from the quantitative analysis due to non-mutually exclusive code levels. Of the 188 documents analyzed, 151 were coded with at least one code (the remaining documents mainly provided background information on the organizations).

Unique code combinations were reclassified into messaging categories: acknowledge, delay, doubt, and deny (Table 3). "Acknowledge” documents acknowledged that the climate is changing or will change (EP1), that human activity is the primary cause (HP1), and/or that impacts are primarily bad or unknown (IP1 or IP2). “Doubt” documents conveyed uncertainty that climate is changing or will change (EP2) and/or uncertainty as to whether human activity is the primary cause of that change (HP2). “Deny” documents either denied that the climate is changing or will change (EP3), denied that human activity is the primary cause of that change (HP3), or denied that there will be significant impacts (IP3). Finally, “delay” documents acknowledged the scientific consensus (EP1, HP1, IP1/2), but questioned the solvability of climate change, using rhetoric to deflect, delay, or distract (SP2/SP3).

Table 3. Messaging Categories.

	Science Questions			*Policy Questions*
Category	**Is the climate changing / projected to change?** *(Endorsement Points: EP)*	**Is human activity the primary cause of climate change?** *(Human-Cause Points: HP)*	**Are the current or projected impacts of climate change serious?** *(Impact Points: IP)*	**Is climate change solvable? If so, does the industry have a responsibility to reduce emissions?** *(Solvable Points: SP)*
Acknowledge: Document must acknowledge / endorse all science questions.	The climate is changing / projected to change (EP1).	Human activity is the primary cause of current or projected climate change (HP1)	The impacts of climate change are, or will be, primarily bad (IP1).	It is solvable, and the (partial) responsibility of utility companies (SP1). OR n/a.
Delay: Document must acknowledge / endorse all science questions.	The climate is changing / projected to change (EP1).	Human activity is the primary cause of current or projected climate change (HP1)	The impacts of climate change are, or will be, primarily bad (IP1).	More research is needed before taking action, it is the (primary) responsibility of another entity, or solutions must include continued use of fossil fuels (SP2). OR Climate change is not solvable (SP3).
Doubt: Document must doubt at least one science question. It may acknowledge the others.	The climate may be currently changing / may change in the future (EP2).	Human activity [may be the cause] [is the cause] of climate change (HP2).	The impacts may be bad (IP2).	n/a
Deny: Document must deny at least one science question. It may acknowledge or doubt the others.	The climate is (will) not changing (change) (EP3).	Human activity is not the cause of climate change (HP3).	The impacts do/will not exist, are overstated, or the benefits will outweigh the costs (IP3).	n/a

Finally, to compare messaging of closely related organizations, we built a network map, showing the relationships between organizations, including founding, funding, and participating in organizational activities. To map the network, we identified organizational connections in the full document sample, in two gray literature reports (Anderson et al. 2017; Triedman et al. 2019), from online repositories, and from Brulle (2019).

Results

Tracing the Industry's Public Climate Statements

If utility public communication tracked with the scientific consensus on climate change, we should not expect to find evidence of doubt regarding the existence and cause of climate change after 1990 at the latest. The industry had access to, and in some cases conducted, climate science before this time, and therefore would be aware of the climate science developments of the 1980s. For example, EPRI authored an internal memo in 1977 stating "the atmospheric CO_2 concentration is projected to double (to ~600ppm) by the year 2030. A simplistic climate model developed at Princeton predicts a 2°C increase in the global mean temperature if CO2 is doubled" (Hakkarinen 1977). This prediction remains largely correct, more than four decades later.

However, our analysis indicates that, on average, the industry communicated doubt and denial throughout the 1990s, after the scientific consensus was established (Figure 3). Doubt documents are the most common documents in the early part of the study period, when uncertainty could be considered reasonable; however, the average year for doubt documents is 1986, where nearly half are found after Hansen's 1988 testimony (Figure 3). Moreover, denial documents are centered in 1996, indicating a shift from doubt to denial during the time the scientific consensus on climate change became public. After 2000, documents in our sample shifted primarily towards communicating delay. During this time, while most (95%) documents implicitly or explicitly acknowledged the existence and human cause of climate change, over half of the documents contained "delay" rhetoric, deflecting responsibility onto other countries or sectors or arguing for the necessity of continued reliance on fossil fuels for electricity generation (described later).

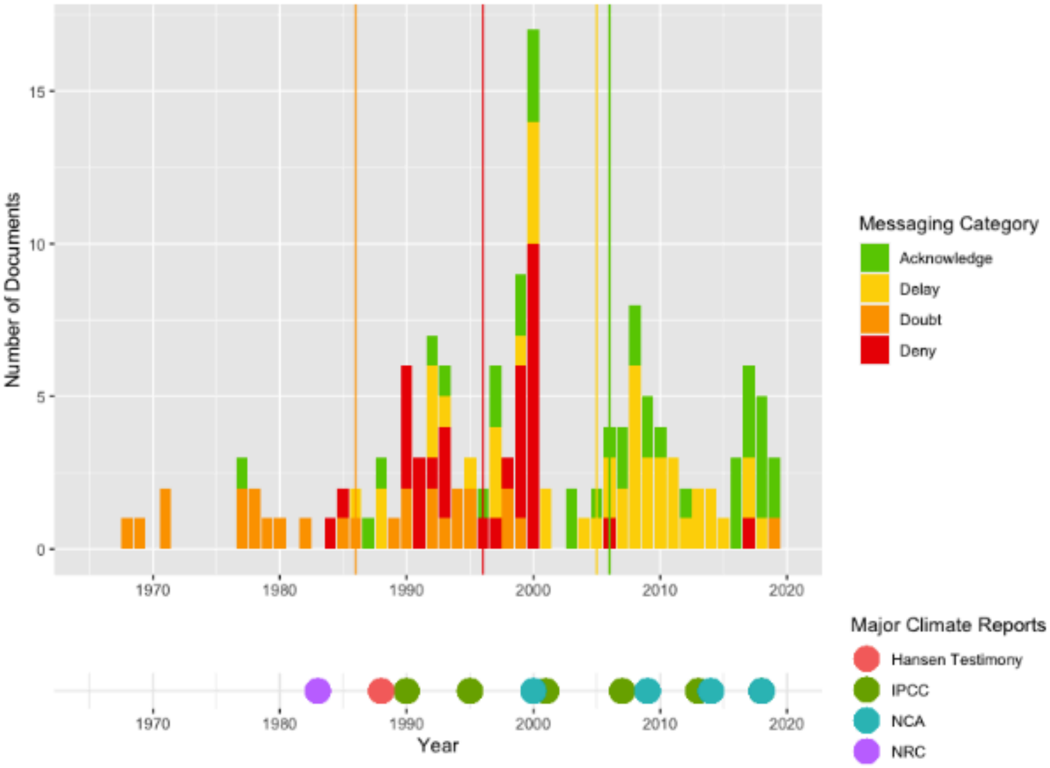


Figure 3. *Temporal distribution of categorized codes for all documents. Taking the average year for documents in each messaging category, acknowledge documents are centered in 2006, delay documents are centered in 2005, doubt documents are centered in 1986, and deny documents are centered in 1996 (years indicated as vertical lines). Major climate reports are shown (bottom) from the IPCC (green), National Climate Assessment (teal), National Research Council (purple), and Hansen congressional testimony (red).*

Comparing Organizations' Public Climate Statements

To examine how individual organizations within the industry communicated publicly about climate change, we examined external-facing documents for five main utility organizations active in our sample. With the exception of GES, each of the primary five organizations is or was connected to one-another (Figure 4). EEI was one of many co-founders of GCC, and both EPRI and EEI were active participants in GCC's Science and Technology

Assessment Committee (STAC) meetings. Moreover, EEI was one of the co-founders of ICE. Finally, WFA founded GES; while there is no direct link between GES and the other primary organizations, WFA was a co-founder of ICE and GCC alongside EEI.

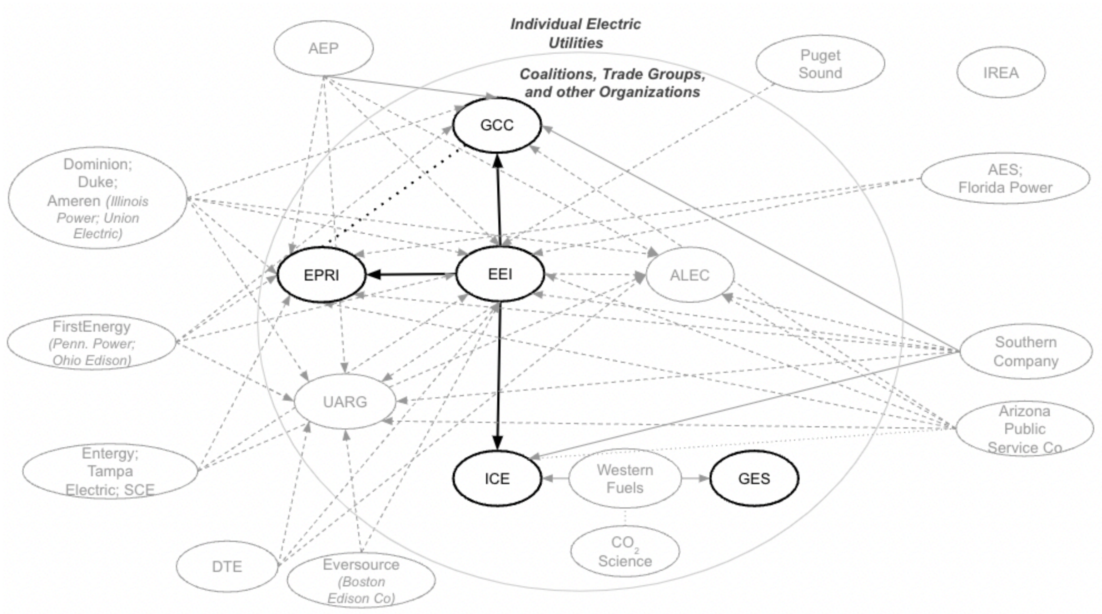


Figure 4. Organizational network map depicting relationships between organizations in the document sample. Network map includes all utility organizations represented in the sample. The five organizations focused on in this study are in black; the rest are grayed out. Solid arrows indicate (a) (co)-founded, is/was a member of (if applicable), and participated in meetings and communications of, (b); dashed arrows indicate (a) is a member of and participated in meetings or communications of (b); dotted lines indicate (a) and (b) participated in meetings or communications together. Several caveats exist. All depicted UARG links are valid for 2017, while all links between organizations and ALEC are included, regardless of year of involvement.

Figure 5 shows the messaging used by each of the five organizations over time. As GCC, ICE, and GES were founded in the late 1980s and early 1990s, and dissolved before 2000, the time periods when these organizations do not exist are shown in black. Comparison across all five organizations is only possible in the 1990s. From 1990-2000, in our sample, both EPRI and EEI had mixed communications that mostly included doubt, with some denial, delay, and even acknowledgment. However, during this same period, the front groups that represented the industry—GCC, ICE and GES—all spread climate denial. As ICE and GCC were cofounded by EEI (Figure 4), this suggests that the electric utility industry, like its counterparts in the oil and gas industry, used front groups to spread climate denial while official industry organizations messaged doubt while occasionally acknowledging the scientific consensus. These front groups were short-lived, all dissolving before 2000. After 2000, official industry organizations messaging transitioned to a mix of acknowledgement and delay.

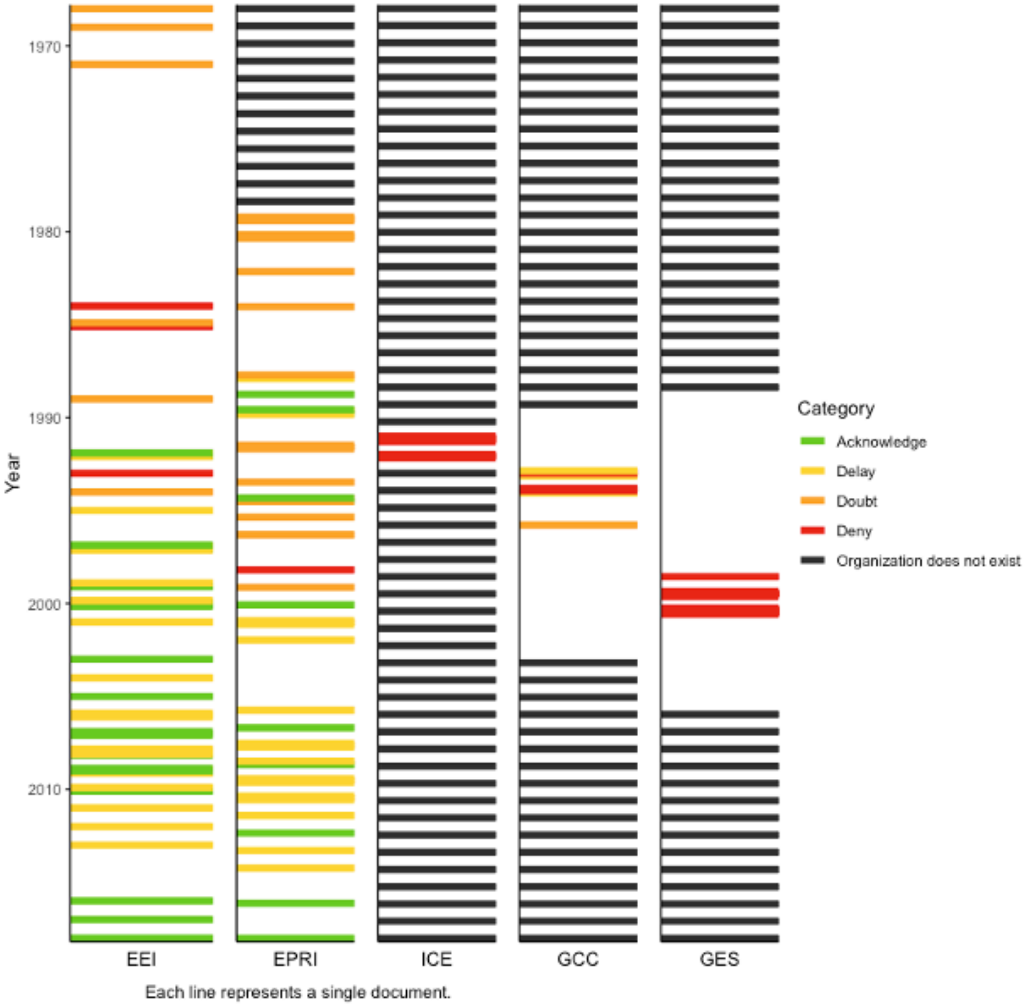


Figure 5. Temporal distribution of categorized codes for primary entities. Years before an organization's founding or after its dissolution are shown in black.

Examining the Electric Utility Industry's Climate Messaging over Time: EEI and EPRI

Given the long temporal coverage of EEI and EPRI documents, it is possible to examine how messaging changed over time for both organizations in our sample. Before 1990, both EEI and EPRI largely communicated doubt about climate change. Yet, even as the scientific consensus on climate change had crystalized, both organizations continued to communicate doubt, with some messages communicating denial and delay, throughout the 1990s. By the 2000s, both EEI and EPRI shifted towards delay, as they more frequently acknowledged the scientific facts of climate change. Since around 2015, both organizations' messages have focused on acknowledging climate change. In this section, we unpack both EEI and EPRI's messaging on climate change over the past 50 years in greater detail.

In the 1970s, both EEI and EPRI recognized that should climate change be proven to be real and human caused, the implications for the industry would be enormous. For example, a 1977 EPRI Journal article stated: "if [climate change turned] out to be of major concern, then fossil fuel combustion will be essentially unacceptable" (Comar 1977). Similarly, in 1971, EEI's bulletin published an article which stated: "[i]f we had to stop producing CO_2, no coal, oil, or gas could be burned, and all modern societies would come to a halt. The only possible alternative is nuclear energy…" (Wilson 1971). During this period, EPRI and EEI documents generally emphasized that, despite the remaining uncertainties in climate science, action should not be delayed given the serious nature of potential climate impacts, and moreover that waiting to know more would mean waiting until it is too late to avoid those consequences. For example, a 1978 EPRI Journal article ended by quoting scientist William Kellog saying, "If we wait to let the atmosphere perform the carbon dioxide experiment…it will be too late to do much about it if a warmer earth should prove to be a sadder earth" (Terra 1978).

Doubt/uncertainty continued into the 1980s. However, unlike the trend during the 1970s, during the 1980s, EPRI and EEI began to communicate the need for more research on climate before acting. An EPRI article from 1986 juxtaposed the viewpoints that “we do know enough to mitigate the greenhouse effect” and “we have to conduct a lot more scientific research before we do anything else” (Shepard 1986), while the same year, an EPRI Journal editorial, discussing “whether to limit emissions of CO_2 and other greenhouse gases”, argued that the “decision will be easier to make and will be better designed if we know more about the science of the issue” (EPRI 1986). A 1989 EEI article stated similarly “we believe that any plan calling for urgent and extreme action to reduce utility CO_2 emissions is premature at best”, and instead called for “increased electrification, conservation, and energy efficiency while continuing to increase our scientific knowledge base on the issue” (McCollam 1989). EPRI and EEI journal articles also began deflecting focus and responsibility onto other entities, as articles emphasized the global nature of the climate problem, the emissions of developing countries, and how the U.S. electricity industry only represents a small percentage of total global emissions. At this time, the U.S. emitted nearly a quarter of global emissions (Global Carbon Project 2020), while the electricity sector contributed to approximately 30% of U.S. emissions (EPA 2021).

By the 1990s, EEI and EPRI documents contained a wide variety of messages: including denial, doubt, and delay. Both EPRI and EEI consistently acknowledge that human activity is the main source of CO_2 emissions. However, in the early 1990s, EPRI focused on the need for more research, while EEI published a denial piece asserting that the data "show cooler days, warmer nights, and better vegetables" (Michaels 1993). By the late 1990s, there was a push for voluntary actions in lieu of binding regulations. This argument was focused in particular on the international climate negotiations that culminated in the Kyoto Protocol, where the industry argued that the U.S. should not need to reduce emissions while other countries continue to emit. EEI published an article in 1997 that argued that the renewable energy required by "even the most modest climate treaty proposal" would leave the electricity sector unable to meet current U.S. energy demand (Edison Electric Institute 1997). EEI instead offered their proposal for climate action in the form of a "portfolio of voluntary climate change actions" (Edison Electric Institute 1999). EEI's stance at the turn of the century was that the targets in the Kyoto Protocol were "unrealistic" and that in order to "[stabilize] atmospheric concentrations of greenhouse gases cost-effectively over the long term…we should focus our near-term efforts on conducting an accelerated climate technology research, development, and deployment program" (Novak 2001). This push for R&D for emissions reducing technology set the tone for the next two decades.

By the 2000s, EEI and EPRI no longer communicated doubt or denial; instead, both frequently argued to delay action on climate. Language deflecting focus onto the emissions of other countries and sectors was still used in EPRI and EEI documents in the early 2000s, though less than in the prior two decades. Instead, after 2000, EEI and EPRI presented carbon capture and storage as the most promising solution to climate change, arguing that because "half of U.S. electricity comes from coal combustion, any policy to reduce electricity's carbon footprint will rely on carbon capture and storage (CCS)" (EPRI 2010). As such, these documents argued that climate action must focus on pursuing "clean coal" via gasification (IGCC) and CCS. From 2000-2019, "clean coal" technologies are discussed the same amount as carbon free energy technologies (word count: CCS and IGCC, n=658; renewable, solar, wind, geothermal, and nuclear, n=654). While most current 'roadmaps' for required emission reductions activities include some form of CCS to meet targets, in these scenarios, the technology accounts for less than 5% of total energy generation by 2040 (and is used for natural gas); instead, these ‘roadmaps’ all highlight decarbonizing energy sources, promoting energy efficiency, and pursuing electrification as the primary necessary activities to be pursued (Larson et al. 2020; Williams et al. 2021; IEA 2021b). Moreover, after more than 40 years of research by EPRI and EEI, CCS has not become scalable. A 1980 EPRI-commissioned study stated that “no cost-effective means has yet been found for storing the captured carbon over long periods to keep it from returning to the atmosphere”, a 1984 EEI-commissioned study reported that “controlling carbon dioxide emissions by scrubbing stack gas…is not economically feasible”, and nearly three decades later, EPRI noted that, still, “current technologies for CO_2 capture are very expensive” (Shepard 1986; Jarratt and Coates 1984; Hannegan 2011). In 2019, there were only 10 commercial CCS facilities in the U.S., only one of which was in the power sector (Beck 2020). This facility was later suspended in 2020, and as of 2021, there are no commercial-scale CCS facilities in the power sector (Global CCS Institute).

Only in the last few years have these organizations’ statements more consistently acknowledged the scientific consensus on climate change and the need for transitioning the fuel mix away from fossil fuels. After 2015, all EPRI and EEI documents in our sample communicated acknowledgement.

Discussion & Conclusion

In this analysis, we examined the American electric utility industry’s public positions on climate change, tracing patterns in public messaging denying, doubting, or acknowledging climate change, or arguing for delayed action. Over the course of our study period, rather than matching the development of the consensus on climate change—which would transition from doubt to acknowledgement—utility organizations' public messaging transitioned between doubt, denial, and delay.

Our findings indicate that, like other organizations in the CCCM, before 2000, American electric utility organizations actively misled the public on the science of climate change, contributing at times to disinformation. While official organizations in the industry knew about the science of climate change as far back as the 1970s, from 1990 to 2000, they used rhetoric publicly to cast doubt on climate change and founded, funded, and engaged in campaigns and coalitions that denied the existence of climate change.

We find that after 2000, while EEI and EPRI no longer publicly doubted or denied the existence of human-caused climate change, these official organizations turned to arguing for delayed action. This rhetoric employed many 'discourses of climate delay' as identified by Lamb et al. (2020), such as deflecting focus onto other countries and sectors and uplifting approaches such as CCS to reduce the emissions intensity of coal, rather than transitioning from coal. This rhetorical shift—from doubt to delay—was similarly identified in ExxonMobil's communications by Supran and Oreskes (2021), with the shift occurring in the mid-2000s and employing rhetoric to frame climate action as a socioeconomic threat, refer to fossil fuels as necessary, and deflect responsibility onto consumers. While delay-based messages do not promote doubt regarding climate science, they have a similar effect—such "privileged accounts" set the norm for what is considered 'necessary' and, therefore, the extent of what is considered politically possible (Freudenberg 2005). In this case, the delay rhetoric justifies a continued reliance on fossil fuels.

By the end of the study period, the industry organizations included in our sample increasingly acknowledged the scientific consensus and began to accept that climate action was necessary. For example, in 2018, the CEO of the public utility, Edison International, wrote in EEI's Journal, Electric Perspectives, that "We need myriad resources and stakeholders to address climate change, but I believe electric companies are central figures. Only electric companies have the size and resources to implement clean energy initiatives on a significant scale" (Pizarro 2018). However, this trend does not apply to all organizations in the industry. For example, a 2014 report prepared for the American Coalition for Clean Coal Electricity, now America's Power, asserted that the science was too uncertain to project any global warming from increased emissions, while simultaneously asserting that increased emissions will lead to improved human health from warmer weather and crop benefits from CO_2 enrichment (Management Information Services 2014). Similarly, in 2017, the CEO of Southern Company—one of the largest utility companies in the country, member of EEI, and founding member of GCC and ICE—responded in an interview that he did not believe CO_2 is the primary cause of climate change as climate change has been happening for millennia (Belvedere 2017).

The shift in rhetoric toward the end of the study period has not corresponded to a shift in the industrywide energy mix. Fossil fuels still comprise 60% of the U.S. electricity mix (EIA 2021a). As of 2020, 79 utilities, responsible for 68% of current U.S. coal-based electricity generation, have only pledged to retire 25% of that generation by 2030, while 32 utilities have plans to build over 36 GW of new gas plants. These same utilities have also only pledged to add renewable electricity generation equaling 19% of current coal and gas generation (Romankiewicz, Bottorf, Stokes 2020). Moreover, the industry has spent over $500 million lobbying against renewable energy and climate policy over the past two decades (Brulle 2018, Mildenberger 2020, Stokes 2020). During this time, the Utility Air Regulatory Group (UARG), whose membership included EEI (see Figure 4), filed a legal brief against Massachusetts vs EPA, supporting the EPA's position to not consider GHGs as air pollutants (Lazarus 2020:150), then later sued the EPA regarding regulating emissions from stationary sources (UARG vs EPA), and later fought the Clean Power Plan in court. UARG ultimately dissolved in 2019 following a Senate investigation.

The International Energy Agency's 2021 report indicates that further investment in fossil fuels must be halted, putting the industry's current plans at odds with federal agency recommendations and robust science. Whether industry's messaging during the last part of the study period will correspond with measurable emissions reductions remains to be seen.

Box 4. What About Our Carbon Footprints? Part 2.

Individuals today make emitting decisions with access to the full knowledge of the climate implications of those decisions. Yet there is a broad web of structural and cultural factors that mediate the extent to which individuals choose to, or even can, change their practices. To put it bluntly, individuals do not make decisions as rational actors, but are rather influenced by broader structures.

Moreover, the individualization of the question of responsibility falls straight out of the oil industry's handbook (Oreskes and Conway 2010). For example, BP released a television ad in 2003 which encouraged you, the consumer, to do more to reduce your carbon footprint, and ended the ad by providing you with a link to their carbon footprint calculator. Toward the end of the ad, the text reads: "We can all do more to emit less. Over the next 4 years, we’re planning to implement projects to reduce emissions by another 4 million tonnes” (BP 2003). The implication is that ‘if BP is working to reduce emissions by 4 million tonnes, you, the consumer, can do more to reduce your own emissions.’ To put that figure—4 million tonnes—in context, by the company’s own estimates, BP’s operations amount to “around 55 million tonnes of CO2 equivalent (MteCO2e) a year, and the carbon in the oil and gas that it produces, equivalent currently to around 360 MteCO2e emissions a year” (BP 2020). ExxonMobil also popularized the individual carbon footprint rhetoric, shown in a peer-reviewed empirical analysis (Supran and Oreskes 2021). Supran and Oreskes 2021 find that ExxonMobil’s “…advertorials disproportionately employ terms that present consumer demand for energy (rather than corporate supply of oil, coal, and gas) as the cause of fossil fuel production, greenhouse gas emissions, and/or [climate change] … [and] disproportionately introduce terms conveying individual and/or demand-side actions as the appropriate response” (Supran and Oreskes 2021:707-708).

The individualizing responsibility frame works particularly well within more individualistic Western societies. As Francis 2020 explains, discussing the view of the nation-state as a site of responsibility, many incorrectly assume that “…a nation’s responsibility is simply the sum of the responsibility of its members and that holding nations responsible just is to hold their members responsible... It is straightforwardly consistent with moral individualism as well as methodological individualism, the doctrine that the explanations of social phenomena must be given exclusively in terms of individual agency and action... Nations have tolerated and even encouraged high-emitting activities for decades through corporate actions empowered by the rule of law…Individual emitters living in wealthy nations act against the backdrop of social, economic, and physical infrastructure conducive to high-emitting lifestyles."

This does not imply that individuals bear no responsibility. Granting individuals immunity from emitting actions further separates humans from their environment and community, breaking down relationships of reciprocity. It is not an either/or. It is an 'all of the above'. Yet quite often the focus is on an either/or, and generally is found in favor of focusing on individuals. If a site is to be chosen on which to focus for pursuing accountability, should it not be with the site where the structural power has led to outsized effects?

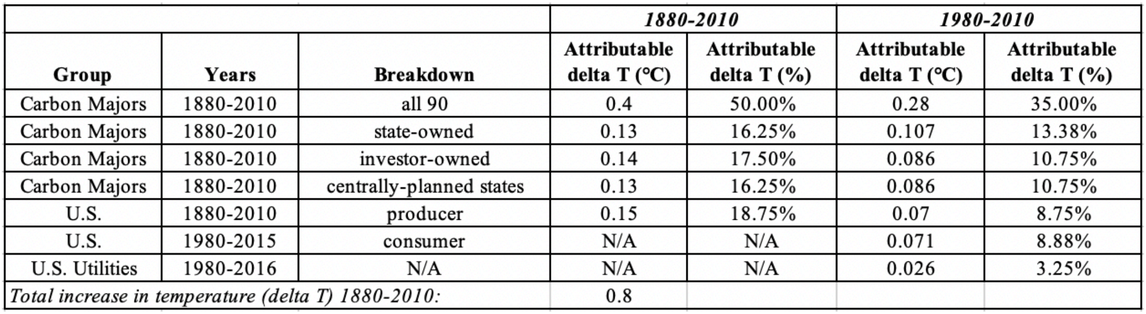
4.4. Source Attribution

The previous sections traced the generalized responsibilities of certain major emitting actors (the U.S. nation-state, Carbon Majors, and electric utilities) in contributing to climate change. For these actors, what are their particularized responsibilities to the climate change drought impacts in the Southwestern U.S. described and analyzed in Chapters 2 and 3? Quantitatively, what proportion of those climate impacts may be attributed to each?

Here, for illustrative purposes, the contribution from each major emitting actor to climate change-related drought impacts in the Four Corners region is estimated. The accounting approaches introduced in Section 4.2 are used here to allocate emissions to each major emitting actor and relate those emissions to climate impacts. This is a multi-step attribution process, whereby contributions to global average temperature rise (GATR) are first attributed to each emitter, and then that GATR is downscaled into local temperature rise and the associated increase in Vapor Pressure Deficits (VPD), a key driver of vegetation desiccation, hydrologic drought, and wildfire risk (see Chapter 2).

The first attribution step (contributions to GATR) employs the model created by Ekwurzel et al. (2017) to determine the contributions from Carbon Majors to GATR. They create a global energy-balance coupled climate-carbon-cycle model which allows the user to select which of the Carbon Majors' emissions to remove, define the period for which to assess emissions contributions, and input user-defined emissions. Here, for this analysis, to estimate GATR increase attributable to each emitting actor, the model was run for each actor for different time periods by switching out annual emissions in the model. The Carbon Majors annual emissions data are from Heede (2014) and is already included in the Ekwurzel et al. 2017 model—therefore, the results presented in Table 4 for Carbon Majors are the same as in Ekwurzel et al. 2017. The electric utilities data were retrieved from the Energy Information Agency (EIA) and are available from 1973-current at five-year increments (EIA 2022). Yearly data were interpolated from the five-year increment data using linear interpolation. The U.S. producer emissions data and consumer emissions data were retrieved from Ritchie and Roser (2020). Producer data are available from 1850-current. However, the consumer emissions data are only available from 1990-current. By examining the relationship between production and consumption data for 1990-current, 1980-1990 consumption data were interpolated. For data that were available from 1880 onward (Carbon Majors and U.S. producer), the model was run twice: removing emissions from each group from 1880-2010, and from 1980-2010. For data only available from 1980 onward (U.S. utilities and U.S. consumption emissions), the model was only run once for each group, by removing emissions from 1980-2010. The results are presented in Table 4.

To relate contributions to GATR and VPD in the study region, several assumptions are made. As the model used by Ekwurzel et al. (2017) only calculates contributions until 2010, I assume the same percent contribution from each entity to 2010 GATR as 2020 GATR. Following Otto et al. (2017), the second assumption is that the contribution of each emitting actor to GATR may be linearly transferred to the local change in temperature in the Four Corners region. In other words, the percent contribution of an emitting actor to GATR will be the same percent contribution to local temperature rise. As Otto et al. 2017 explain, “While a strong assumption, the only way to explicitly test this would be to employ large ensembles of high-resolution coupled climate models where [actors’] individual emissions could be removed. Lacking the capability for such a test, we assume that the assumption holds for extreme events where the anthropogenic contribution is mainly through thermodynamics...” (Otto et al. 2017:758). As the local temperature increase is largely due to thermodynamics, this assumption is made. The local increase in temperature rise attributable to the major emitting entities is then translated into the local increase in VPD using the equations from Daly et al. 2015 and the methods in Chapter 2. The results are show in Figure 6.



			1880-2010		***1980-2010***	
Group	**Years**	**Breakdown**	**Attributable delta T (°C)**	**Attributable delta T (%)**	**Attributable delta T (°C)**	**Attributable delta T (%)**
Carbon Majors	1880-2010	all 90	0.4	50.00%	0.28	35.00%
Carbon Majors	1880-2010	state-owned	0.13	16.25%	0.107	13.38%
Carbon Majors	1880-2010	investor-owned	0.14	17.50%	0.086	10.75%
Carbon Majors	1880-2010	centrally-planned states	0.13	16.25%	0.086	10.75%
U.S.	1880-2010	producer	0.15	18.75%	0.07	8.75%
U.S.	1980-2015	consumer	N/A	N/A	0.071	8.88%
U.S. Utilities	1980-2016	N/A	N/A	N/A	0.026	3.25%
Total increase in temperature (delta T) 1880-2010:			0.8			

Table 4: Attributable contributions from each emitting group to GATR in 2010. Results for Carbon Majors is from Ekwurzel et al. 2017. Results for the U.S. producer and consumer, and for utilities, employ the Ekwurzel et al. 2017 model with external data described above.

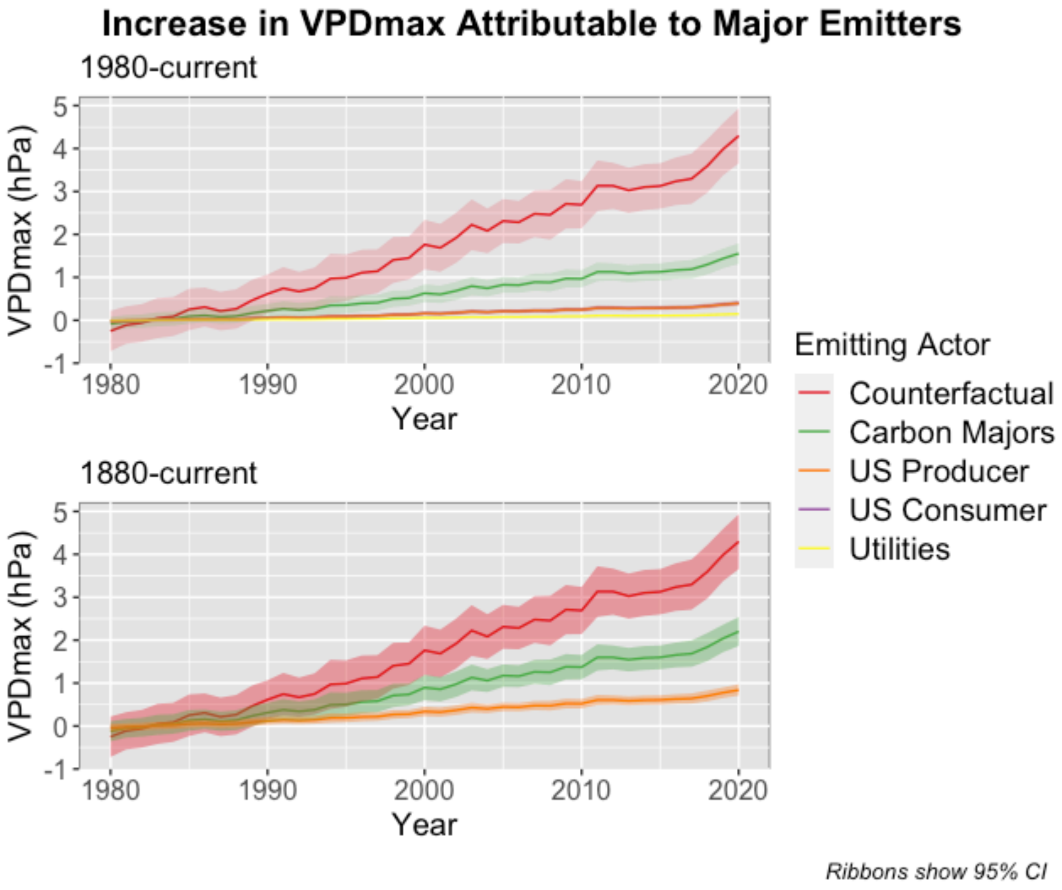


Figure 6. Contributions of major emitting actors to increases in maximum VPD (VPD$_{max}$) in the Four Corners region (spatially averaged over 34-39N, 112-105W). The counterfactual (red) shows the contribution of all anthropogenic emissions, while the other emitting actors' contributions to VPD$_{max}$ are shown in their corresponding colors. The top panel depicts contributions for emissions removed from 1980-current, while the bottom panel includes contributions from 1880-current. Note counterfactual in both plots includes emissions removed for the full period (1880-current). Note in the top panel that U.S. Consumer and U.S. Producer are nearly equal.

The raw and percent contributions of each emitting actor to GATR are shown in Table 4. Emissions from 1880-2010 generally contribute to observed climate change over the past two decades. Conversely, the post-1980 percent contribution category captures only the highly defensible contributions with full knowledge of the climate consequences of the emissions. Beginning with 1880-2010 emissions, the Carbon Majors collectively have contributed significantly more to GATR than the U.S. (producer accounting approach) (50% vs 19%). However, the U.S. is on par with each individual group (state-owned, investor-owned, centrally planned states) within the Carbon Majors. Turning to post-1980 emissions, the Carbon Majors remain the largest contributor, while state-owned Carbon Majors become the largest emitting sub-group (instead of investor-owned). The U.S. producer and consumer accounting methods are on par with each other. Finally, for post-1980 emissions, U.S. utilities are the smallest contributor at 3.25%.

Figure 6 depicts the consequent contributes to local increases in maximum VPD (VPD_{max}) based on the contributions to GATR. The same patterns are seen in VPD_{max} as in GATR. Carbon Majors' contribution to increases in VPD_{max} in the greater Four Corners region is significant, accounting for ~ ¼ - ½ of the anthropogenic contributions to increases in VPD_{max}.

4.5. Summary

This chapter has largely focused on how responsibility and accountability for climate change can be conceptualized and delineated. To summarize, the primary considerations for identifying responsible actors are: is your scale of contributions significant for current climate change; do you have agency; did you know, and when; did you make changes based on that knowledge; and did you wield forms of power to violate social principles?

As described in section *4.2.1 Causal Responsibility* and depicted in section *4.4 Source Attribution*, many of the larger emitting actors (nation-states, Carbon Majors, and utilities) have contributed significantly to emissions and to GATR. Is there a specific cut-off for what is considered significant? Chapter 1 introduced four approaches for demonstrating specific causation in lawsuits when the traditional 'but for' test fails (generally in environmental pollution or epidemiology cases): (1) the "substantial-factor"/material contribution test, (2) the co-mingled product approach, (3) the market share approach, and (4) the doubling of risk test. As the impacts are estimated as a change in intensity rather than risk, the fourth approach is not applicable here. The first approach would require that contributions from a specific emitting actor to be sufficient to bring about a harm—this may be true for Carbon Majors at 50% of the GATR, but likely not for the others. The second approach would consider all to be significant contributions, while the third would multiply the monetary cost of the harms by the percent contribution.

For example, the 2020 Southwestern drought is estimated to have resulted in $700 million in damages (NOAA 2022c)[10]. For illustrative purposes, assuming half of the damages were related to reduced vegetation health—impacting agriculture and forage—then reduced net primary productivity (NPP) from drought would amount in approximately $350 million of those damages. As indicated by the results in Chapter 2, nearly half of the reductions in net primary productivity (NPP) on rangelands for that year were found to be due to anthropogenic forcing; therefore, the anthropogenic climate change component of damages related to increased VPD and decreased NPP would be ~$175 million. Under the third approach, the market share of the Carbon Majors would be ~$88 million, while U.S. utilities (for post-1980 emissions) would have a market share of ~$6 million. Given these alternative approaches, each of the major emitting actors considered in this chapter have contributed significantly enough to satisfy causal responsibility.

The next question—do you have agency—helps to disentangle complex networks of actors to identify where decision-making and, in this case, violations of social principles occur. The evidence presented in this chapter indicates that there are in fact multiple sites of agency which therefore means multiple sites that bear some form of responsibility for climate

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[10] Summary statistics for the Southwestern climate region for 2020.

change and impacts. When comparing the state and the firm, though, there is both a persuasive and strategic reason to focus on the firm—firms have wielded power in more direct and intentional ways, and evidence points to more agency at the firm-level than at the state-level regarding decision-making around fossil fuels. There is an extensive interplay between firms, individual politicians and parties, and organizational spaces where these agents come together. Levy and Egan 1999 highlight that firms may "act cohesively in the political arena…through a dense network of relationships between business and the state…" (Levy and Egan 1998:342). For example, in ALEC, state legislators actively engage in a coalition to undermine climate action alongside firms. In this interplay, this chapter has questioned where direction is coming from in this space, whether concessions are being made, and if so, by whom? The state has made concessions to, or in some cases fully supported, firms (Carter 2021). Levy and Egan 1998 wrote about this interplay at the UNFCCC negotiations, which, they contend, "illustrate a Gramscian political dynamic in which major sectors of capital attempt to utilize multiple channels of influence on policy, but seeing the inevitability of some form of agreement, are prepared to accept a compromise...." (Levy and Egan 1998:355). As the denialism found in the State stems from a party with traceable ties to industry, there is moreover evidence of a corporate capture of State actors who promote climate denialism. While the state maintains some form of responsibility, this evidence—coupled with the outsized contributions from Carbon Majors—indicates the clear demonstration of agency and hence unique responsibility of the firm.

The remaining questions relate to violations of social principals: did you know, and when; did you make changes based on that knowledge; and did you wield forms of power to violate social principles? There is an argument for foreseeability being irrelevant to determining responsibility. For example, Allen 2010 compares the industry to deodorant manufacturers, stating "If I were to sell you deodorant contaminated with dioxins, you would be unimpressed by the defence that the chemicals were doing no harm to anyone while in the can. Does the same logic apply to fossil fuels?". Yet, if foreseeability is a requirement of the courts, all emitting actors knew after 1990, all likely after 1980 (in the lead-up to the formation of the IPCC and James Hansen's testimony), and some as early as the 1950s (particularly some of the oil companies in the Carbon Majors). There is evidence for many of the emitting actors that, despite the knowledge of the harm, they did not change their actions. This is evidenced in that at least half of all emissions from the Carbon Majors have occurred after 1988 and that the U.S. producer emissions have not decreased overall. While the carbon intensity of electricity production has declined overall, certain actors continue outsized contributions. For example, Southern Company continues to be one of the biggest emitters in addition to engaging in disinformation campaigns and lobbying, wielding discursive and instrumental power. Finally, as described throughout this chapter, both oil and gas firms and utilities have wielded discursive (through promoting disinformation) and instrumental (through lobbying and other forms of obstructionist actions) power to continue reliance on fossil fuels.

Importantly, pursuing accountability from an entity does not immunize others—it does not somehow erase any responsibility that other entities may hold. Yet, in pursuing responsibility, several major emitting actors clearly emerge as responsible. Within that context, the Carbon Majors followed by the U.S. nation-state have contributed significantly to global emissions, while the Carbon Majors and electric utilities have most directly and tangibly violated social principles. Determining whether to focus on all, a subset, or a single actor will depend on which mechanism is pursued—and which alternative to the ‘but for’ test in litigation will likely be wielded. Those questions are left to the lawyers.

Acknowledgements & Author Contribution Statements

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Conclusion

Since I set out on this dissertation project in 2016, much has changed in the field. Nearly 20 climate lawsuits have been filed in the U.S. since 2016, and a handful are heading to state court where they may proceed to the next stage (Drilled 2022). Similarly, interdisciplinary centers have been formed to guide this field, such as the Union of Concerned Scientists (UCS) Science Hub for Climate Litigation. Moreover, other nations have made headway—in May 2022, the Philippines Commission on Human Rights issued findings that fossil fuel companies have responsibilities under human rights law, and if those responsibilities are breached, they may be held liable (Commission on Human Rights of the Philippines 2022).

Over the same six-year period, global atmospheric CO_2 concentrations have continued to rise—from May 2016 to May 2022, CO_2 concentrations rose from 408ppm to 420ppm (NOAA 2022a). This dissertation was also written during the biggest global pandemic in the past century. Due to stay-at-home orders due to the COVID-19 pandemic, emissions temporarily dropped, but then skyrocketed after shelter-in-place orders were lifted, indicating that individual behavioral change without large-scale infrastructure and systematic changes will not facilitate substantial emissions decline (IEA 2021a). Since pre-industrial times (1850-1900), global average temperature has risen by approximately 1°C due to human activities (IPCC 2015). Moreover, annual temperature anomalies indicate that land surfaces have been warming faster than the global average, with approximately 1°C of warming over the full globe in 2020, and over 1.5°C of warming over land surfaces (NOAA 2022b). With projected increases in CO_2 concentrations and global average temperatures, climatic hazards are likely to intensify and become more frequent over the coming decades.

Similarly, while international negotiations through the UNFCCC have brought about national emissions targets which could limit warming, that warming is still on track for approximately 3°C by the end of the century (Climate Action Tracker 2022). Similarly, studies have indicated that to keep warming below 1.5°C, no new fossil fuel infrastructure may be built, and that current, discovered-yet-undeveloped fossil fuel reserves must remain untapped (IEA 2021b; Trout et al. 2022; Welsby et al. 2021). Yet, many nation-states, oil and gas companies, and utilities have plans to continue to develop and burn fossil fuels (SEI et al. 2021; Oil Change International 2022; Romankiewicz et al. 2020).

Together, these trends paint a serious picture—based on current, observed impacts in a 1°C warmer world and projected further warming of 3°C due to continued emissions, impacts will grow around the world. As such, the question of climate accountability will become more pressing.

In this dissertation, I explored this rapidly developing field to understand where it currently stands, how advancements in research methods and approaches may support it, and identify current challenges associated with it. This dissertation asked: (A) How can scientific advancements in demonstrating causation between emissions sources and sites of impacts help progress this field of climate accountability? Moreover, in doing so, (B) how can we—as scientists and practitioners—ensure that these advancements center justice and community choice? To answer these questions, I created a framework to facilitate demonstrating climate responsibility and applied it to a case study. Specifically, I conducted end-to-end attribution to demonstrate causal responsibility and moreover examined social principles that translate causal responsibility into moral responsibility (Shue 2017). In doing so, I demonstrated that end-to-end attribution is doable, yet there are certain challenges that face this field in ensuring this work centers justice.

Here, in the conclusion, I summarize the primary results from my research, key themes that emerged through the interdisciplinary approach I took, lessons learned from conducting the research, and recommendations for the field moving forward.

Key Takeaways

In this dissertation, I demonstrated that:

1. While industrial carbon extractors and producers (or Carbon Majors), the U.S. as a nation-state, and electric utilities have contributed substantially to GHG emissions and subsequent global average temperature rise, some of these actors have contributed to measurable increases in VPD (Chapter 4). Moreover, there are clearly documented violations of social principles that have accompanied these emissions—including having knowledge about the link between fossil fuels and climate change, avoiding alternatives, and making evaluative judgements to wield structural, instrumental, and discursive power to keep relying on fossil fuels and sow disinformation. Therefore, each of these entities has unique responsibilities, with Carbon Majors and the U.S. as a nation-state having outsized causal responsibility.
2. Increased temperature from anthropogenic forcing has increased VPD in the greater Four Corners region, including for the Zuni Pueblo, with negative impacts on rangeland vegetation productivity (Chapter 2). While vegetative drought here is constrained primarily by precipitation, I demonstrated that increased VPD from human-caused climate change is having a large, persistent, and damaging effect on

vegetation health. The most pronounced effects of VPD on vegetation health are in water-limited areas likely where soil moisture anomalies have not yet constrained that growth.

3. Increased temperatures have led to significant impacts for the Zuni, including impacts on waterways, agriculture, and livestock, and disrupted socio-environmental relationships (Chapter 3). In particular, certain plants are no longer found, forage for livestock is poor, soils are drier, and there is a year-long fire season, all linked to increased vapor pressure deficits (VPD). However, the recent effects of drought are layered on top of historical enclosure of land and damage to agriculture and water from settler colonialism. Moreover, the enclosure of land has allowed for accumulation of resources and extraction of fossil fuels. Climate change has occurred as a failed responsibility to an animate earth through these processes, and that failed responsibility must be addressed before harms will stop.

Taken together, these findings demonstrate the moral responsibility of multiple emitting parties to the impacts experienced by Zuni. Moreover, they offer lessons learned for the larger field of climate accountability. Any attempt at climate accountability needs to uphold the three types of justice core to climate accountability as introduced in Chapter 1—distributive, procedural, and corrective.

Again, **distributive justice** is concerned with the inequitable distribution of harms or benefits (Gardiner 2011; Schlosberg 2013). Accountability efforts thus should focus on areas where inequitable distributions of harms are present—those places that have borne the brunt of climate change and social, political, economic, and cultural marginalization. For Zuni, issues of distributive (in)justice are clear through their layered experience of settler colonialism, extractivism, and disproportionate climate change impacts. Moreover, the animate earth is a party to distributive (in)justice as it is harms to her that have occurred from extractivism.

Procedural justice ensures that the knowledge systems, perspectives, and needs of the impacted community—and the community itself—guide any accountability work. Procedural justice teaches that there is not a one-size-fits-all approach to accountability but is rather guided by the unique experiences of the impacted community. Therefore, for Zuni, procedural justice includes learning from Zuni knowledge systems and worldviews meant for non-Zuni people, such as understanding humans as in a relationship with the earth and pursuing accountability with a goal of helping people (re-) enter that relationship of respect.

Corrective justice is concerned with bringing to account responsible actors who have held a role in creating harms (Gardinier 2011). Corrective justice will look different in different cases, depending on the impacted community. For Zuni, corrective justice looks like stopping actors from emitting further greenhouse gas (GHG) emissions through disrespectful extractivism, which would otherwise lead to further harms to the lands and waters. The corrective behavior would be between the earth and the emitters, rather than the people holding the emitters accountable for their own interests. If money is involved through corrective justice, it is to invest in actions to repair or otherwise address that which has been harmed, rather than as direct payments for damages.

Lessons Learned from the Research Process

I found that beyond the key research findings, the *process* of conducting this research offered lessons learned that may be relevant for the larger field of climate accountability. My dissertation sits somewhere between cross-disciplinary and interdisciplinary research, cutting across different disciplines and methodologies, as well as touching on different ontologies of climate change, accountability and responsibility, and justice. Cross-disciplinary approaches are those in which components of research are methodologically and ontologically couched squarely in their respective disciplines, while interdisciplinary approaches work to integrate approaches of multiple disciplines into a hybrid methodological approach (Stokols et al. 2008).

Each of my chapters largely rested within their unique disciplines (cross-disciplinary), while the translations that I've touched on between each link approaches interdisciplinary research. In this way, I was able to do a deep dive into not only the feasibility of practicing climate accountability but also the challenges that need to be confronted in this pursuit. By doing the empirical research in each chapter, as noted by a committee member, in a sense, I was doing participant observation of each field—of the scientific detection and attribution community within the broader field of climate science and climate hazards science, of political and historical ecology approaches through situated ethnographic studies, of content analysis in source attribution, and of philosophy of responsibility in creating my conceptual framework. As I conducted cross-disciplinary participant observation, concepts that I encountered in one space emerged in another. These threads surfaced in various disciplines while asking different questions and seemed to follow me as I navigated the questions of my dissertation. They are largely related to the two dominant questions guiding this dissertation.

The first thread that emerged was how to show causation. There seems to be significant weight given to certain forms of knowledge and certain methodological approaches to demonstrating causality. Why do such certain frames get picked up more than others (e.g. econometrics vs ethnographic work)? Often, impact attribution is based on a quantitative indicator of impacts—mortality rates in the case of the European 2003 heatwave, or perhaps crop yields—rather than a qualitative measure of impacts, including community testimonies (see Chapter 1). Economic indicators can be assessed at the same scale of climate science. However, more local-based assessments of impacts require translating causality across scales. It is easier to translate quantitative indicators of human impacts of climate change to methods in climate science, leading to a quantitative dominance in the field. The issue of a mismatch between scales of disciplines is a fundamentally geographical problem. The indicator-based studies tend to exist at a coarser scale (meso-scale, e.g. census-tract, county, state), while the 'human voice' studies exist at a finer scale (e.g. community- or household-level). To assess how climate change leads to impacts, the human impacts are either scaled up (in the case of the indicator-based studies), or the climate impacts are downscaled (for the 'human voice' studies).

In conducting impact attribution, quantitative, indicator-based approaches to describing climate impacts kept emerging, such as relating NPP and locations of livestock in Chapter 2 to attributable increases in VPD. It is the most straightforward way to do this work—it is easily understood by hegemonic institutions, the methods are clear, the p-values are significant, the uncertainty from each attribution step may be extended to the next, and the methodology is reproducible. But what about other approaches? Do other approaches—such as those based in different knowledge systems—merely provide context to the "strong core" of quantitative indicators? Is the purpose of stories just to make the statistics resonate? If we take that approach, we miss the descriptive power of stories, of ethnographic information, of other forms of knowledge. If Chapter 3 were based on indicator-based assessments of climate impacts, it would miss the unique descriptions of impacts. It would describe impacts to the Zuni River in terms of impacts on water use sectors and miss the importance of intergenerational knowledge held in the water. It would place a price on land and water, monetarily valuing the invaluable. Therefore, while quantitative, indicator-based analyses provide useful information—and can address in part the "what" of climate change impacts—they are insufficient to truly capture the comprehensive *what, why, and how* of climate impacts (Cheong et al. 2012).

Yet it is difficult to connect to non-quantitative measures of impacts to the output of D&A studies—you can put error bars on quantitative metrics and more easily relate them via multi-step attribution studies. As described in Chapter 2, multi-step attribution analyses involve determining the attributable change in a climatic variable due to anthropogenic forcing, and then using statistical or physical models to demonstrate that change is related to a different variable, carrying measurements of uncertainty. Notably, "[o]verall conclusions can only be as robust as the least certain link in the multi-step procedure" (Bindoff et al. 2013:878). Yet are these metrics necessary to demonstrate causation? This depends on the scale of analysis and the desired application. As described in Chapter 1, different levels of certainty are required for different applications. For civil lawsuits, a 'preponderance of evidence' is needed to demonstrate causality—while still robust, it means that carrying a single measure of uncertainty across the full causal chain may not be necessary. Instead, additional evidence—in the form of qualitative analyses—may be presented alongside D&A studies.

Much of what has been described thus far has impeded addressing distributive justice in current approaches to climate accountability. In chasing strong p-values and prioritizing limiting uncertainty, linear causal chains with few confounding factors are often pursued, so that the context within which impacts occur is sometimes ignored. In response, Smith (2006), Lahsen and Ribot (2022), Hulme (2014), and Dayeneni (2009) all make the plea: (a) to not look at climate change as a siloed issue separate from the actions that created it, and (b) to not fall into a climate-centric framing which will obscure the very real social dimensions that create impacts. Smith (2006), Lahsen and Ribot (2022), and Freudenburg et al. (2009) highlight the responsibility of decision-makers who created local vulnerability. Lahsen and Ribot (2022) explain how a climate-centric framing can in a sense ‘naturalize’ a disaster by removing focus on the responsibility of local decision makers for reducing vulnerability and exposure. Similarly, Smith explained how “…supposed “naturalness” of disasters…becomes an ideological camouflage for the social (and therefore preventable) dimensions of such disasters, covering for quite specific social interests” (2006:1). Similarly, Freudenburg et al. (2009) trace the decision-making by local and non-local government that allowed for the tragedy that was flooding from Hurricane Katrina, and describe how the “hubris” of decision makers in creating local harms coupled with climate-change fed intensified storms is what creates disaster.

Hulme (2014) and Lahsen and Ribot (2022) caution about a climate-centric view fed by attribution studies. Hulme asks: “… which extreme weather events should be investigated: the cases where human influence on meteorological extremes is easiest to detect or the cases where the political, economic or ethical consequences of extreme weather attribution are greatest…” (2014:8). If the focus is on climate, it can detract from the poor decision-making, the disinvestment, and the marginalization which creates vulnerability (Lahsen and Ribot 2022). Put another way, it can lead to tunnel-vision regarding responsibility, ignoring all the causal factors that influenced vulnerability and exposure, and instead just focus on hazards. This is a relic of approaching this issue as a single causal chain, in which other contributing factors to impacts are ignored.

There is a similar critique that exists on the emissions source end. Just as with the impact end of the causal chain, there are many factors that contribute to the conditions within which GHGs are emitted. Yet ignoring the systemic contributors to climate change (see Chapter 3 and 4) leads to viewing climate change as a siloed issue. Dayeneni (2009) describes this climate-centric view as 'carbon fundamentalism'—in which a narrow framing on atmospheric carbon concentration levels serves to hide the larger context which created climate change in the first place. This lesson similarly emerged in Chapter 3—if climate change is understood as the most recent manifestation of accumulation by dispossession, then addressing climate needs to not be at the expense of addressing all the other symptoms of that same dispossession.

These threads come together most clearly when looking at current lawsuits and attribution studies. First, the most impacted places are generally not where lawsuits are being filed (see Table 1 in Chapter 1). Instead, the lawsuits are largely being filed in the places with the most expensive infrastructure at risk to sea level rise. These places are where the plaintiffs have standing (or large enough demonstrable impacts) and where the science is straightforward. Yet, ironically, there are plenty of easy-to-attribute places which are not focused on—these are largely inland and experience drought and heatwaves. Also described in Chapter 1, there is bias in where attribution studies are conducted, related to type of extreme event and location. Furthermore, for attribution studies that approach impact attribution, they are done within the single causal chain approach, meaning they are in places and for impacts for which it is easier to ignore 'confounding' factors—or the context identified by Hulme (2014), Lahsen and Ribot (2022), and Freudenburg et al. (2009).

Limitations and Areas for Future Research

In light of these insights, I note the strengths and limitations of various approaches to climate accountability. Each approach is necessary but only partial in its perspective on the field of climate accountability. Each operates within its own disciplinary parameters, and as such, faces distinct difficulties in expanding its points of view to interface with other links along the causal chain.

Ethnographic impact attribution: Ethnographic methods rooted in political and historical ecology have enormous potential for this field. Almost by definition promoting procedural justice, these methods center community voices in describing the experiences and relevant history for the community. These methods can help illuminate *how* impacts have occurred and are experienced. They moreover may identify impacts that would otherwise be missed through quantitative or qualitative methods which do not include community voices.

These methods however have been historically difficult to integrate with climate assessments and detection and attribution studies. As stated in Chapter 1, to the best of my knowledge, no ethnographic-based analyses of climate impacts have been integrated with detection and attribution (D&A) studies of anthropogenic forcing on hazards. I similarly found it difficult to do such integration. In this dissertation, I conducted the analyses presented in Chapters 2 and 3 iteratively, through sequential mixed methods. While I was able to indicate a link between the chapters and reference some D&A research in interview questions in

Chapter 3, largely due to time constraints, I was unable to fully integrate the two sets of analyses. Future research may more explicitly conduct sequential mixed methods procedures in doing both D&A of anthropogenic forcing on local climatic hazards and ethnographic-based analyses of climate impacts. This should be done by engaging the community in designing the studies, sharing preliminary outcomes of the studies with the community, and conducting further D&A studies based on those conversations.

Detection & Attribution Science: D&A analyses have enormous strengths. Having rapidly developed over the past two decades, methods have been developed to identify the human fingerprint on trends (sea level rise, glacial melt, desertification, etc.) and events (hydrologic and agro-pastoral drought, heatwaves, extreme precipitation, etc.). From the early development of the fraction of attributable risk (FAR) approach introduced to the climate field by Allen (2003) to the explosion of studies in the *Bulletin of the American Meteorological Society* (BAMS) annual "Explaining Extreme Events" publication, D&A of climate change on events and trends has rapidly and robustly developed, and the human fingerprint on many of the large events of the past decade have been attributed to anthropogenic forcing.

While FAR is the most common D&A method, there are other approaches—such as storyline-based approaches and those which attempt to identify a change in intensity or absolute value of a variable (such as in Chapter 2). Indeed, by showing the percent change in a variable rather than in the likelihood of an event occurring, such findings may be more easily applied to climate litigation (Stuart-Smith et al. 2021). Similarly, following a story-line based approach may be more appropriate for cases in which the climatic hazard occurs against a complex backdrop (Trenberth et al. 2015; Lloyd and Oreskes 2019). Yet such approaches have been met with criticism by some in the D&A scientific community—namely, as they do not examine all causal components of an event and as they have priors[11], that there is a risk of Type 1 errors.

As with much of climate (and other) science, D&A methods traditionally maintain a high threshold for certainty (Lloyd and Oreskes 2019). In this body of research, Type 1 errors (false positives) are seen as more serious than Type 2 (false negatives), so they are minimized. In doing so, it becomes more likely that events that may in reality be exacerbated by anthropogenic forcing are found to have no anthropogenic fingerprint. Put simply, most D&A studies are conservative estimates of the anthropogenic fingerprint on an event. I too, in conducting D&A research, found myself choosing a case study based on desired avoidance of Type 1 errors, having explored no fewer than four potential places before arriving at the Southwestern drought. To make this dissertation tractable, I had to choose a place that would likely be attributable. It is for this reason that my dissertation begins with the central link in the causal chain (from anthropogenic forcing to hazards), and then moves to impact attribution, rather than beginning with the communities, which would be more in-line with the three types of justice. Based on this experience, I would argue that the *attributability vs vulnerability* tension largely comes out of D&A methods and furthermore due to the ways in which political actors have attempted to twist findings. The fear of Type 1 errors has been used to misconstrue findings and promote climate denial and doubt. In all, in attempting to minimize confounding factors and have high certainty and avoid Type 1 errors, generally,

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[11] A ‘prior’ in this case refers to a physical understanding about a (usually) thermodynamic principle that relates a change in a variable (e.g. VPD) to anthropogenic forcing. Approaching attribution with such priors allows for leveraging that existing physical knowledge of how forcing may affect a variable to inform the attribution methodology. This is opposed to approaching attribution with no prior assumptions of how anthropogenic climate change may affect a certain variable.

specific types of events are analyzed—the easiest-to-attribute places, creating a selection bias (NAS 2016:42).

Source Attribution Methods & Theory: Similarly, there have been advancements in source attribution. For causal responsibility, there is now good coverage on historical emissions (from 1990 onward) for much of the world, and for many countries, there are sectoral breakdowns of emissions contributions. With this data, there have been approaches developed to allocate emissions contributions based on extractors, producers, and consumers. Moreover, with the data available, researchers have attributed contributions from Carbon Majors (Ekwurzel et al. 2017) and nation-states (Otto et al. 2017) to global average temperature rise and local heatwaves, respectively.

However, there is limited data for certain sectors. For instance, while producer-level information exists back to 1750-1850, data for nation-state consumers and for U.S. electric utilities only exists for the past few decades. This limited my ability to extend Ekwurzel et al.'s (2017) methods to the U.S. as a consumer or to electric utilities for 1880-2010. There is, furthermore, a need for advanced modelling power in allocating causal responsibility. As noted by Ekwurzel in personal communications and by Otto et al. (2017), unless models are run by feeding emissions data from various actors into global climate models as counterfactual experiments, assumptions have to be made regarding the removal order and regarding linearity. While these assumptions largely hold for thermodynamic events, they do not hold as well for dynamic aspects of the climate system.

Research on social principles has similarly advanced—from analyses of lobbying to disinformation, sociological, political, and STS research has examined these questions. There are still limitations for this area, however. First, while there are ample theories with great potential relevance to source attribution (including Freudenburg's (2005) *Double Diversion*, Jenkins's (1994) theories of state versus firm power, and Gould et al.'s (2004) *Treadmill of Production*), few are currently applied to source attribution. These theories may help guide research on social principles. Similarly, much of the current empirical research on social principles in the case of climate accountability is focused on disinformation; while highly relevant, it is not the only relevant social principle. Further systematic inter- and intra-sectoral research on lobbying, for example, would also be relevant. This area of research will likely grow in coming years as further information is revealed through the discovery stages of lawsuits.

<u>Law</u>*:* Finally, there are areas for legal approaches to further develop. Climate litigation is based on the precedence of legal approaches to other environmental harms, from secondhand smoke to asbestos to toxic pollution. New approaches to ruling on environmental harms were developed in these cases which lay the groundwork for dealing with climate change-related damages.

Yet there is still not a clear precedence for how to address climate change-related damages as the source of emissions occurs far from the site of impacts in many cases. As described in Chapter 1, this has made establishing standing as much based on chance as on evidence and is in the realm of judges to determine how they wish to create such precedence. There is opportunity for the legal community to engage in developing more robust measures of how causality and proportion of damages may be established, which is being undertaken by legal scholars such as Burger, Wentz, and Horton (2020). Moreover, there seems to be a missed opportunity in applying scientific knowledge to lawsuits. As of 2021, over 73% of climate change-related lawsuits did not include peer-reviewed attribution studies (Stuart-Smith et al.

2021). Is it because the attribution studies are less applicable for these lawsuits, because the current approach to D&A methods is harder to build a case on, or because the lawyers don't have access to the research in an accessible manner? These would be important questions to answer in future research.

Returning to the field: recommendations for the field to move forward

How can this field move forward while addressing these challenges? The previous section identified areas for future research. Many of these areas relate to advancing end-to-end attribution, and there are some key recommendations for how this research may move forward. To overcome the selection bias in attribution research involves encouraging more research on harder-to-attribute hazards and impacts, while accepting failure as part of the scientific process which may then avoid penalizing studying the more strongly impacted places. This may also involve embracing other approaches to D&A science such as story-line based approaches, with the intention to be careful to not let desire for minimizing uncertainty and maximizing model fit mean that we focus on highly attributable places at the expense of highly impacted places. Furthermore, more explicit attempts at iterative or sequential studies which incorporate source and impact attribution by leveraging both quantitative and qualitative methods can help to understand causality for climate impacts as they actually occur—against a complex backdrop of pre-existing and unfolding conditions. This could involve bringing different disciplines into this work. For instance, geography, environmental justice, and sociology scholars have much theoretical and empirical expertise to bring to this work, and intentionally inviting that expertise to this field could help it to grow and be more explicitly based in the three types of justice.

Furthermore, there is an opportunity for this field to develop frameworks to support a more comprehensive understanding of causality which would address some of the challenges identified in this dissertation. Such frameworks could be created through collaboration between those scholars in the source and extreme event attribution community, representatives from impacted communities, and those scholars who have leveraged critiques of the narrow causal chain—including geographers, environmental justice scholars, and sociologists. By working with more complex causal chains, and more explicitly engaging relevant theories from participating disciplines, such collaborative efforts may allow for building out further conceptual frameworks to guide justice-based accountability research and practice. Such frameworks—such as the one I proposed in Chapter 1—can provide a foundation for guiding cross- and interdisciplinary research across the causal chain, accounting for more complex causal networks. These could provide a 'best practices' rubric for how to best conduct research in this field, frame this field in the public sphere (including in media), and engage with existing mechanisms. Such a collaboration could also examine current mechanisms—across policy and legal spaces—to advise on how this work may advance in practice.

Such advancements in attribution research can provide some support for lawsuits to be filed in other places. This does not mean *instead* of the current lawsuits—the current lawsuits have been filed in places with clearly demonstrable impacts and strong cases for both causal and moral responsibility of defendants in contributing to those impacts. Yet the development of research in other places may similarly support strong cases for other places that are just as—if not more—climate-impacted.

Where is this field now? As described in Chapter 1, there are two primary domains in which responsibility for past GHG emissions are being interrogated—within the United

Nations Framework Convention on Climate Change (UNFCCC) and via national litigation. While operating in different spaces, these two mechanisms influence each other. For an insurance pool-based approach under the UNFCCC (see Chapter 1), the evidentiary requirement would be significantly lower than what is currently required by lawsuits. Therefore, while the attributability versus vulnerability tension would still be present in this approach (Hulme 2014; Wrathall et al. 2015), it would likely be less significant. However, as the UNFCCC follows a consensus decision-making process—leading to decisions with are the lowest-common denominator— conversations around loss and damage have been stalled due to the specter of climate liability (Wrathall et al. 2015; Warner and Zakieldeen 2011). At COP 26 in Glasgow, Scotland in 2021, the U.S., alongside other Global North countries, blocked the Glasgow Loss and Damage Facility "…because they don't want to face a deluge of compensation claims due to the impacts of their historical emissions" (Pardikar 2021). Yet ironically, that very unwillingness to address L&D in the UNFCCC since the earliest proposals has functioned to usher in litigation under national jurisdictions under the 'polluter pays' principle (Pardikar 2021; Huq 2022). Unlike the UN context, responsibility in domestic litigation does not follow the lowest-common denominator problem. Yet it is also still contested—no domestic litigation cases have yet been heard on their own merits. However, they soon likely will be, at which point the challenges and advancements in demonstrating causation as examined in this dissertation will be put to the test. Similarly, the Philippines climate probe provided a model that other nations may be able to pursue in the absence of action under the UNFCCC (Commission on Human Rights of the Philippines 2022). With implications for climate liability under human rights law, this probe may support accountability efforts for countries aiming to hold companies headquartered in other nation-states, or other nation-states themselves, accountable (Kuznets 2022). If approaches such as litigation or international probes succeed, that success could then push nation-states that have historically blocked climate reparations through the UN to work in good faith on an international and national loss and damage policy.

Climate accountability represents an imperfect justice. Even with the critiques of the field as it is, it still amounts to an enormous leap toward justice, bringing the conversation around climate much closer toward corrective and distributive justice in particular. If the current lawsuits were to win—or if the loss and damage mechanism through the UNFCCC moved forward based in liability and compensation—this would lead to significant change and promote issues of climate justice. Would the change be meaningful? It depends on what we define as meaningful. Is it a change in public perception? Is it getting financial resources to impacted groups? Is it having the polluter pay and change their actions? Climate accountability does not—and never could—address all historic harms related to climate change. Just as climate change has come about as a result of industrialism, colonialism, and exploitation, the impacts won't be addressed until those are addressed. Yet it does promote meaningful change in these three ways (public perception, resource transfer, and polluter pays). It thus amounts to an imperfect, yet nonetheless very tangible, justice.

With warming likely to continue due to current infrastructure and slow policy movement, and adaptation measures falling short, impacts are likely to worsen in the near term. While it is uncertain what will happen for these various mechanisms, it is certain that these questions will only grow more relevant. Now is therefore the moment to build frameworks and methods to ensure their success, and moreover, that they are rooted in distributive, procedural, and corrective justice.

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