Title
Blue Carbon Ecosystems in San Diego: Exploring the Soil and Challenges of Restoring Coastal Wetlands

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Exploring the Soil and Challenges of Restoring Coastal Wetlands

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Executive Summary

Recent research and publications have highlighted the importance of protecting and restoring coastal wetlands to sequester carbon. Blue carbon, the term for the carbon stored in vegetated coastal ecosystems, has spurred an increase in research to better understand the sheer amount and value of carbon stored in those ecosystems. Global and local coastal wetlands provide a multitude of benefits to society in addition to carbon sequestration. For example, providing protection from storms and sea level rise, pollution abatement, biodiversity, fisheries value, and outdoor space for communities. Given the many benefits of coastal wetlands, there has also been an increase in restoration efforts. Restoration is complex, requiring an understanding of a variety of fields from biology to politics. In the case of wetlands, restoration requires soils suitable to optimal growth of vegetation so that the various and vital ecosystem services provided by wetlands can be maximized. Potential added benefits to restoration include augmenting restoration sites with biologically inactive carbon, biochar, in order to maximize blue carbon stocks, carbon credits to offset restoration costs, and sustainable practices.

Introduction

Climate Crisis

The climate crisis is a serious problem resulting from human remobilization of previously buried greenhouse gasses. To reverse the major climate impacts of anthropogenic greenhouse gas production, emissions of greenhouse gasses need to be cut drastically, excess atmospheric carbon needs to be returned to the earth and stay there for thousands of years. Popular and important climate mitigation strategies include reducing emissions from factories, transportation, and technological carbon capture and storage. An equally important strategy is utilizing natural climate solutions. Natural carbon sinks that have traditionally kept the system in balance need to be leveraged in carbon removal efforts. Additionally, natural spaces "provide valuable resilience benefits and services, such as cleaner air, flood water management and cooler neighborhoods.[1]" Natural climate solutions provide opportunities to champion both climate mitigation and adaptation efforts.

Ecosystem Services of Coastal Wetlands

Restoring, conserving, and improving land management of coastal wetlands is one promising and important natural climate solution. Poppe and Rybczyk aptly summarize the importance of these ecosystems: "coastal wetlands are among the most valuable ecosystems in terms of the ecosystem services they provide and they have been recognized for their role in blue carbon sequestration and climate change mitigation.[2, 3]" Ecosystem services of wetlands range from providing protection from storms, growing vertically as sea level rises, serving as nurseries for fish of valuable fisheries, providing habitat for waterfowl to support bird-watching activities, and improving water quality. Examples of calculated values of the ecosystem services of coastal wetlands are: $4,291 per acre of salt marsh[4] and $23 billion in annual coastal protection services for the entire United States.[5] Protecting coastal wetlands as a natural climate solution will preserve many valuable and important ecosystem services.

Blue Carbon

Another ecosystem service of coastal wetlands that has been garnering additional attention is carbon sequestration and a potential role in the mitigation of anthropogenic carbon dioxide pollution.[6] The term blue carbon was coined in 2009 to highlight the disproportionate abundance of carbon captured and stored in coastal vegetated marine habitats, specifically mangroves, seagrass beds, and coastal wetlands.[7] These blue carbon ecosystems represent a small area compared to terrestrial ecosystems such as forests, yet their total contribution to long-term carbon sequestration is comparable to that of terrestrial ecosystems due to their higher rate of organic carbon sequestration in sediments.[8] It is estimated that the total global carbon burial for salt marshes is 5-87 Tg C yr^{-1} and 78.5 Tg C yr^{-1} for tropical forests.[8]

Wetland Loss

However, the value of wetlands has not historically been recognized. Globally, vegetated coastal ecosystems have been lost through land-use change and are still being lost. The global loss of salt marshes is estimated to be 25% since the 1800s and at an annual rate of loss of 1-2%.[8] Locally, about 91% of California's historical coastal wetlands have been lost due to land conversion.[9] In the San Diego area, all of the salt marshes have declined drastically compared to historical records dating back to 1856.[10] Wetland habitat loss and degradation leads to loss of biodiversity and ecosystem services including carbon sequestration. In fact, land-use change and anthropogenic disturbance can have substantial impacts on wetlands by changing them from being a net sink to a net source of carbon dioxide, therefore contributing to climate change.[8]

Increase in Recognition of Blue Carbon Policy and Effort for Restoration

Restoring and maintaining wetlands and other blue carbon ecosystems is seen as an important strategy in mitigating climate change and adapting to impacts. Correspondingly, there has been an increase in restoration efforts for blue carbon ecosystems. Large companies such as Apple, Gucci, and Procter & Gamble have announced funding of blue carbon projects in 2021.[11]The market for blue carbon credits is also expected to grow as demand for carbon credits, methodologies and registries for projects improve.[12]

In San Diego, this potential is reflected in an increase in restoration efforts, blue carbon-specific initiatives, and support from local politicians. For example, one of the efforts of the local environmental nonprofit, WILDCOAST, is to conserve and protect blue carbon ecosystems in San Diego and Mexico. Additionally, Assemblymember Boerner Horvath, D-Encinitas, introduced Assembly Bill 2593 in February 2022 which would require coastal development projects on public lands to build or contribute to blue carbon projects in California.[13] AB 2593 passed successfully through the Assembly Natural Resources Committee in April 2022, and could potentially be signed into law and take effect January 1, 2023.

Restoration Ecology

A blue carbon project is defined in AB 2593 as, "the conservation, restoration, or creation of coastal ecosystems and vegetation, including, but not limited to, seagrasses and wetlands, which capture and store carbon.[13]" These projects are ecological restoration projects which are the practice of restoration ecology. Restoration ecology is the field of study and experimentation that provides the scientific background for practical ecological restoration.[14] Restoration ecology and its implementation has also been gaining more attention because of the need to regulate people's footprint on the global environment.[14] The purpose of ecological restoration is to safeguard and repair nature (ecosystems, biodiversity) and natural capital (renewable and nonrenewable resources).[14]

These projects are complex and challenging. For instance, it may be nearly impossible to restore an impacted ecosystem to how it was in the past if the entire landscape has been drastically altered; the biophysical, socio-economic, and political context all need to be considered when planning, financing, and implementing a restoration project. Also, salt marsh restoration can be costly, averaging $68,000 per hectare in developed countries.[2] Salt marsh restoration projects are also on timelines of decades partly due to multiple permit requirements and grant applications. Climate change also adds an additional layer of complexity and uncertainty to restoration projects. Should ecosystems be restored to a past status if the future climate will be different? Should ecosystems be restored to a state in which we believe they will be able to survive the changes? In which state will they be functional? Traditional and new challenges need to be addressed in restoration projects.

Goal of Capstone Report

This capstone report will explore coastal wetland restoration in San Diego County, including the ecological, economic and logistical components of local restoration efforts.

- Part one will discuss an ecological component, specifically the characteristics of ideal coastal wetland soil, and soil amendments.
- Part two will discuss the economic and logistical components and challenges of restoration efforts, namely sourcing sediment and soil amendment to create ideal soils in cost-effective and sustainable ways in San Diego.
- Finally, part three will include policy recommendations based on the literature review and survey results from local nonprofits engaged in salt marsh restoration will be presented.

Part 1: Coastal Wetland Soil

The following section will cover a key scientific component necessary to understand and restore coastal wetlands - the soil. Soil reacts, interacts with and influences everything associated with wetlands from the water to the microbiology. Soils also are critical to the success of wetlands restoration programs since their qualities influence the values of most ecosystem services provided by those wetlands.

Overview of Wetland Soil Characteristics

There are many different types of wetlands. Salt marshes, bogs, swamps, and fens all represent water-saturated soils.[15] The definition used to define wetlands in the Clean Water Act is "those areas that are inundated or saturated by surface or groundwater at a frequency and duration sufficient to support, and that under normal circumstances do support, a prevalence of vegetation typically adapted for life in saturated soil conditions.[15]" Wetland soil is categorized as hydric soil, defined as soil that is formed under conditions of saturation, flooding, or ponding long enough to develop anaerobic conditions.[15] Generally, wetland soil is also loamy, a mixture of sand, silt and clay. The presence of water in the soils creates anaerobic conditions by displacing air and oxygen from the pores, and the lack of oxygen alters the microbial activity and chemical reactions occurring in the soil. In addition, dissolved oxygen is limited due to aerobic microorganisms consuming organic matter in top layers of the soil, therefore contributing to anaerobic conditions in the subsoil. Plants in wetlands have adapted to live in waterlogged soils by transporting oxygen for respiration to their roots through hollow structures in their stems and roots known as aerenchyma tissues.[15] Anaerobic conditions facilitate the presence of facultative aerobes (microorganisms that can live without oxygen), and lower redox potentials within the soil profile.

The soil profile of wetlands typically has a thin aerobic zone (higher redox potential) at the surface, then a transition zone followed by an anaerobic zone with the redox potential lowering in each zone. The dominance of facultative aerobes and the reducing environment of the anaerobic soils result in organic matter being decomposed at a slower rate and accumulating in higher amounts than in aerobic soils. The slow decomposition of organic matter is a characteristic of particular interest in climate mitigation because people are interested in protecting and possibly increasing the amount of organic matter (carbon) stored in the wetlands. There are efforts to avoid the carbon stocks, also called blue carbon, from being oxidized and transformed into carbon dioxide in the atmosphere through disturbances such as urbanization and sea level rise. In addition, restorationists and scientists are researching ways to augment the soil to enhance the carbon sequestered in wetlands in an effort to mitigate climate change.

What is Ideal Coastal Wetland Soil in Southern California?

This report focuses on coastal wetlands in San Diego County. They are lagoons, and salt marshes, also called saline tidal marshes. Lagoons are defined as bodies of water separated from a larger body of water by a natural bank.[16] The lagoons in San Diego are coastal lagoons separated from the ocean by sand banks, and connected through an inlet. Marshes are wetlands frequently or continually saturated with water and characterized by soft-stemmed vegetation (not woody plants) adapted to saturated soil.[17] Saline tidal marshes are influenced by the ocean tides and their water is salty. The ocean's salinity averages 35ppt, and the salinity levels of salt marshes varies considerably due to rainfall, tidal flooding frequency, elevation and more.[18] Typical salinity levels range from 40 ppt to 100 ppt. Los Peñasquitos Lagoon in San Diego ranges from 30 to 31 ppt.[18] This is in contrast to other types of tidal marshes with freshwater or brackish water due to having a larger freshwater input; the salinity of brackish water can range from 0.5ppt to 30 ppt.[18] This report will refer to San Diego's coastal wetlands as such, or as salt marshes, but is referring to the lagoons as well.

The salt marshes in San Diego share the general characteristics of wetlands but also have unique characteristics and challenges. For example, a growing human population and coastal development in a region with a narrow continental shelf, a nearby mountain range, and small coastal watersheds has resulted in small, isolated and human-impacted salt marshes.[18] The Mediterranean climate also influences the amount of organic matter accumulated in San Diego salt marshes.

Hydrology

The hydrology of a coastal wetland is the central force for wetland development and functioning.[18, 19] Hydrology, broadly defined as water flow, of the salt marsh greatly influences the soil conditions. While not all salt marshes are exactly the same in their geomorphology, their shape is carved out by tidal inundation and tidal creeks, water coming in and flushing out through a complex network of tidal channels. Tidal wetlands are primarily depositional systems, meaning water travels slow enough through the marsh for finely textured and highly organic sediments to settle and accumulate.[18] In addition to maintaining adequate tidal flushing, multiple tidal creeks of varying sizes contribute to important functions including access to food for organisms, sediment and organic matter accumulation, and flushing of salts and other materials.[18] Furthermore, the degree of localized flooding within a wetland can affect soil processes including the rate of organic matter accumulation, nutrient dynamics, redox chemistry, and salt accumulation.[18] Hydrology and soil together are the key abiotic factors that influence wetland health, functions, plant and animal distributions.[18]

Chemistry

The central characteristic of wetland chemistry is a low redox potential as a result of anaerobic conditions. In aerobic conditions, redox potential is high, organic carbon is readily decomposed by aerobic microbes and the process is efficiently driven by oxygen acting as an electron acceptor in the reaction. As conditions become anaerobic, the redox potential lowers, organic carbon is less readily decomposed by microbes using anaerobic metabolisms, and organic matter usually deposited as organic-rich soil.[20] Variation in redox potentials is associated with soil depth and periods of inundation leading to oxidizing conditions alternating with reducing conditions; in other words, there are alternating aerobic and anaerobic zones.

Overall, low redox potential is a dominant feature of coastal wetlands.[15] When oxygen is eliminated from the soil, the redox potential becomes low enough for bacterial metabolisms such as nitrate reduction, iron reduction, and even sulfate reduction to occur. Nitrate, iron and sulfate are used as electron acceptors and are less efficient at organic matter consumption than aerobic metabolisms. Sulfate reduction will produce the rotten egg-smelling hydrogen sulfide gas.[15] Carbon dioxide can be used as an electron acceptor and as an energy source by a select group of microbes called methanogens. This reaction does contribute to atmospheric methane, and wetlands are a natural source of methane. However, methane emissions are usually higher in freshwater and inland wetlands than in coastal salt marshes because of the higher salinity.[21]

In addition, natural coastal wetland soil tends to have a neutral or slightly acidic pH and are well buffered.[18] The soil pH can change drastically following oxidation of sulfides to sulfuric acid (oftentimes due to exposure from dredging or drainage); in this case, the soil is called acid sulfate soils or "cat clays" and are a major concern because values lower than pH 4 are detrimental to the establishment of salt marsh plants.[18, 22]

Microbiome

Flooding and associated changes in oxygen levels is a primary determinant of soil microbial community in wetlands.[23] Depending on the oxygen availability, the surface layers may support aerobic bacteria. The anaerobic soil below the surface layer in salt marshes cultivate anaerobic or facultative organisms instead of aerobic microbes.[20] Coastal wetland soil microbiota are integral to organic decomposition in wetland soils. Microbial decomposition is severely reduced in strongly anaerobic soils because anaerobic microorganisms' activity is much lower than that of aerobic microorganisms. This results in organic matter, including organic carbon, rapidly accumulating (some estimates are 300-3000 kg/ha annually) and remaining in wetlands for long periods of time.[15] In addition, organic matter provides the fuel for reactions carried out by the anaerobes characteristic of organic-rich wetland soils - iron reduction, sulfate reduction and denitrification.[24] A unique consequence of wetlands in warmer climates is an increase in microbial activity (including breaking down organic matter) which contributes to the lower levels of organic matter found in San Diego coastal wetland soils. **Figure 1** shows how oxygen is used first as an oxidant as microbial decay of organic matter, yielding the most energy. As oxygen is depleted, other oxidants are reduced but yield less energy, therefore are less efficient than aerobic respiration.[25]

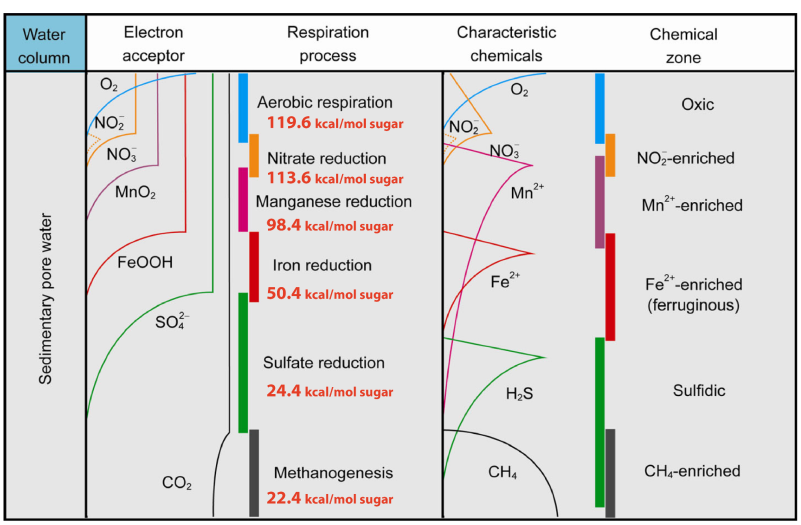


Figure 1: Figure 1 from Li et al. 2015[25] demonstrating the chemical zonation and turnover in microbial metabolic systems with depth in a sediment column. The numbers in red (taken from Table 1 of Li et al. 2015[25]) are the amount of energy yielded by the reactions. It can be concluded that aerobic respiration is much more efficient than methanogenesis.

Organic Matter

Most salt marsh organic matter content is from 10% - 40%, while salt marshes in Southern California usually have from 5% - 10%.[18, 26] It is thought that the lower organic matter content of Southern California marshes is due partly to year-round decomposition because of warmer temperatures and higher salinity levels.[18] The saturated and anaerobic conditions in wetland soils slows the decomposition of organic matter and leads to its accumulation. Significant amounts of moderately decomposable organic matter and recalcitrant materials like lignin are able to accumulate in the aerobic conditions.[20] This is important because soil organic matter affects soil structure and chemistry of salt marshes. It is a source of nutrients for plants and soil microbes, improves soil structure, buffers soil pH, adsorbs toxic organic compounds, in addition to adding to the blue carbon stock.[18, 20, 27]

Soil Salinity

Soil salinity naturally varies within a wetland due to elevation changes. Evaporation of the tidal sea water will cause salt to accumulate on the surface. Soils at higher elevations are exposed for longer periods of time between high tides resulting in higher soil salinity. In San Diego, the Mediterranean-type climate leads to year-round hyper salinity due to warmer temperatures and variable freshwater inflows; evaporation usually exceeds the low, seasonal precipitation characteristic of the region.[18, 28] Wetland soils of San Diego usually have a soil salinity >40 ppt, while salinity of several coastal marsh sites in Washington state averaged 15.5 ppt.[2, 18] Salinity affects several components of wetland soil including sediment composition and organic matter accumulation. For example, salinity promotes flocculation of clay particles and marsh plants promote the clay particles to settle. Additionally, saline tidal marshes usually contain less organic matter than tidal fresh and brackish marshes.[24, 29]

Sediment Texture

Substrate conditions are important for supporting wetland functions such as water filtration and providing a habitat for plants and animals. Be that as it may, basic information of substrate conditions including distribution of sediment size from natural coastal wetlands is lacking.[18] It is known that coastal wetland soil is a combination of sand, silt and clay (loamy), but because natural wetlands develop in areas with slow-moving tidal water, their soil has relatively more clay compared to other soil types, but conditions within each wetland and habitat varies as well. Craft[24] writes that the ideal texture for restoration consists of a loamy soil with relatively equal proportions of sand, silt and clay. Lower marsh soils were characterized at Tijuana Estuary and revealed that the soils were generally clayey, with 46-58% clay, 2-8% sand, and 23-32% silt.[22, 30] A separate sampling of a natural site (not restored) at the Tijuana Estuary reported that a core sampling 10 cm deep consisted of 42.5% sand, and a core sampling 30 cm deep was 46.4% sand.[31] Soil bulk density is usually low in wetlands due to the high amount of organic matter. Elgin[31] reported percent organic matter and bulk density of sites in Tijuana Estuary- 17.45% organic matter correlated with a bulk density of 0.479 g/cm^3 and 7.97% organic matter correlated with a higher bulk density of 0.785g/cm^3 (**Table 1A**). Another interesting finding was that restored sites generally had lower percent organic matter, soil organic carbon values, and higher bulk density values compared to the natural sites, as noted in **Table 1B**.

Location	**Core Depth (cm)**	**% Organic Matter (OM)**	**% Soil Organic Carbon (SOC)**	**Bulk Density(g/cm^3)**	**% Sand**
Mugu Lagoon, CA	0-10	11.6 ±1.14	5.09±0.55	0.628±0.022	33.0±2.6
	10-30	5.33±0.36	2.09±0.15	0.887±0.029	39.7±3.7
Tijuana Estuary, CA	0-10	17.45±1.67	7.95±0.89	0.479±.024	42.5±3.3
	10-30	7.97±0.51	3.25±0.21	0.785±0.060	46.4±2.4
Carpinteria Salt Marsh, CA	0-10	15.28±1.60	6.88±0.80	0.504±0.042	45.6±3.3
	10-30	6.10±0.53	2.52±0.22	0.966±0.044	43.1±3.7

Table 1A: Data from Natural sites divided into two depth categories. Notice the decrease in percent soil organic carbon and the increase in bulk density with depth.[31]

Location	**Core Depth (cm)**	**% Organic Matter (OM)**	**% Soil Organic Carbon (SOC)**	**Bulk Density(g/cm^3)**	**% Sand**
Mugu Lagoon, CA	0-10	6.34±1.23	2.75±0.56	0.974±0.060	51.4±4.6
	10-30	1.65±0.17	0.66±0.07	1.470±0.025	59.7±4.1
Tijuana Estuary, CA	0-10	8.90±1.24	3.81±0.58	0.496±0.032	26.3±2.1
	10-30	2.27±0.23	0.92±0.09	1.228±0.049	44.2±3.5
Carpinteria Salt Marsh, CA	0-10	12.63±3.09	5.79±1.50	0.826±0.121	60.7±3.9
	10-30	4.19±0.49	1.80±0.21	1.182±0.056	52.7±5.6

Table 1B: Data from Restored Sites divided into two depth categories. Notice the higher bulk density values as well as the lower percent organic matter and soil organic carbon values particularly with depth.[31]

Porosity is high allowing for higher infiltration and percolation rates of water.[27] A porosity 35% is commonly used to calculate velocity of groundwater in habitats other than wetlands. In comparison, the porosity of several San Francisco wetlands ranged from 76-82%.[32] However, if the wetland is created with larger, coarse textured sediment (such as sand), problems can arise such as low water retention and low organic matter content.[18]

Nutrients

Nitrogen and phosphorus are essential for all living organisms and play key roles in aquatic ecosystems. The limiting nutrient for most coastal wetlands is nitrogen because it is readily lost through denitrification, and phosphorus is more prevalent in seawater.[18, 24] Added nitrogen was shown to shift community dynamics in a marsh in San Diego Bay; more nitrogen promoted the growth of the annual *Salicornia bigelovii* (pickleweed, a native annual forb) over the perennial *Spartina foliosa* (cordgrass, a native perennial grass).[18] Furthermore, additional nutrients can cause eutrophication and large macroalgae blooms. Several consequences are possible, for example hypoxia and seedling mortality among desirable species of vegetation naturally establishing at wetland restoration sites.[18] The accumulated organic matter in wetlands brings in nitrogen and other plant nutrients in unavailable forms, but can be converted into available forms by microbes during decomposition.[27] Both organic matter and nitrogen are critical in supporting the health and growth of plants, animals, and microbes in salt marshes.[24]

In sum, it is difficult to say what exactly is ideal coastal wetland soil in San Diego, especially for natural coastal wetlands. The majority, if not all, wetlands in San Diego have been affected by anthropogenic factors so the argument could be made that there are no natural wetlands left. Nevertheless, there are still protected coastal wetlands that are being restored and rehabilitated. Generalizations can be made about ideal soil for coastal wetlands, such as having high organic matter (5%-40% organic matter), higher amounts of fine sediment than other types of soil, and anaerobic conditions supporting a microbial community of predominantly anaerobes. Going forward, the soil conditions at all of the current wetlands in San Diego should be measured, monitored, and then have the data easily accessible to contribute to future restoration projects.

How Can The Soil Be Amended, Even Augmented?

The soil or substrate conditions of a restoration site need to be evaluated in any restoration project, especially in large projects that require grading or excavation. Physical, chemical and biological parameters such as soil salinity, compaction, texture, moisture and organic matter will need to be evaluated to determine whether or not soil amendment is needed to create typical conditions of salt marsh soil that support plant growth.[18] Soil amendment is defined as, "any material, such as lime, gypsum, sawdust, or synthetic conditioner, that is worked into the soil to make it more amenable to plant growth.[15]" There are a variety of soil amendment options depending on the targeted soil characteristic. However, there are still gaps in understanding soil amendments in wetland soil; the hydrology and salinity levels characteristic of salt marshes warrant long-term studies and monitoring.[18]

Common soil amendments used in wetland restoration projects target texture, organic matter, and nutrients. Fine-texture amendments are meant to remedy problems associated with too much coarse soil at restored wetlands that could contribute to poor vegetation growth. Potential amendments include clay, silt, salvaged soil from excavation sites, and fine-textured dredge spoils. However, toxicity is a potential issue for fine-sediment amendments, especially dredge spoils. These spoils tend to accumulate more pollutants (including heavy metals and organic pollutants) than coarse soils and there is a risk of the pollutants transforming into soluble and mobile forms in the soil in various conditions (i.e. seawater solution, aerobic vs. anaerobic).

Composted kelp, alfalfa, straw, and sewage sludge have all been used for organic matter amendments in wetland soils. In San Diego Bay, composted kelp along with freshwater irrigation was used to establish high marsh plants in highly compacted and saline soils. It was found that the increase in organic matter helped reduce soil compaction, improved water retention and increased soil structure.[18] The alfalfa and straw amendments have shown to increase organic matter in wetland soils but also have low nitrogen content.[18, 33] These amendments could potentially reduce the amount of nitrogen even further in a nitrogen-limited wetland due to promoting microbes that immobilize nitrogen, so it is recommended that these kinds of amendments be used in areas with excess amounts of nitrogen.[18] Lastly, sewage sludge has been used because it is readily available and high in nutrients. However, contamination and toxicity are also a potential issue that needs to be evaluated before use in restoration projects.

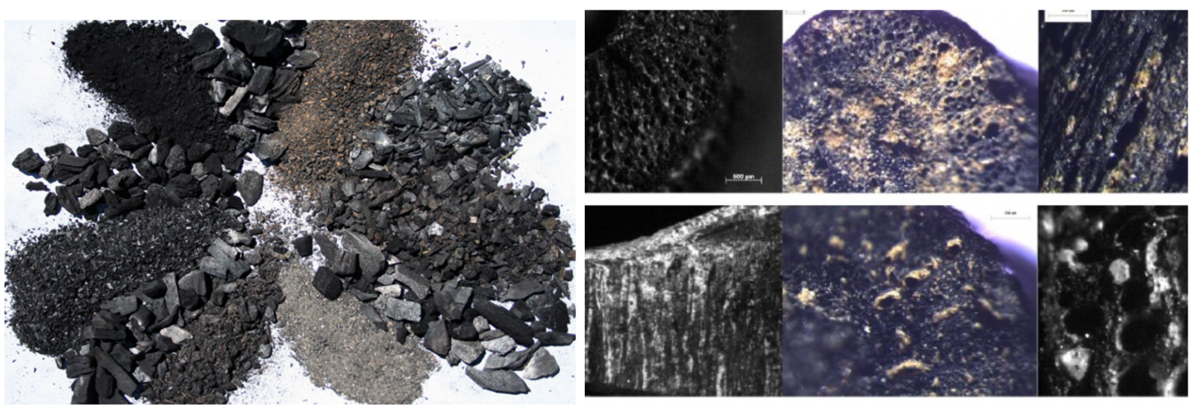
Nitrogen is consistently the limiting nutrient in salt marshes so soil amendments specifically targeting the nutrient content of wetland soils usually focus on nitrogen rather than phosphorus.[18, 19] Studies of fertilizer additions have resulted in great variability of impact to aboveground growth, accumulation of belowground biomass, and nutrients in sandy dredge soils.[18, 34] The long-term ability of fertilization to create a self-sustaining system is questionable, so it is recommended that fertilization is used only in special cases with proper soil texture.[18]

Biochar: **What is Biochar and How is it Produced?**

An emerging soil amendment with the potential to improve soil conditions, promote plant recolonization in wetlands, and mitigate climate change is biochar. Biochar is an umbrella term used to name the charcoal produced from biomass. The biochar can be made from a variety of different types of biomass and through slightly different processes. The structure and properties of the biochar can also vary depending on its feedstock and method of production, but generally, biochar is a fine-grained highly porous type of charcoal.[35] Biomass can be thermochemically converted in three main ways: pyrolysis, gasification, and combustion. Each process requires burning the biomass at high temperatures but differ in the amount of oxygen used; pyrolysis occurs with no oxygen, gasification occurs with a limited amount, while combustion requires oxygen.[35] Pyrolysis was found to be the most common method reported in the literature search, so the rest of this report will focus on biochar produced through pyrolysis, unless otherwise noted.

Individual types of biomass, or organic waste, used in the production of biochar are called feedstocks. Common feedstocks include food waste, agricultural byproducts, hardwood and softwood, and sewage sludge. The process of converting organic waste results in three different products: biogas, bio-oil, and the solid carbon-rich biochar. Again, the amount of each product depends on the process and methods used. However, there is potential for the biogas and bio-oil to be captured and used as energy sources to produce more biochar, or to be used in other locations such as heating and cooling homes.[35]

Biochar can be produced through pyrolysis at an industrial scale or small scale using a kiln. It is described as looking like broken coal, and the grain size depends on the scale of production. Commercially produced biochar is typically granular in size. The biomass is burned at temperatures ranging from 200℃ - 1,000℃, for a specific amount of time. One paper concluded that the pyrolysis reactions were completed within 30 minutes.[36] It was also found that an increase in pyrolysis temperature results in a significant decrease in biochar yield and an increase in biochar surface area.[36] The amount of time burned also alters the biochar- longer burn times result in more recalcitrant biochar while shorter burn times result in more labile biochar.[37] Furthermore, the structure of the feedstock also greatly influences the structure and porosity of the biochar. If the feedstock is a hardwood type with a lignan structure, the biochar will be more stable (decomposes slowly). In contrast, if the feedstock is a softwood or has a loose structure, the biochar will also have a loose, less stable structure (decomposes quicker).[37]



A. UC Davis Biochar[38] **B.** (Wilburn, Sorrenti et al., 2016)[39, 40]

Figure 2: A. Biochar comes in a variety of textures and sizes. **B.** Microscopic imagery of biochar particle surfaces and interiors reveal the porous structure of biochar.

Biochar: Uses

The inherent variety in biochar characteristics can be seen as a benefit and limitation. For example, biochar could potentially be created to amend soil, to fulfill one goal such as increasing the water capacity in soil. Studies have shown that biochar's irregular shape and porosity increase the water holding capacity of soils, especially in sandy (coarse) soils.[39, 41] In addition, biochar can be a source of organic carbon and some essential nutrients for the microbial communities and vegetation in depleted soils.[39, 42, 43] Other benefits of using biochar have been reported as regulating carbon dioxide emission rates and removing organic and inorganic contaminants from wastewater, both due to adsorption and its high surface area.[36] Furthermore, agricultural waste, or invasive vegetation that would otherwise decompose and release carbon dioxide into the atmosphere can be turned into biochar. Global implementation of soil carbon storage with biochar has an annual carbon sequestration potential of around 0.7-1.8 Gt CO_2-C_e.[44, 45] Furthermore, Lehmann et al.[46] reported that low-temperature pyrolysis of biomass combined with the capture of gas and liquid products for bioenergy production and soil application of biochar could sequester about 10% of the annual US fossil fuel emissions.[47] Regarding local coastal wetlands, biochar could be stored in the anaerobic soils for a long period of time especially if its feedstock has a lignan structure, therefore making the biochar recalcitrant, increasing the blue carbon stock in the wetland.

Challenges in Using Biochar

There are limitations to the potential use of biochar as a soil amendment in salt marshes. The majority of research exploring biochar's role in improving soil properties has focused on agricultural soils, so little is known about how biochar will be affected by and in turn impact aquatic ecosystems such as coastal wetlands.[39] For example, biochar can alter the soil bulk density of soils depending on the granular size of the sediment and biochar. Sediment with larger grain sizes (i.e. sand) with biochar of larger particle sizes could result in decreasing in soil bulk density, which could be detrimental to a salt marsh that is lacking fine-grain sediment. This is because nutrients are quickly leached in sandy soils because fine-grain sediment such as clay is absent to help increase the concentration of nutrients and substances.[20] Theoretically, biochar in this case would exacerbate the sandy soil problems. On the other hand, if biochar with smaller particle sizes is placed with fine-grain sediment, the soil bulk density could increase and create compacted soil.[37] In summary, little is known about biochar's ability to increasevegetative productivity, moderate soil chemistry, and promote a healthy microbial community in soils characteristic of salt marshes including low oxygen, and variation in salinity and redox potential.[39]

Amending and Augmenting: Can Biochar Be Used in Coastal Wetlands to Increase Blue Carbon Stock?

Despite this lack of data about the effects of biochar on wetland soil, there have been some salt marsh restoration projects which used biochar as a soil amendment to test its effectiveness in increasing plant growth and blue carbon. Two case studies will be explored below. The first is Hester Marsh on the central coast of California, and the second is Mugu Lagoon in Southern California. Each project set goals to return each site to a functional ecosystem, but only Hester Marsh explicitly stated a goal to increase blue carbon function.

Case Study: Hester Marsh at Elkhorn Slough

Elkhorn Slough in Monterey, California restored a section of the wetland complex, Hester Marsh, and included small-scale restoration experiments using biochar to determine if restoration success can be enhanced. The goal of the experiments was to see if biochar as a soil amendment would improve salt marsh plant colonization, growth, or survival.[48] Biochar was created onsite from eucalyptus trees sourced from another part of Elkhorn Slough. Then, a tablespoon of biochar was placed in the planting hole of about 6% of transplanted seedlings. The biochar aspect of the project started in 2020, and as of the publication of the 2021 annual report of the

Hester Marsh restoration project, no significant growth or benefit to vegetation was observed in the sections with the biochar soil amendment.[48] Another small-scale experiment was set up to examine biochar's impacts on soil with granite in 12x12 plots. Biochar was mixed 10% by volume into top 4-8 inches (10-20 cm) of sediment.[48] No results were reported as of the publication of the 2021 annual report.

Although there are no significant results indicating that the biochar enhanced the restoration, there are several factors worth exploring and considering in future experiments. First, the teaspoon of biochar was probably not large enough to have a chance of increasing water capacity, organic matter, etc. Brittany Wilburn, a grad student studying biochar's effects in wetlands and who was partly involved in the Hester Marsh project, reported that most experiments mix the amount of biochar and sediment by volume, such as mixing 10% or 20% by volume[37]. Second, the Hester Marsh project was unique in that it also restored the elevation of the marsh to a higher elevation to allow for resilience to future sea level rise. Approximately 230,000 yds^3 (175,848 m^3) of sediment across 61 acres (25 ha) was added so that the marsh plain elevation would be just above Mean Higher High Water (MHHW), or 6.2 feet (1.89 m) NAVD.[48] This is unique because usually wetlands are restored "to raise surface elevations to conditions suitable for tidal marsh to be re-established at the site," or a thin-layer of sediment addition raises the elevation primarily 10cm-20cm.[49, 50] The large plot biochar experiment may be more successful due to a larger amount of biochar being mixed in, but a large amount of the sediment is granite, so the larger granular size will likely negatively impact plant colonization and growth. There were many variables involved in the experiment including the biochar, making it difficult to confidently determine the impact of biochar on vegetation in Hester Marsh.

Case Study: Mugu Lagoon

Mugu Lagoon, part of Naval Base Ventura County in Point Mugu, California, was restored and also used a biochar soil amendment to increase plant survival and growth. The goal of the project was "to return the site to a high-quality, biologically diverse wetland habitat that functions ecologically as close as possible to pre-construction conditions.[51]" This project did result in an increase in plant growth. There are some significant differences in the methods used in the Mugu Lagoon restoration project from Hester Marsh that could explain the success at Mugu Lagoon. First, the soil amendment was a combination of biochar (20%) and compost (80%). Second, the soil amendment was mixed with additional compost and fill soil at ratios of 1:0.5:1 or 2:0.5:1, and then placed into each hole before transplanting the vegetation in the intertidal area.[51] Additionally, six 50-foot trenches were also excavated in the intertidal area and filled with the biochar-compost mixture to promote recruitment of native plants.[51] Results showed that five years after the large-scale planting, growth of intertidal plants was largely restricted to areas with biochar-compost: where the biochar-compost mix was buried in trenches, and where the mix had accumulated on the surface at the border between the intertidal and upland zones.[51] While these are promising results, more research is needed on different ratios of mixture, and changes in the biochar-compost soil amendment over time.[51]

Discussion of Hester Marsh and Mugu Lagoon

Although the results from Hester Marsh and Mugu Lagoon are different, it is important to state the importance of goals and the desired function of the biochar. For instance, Hester Marsh aimed to increase the blue carbon function of the restored marsh by increasing the extent of healthy salt marsh and sequestering atmospheric carbon dioxide in marsh sediments and standing biomass marsh vegetation.[48] Even though the biochar soil amendment did not show any improvement in plant growth or survival, there is more carbon stored in the sediment in the form of biochar. Additionally, since the biochar was sourced from eucalyptus trees in Elkhorn Slough, this process provided several other benefits: it removed nonnative trees, prevented the carbon in the trees from entering the atmosphere, and did not have to be bought and shipped from a far distance. In the case of Mugu Lagoon, it could be argued that the success of the biochar-compost amendment increased the amount of blue carbon through storing the carbon-rich biochar in the soil and increased the functionality of blue carbon by improving the growth of marsh plants.

<u>Part 2: Implementation Challenges</u>

Overview of Challenges

Effective ecological restoration is transdisciplinary and incorporates the biophysical context, socioeconomic and political matrix when planning, funding, and implementing the project.[14] Effective restoration projects are holistic and work at a landscape scale. The goals are specific yet flexible. There ideally is a reference ecosystem that can be used to help guide the planning and implementation of the project. However, these foundational points are difficult to follow because there are many challenges involved in ecological restoration. For example, each project site is unique in terms of its biophysical context and socioeconomic and political matrix. There may not be a reference ecosystem available, there may be a lack of political will to support restoration projects, and funding may run out before completion because projects should last for decades to be effective. On top of that, climate change adds another challenge to ecological restoration. For example, restoration managers need to consider if they should continue trying to restore the site to a historical reference if it’s known that the future climate will be different, possibly unconducive to the historical reference ecosystem.

San Diego Overview of Challenges

In San Diego, restoring coastal wetlands has its own set of challenges, and each individual site has its own. Generally, coastal wetlands are challenging to restore due to their complex physicochemical environment, biodiversity, and vulnerability to sea level rise.[18] Salt marshes are complex in their topography and hydrology regimes, many organisms living there require specific habits and connections to other habitats, and salt marshes are subject to subsidence as their surroundings are altered due to sea level rise or anthropogenic impacts. In fact, salt marshes in San Diego and Southern California are particularly impacted and challenged by the growing population of people. A high population density led to urbanization, draining wetlands, building over them, and altering the river tributaries throughout the watershed.

Wetland habitats have been lost, fragmented, altered and isolated. The coastal landscape has been altered so much that ocean inlets of lagoons often close and require yearly dredging of the inlets as a part of management. If the ocean inlets remain closed preventing tidal flushing, the extremes of the temperature, oxygen and salinity conditions are increased, leading to stagnant water and fish die-offs. Los Peñasquitos Lagoon near Torrey Pines has reported instances of fish die-offs when the ocean inlet has closed and cited a risk of an increase in insects and West Nile virus due to the stagnant water in the lagoon.[52] The Los Peñasquitos Lagoon Foundation, a nonprofit, partners with California State Parks and other agencies to manage the lagoon including dredging the inlet.

Challenge: Where Can Coastal Wetland Restoration Projects Source Sediment?

The unique and complex natural features and processes of coastal wetlands makes it difficult to restore or create them, in particular where the natural landform has been greatly altered.[18] Field evaluations of potential restoration sites and mitigation projects are necessary to evaluate the opportunities and constraints of the site.[18] For instance, historical wetlands could have been drained, leveled and filled with concrete resulting in compacted soil and loss of fine-sediment with organic matter. The hydrology, vegetative cover, and soil conditions all are likely to have been greatly altered. Large restoration projects usually require construction and earthworks.

Oftentimes the substrate underneath the surface that is revealed after excavation differs from the surface substrate. It may be buried wetland soil or coarse subsoil. Using wetland soil is best to use for restoration, but effort and associated costs often influence the decisions on what to do. The original wetland soil will be buried under fill material so extensive over-excavation would be required, then stockpiling the wetland soil, then regrading the area to correct the elevation.[18] Data on the soil quality would be beneficial to the restoration plan by dictating the need for soil amendments or not. Additionally, careful management of the excavated sediment will be necessary due to the chance of oxidation and creation of acidic soils.[18]

Alternatives for disposing soils need to be evaluated, in addition to identifying the amount and quality of the sediment excavated. For example, is the soil fine, coarse, or contaminated? Coarse sediment may be able to be deposited on a nearby beach contributing to beach nourishment, or contaminated soil may need to be trucked off-site.

Soil would need to be imported to raise the elevation of the wetland. Oftentimes, coarse-textured fill is used for restoration projects because it is more readily available than fine sediment. However, coarse-textured sediment is not ideal for coastal wetlands because organic matter cannot accumulate well. The coarse soils drain more compared to the fine-sediment soils characteristic of salt marshes.[18] The better options are using salvaged soil from a wetland if the restoration is a mitigation project, using soil from a reference wetland, using top soil, and dredged material.

San Diego: ReWild Mission Bay and Pond 20 at Port of San Diego

Coastal wetland restoration efforts are anticipated to continue and increase in the San Diego region as climate mitigation and adaptation efforts increase. Restoration and creation of wetlands requires sediment, so finding enough sources of sediment to be used as fill and top soil is of great importance. Additionally, finding local sources is important to reduce costs. As a project manager of the Pacheco Marsh restoration project in San Francisco stated in a news article, "'Dirt is cheap…but moving the dirt from one place to another is expensive.[53]'"

The ReWild Mission Bay Wetlands Restoration Feasibility Study Report presents three restoration plans: Wild, Wilder, Wildest. They vary in several ways, but of interest for this report is the proposed use of excavated soil and implementation costs for each alternative. The Wild Plan proposes to excavate 1,310,00 yds^3 of soil from the site, use 110,000 yds^3 for fill, therefore exporting 1,200,000 yds^3. [54] The exported soil would either have to be disposed of in the open ocean at the Los Angeles 5 Ocean Dredged Material Disposal Site (LA-5) site or disposed of upland. Cost estimates for implementing the Wild Plan with LA-5 disposal is $97.8 million, and the cost estimate with upland disposal is $91.4 million.[54] The Wildest Plan proposes to excavate 1,140,000 yds^3 of soil, and use all 1,140,000yds^3 for fill onsite.[54] Implementation cost estimates for the Wildest Plan with on-site disposal is $62.6 million. A summary of price comparisons can be found in **Table 2** from page 189 of ReWild Mission Bay: Wetlands Restoration Feasibility Study Report. The price differences between the Wild and Wildest Plans can be attributed to the differences in transportation costs of using barges or trucks hauling large amounts of sediment.

Summary of Implementation Cost Estimates (in 2017 Million of Dollars)

Item	*"Wild"*		*"Wilder"*		*"Wildest"*
	LA-5 Disposal	*Upland Disposal*	*LA-5 Disposal*	*Upland Disposal*	*On-Site Disposal*
Total Cost ($Million)	97.8	91.4	46.4	46.2	62.6
*Restoration Unit Cost ($million/Acre of habitat***)*	0.41	0.38	0.16	0.15	0.16
Restoration Unit Cost ($million/Acre of wetland habitat)*	0.54	0.50	0.19	0.19	0.22
*Restoration Unit Cost ($million/Acre of wetland restored**)*	1.07	0.99	0.34	0.33	0.35

** mudflat, low, mid and high salt marshes, includes existing wetland in KFMR/NWP but excludes public access features*
*** mudflat, low, mid and high salt marshes, excludes existing wetland in KFMR/NWP and public access features*
**** mudflat, low, mid and high salt marshes, transitional, uplands, includes existing habitats at KFMR/NWP but excludes public access features*

Table 2: Summary of implementation costs for ReWild options from ReWild Mission Bay: Wetlands Restoration Feasibility Study Report.

Potential sediment sources in San Diego were explored with the idea that future coastal wetland projects in San Diego may not be able to reuse the excavated soil and sediment onsite. For instance, the proposed wetland mitigation bank at Pond 20 in the Port of San Diego is a former salt evaporation pond so its soil is very poor; it is isolated from tidal influence and has a high salinity content. A conversation with two employees involved in the restoration project stated that a large amount of the soil will need to be excavated and exported likely to a landfill because the soil salinity is too high to be reused onsite.[55] They stated that the estimated costs of exporting sediment is $24,200,000.[55, 56] While exporting contaminated soil is an unavoidable cost in some projects, costs could be reduced elsewhere such as in sourcing local sediment from other construction sites.

SediMatch in San Francisco

San Francisco, California provides a possible solution to connecting actors who have sediment and those who need sediment. The San Francisco Estuary Institute has SediMatch, a collaborative program of several regional conservation groups, estuary groups and others. Its goal is to bring together wetland habitat restoration, flood control, and dredging communities to maximize beneficial reuse of dredged sediment.[57] The SediMatch Web Tool is an easily accessible database where sediment needs can be matched with surplus sediment.[57] Partners can add their project, indicate the amount and type of sediment they either have or need, and the transportation and access available to move or receive the sediment. The website can be accessed at https://sedimatch.sfei.org/. Creating and implementing a similar web tool for the San Diego region could be beneficial to meet current and future sediment supply needs.

Sediment in San Diego

The sources of available sediment are mainly based upon SANDAG's Regional Sediment Management Plan/Regional Beach Sand Projects. While the focus of the Regional Beach Sand Projects is sourcing sand/coarse grain sediment, it does include a compilation of sources of other sediment types. **Table 3** from the SANDAG Regional Sediment Management Plan 2009 shows estimations of the grain size, chemistry, available quantity and typical availability of sediment sources in San Diego. For wetland restoration projects, the fill material could be composed of coarse sediment given that salt marsh vegetation will not be growing from it. Finding an adequate amount of fine-sediment such as clay and silt, and topsoil will be the challenge.

Top soil of upland sources will have fine sediment. Upland sources include development sites, dry river beds, dry flood control channels, dry sediment detention basins, and roadway widening projects.[58] Dredging of bays and harbors have the potential to be a source of fine sediment, but these projects happen intermittently in San Diego. Mission Bay was dredged in 2018, resulting in an estimated amount between 122,000 yd^3 and 22,850 yd^3, all of which was reused in other parts of Mission Bay to renourish sections of beach.[59] San Diego Bay was dredged in 2020; 240,000 yd^3 of sand were removed with about 175,000 yd^3 of it deposited offshore and 65,000 yd^3 deposited at Silver Strand Beach.[60] In addition, sand or sediment from dredging or maintenance projects in lagoons, harbors, and the open ocean is free, and upland soil usually comes with a minimal cost.[61] Future projects requiring fine sediment may benefit from the variable dredging projects.

Property	Upland Soil	Flood Control Basin/Corridor	Lagoon	Bays/Harbors	Offshore Ocean
Grain Size	Narrow range, but more fines near surface (25%+)	Broad range, rocks to silts, also debris	Narrow range, mainly fine to medium sand	Moderate range, sandy to silty	Narrowest range, medium sand
Chemistry	Potential contaminants in top 5 feet	Potential contaminants throughout	Typically clean	Clean to contaminated	Clean
Quantity	Very small to Small, (<25,000 to 100,000 cy)	Very small (<25,000 cy); Dams can be significant (500,000 cy)	Small-Moderate * (25,000's to 500,000 cy)	Moderate to large* (100,000's to millions cy)	Largest (>1,000,000 cy)
Typical Availability	Annually or semi-annually	Annually to bi-annually	Annually to every 3 years	Annually to every 5 or more years	Every 5 to 10 years or more

*Restoration or development may generate very large volumes

Table 3: Table showing existing sediment sources in San Diego County taken from Regional Beach Sand Project report.

Extra soil from construction projects also needs to be stored. Currently in San Diego, Miramar Landfill receives soil from projects generating soil as a part of their Clean Fill Dirt Program. The soil needs to be clean to be used as daily cover and resurfacing of the tipping decks at the landfill.[62] It may be possible that some of the clean fill soil at Miramar Landfill could be accessed to use in future restoration projects.

Challenge: Where can the organic matter to make biochar be sourced?

The supply of fine sediment may not meet the increase in demand for wetland-appropriate sediment. Less-than-ideal sediment is already commonly used for wetland restoration projects which leads to poor hydrology, vegetation growth, and a need for soil amendments. As already discussed, biochar is a potential soil amendment. More research is required to better understand which types of biochar may benefit wetland soil best, but producing biochar could also contribute to other climate and sustainability goals, including carbon sequestration and reducing organic waste in municipal landfills.

Regardless of the purpose of the biochar (i.e. increase water capacity, plant growth, or blue carbon), large quantities of organic matter would be required to produce enough for a large restoration site. Agricultural Research Service scientists, part of the US Department of Agriculture, test biochar produced from various feedstocks at various temperatures and times. They have experimented in agricultural settings with applying 8,800 pounds of biochar per acre, 16,000 pounds per acre, and 20,000 pounds per acre.[63] Other reports state that it is possible to obtain up to 50% mass yield of biochar under moderate pyrolysis.[44] Using 20,000 pounds of biochar produced from a 50% mass yield reaction, the starting amount of biomass required is ~40,000 pounds.

This brings up the question of where to source local organic waste to produce enough biochar, minimize costs and reduce the total carbon footprint of production. Thengane et al.[44]

report that biomass collection, transportation, and conversion costs were identified as major challenges to the production of market-responsive bioproducts including biochar.[44] As for the carbon footprint of biochar production, Massana et al.[64] analyzed the distribution of carbon emissions of a small-scale biochar production in Europe and found that low transportation distances of the feedstock and biochar help avoid emissions. However, the majority of emissions and energy loss came from the pyrolysis process; therefore, ensuring the pyrolysis process is energy efficient may result in a significant reduction of emissions.[64]

Common feedstocks of biochar are: food waste, agricultural byproducts, hardwood and softwood, and sewage sludge. This next section will briefly discuss the possibility of using food waste, hardwood, and sewage sludge in San Diego as feedstock. Agricultural byproducts won't be explored due to the absence of a large local agricultural community in San Diego County. Nevertheless, future efforts could include agricultural byproducts from the Imperial Valley and Mexicali. Softwood feedstock won't be explored because softwood trees include pine, spruce, cedar and fir trees and these are not commonly found in San Diego County. In contrast, hardwood trees, such as eucalyptus, are found in San Diego County in large amounts.

Source: Food Waste

Food waste is a form of organic waste that traditionally goes to landfills and emits methane gas. In the US in 2019, 35% of the 229 million tons of food available was unsold or uneaten.[65] In 2019, California produced 10.4 million tons of food waste and 2.35 million tons of it went to landfills.[65] In terms of climate change, this is detrimental because as food waste decomposes in landfills, methane is produced, released into the atmosphere and contributes to climate change.

In addition, the Miramar Landfill in San Diego is reaching capacity. According to the City of San Diego's 2012 waste characterization study, food comprised 15% of material in Miramar Landfill, equal to about 189,000 tons.[66] California Senate Bill 1383 (SB 1383) was signed into law to address the issue of organic waste in landfills contributing to pollutants.

California is implementing statewide organic waste recycling and surplus food recovery.[67] Cities, including San Diego, must meet new reduction limits through waste reduction and recycling starting in 2022.[68] Organic materials can be recycled using recycling facilities such as "anaerobic digestion facilities that create biofuel and electricity, and composting facilities that make soil amendments.[67]" Producing biochar from food waste that would otherwise go to landfills is a possibility. Furthermore, a 2020 California Energy Commission report commentating on the benefits of utilizing food waste stated, "food waste diversion began to develop as a cost-saving mechanism for large food waste generators to reduce their waste disposal costs…food waste is rich in energy content and its addition to an anaerobic digestion system could significantly improve the biogas yields.[69]" However, the correct equipment and upkeep of it will be necessary to develop and incorporate in recycling facilities. According to the CalRecycle Conversion Technologies: Organic Materials Management webpage, the residue from thermochemical, biochemical and physicochemical pathways may or may not have market value, may contribute to fouling of high temperature equipment, and increase disposal costs.[70]

Source: Hardwood/Eucalyptus

Woody biomass, such as eucalyptus trees, is another potential feedstock to produce biochar. There are 10 nonnative and naturalized species of eucalyptus trees in San Diego, meaning the trees are persisting or spreading in natural, non-cultivated areas.[71] The eucalyptus trees have negative impacts on the environment such as altering soil quality, light availability, fire patterns, and nitrogen mineralization rates, and outcompeting native species.[72] Despite the associated negative impacts, it is difficult to remove eucalyptus trees due to costs and policies protecting all trees in San Diego. Costs could be offset if biochar is produced from the removed eucalyptus trees and sold as a soil amendment, or if the biochar could be a source of carbon credits. Support to remove eucalyptus trees could be generated if native trees are planted to replace them, such as the endangered and endemic Torrey Pine. UC San Diego has a Thousand Tree Initiative to plant 1,000 trees, including Torrey Pines, on campus. Regular maintenance and increased thinning of the eucalyptus forest on campus presents the possibility of providing a source of biomass for biochar production and providing more space to plant Torrey Pines.

Source: Sewage Sludge

Biochar can also be produced from sewage sludge, also referred to as biosolids. Sewage sludge is a difficult waste to manage due to high quantities produced and to its high concentration of heavy metals and pathogens.[36] In order to increase sustainability, reduce waste, and reduce costs, Encina Wastewater Authority (EWA) in Carlsbad, California manages biosolids to produce bisolid pellets and energy. Biosolids are dried and processed to Class A biosolids, which have unrestricted use. Approximately 5,450 dry tons of biosolids are produced per year. Then, after more drying and sorting, the biosolids become a clean, dry, stable and granular material. They can be used as a biofuel or organic fertilizer. EWA has reduced its costs for biosolids disposal after implementing the new process of creating biosolid pellets by reducing transportation costs and is generating revenue from the sale of fertilizer. According to EWA's website, the total savings is about $2 million per year.[73] In addition, EWA also recovers biogas produced from the anaerobic treatment process of wastewater, and has an Alternative Fuel Receiving Facility that produces energy (biogas) from alternative fuel, such as grease from restaurants. Despite this, email correspondence with EWA representatives disclosed that factors such as high upfront costs of the heat dryer used in the drying process and a lack of biosolid pellets/biochar market are making the costs of reusing biosolids outweigh the benefits.[74]

The City of San Diego contracts its biosolid management and hauling services to San Diego Landfill Systems LLC, a subsidiary of Republic Services, Inc. According to the 2021 Point Loma Pretreatment Report, no biosolids were shipped to, disposed of, or beneficially used at Otay Landfill in Chula Vista, CA.[75] Instead, the biosolids were shipped to Yuma, Arizona to be used for land application or lime stabilization. The total wet tons of biosolids shipped to Yuma for 2021 was 128,733.26. And according to the city contract (resulting from a Request for Proposal) with Republic Services, the base cost to haul biosolids to Yuma for land application is $53/wet ton, and for lime stabilization is $63/wet ton.[76] Republic Services' application to the Request for Proposal states that the company also has additional proposed options for biosolid management such as "soil amendments for use as alternative daily cover at landfills, as well as emerging technology alternatives.[76]" The base cost for delivery to Otay Landfill for soil/alternative cover is $52/wet ton.[76] Their application also states that they are validating innovative processes that aligns with the City of San Diego's Climate Action Plan goals, such as "blending biosolids with compost to make a soil amendment [which could] provide the City with recycling credits.[76]" Producing biochar locally has the potential to reduce the amount of biosolids shipped to Yuma and increase the City of San Diego's sustainable practices.

Possibility for Offsetting Costs: Carbon Credits for Blue Carbon, Biochar

Carbon credits are seen as a promising incentive to reduce greenhouse gas emissions and offset the high costs of restoration projects by selling the credits. Blue carbon projects are poised to enter the carbon market given the high amount of carbon captured and stored in the ecosystems once methodologies to account for the carbon and rules to allow blue carbon ecosystems to claim credits are finalized. Preliminary estimates of the blue carbon value for Kendall-Frost Marsh Reserve in Mission Bay were calculated in the MAS MBC capstone project of Patti Clark in 2021; depending on the carbon value used, the calculated value ranges from a low of $69,461 to a very high estimate of $1,609,173.[77] The low estimate was calculated using California's 2021 carbon value of $18/MTCO_2e$, and the very high estimate was calculated using the global social carbon cost found by Ricke et al 2018 of $417/MTCO_2e$. An intermediate carbon value is the Federal Carbon Price under the Biden Administration at $76/MTCO_2e$, resulting in a blue carbon value of $293,278.[77]

High carbon values are possible if biochar is used as a soil amendment in wetland restoration projects as well. If the $18//MTCO_2e$ carbon price was applied to the Wildest plan assuming half of the weight of 1,140,000 yd^3 of soil was organic matter (~566,865 MT), and amending it to 25% carbon content with biochar, the resulting 141,716 MT of carbon would be worth $2,550,892 in carbon credits. If the same price and method of amending to 25% carbon content is applied to Hester Marsh's application of 230,000yd^3 then the resulting value would be $514,355 in carbon credits.

Challenges for Nonprofits

Nonprofit organizations play a unique role in the management and protection of coastal wetlands. The salt marshes of San Diego are managed by a myriad of organizations and partnerships including local environmental nonprofit organizations, municipalities, state and federal agencies. Local nonprofits, such as WILDCOAST, are working to conserve, study, and organize the appropriate data and information about coastal wetlands and blue carbon to provide to policymakers and maximize the areas preserved and restored. Other local nonprofits formed as a result of people sharing an interest in and concern for salt marshes organizing to act as environmental watchdogs, protecting and conserving the habitats. This demonstrates how the public can become empowered to become involved in the bureaucratic process of establishing and managing state or federal lands. An example of such a group is Friends of Famosa Slough (FFS), a nonprofit "established to protect and restore the Slough as a natural wetland preserve and promote public awareness of wetlands.[79]" Famosa Slough State Marine Conservation Area is located in the Point Loma Heights neighborhood. It is managed as a wetland preserve by the Park and Recreation Department of San Diego and with help from Friends of Famosa Slough.[80] FFS helps by leading necessary and time consuming projects such as removal of nonnative plants, trail maintenance and data collection through bird surveys.

This section of the report will discuss challenges in implementing coastal wetland management and restoration faced by nonprofits in San Diego, but given the interconnectedness of agencies managing the habitats, many of the challenges also apply to the other groups.

Summary of Challenges and Best Practices Survey

A simple 15-question survey was emailed to several nonprofit organizations and one public agency (Port of San Diego) to get a broader understanding of the challenges in implementing wetland restoration projects in San Diego. This survey was inspired by several conversations with organizers, managers, and scientists involved in various wetland restoration projects in San Diego. An emergent theme from the conversations was that having a recorded baseload of information about challenges would be beneficial. The survey questions focus on collecting information about challenges in the different stages of implementation, best practices, and potential resources needed. The different stages were divided as follows: data/research, planning, funding, costs, permitting, physical restoration, social outreach, monitoring, maintenance, land access/right to entry, neighborhood support, and forming partnerships. The survey questions can be viewed in the Appendix section. Several aspects of the responses will be discussed in the following sections.

The survey was sent to 13 local organizations and received 6 total responses representing 5 different organizations. This capstone report started with the assumption that organizations experience challenges in implementing wetland restoration. In an effort to collect some data to be able to state a bit more confidently that local organizations experience challenges, **Figure 3** shows the responses to the question, "Have you experienced challenges in restoring wetlands in San Diego?" 100% of respondents stated that they have experienced challenges.

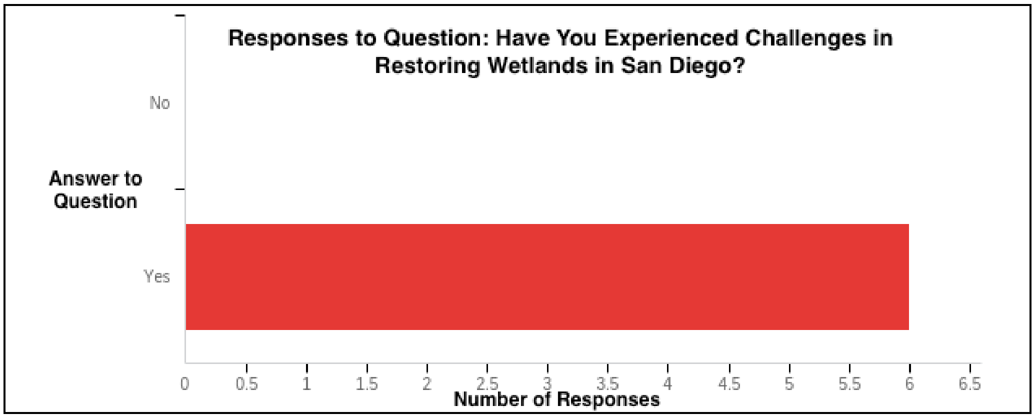


Figure 3: The x-axis is the number of participants who selected each choice. All participants indicated that they have experienced challenges in restoring wetlands in San Diego.

In response to the question asking to indicate which stages of restoration organizations have experienced challenges, each stage was selected at least once, with "land access/right to entry" receiving 5 out of 6 votes and "funding" receiving 6 out of 6 votes. **Figure 4** shows the distribution of answers. One respondent indicated there were other challenges, explaining by writing, "impacts of urban runoff and of weed seeds from the region." Urban runoff and weed seeds could be incorporated in several restoration stages, such as planning, maintenance and monitoring, but this response speaks to the connectivity of wetlands to their surroundings and the complexity that adds to these projects. The coastal wetlands are not isolated in mesocosms. They are naturally part of watersheds and are impacted by the natural and urban environment, so these considerations need to be incorporated while implementing restoration.

Respondents were also asked to provide any suggestions for resources or changes to reduce or remove the challenges in each stage. The questions were written broadly to allow for a wide range of suggestions. Common suggestions were state or federal databases, and streamlining the permitting and grant application processes. There is a need for accessible and comprehensive database(s). Suggestions of types of databases included: state and/or federal databases for wetland data/research, wetland monitoring, grants and other funding specifically for wetlands, list of acceptable herbicides (not Prop 65 chemicals), and a list of land owners of coastal wetlands with contact information. In terms of the permitting process, it was suggested to streamline the process with clear steps for permits that all agencies are aligned with and to have a quicker turnaround. These changes are especially important for smaller nonprofits, as stated by one respondent's input, "permitting process is confusing and time consuming, especially for [an organization] with smaller capacity." Suggestions about grants were similar to suggestions about permits, namely in the fact that grant applications are cumbersome and time consuming. Grants also usually do not align with the true costs of wetland restoration projects, including funding to support monitoring and maintenance of restored wetlands. As another respondent stated, "alignment of grant funding caps (which are usually $1 million or less) with the true cost of restoration (usually multiple million dollars). This is probably the biggest funding challenge."

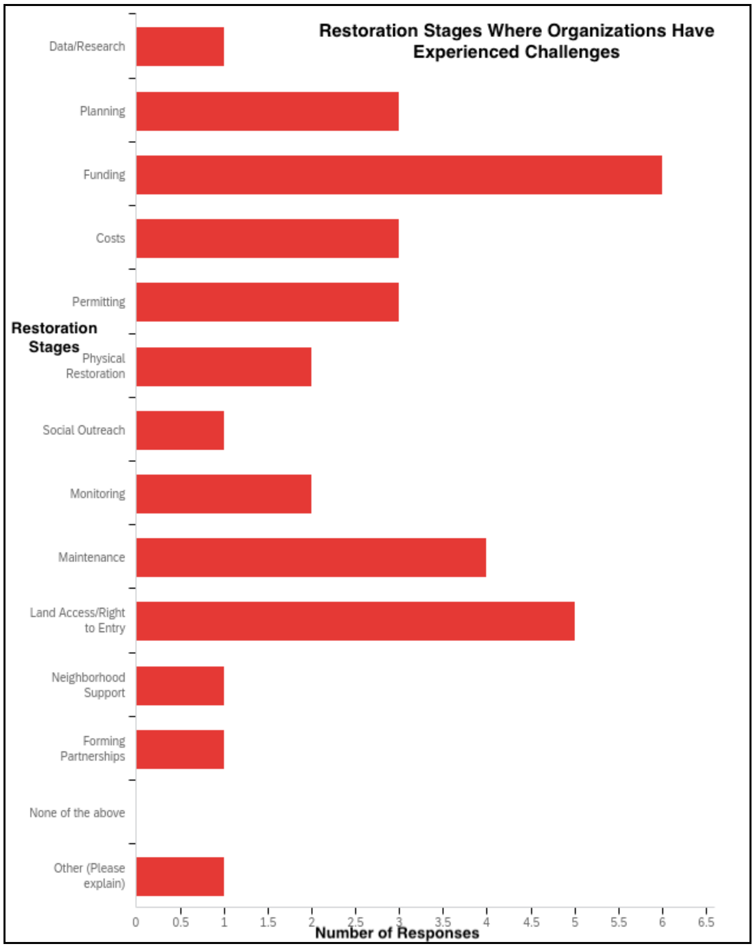


Figure 4: The y-axis lists the various stages of implementing restoration projects. The x-axis is the number of times the stage was selected by participants. Note that funding was selected the most times followed by land access/right to entry, and maintenance.

The survey participants were also asked to input actions or strategies they commonly use for each restoration step. Less answers were inputted in this section than in the previous Challenges section. This could possibly be due to survey fatigue, confusion about the questions, a lack of best practices implemented by the organizations, or the respondents had not been involved in certain aspects of implementing restoration projects. For example, one response stated that the nonprofit hires specialists to perform restoration. This indicates that the nonprofits have more experience with the initial steps of restoration (i.e. funding, applying for permits) than the latter half of the restoration process (i.e. physical restoration). The rest of the answers for commonly used actions or strategies reflect the value and importance of collaboration. Relationships with other nonprofits, agencies, consultants, and the local community are all mentioned as being beneficial to implementing restoration projects.

Part 3: Recommendations

Policy Recommendations

The City of San Diego has the potential to be a leader in developing and enhancing wetland restoration and other blue carbon projects (i.e. seagrass beds). The following are policy recommendations to incentivize and support wetland restoration projects, beneficial reuse of sediment, and biochar:

- Integrate blue carbon ecosystems fully into the City's Climate Action Plan and Climate Resilient Plan
- City of San Diego or a third party create a centralized database of blue carbon data to incentivize coordination in all steps of wetland restoration projects. The database could have information about current coastal wetlands (i.e. carbon stock, biodiversity), historic wetlands, possible sites for future/restored wetlands, sediment sources, etc.
- City of San Diego explore the feasibility of creating biochar from local biomass (organic waste like food waste and tree trimmings, biosolids) and utilizing biochar in local wetlands or other areas to create a market

Map of Coastal Wetlands and Associated Nonprofits

In the spirit of creating resources that promote connectivity and matching communities and organizations, an idea to create a map with the coastal wetlands of San Diego County and the nonprofit organizations involved with managing and restoring them came into existence. The map could be the foundation of a local database of coastal wetlands (restored and created) including data about their soil, vegetation, blue carbon stocks; data about the managing agencies and nonprofits, and any assistance the wetlands or nonprofits require (i.e. SediMatch connecting dredging communities with wetland restoration projects). Additionally, this map could potentially be used by philanthropies and coastal construction projects looking to connect with groups involved in blue carbon projects or natural climate solutions.

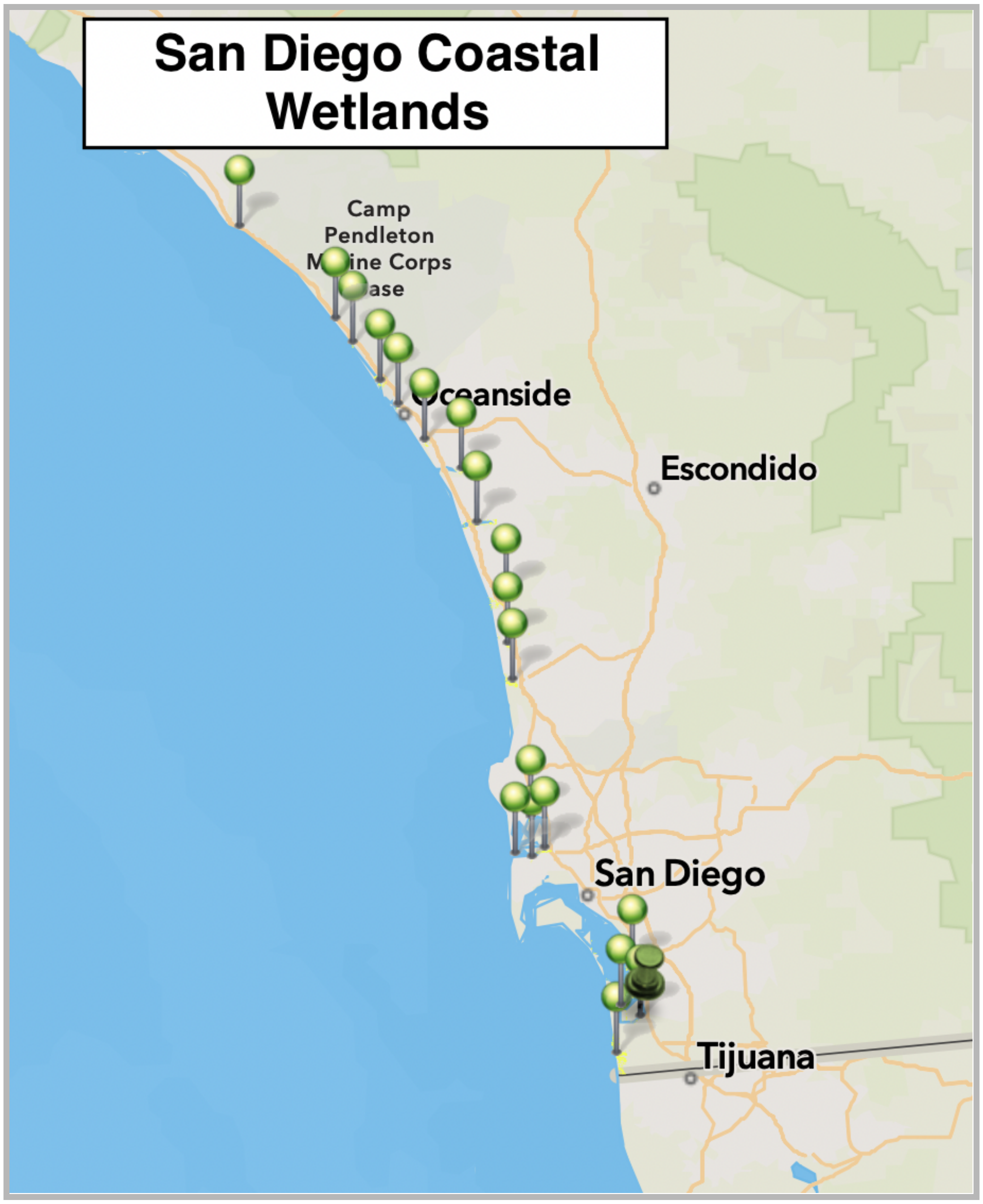


Figure 5: Map of San Diego County Coastal Wetlands. A future map and web tool could be developed that would have a compilation of data on local blue carbon, natural and restored wetlands, and the associated organizations.

Coastal Wetland Restoration Recommendations

The following are recommendations specific to implementing wetland restoration projects:

- Monitor and record a wide range of wetland attributes in all wetlands in San Diego County for natural and restored habitats (list of suggested priorities in **Table 4)**
- Measure, monitor, and record carbon accumulation rates of natural and restored wetlands
- Develop research projects in wetlands to explore the impacts of adding large amounts of biochar as a soil amendment or part of the fill in created wetlands
- Explore carbon crediting opportunities with biochar and blue carbon projects

Table 4: Modified table of priorities for wetland attributes to be monitored from Handbook for Restoring Tidal Wetlands[18]:

Hydrology and Topography	**Water Quality**	**Soils**	**Vegetation**	**Fauna**
Inundation regime	Water temperature and dissolved oxygen	Water content	Vegetation mapping	Invertebrates (macrofauna, meiofauna, insects)
Ground water levels	Water salinity	Bulk density	Cover and height of vascular plants	Fishes
Flow rates	Water pH	Soil texture	Canopy architecture	Birds (migratory periods, nesting, fledging of young)
Elevation	Turbidity and water column stratification	Soil salinity	Patch size, distribution of target plants	Reptiles
Sediment accretion and erosion	Nutrients	Soil pH	Aboveground biomass	Mammals
Creek morphology		Redox potential	Belowground biomass	
		Organic matter	Visual estimate of algal cover	
		Nitrogen, phosphorous	Tissue nitrogen concentrations	
		Decomposition		
		Toxic substances		

Conclusion

Natural climate solutions must be utilized to meet the challenge of climate mitigation and adaptation. Future efforts to protect, restore and enhance blue carbon ecosystems in San Diego will require more data, resources, and coordination to accomplish restoration goals. These challenges also represent opportunities to increase the region's sustainable practices, preparedness for climate change impacts and carbon market opportunities. The SediMatch web tool provides a model for coordinating the beneficial reuse of sediment that could be implemented in San Diego and modified to include other important data pertaining to coastal wetlands. The sediment and soil of current and future wetlands could be amended with locally produced biochar. Co-benefits of producing biochar include increasing sustainable practices, carbon sequestration, increasing the carbon value of wetlands and the value of organic waste. Innovative approaches and increased coordination are vital in ensuring the success of coastal wetland restoration projects.

Appendix

Wetland Restoration Challenges & Best Practices Survey

Section: Instructions, Definitions

This survey is designed to informally get a broad overview of the challenges, needs, and best practices of wetland restoration efforts in the San Diego region.

These are definitions of terms commonly used in the survey:
Challenge = obstacle, barrier, delay
Restoration = repairing and restoring ecosystem to a certain state

- This term is used in this survey to describe projects with the goals of restoration projects (to repair and restore site to a certain state), and the goals of rehabilitation projects
- Except for one question!

Rehabilitation = improvement of ecosystem functions without necessarily a return to pre-disturbance conditions

General restoration stages:

- Data/Research = information about the site
- Planning = project proposal, goals, design
- Funding = money to support project
- Costs = expenses related to the project
- Permitting = local, state, federal permits/requirements required to do the project
- Physical Restoration = site preparation, infrastructure removal, plant preparation, installation and creation
- Social Outreach = publicity, education and outreach
- Monitoring = measuring the success of the restoration, adapting the plan
- Maintenance = physical activities to ensure the health of the wetland (i.e. trash removal)

Other restoration stages:

- Land access/right to entry = are you able to do restoration or rehabilitation work onsite?
- Neighborhood support = do you have the support of the surrounding community to do the restoration or rehabilitation work?

- Forming partnerships = are you able to collaborate with other organizations and stakeholders to implement restoration work?

Section: Names, Organization

1. Organization you represent
2. What is the name of the wetland(s) your organization is involved in?
3. What types of projects does your organization usually carry out?
    - Restoration Projects
    - Rehabilitation Projects
    - Both
    - Other
        - If other, please describe

Section: Challenges to Implementing Coastal Wetland Restoration

This section is meant to get a sense of the barriers and challenges organizations face in San Diego when conducting wetland restoration projects.

4. Have you/your organization experienced challenges in restoring wetlands in San Diego?
    - yes/no
5. Please select the restoration stages in which you have experienced challenges.
    - Data/Research
    - Planning
    - Funding
    - Costs
    - Permitting
    - Physical Restoration
    - Social Outreach
    - Monitoring
    - Maintenance
    - Land access/right to entry
    - Neighborhood support
    - Forming partnerships
    - Land access/right to entry
    - Neighborhood support
    - Forming partnerships
    - None of the above
    - Other
        - If other, please describe
6. Do you have access to resources (i.e. websites, groups) that catalog wetland restoration efforts (i.e. inventory of restoration sites, helpful information)?
    - yes/no/maybe
    - If yes, please list the resources you use
7. If yes, do you regularly use those resources to guide your restoration efforts?

- yes/no

8. If no, would you find it helpful to have access to resources that catalog wetland restoration efforts?

- yes/no/maybe

Section: Possible Solutions/Resources/Policies to Address Challenges

This section is meant to collect information about the type of support organizations need to improve wetland restoration projects.

9. Please input suggestions of <u>resources</u> you would like to see in each of the stages:

- Data/Research:
- Planning:
- Funding:
- Costs:
- Permitting:
- Physical Restoration:
- Social Outreach:
- Monitoring:
- Maintenance:
- Land access/right to entry
- Neighborhood support
- Forming partnerships
- Other:

10. Please input suggestions of <u>changes</u> you would like to see in each of the stages:

- Data/Research:
- Planning:
- Funding:
- Costs:
- Permitting:
- Physical Restoration:
- Social Outreach:
- Monitoring:
- Maintenance:
- Land access/right to entry:
- Neighborhood support:
- Forming partnerships:
- Other:

11. Does the local city that you do wetland restoration work in need to change rules/policies to support the projects? Please briefly explain?

- yes/no/maybe

Section: Best Practices for Coastal Wetland Restoration

This section is meant to collect information about wetland restoration practices that are working well.

12. What are some actions/plans/strategies that you consistently use on restoration projects?

- Data/Research:
- Planning:
- Funding:
- Costs:
- Permitting:
- Physical Restoration:
- Social Outreach:
- Monitoring:
- Maintenance:
- Land access/right to entry:
- Neighborhood support:
- Forming partnerships:
- Other

Section: Miscellaneous

13. What other organizations/agencies have you partnered with? These can be official partners or organizations that you have worked informally with.

14. Does your organization have a specific blue carbon project(s)?

15. Last Question- any final thoughts or comments on wetland restoration in San Diego?

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