

TECHNICAL ASSESSMENT FOR COASTAL WETLANDS PROTECTION

SECTOR: OCEANS

AGENCY LEVEL: GOVERNMENT

KEYWORDS: AVOIDED DEFORESTATION,
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*Note: For some of the technical reports, the result section is not yet updated. Kindly refer to the model for the latest results.

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ACRONYMS AND SYMBOLS USED

- EEZ – Exclusive Economic Zone
- GAEZ – Global Agro-Ecological Zones
- GHG – greenhouse gasses
- MCI – Marine Conservation Institute
- MPA – Marine Protected Area
- RSIS – Ramsar Sites Information Service
- UNEP-WCMC – United Nations Environment Programme –
World Conservation Monitoring Centre

EXECUTIVE SUMMARY

Project Drawdown defines *coastal wetlands protection* as: the legal protection of carbon-rich mangroves, seagrasses, and saltmarshes, leading to reduced degradation rates and the safeguarding of carbon sinks. This solution secures otherwise vulnerable coastal wetlands whose destruction would be a source of greenhouse gasses.

Coastal wetlands significantly impact global carbon cycles and their disturbance contributes to an estimated 1-10% of anthropogenic carbon emissions. Unlike most terrestrial ecosystems, coastal wetlands can continue sequestering carbon for centuries without becoming saturated. As a result, they have accumulated vast stores of carbon, making their global significance high despite their small area. Yet, these ecosystems are being degraded rapidly due to human activity, and relatively few are protected.

Coastal wetlands also provide important ecosystem services. These ecosystems are being replaced for other uses, including coastal development and agriculture, releasing their stored carbon and preventing future sequestration. The *coastal wetlands protection* solution proposes increased protection of these important carbon reservoirs, with mitigation impact via emissions reduction and biosequestration.

In the *Plausible* Scenario, 28.58 million hectares come under protection. Climate impact is 1.60 gigatons of carbon dioxide equivalent, with a total protected stock of 37.25 gigatons carbon dioxide equivalent.

In the *Ambitious* Scenario, 31.93 million hectares come under protection. Climate impact is 2.15 gigatons of carbon dioxide equivalent, with a total protected stock of 41.95 gigatons carbon dioxide equivalent.

In the *Maximum* Scenario, 35.10 million hectares come under protection. Climate impact is 2.70 gigatons of carbon dioxide equivalent, with a total protected stock of 45.90 gigatons carbon dioxide equivalent.

Financials are not modeled.

1. LITERATURE REVIEW

1.1. STATE OF THE PRACTICE

The term “coastal wetlands”, also called “blue carbon ecosystems”, encompasses many different ecosystems adapted to tidal environments where shallow water often covers the surface. These diverse and interconnected ecosystems include mangroves (forested wetlands in low-lying areas), saltmarshes (salt tolerant grasses), and seagrasses (vascular plants in shallow waters). The global distributions of mangrove, seagrasses and salt marshes are presented in a variety of other locations (B. C. Murray et al., 2011) (e.g. [UNEP-WCMC interactive data viewer](#)). Coastal wetlands have a global reach: mangrove forests are limited to tropical and subtropical coasts, while tidal marshes are more prevalent in temperate regions; seagrasses can survive globally, from the equator to subpolar regions (UNEP, 2020).

As complex open systems, coastal wetlands receive carbon and other nutrients from both rivers and oceans. Healthy coastal vegetation traps organic carbon in tidal flood sediments and atmospheric carbon through photosynthesis, while microbial decomposition and tidal currents remove carbon from the wetland to the atmosphere, the ocean, or adjacent beaches (Cai, 2011; Kristensen et al., 2008). Carbon accumulation in coastal wetlands thus depends on many factors: upland terrestrial primary productivity and decomposition rates, wetland primary productivity and decomposition rates, and tidal cycles. While living and dead plant material contains carbon, soils accumulate the majority of carbon in coastal wetlands (Kauffman et al., 2011). The saturated soils of coastal wetlands lack oxygen, which limits decomposition rates of organic matter and subsequent release of carbon. In wetlands, unlike in terrestrial systems, soil carbon stacks vertically and can accumulate over thousands of years in layers of sediment up to 10 m thick (Brevik & Homburg, 2004; McKee et al., 2007).

The coastal wetlands hold tremendous carbon stocks and have high rates of carbon sequestration, burying carbon at per-unit area rates two orders of magnitude greater than forests (Mcleod et al., 2011). A literature review estimates that coastal wetland soils store more than 10,000 TgC globally (DeLaune & White, 2012) or 18 percent of the world’s oceanic carbon (UNEP, 2020).

Thus, it is clear that coastal wetlands have a significant amount of carbon, but they also have tremendous variation in carbon storage and accumulation rates: a number of interacting geological, hydrological, and biological factors influence carbon cycling in coastal wetlands, and these mechanisms are not well understood (Macreadie et al., 2014a; Mcleod et al., 2011; Stankovic et al., 2021). Eutrophication may increase carbon in microalgae, but decrease overall carbon sequestration in seagrasses (Macreadie et al., 2012). Differences in suspended sediments and tidal flooding may drive high variability in carbon

sequestration among salt marshes (Chmura et al., 2003). Similarly, sedimentary inputs shape the types of species present in mangrove forest and their sequestration potential (McKee et al., 2007). For example, on ocean islands, mangrove forests receive little sediment input; instead, organic matter accumulates in the soil and forms peat, up to 8-10 feet deep (McKee et al., 2007). Like other forest ecosystems, mangrove leaf litter and carbon assimilation generally decreases with latitude, although the temperature may minimally impact carbon sequestration (Chmura et al., 2003; Kristensen et al., 2008). Animal behavior may also influence carbon accumulation in wetland soils: crab burrows increase exposure of soil organic matter to air, which increases decomposition rates and releases carbon to atmosphere and ocean (Kristensen et al., 2008). On the other hand, sea turtle grazing reduces carbon uptake in seagrasses but it does not trigger release of stored carbon (R. A. Johnson et al., 2017). Coastal wetlands' nutrient input, bioturbator populations, and sediment input may be managed to optimize their carbon storage but this approach has not yet been fully quantified (Macreadie et al., 2017).

Degradation of coastal wetlands

Coastal wetlands have degraded to a great extent and the process is ongoing. Mangrove forests have declined by 19% and seagrasses have declined by 29% (Davidson & Finlayson, 2018; Waycott et al., 2009). Other studies estimate the annual loss of coastal wetlands globally at around 1-3%, due to ecosystem conversion, modifications in terrestrial inputs, and climate change (Duarte et al., 2008; Valiela et al., 2001). Coastal and marine resources have long drawn humans to coastal areas; humans have used salt marshes since the Neolithic for agriculture and pasture for livestock (Gedan et al., 2009). High rates of unsustainable development on the coasts, coupled with high human population coastal densities, have destroyed and degraded large areas of coastal wetlands (Sale et al., 2008). Urbanization modifies sediment loads and increases pollutant and nutrient loads, indirectly endangering the health of coastal wetlands (Lee et al., 2006). Habitat modification, particularly for agriculture and aquaculture, eliminated between 25-50% of coastal wetlands in the 20th century (Kirwan & Megonigal, 2013). Altering species abundance can endanger vegetation through trophic cascades: fish farming reduces top predators and increases herbivory on seagrasses (Ruiz et al., 2001). The San Francisco Bay estuary lost 90% of its salt marshes to diking and filling for agriculture or salt harvesting (Williams & Faber, 2001). In other areas, salt marshes have also been treated as a nuisance and eliminated to control mosquito populations (Bromberg & Bertness, 2005). However, despite of all those threats, recently a reversal trend of seagrass loss has been observed in Europe thanks to management of wastewater and improvement of water quality (de los Santos et al., 2019).

Emissions from degraded coastal wetlands

The loss of the coastal wetland area as a result of ongoing degradation not only limits their carbon sequestration potential, but also makes them the source of greenhouse gas (GHG) emissions. Disturbance or destruction of coastal wetland releases carbon from both from living biomass and, more importantly, the biomass built up in the soil, within a few decades (Crooks et al., 2011). Loss of vegetation eliminates carbon sequestration in the soil; the lack of roots triggers erosion, which disturbs soil carbon sinks. Converting wetlands to other land uses requires draining, which lowers the water table and exposes soil organic matter to oxygen. These higher levels of oxygen stimulate the decomposition rate of soil organic matter and release of carbon to the atmosphere. Thus, the degradation of coastal wetlands makes them a strong net source of GHG emissions, irrespective of their GHG balance in the natural state (Crooks et al., 2011). Damaged coastal wetlands produce estimated annual emissions of 0.15-1.02 GtC, or around 1-10% of total global carbon emissions (IPCC, 2013; Le Quéré et al., 2018; Pendleton et al., 2012).

Other threats to coastal wetlands

Coastal wetlands are sensitive to climate change, particularly mean sea level rise and the increasing frequency of extreme events. The literature suggests that mangroves and salt marshes require daily tidal flooding to flush toxins, balance salinity, and provide a source of sediment (Kathilankal et al., 2008). The area, frequency, and duration of this flooding depend on the wetlands' elevation, which varies with both sea level and sediment accretion (Morris et al., 2002). Both mangroves and salt marshes have developed sensitive feedbacks which modify sediment accretion based on relative sea level. These processes have enabled the plants to maintain relative elevation under rising sea levels over the last several thousand years (McIvor et al., 2013). Higher primary production at low elevations and high sea levels traps sediment and organic matter, which increases the elevation of the plants (Kirwan & Megonigal, 2013). Thus, modest sea level rise increases the rate of carbon burial; however, if sea level rises too rapidly, the marsh drowns and converts to open water. The loss of vegetation can cause erosion and carbon release (Kirwan et al., 2010). Current evidence suggests that sea levels may be rising too fast, although some coastal wetlands can migrate inland and maintain elevation as sea level rises (Gilman et al., 2008). While coastal wetlands have some adaptive capacity, several stressors associated with climate change may increase their vulnerability. Coastal wetlands depend on temperature and precipitation for maintenance of appropriate water chemistry (Erwin, 2009; McKee et al., 2007). Hurricanes damage both mangrove trees and soil, leading to carbon loss (DeLaune & White, 2012). Intense hurricanes can limit mangrove forests' ability to naturally regenerate through seedbank in peat due to hurricane-induced tree mortality causing peat collapse (Cahoon et al., 2003). Moreover, diseases from pathogens might also be a great threat to seagrasses e.g. wasting disease

caused by *Labyrinthula* sp. was responsible to decline of 25 percent of European seagrass meadows in the last century (de los Santos et al., 2019).

The carbon storage capacity of coastal wetlands has a complex relationship with nutrient enrichment (McKee et al., 2007). Under elevated nitrogen and carbon dioxide levels, plants increase their root growth, increasing their resilience to sea level rise, particularly in marsh areas with low levels of sediment (Langley et al., 2013). However, at high levels of nutrient input, eutrophication can cause salt marsh loss by decreasing the root-shoot ratio and increasing the rate of microbial decomposition. Loss of root stability can cause creek banks to collapse, transforming the salt marsh to unvegetated mud (Deegan et al., 2012). Moderate levels of nutrient enrichment can increase carbon storage, although high levels can cause algal blooms that kill seagrasses (Armitage & Fourqurean, 2015).

Seagrasses require high light levels for photosynthesis and moderate water movement for nutrient and sediment delivery. Reductions of water quality and clarity, including turbidity, dominate seagrass degradation (Biber et al., 2008; Erftemeijer & Lewis, 2006; Waycott et al., 2009). Pollution from oil spills and raw sewage causes plant death and erosion (Sale et al., 2008; Silliman et al., 2012). Dredging to maintain channels for boats and sand mining generate rapid water movement and high sediment loads, which can damage or bury seagrasses (Björk et al., 2008; Erftemeijer & Lewis, 2006; Park et al., 2009). Anthropogenic impacts on oysters from overharvesting or eutrophication also can affect water quality, indirectly threatening coastal vegetation (Lotze et al., 2006).

Protection of coastal wetlands

Healthy coastal wetlands generate positive impacts on the global climate, while degraded coastal wetlands emit significant amounts of GHG emissions into the atmosphere. Thus, the protection of coastal wetlands is necessary in order to reduce carbon emissions from degraded coastal wetlands and allow these ecosystems to continue to bury carbon. It has been proven that the carbon sequestration from avoiding degradation would far exceed sequestration from coastal restoration, making protection of coastal wetlands critical (Moritsch et al., 2021).

Protection and Management

In 1971, the Ramsar Treaty established the importance of wetlands, particularly for habitat and human well-being. This international treaty provides support for conservation and sustainable use of wetlands. Many countries protect coastal wetlands by law, including restrictions on aquaculture and regulations requiring environmental impact statements for other uses (FAO, 2007). However, many of these laws lack effective

enforcement, particularly in developing countries (Ellison, 2000). The upcoming COP26 agenda includes mobilization of financing nature-based solutions which hopefully will bring opportunities to many nations for enhanced protection efforts (Earth Security, 2020). Recent estimation shows that the potential of mangroves in climate change mitigation is small at the global scale due to their small areal extend but its more significant in the tropics where majority of mangroves exists (Alongi, 2020a). Coastal wetlands are therefore an assets in fight against climate change especially in developing countries (Earth Security, 2020).

The health of coastal wetlands requires whole-watershed management of nutrient and sediment inputs and buffer zones for coastal development (Erwin, 2009; Gilman et al., 2008; Greening & Janicki, 2006). In areas with high nutrient loads, riparian buffers and retention ponds can absorb excess flow (Björk et al., 2008). Reduction of pollution has restored ecological structure and functioning for some wetlands (Greening & Janicki, 2006; Stein & Cadien, 2009). Particularly in Europe, significant gains in seagrass area has been gradually reported since the implementation of European Union Water Framework Directive in year 2000 (de los Santos et al., 2019). However, it has been hypothesized that multiple stressors may prevent some ecosystems from returning to reference states after nutrient removal (Duarte et al., 2009).

Emissions from Coastal Wetlands

The coastal wetland ecosystems, apart from carbon sequestration, also release minimal amounts of other methane emissions. However, the net GHG sink is broadly positive, as the greater carbon sequestration subdues the smaller methane emissions. Like many other biogeochemical processes, methane emissions in coastal wetlands depend on salinity, and are highest in brackish marshes, which are not considered in this study (Poffenbarger et al., 2011). Nevertheless, the first global estimation shows that as much as 20 percent of blue carbon burial rate could be potentially offset by high methane evasion rates in mangroves ecosystems (Rosentreter et al., 2018). Coastal wetlands also produce negligible amounts of nitrous oxide, another greenhouse gas, although nitrous oxide emissions vary with nitrogen inputs (R. H. Murray et al., 2015).

1.2. ADOPTION PATH

1.2.1 Current Adoption

Estimates of current area of protected coastal wetland vary as shown in Table 1.

Table 1.1 Current adoption of coastal wetland protection

Coastal Wetland Type	Location	Current protection rate (%)	Source
Coastal waters	Global	12.1	(M. D. Spalding et al., 2008)
Territorial Waters	Global	10.45	(Marine Conservation Institute, 2021)
Mangroves	Global	28.10	(Juffe-Bignoli et al., 2014)
Mangroves	Global	6.90	(Giri et al., 2011)
Mangroves	Global	25	(M. Spalding, 2010)
Mangroves	Global	29.00	(UNEP-WCMC, 2008)
Mangroves	Global	16.00	(Brooks et al., 2004)
Mangroves	Global	22.6	(Butchart et al., 2015)
Mangroves	Global	43	(M. Spalding, 2010; UNEP-WCMC, 2021)
Mangroves	Global	41.7	(UNEP-WCMC, 2021)
Seagrasses	Global	30.5	(Butchart et al., 2015)
Seagrasses	Global	26	(UNEP-WCMC & Short, 2018)
Seagrasses	Global	26	(UNEP, 2020)
Salt marshes	Global	42	(Mcowen et al., 2017; UNEP-WCMC, 2021)

Since the Drawdown models for mangrove, saltmarsh, and seagrass protection are independent and use data from different sources, the current adoption rates were determined separately for each type of wetland. For mangroves, the average of the published global current protection rates in the table above, 24.37 percent, was used. A conservative estimate for current saltmarsh and seagrass protection is the current rate of fully implemented global ocean protection, 4.8 percent or just 2.2 percent in strongly protected marine reserves (Marine Conservation Institute, 2021). However, the protection rate of the global ocean is biased low by the comparatively larger and much less protected high seas (1.2% overall, or 0.8% strongly protected); the global, fully implemented, protection rate of just territorial waters is higher (10.45 percent overall, or 4.40 percent strongly protected). If proposed and committed MPAs are included in addition to the fully-

implemented MPAs, the percentages of protected area rise to 7.45, 17.3, and 1.18 percent for global, national waters, and waters beyond national jurisdiction, respectively (UNEP-WCMC, 2020). These higher protection rates are not used here because they are not yet fully implemented but they do provide some guidance on future adoption potential. Roughly 12.1 percent of coastal waters are protected (M. D. Spalding et al., 2008); in this case, the coastal waters are contained within 12 nautical miles of the coast while the protection rate of 10.45 percent discussed above applies to EEZ waters within 200 nm of the coast. Since seagrass meadows and saltmarshes cannot exist on the high seas or beyond the 12 nm coastal waters limit, the coastal waters rate of 12.1 percent is a better estimate of their protection and closer to the protection rate of mangroves. To account for greater MPA coverage in the decade since Spalding et al. (2008) prepared their estimates and the adoption overestimate effect documented below, we have averaged their protection rate with the likely overestimates of seagrasses and salt marshes protection (UNEP, 2020; UNEP-WCMC, 2021) resulting in current adoption rates of 23.1 percent and 27.1 percent, respectively.

An important caveat to all of the protection rates presented here and in the literature in general is that they are overestimates. Recent work estimating the total areal extent of wetlands has shown that although global estimates in total wetland area have grown over time from study to study, these estimates have grown because of improvements in mapping technology and not because of any actual increase in wetland area (Davidson et al., 2018). In reality, the decreases in wetland area dominate globally (Waycott et al., 2009), however some exceptions from this trend are already noted e.g. the seagrass in European waters are experiencing reversal trend since year 2000 (de los Santos et al., 2019). This discrepancy means that all global estimates in wetland area must be interpreted as underestimates. Furthermore, estimates of the area of protected wetlands are overestimates because while it is possible to intersect wetland presence with protected area polygons (UNEP-WCMC, 2021), the actual functional level of protection varies greatly from site to site as well as country to country, precluding a fully consistent global analysis (M. D. Spalding et al., 2003). Because the likely biases in total and protected areas do not compensate for each other, the net result is that the current adoption percentages presented here are very likely to be overestimates:

$$\text{Adoption \%} = \frac{\text{protected area of wetland (too big)}}{\text{total area of wetland (too small)}} = \text{too big}$$

Another option to provide a guideline for current adoption is to estimate the percentage of sites which are protected. The Ramsar Sites Information Service (Ramsar Convention on Wetlands, 2019) provides lists of wetland sites, what type of wetlands are in each site, and whether a management plan is in place for the site. Management plans are an indicator of at least some degree of protection (Ramsar Convention on Wetlands, 2018). Although the Ramsar database does not disaggregate the areas of the wetland types that contribute to each Ramsar site, it is possible to use the Ramsar data to estimate the percentage of sites that have management plans in place and contain each wetland type. The end result is not area-based but a site-

based estimate of protection. Each of the wetland models contains a sheet (Mangrove-Data, Seagrass-Data, and Saltmarsh-Data, respectively) that contains the relevant Ramsar data from 2008 to 2018. These data show that about 44%, 58%, and 56% of Ramsar sites with mangrove forests, seagrass meadows, and saltmarshes, respectively, have a management plan in place. On the other hand, there are no significant changes in these percentages over the last decade so it is difficult to use the Ramsar data for predictions.

1.2.2 Trends to Accelerate Adoption

In 2013, the IPCC developed guidelines to account for wetlands in national greenhouse gas inventories; these methodologies will encourage countries to recognize these ecosystems as important sources of carbon emissions and protect coastal wetlands.

Globally international and national commitments have been made to protect and restore coastal wetlands. Some of the latest commitments are listed below:

- An investment of \$50 million has been made under the Livelihoods Fund of Ramsar Convention and IUCN towards wetland restoration, re-forestation, and rural energy projects that also benefit the livelihoods of people. The Senegal projects of this fund has already replanted over 10,000 hectares of coastal mangrove wetlands.
- The World Bank's Global Environment Facility, has directly invested \$2 billion and leveraged a further \$11 billion in wetlands related projects and activities.
- The new Green Climate Fund has already received pledges of over \$10 billion and should certainly consider wetlands related opportunities.
- China recently submitted their wetlands strategy to the Ramsar Convention, which calls for investments of \$7.14 billion to restore 0.98 million hectares of wetlands by 2020.
- Globally, the number of marine protected areas and the total protected area of the ocean is increasing. Due to national control over Exclusive Economic Zones (EEZ), defined by a 200 mile offset from the coast, most of this added protection is within EEZs (UNEP-WCMC, 2020).
- In 2020, 14 countries has committed to sustainable manage 100 percent of their national water as a part of High Level Panel for a Sustainable Ocean Economy, which collectively represent 40 percent of the world's coastal area and almost 30 percent of the ocean area in Exclusive Economic Zones (EEZs) (Lubchenco et al., 2020). The nations represented in the Ocean Panel committed to this ocean protection goal and called upon other world leaders to do the same (National Geographic, 2020).
- In January 2021, U.S. President Biden committed via Executive Order to protect 30 percent of U.S. land and coastal ocean by 2030 (National Geographic, 2021).

- The launch of UN Decade of Ocean Science in 2021 that aims to ensure that science can fully support the effort by countries to achieve a sustainable healthy ocean.

Similar opportunities for coastal wetland protections can be leveraged from other ongoing global conservation programs such as reducing emissions from deforestation and forest degradation (REDD+), nationally appropriate mitigation actions (NAMA), and clean development mechanism (CDM).

Education on the benefits of coastal ecosystems is a crucial first step for supporting their protection. Highlighting ecosystem services, including carbon sequestration and connections with other ecosystems, may encourage the conservation of these areas. Ecosystem services are increasingly important in the face of sea level rise, as storm intensity threatens coastal development (Wamsley et al., 2010). Local valuations of ecosystem services can support policies that protect these services, although ecological services do not necessarily scale linearly with area (Barbier et al., 2008).

1.2.3 Barriers to Adoption

Despite their importance in the global carbon cycle, coastal wetlands lack “charisma,” as one researcher has noted, which limited publications in both the scientific literature and the popular press until the last decade (Duarte et al., 2008).

Only in 2013 did the IPCC offer methods to include coastal ecosystems national carbon budgets. The IPCC’s guidelines do not include emissions from seagrass meadows; lack of representative data and well-established measurement methodologies restrict scientific understanding of global carbon fluxes from these ecosystems (Macreadie et al., 2014a). Multiple definitions of mangrove forests, methods of measuring carbon accumulation rates in coastal wetlands, and lack of consistent definitions of carbon accumulation provide challenges for establishing carbon sinks and fluxes in wetlands (Chapin III et al., 2006; FAO, 2007). Additionally, the severity of the degradation may affect the amount of soil carbon released (Pendleton et al., 2012).

1.2.4 Adoption Potential

The United Nations sustainable development goal 14, target 5 is that 10% of the global coastal and marine environment will be protected by 2020 (UN, 2015). This goal is the same as the Aichi target 11 adopted by the 2010 Convention on Biological Diversity. The global ocean is currently 7.7 % protected as of July 2021 with an additional 2.4% of pending but unimplemented protection (Marine Conservation Institute, 2021) and more than enough additional area to achieve 10% protection is pledged but not yet formally

established as marine protected areas (MPA). For just EEZ waters, including unimplemented but established MPAs, protection jumped from about 2% of the total area in 2000 to about 18% of the total area in 2018 (UNEP-WCMC, 2020). Converting these percentages to protected areas, the average year-on-year percentage increase of protected area, the “protection rate,” is about 15%. At least 21 percent of global coastal wetlands are in marine UNESCO’s World Heritage List (UNEP, 2020). Another possible indicator of adoption potential is the rate of growth of area of Ramsar sites. For the ten years from 2008 to 2018, the average annual rate of growth in the total area of coastal and marine Ramsar sites is about 2.2% (Ramsar Convention on Wetlands, 2019). Ramsar sites are not protected in the same way as MPAs and Ramsar sites may or may not overlap with MPAs, so it is not straightforward to compare and contrast these figures. Furthermore, Ramsar data does not partition sites by land or ocean type so these rates include peatlands and maritime forests as well as the coastal wetlands of interest here. Finally, for just mangroves, while mangroves are still being lost globally, their estimate of the upper range of the annual degradation rate from 2000 to 2012 of 0.39% is significantly lower than degradation rates estimated over the 1980’s and 1990’s at 0.99% and 0.7%, respectively (Hamilton & Casey, 2016). This long-term trend of decreasing degradation rates suggests that the message about the global importance of mangroves is taking root and roughly 30 basis points are dropped from the degradation rate per decade.

1.3 ADVANTAGES AND DISADVANTAGES OF COASTAL WETLANDS PROTECTION

1.3.1 Similar Solutions

The ecosystem services provided by the coastal wetlands can also be achieved by the adoption of engineering-based approaches, especially for flood and erosion control, water purification, fishery management, etc. However, these solutions are not sustainable because of the high establishment and maintenance cost (Kabat et al., 2009; van Slobbe et al., 2013). Moreover, many times these structures fail to control flooding because of the underestimation of flood overflow. The establishment of hard structures also impacts the natural processes of nutrient and gas regulation and biodiversity growth (Temmerman et al., 2013). Thus, coastal wetlands prove to be an economical and environmental solution, which not only provides vast ecosystem services, but also aids in climate change mitigation through carbon sequestration and avoided GHG emissions. There are other land use systems which also help in avoiding GHG emissions by avoiding deforestation, like coastal wetlands. However, because of the high carbon stock in the coastal wetlands, the deforestation of the same results in much higher emissions of GHGs. Thus, avoiding deforestation of coastal ecosystem avoids much more GHGs in comparison with non-coastal avoided deforestation.

1.3.2 Arguments for Adoption

At the interface between terrestrial and marine ecosystems, coastal wetlands provide important ecosystem services such as limiting flood damage, nutrient cycling, and habitats for a diverse range of species. The human population density along the coasts attests to both market and cultural values of coastal resources. Coastal wetlands support both the food supply and economic base of local communities through agriculture, fisheries, and aquaculture. Mangroves increase fishery yields and provide coastal communities with wood and medicine (Aburto-Oropeza et al., 2008). Mangroves also protect freshwater sources by absorbing pollutants and buffering against saline water. Coastal wetland restoration and management can strengthen coastal communities through sustainable livelihood development and some protection against extreme weather events. Sustainable use of wetlands, including timber and non-timber forest products from mangroves and salt-water grain production, can encourage communities to protect local coastal wetlands (Pearlstein et al., 2012).

Coastal wetlands can also protect against some natural hazards, such as wind waves, although they offer little protection against storm surges (Feagin et al., 2010). Areas of denser vegetation suffered less property damage in hurricane storm surges (Barbier et al., 2013). The presence of mangroves reduced cyclone-induced mortality (Das & Vincent, 2009). Coastal wetlands filter nutrients and reduce coastal erosion, protecting coral reefs, seagrass meadows and shipping lanes (FAO, 2007). A summary of economic values derived from various ecosystem services from the coastal wetlands is listed in Table 1.2.

Table 1.2 Value of ecosystem services from coastal wetlands

Location	Ecosystem Services	Economic Value (US\$/ha/yr)	Source
USA, coastal wetlands	Hurricane protection	250-51000	(Costanza et al., 2008)
Global, coastal wetlands	Provisioning services (food, water, raw material, genetic resources, medicinal and ornamental resources)	55725	(de Groot et al., 2012)
Global, coastal wetlands	Regulating services (air quality regulation, climate regulation, disturbance moderation, regulation of water flows, waste treatment, erosion	171478	(de Groot et al., 2012)

	control, nutrient cycling, pollination and biological control)		
Global, coastal wetlands	Habitat services (nursery service and genetic diversity)	16210	(de Groot et al., 2012)
Global, coastal wetlands	Cultural services (aesthetic information, recreation, inspiration, spiritual experience and cognitive development)	108837	(de Groot et al., 2012)
Rekawa mangrove ecosystem, Sri Lanka	Forestry, fisheries, erosion control,	1088	(Gunawardena & Rowan, 2005)
Global, mangrove ecosystem	Fisheries, forestry, coastal protection, recreation and tourism, nutrient retention, carbon sequestration, nonuse, biodiversity, water and air purification, assimilation, traditional use	126069	(Salem & Mercer, 2012)
Southeast Asia, mangrove ecosystem	Fisheries, fuelwood, coastal protection, flood control, water purification	4185	(Brander et al., 2012)
USA, mangroves	Raw material and food	484-585	(Barbier et al., 2011)
USA, mangroves	Coastal protection	8966-10821	(Barbier et al., 2011)
USA, mangroves	Erosion control	3679	(Barbier et al., 2011)
Global, seagrass	Fisheries	3500	(Watson et al., 1993; Waycott et al., 2009)
USA, salt marshes	Reduced hurricane damages	8236	(Barbier et al., 2011)
USA, salt marshes	Water purification	1939-37050	(Barbier et al., 2011)
USA, salt marshes	Fisheries	2423-15983	(Barbier et al., 2011)

1.3.3 Additional Benefits and Burdens

Here this solution is compared with other solutions in the ocean sector in terms of ecosystem, social and climate impact. Coastal wetlands protection represents intermediate climate impact within all ocean solutions with low adoption potential and high social benefits.

Table 1.3 Ocean Solutions Comparison.

Ecosystem Services is subjective based on impacts on biodiversity, habitat restoration, protection from extreme weather events etc. **Social Justice Benefits:** If a solution is causing a positive impact on local societies. **Climate Impact:** GHG reduction potential in GT CO₂ eq, 2020-2050: low >1, middle between 1 and 3, high <3. **Global Adoption Potential:** TOA in Mha: low > 100, the middle between 100 and 400, high < 400; TAM is applicable for only two solutions Improve Fishery and Improve Aquaculture therefore direct comparison with other ocean solutions is not possible, however, both solutions represent high total adoption potential. n/a – not applicable.

	Ecosystem Services	Social Justice Benefits	Climate Impact	Global Adoption Potential
Conventional fishery	Low	Low	n/a	n/a
Conventional aquaculture	n/a	Medium	n/a	n/a
Conventional seaweed farming	Medium	Medium	Low	n/a
Improve Fishery	High	High	Middle	High (TAM 94 million tons landings)
Improve Aquaculture	n/a	Medium	Middle	High (TAM 126 million tons live weight)
Seaweed Farming	Medium	Medium	High	High
Macroalgae Forests Protection	High	High	Middle	Middle
Macroalgae Forests Restoration	High	High	Middle	Middle
Coastal Wetlands Protection	High	High	Middle	Low
Coastal Wetlands Restoration	High	High	Middle	Low
Seafloor Protection	High	Medium	High	High

Table 1.4 Ecosystem Management Solutions Comparison: On-Farm Impacts Social and Ecological Impacts.

Ecosystem Services is subjective based on impacts on biodiversity, water quality, etc. **Social Justice Benefits:** Is solution Targeted to disadvantaged producers like smallholders and women, Relevant to them, or Not Applicable (n/a). **Climate Impacts per Hectare:** Low 0-3.7 t CO₂-eq/ha/yr (0-1tC), Medium 3.8-11.0 t CO₂-eq/yr (1-3 tC), High 11.1+ tCO₂-eq/yr (3+tC). **Global Adoption Potential:** Low 0-100Mha, Medium 101-500 Mha, High 500+ Mha

	Ecosystem Services	Social Justice Benefits	Climate Impact/ha	Global Adoption Potential
Coastal Wetlands Protection	Very High	Relevant	Low to High	Low

	Ecosystem Services	Social Justice Benefits	Climate Impact/ha	Global Adoption Potential
Forest Protection	Very High	Relevant	Medium	Medium to High
Indigenous People's Forest Management	Very High	Targeted	Medium	High
Peatland Protection	Very High	Relevant	High	Medium
Temperate Forest Restoration	Very High	Relevant	Medium	Low to Medium
Tropical Forest Restoration	Very High	Relevant	High	Medium

2 METHODOLOGY

2.1 INTRODUCTION

Project Drawdown's models are developed in Microsoft Excel using standard templates that allow easier integration with each other since integration is critical to the bottom-up approach used. The template used for this solution was the Land Model which accounts for sequestration of carbon dioxide from the atmosphere into plant biomass and soil, and reduction of emissions for a solution relative to a conventional practice. These practices are assumed to use land of a specific type that may be shared across several solutions. The actual and maximum possible adoptions are therefore defined in terms of land area (million hectares). The adoptions of both conventional and solution were projected for each of several Drawdown scenarios from 2015 to 2060 (from a base year of 2014) and the comparison of these scenarios with a reference (for the 2020-2050 segment¹) is what constituted the results.

Agency Level

Government is selected as the agency level for this solution. Though certainly other agents can, do, and should play an important role in this solution, government is the most critical player in implementation.

2.2 TOTAL AVAILABLE LAND

Drawdown's agricultural production and land use model approach defines the Total Land Area as the area of land (in million hectares) suitable for adoption a given solution. Data on global land is acquired from Global Agro-Ecological Zones (GAEZ) database, developed by the Food and Agriculture Organization of the United Nations (FAO) and the International Institute for Applied Systems Analysis (IIASA). The Drawdown Land-Use Model categorizes and allocates land according to agro-ecological zones based on the following factors: thermal climate, moisture regimes, soil quality, slope, cover type, and degradation status. These characteristics influence the suitability of different practices, and solution adoption scenarios are restricted by one or more of these factors.

Determining the total available land for a solution is a two-part process. The technical potential is based on: current land cover or land use; the suitability of climate, soils, and slopes; and on degraded or non-degraded

¹ For most results, only the differences between scenarios, summed over 2020-2050 were presented, but for the net first cost, the position was taken that to achieve the adoptions in 2020, growth must first happen from 2015 to 2020, and that growth comes at a cost which should be accounted for, hence net first cost results represent the period 2015-2050.

status. In the second stage, land is allocated using the Drawdown Agro-Ecological Zone model, based on priorities for each class of land. The total land allocated for each solution is capped at the solution's maximum adoption in the *Maximum* Scenario. Thus, in most cases the total available land is less than the technical potential. For the case of coastal wetlands models, additional data from global inventories specific to each wetland type were used to fill in land cover types relevant to wetlands in the GAEZ database to make higher fidelity estimate of wetland total land area (TLA).

Mangrove forest extent was estimated at 13.76 Mha for the year 2010 based on satellite observations (Bunting et al., 2018). Since 2010, there are only two other original published global estimates of mangrove extent (Giri et al., 2011; M. Spalding, 2010) which were constructed with data up to 2000 and 2003. These values, while numerically comparable with the newest estimate, have been excluded here because they were constructed with different methods and temporal trends in wetland extent have been biased by historical data gaps and improvements in mapping technology (Davidson et al., 2018). Since global mangrove forest coverage is changing over time due to degradation and global inventory of mangrove forests is sufficiently detailed that it can be given a date (Bunting et al., 2018), the area of mangrove forests was reduced from its given value at 2010 to a 2014 value by the annual rate of degradation specific to mangroves. In 2014, the global mangrove area is estimated to be 13.22 Mha.

As for 2018, seagrass meadows occupy an estimated 34.50 Mha based on the global synthesis in the Global Distribution of Seagrasses (UNEP-WCMC & Short, 2018), formerly the World Atlas of Seagrasses (M. D. Spalding et al., 2003). This global area is within 1 Mha of the average of values from previously accepted values in the literature (Lavery et al., 2013; Waycott et al., 2009) which are derived from previous versions of the World Atlas of Seagrasses or a very rough estimate (Charpy-Roudaud & Sournia, 1990). The most recent estimate of global seagrass distribution, their area extend between 16.04 and 26.66 Mha (low and high estimates accordingly) (McKenzie et al., 2020). Therefore, by averaging (UNEP-WCMC & Short, 2018) and (McKenzie et al., 2020) estimates the seagrasses extend 25.73 Mha. Seagrass extent was determined by collating many records of seagrasses that span 1934 to 2015 so this value cannot be assigned a specific date as is done with the mangrove extent.

Saltmarsh extent was estimated at 5.50 Mha (Mcowen et al., 2017). While there are other, older published estimates of saltmarsh extent, none are global compilations of saltmarsh records as done by Mcowen et al. (2017). Furthermore, because only mapped saltmarshes are included in the inventory, the value used here is a lower bound on saltmarsh extent, so smaller areas (Chmura et al., 2003; Pendleton et al., 2012) can be safely excluded. Finally, while Mcowen et al. (2017) underestimate global saltmarsh area, their estimate does cover the majority of saltmarshes so the dramatically larger estimate of 40Mha (Woodwell & Pecan, 1973) later cited by many others (Duarte et al., 2005) can also be excluded. Since the global saltmarsh

inventory draws on data spanning 5 decades, we do not perform a temporal adjustment on this value before including it in the Drawdown model.

In 2014, the total global area of coastal wetlands is 44.45 million hectares, of which 10.65 million hectares are already protected. The resulting total available land for the *coastal wetlands protection* solution is 33.80 million hectares. The modeling of the coastal wetlands was based on the individual modeling of mangroves, seagrasses, and salt marshes. To account for degradation over time, time series of the coastal wetland area available for protection was determined by applying the annual rate of degradation for mangroves, seagrasses, and salt marshes based on the total available land for each wetland type presented above. For each wetland type, this calculation was implemented on the TLA_Envelope sheet added to the model. The annual degradation rate for mangrove forests is estimated to be 0.99% based on 4 sources (FAO, 2007; Hamilton & Casey, 2016; Strong & Minnemeyer, 2015; Valiela et al., 2001). For seagrasses, the annual degradation rate is estimated at 2.18% based on 3 literature reviews (Duarte et al., 2008; Pendleton et al., 2012; Waycott et al., 2009). The annual loss rate of saltmarsh is estimated at 1.50% (Duarte et al., 2008) which is the same rate cited by later sources. Thus, an estimate was made for future degraded and non-degraded mangroves, seagrasses, and salt marshes, and the non-degraded area (which is not yet protected) was considered the available area for protection as part of this solution.

2.3 ADOPTION SCENARIOS

Two different types of adoption scenarios were developed: a Reference (REF) Case which was considered the baseline, where not much changes in the world, and a set of Project Drawdown Scenarios (PDS) with varying levels of ambitious adoptions of the solution. Published results show the comparison of one, or many merged, PDS to the REF, and therefore focus on the change to the world relative to a baseline.

Eight custom adoption scenarios were developed for each of the three coastal wetlands using a linear growth curve. Given the small area of coastal wetlands, the high urgency because of the annual degradation of unprotected coastal wetlands, and the high mitigation efficiency of protection, the scenarios assume that 80 or 100% of the remaining wetlands in 2030 or 2050 will be protected. Another key variable governing the PDS is the potential for change in the degradation rate over time. As discussed in Sections 1.2.1 and 1.2.4, although direct measures of the growth of protection are elusive, annual rates of mangrove degradation appear to be decreasing by 30 basis points per decade. Therefore, we created PDS with constant degradation rates as a lower bound on adoption and PDS with degradation rates that decrease by 30 basis points per decade as a plausible measure of the global response to the critical importance of coastal wetlands. For each scenario and for each coastal wetland type, the annual protection rate, figured as the annual percentage

increase in protected area, was adjusted so that the adoption targets for that scenario are reached. These protection rates are listed in parentheses next to the description of each scenario below in the order of mangroves, seagrasses, and saltmarshes.

1. ***Custom adoption scenario one:*** This scenario assumes constant degradation rates and that 100% of the remaining coastal wetlands are protected by 2050 (protection rates: 3.0%, 2.2%, and 2.0%).
2. ***Custom adoption scenario two:*** This scenario assumes constant degradation rates and that 80% of the remaining coastal wetlands are protected by 2050 (protection rates: 2.3%, 1.5%, and 1.3%).
3. ***Custom adoption scenario three:*** This is scenario one with the assumption that 100% of the remaining coastal wetlands are protected by 2030 (protection rates: 8.5%, 7.3%, and 7.8%).
4. ***Custom adoption scenario four:*** This is scenario two with the assumption that 80% of the remaining coastal wetlands are protected by 2030 (protection rates: 6.6%, 5.4%, and 5.8%).
5. ***Custom adoption scenario five:*** This is scenario one with the assumption that degradation rates will decrease by 30 basis points per decade (protection rates: 3.5%, 2.7%, 2.5%).
6. ***Custom adoption scenario six:*** This is scenario two with the assumption that degradation rates will decrease by 30 basis points per decade (protection rates: 2.9%, 2.0%, and 1.8%).
7. ***Custom adoption scenario seven:*** This is scenario three with the assumption that degradation rates will decrease by 30 basis points per decade (protection rates: 8.8%, 7.6%, and 8.0%).
8. ***Custom adoption scenario eight:*** This is scenario four with the assumption that degradation rates will decrease by 30 basis points per decade (protection rates: 6.8%, 5.65%, and 6.0%).

For scenarios with the time varying degradation rate applied to our estimate of the annual degradation rate of mangrove forests (0.99%), the degradation rate of mangrove forests will approach zero by 2047, effectively protecting all mangroves if those regions are not explicitly protected already. This estimate for the 2047 mangrove area, 11.16 Mha, is more than 84% of the 2014 mangrove extent. Note that if protection rates are high, portions of coastal wetlands are protected before they can be degraded (Scenarios 3, 4, 7, & 8) and no additional degradation occurs. Constant degradation rates are included in the PDS because while mangrove degradation appears to be decreasing globally, there are hotspots of degradation; some regions with the large mangrove stocks exhibit more than 8% annual degradation (Hamilton & Casey, 2016). Maintaining the global decrease in degradation rates may become a challenge in the future. There are insufficient seagrass or saltmarsh observations to make similar assessments for these wetland types so in lieu of this data we will use the annual change in degradation rate based on mangrove data to estimate the impact of decreasing degradation rates. Finally, it is important to note here that all the annual protection increase rates used here are within the roughly 2%-15% window determined from other data sources as outlined in Section 1.2.4.

2.3.1 Reference Case / Current Adoption

Current adoption is 10.65 million hectares and is based on applying the separate protection rates for mangrove forests, seagrass meadows, and salt marshes presented in Section 1.2.1 to the total land areas for each wetland type presented in Section 2.3.

2.3.2 Project Drawdown Scenarios

Three Project Drawdown scenarios (PDS) were developed for each wetland type, to compare the impact of an increased adoption of the solution to a reference case scenario, being:

Plausible Scenario - This scenario is based on the “average of all” custom PDS adoption scenarios.

Ambitious Scenario – Adoption is intensified under this scenario by using the high of all custom PDS adoption scenarios. The high range is determined by adding one standard deviation to the average of all custom adoption scenarios (i.e. the Plausible Scenario).

Maximum Scenario - Adoption is intensified under this scenario using high (2 standard deviations) of All custom PDS scenarios, the most aggressive adoption scenario.

For seagrasses, different scenarios were created given that the “average of all” resulted in low adoption which is not in favor of protection of the ecosystem. The following PDS scenarios were defined instead:

Plausible Scenario - This scenario is based on the “high of all” custom PDS adoption scenarios.

Ambitious Scenario –This is custom PDS Scenario 7

Maximum Scenario - Adoption is intensified under this scenario using high (2 standard deviations) of All custom PDS scenarios, the most aggressive adoption scenario.

Achieving 100 percent protection of unprotected coastal wetlands, even under the most aggressive adoption scenarios, was assumed to be unachievable due to the continuous annual degradation of coastal wetlands.

2.4 INPUTS

2.4.1 Climate Inputs

Sequestration rates for mangroves are set at 1.82 tons of carbon per hectare per year, based on meta-analysis of 12 data points from 11 sources. Six data points are global estimates as the results of meta-analyses using different methods and primary sources, that are usually based on hundreds of primary sources, some of which are reused in different studies (Alongi, 2016; Bouillon et al., 2008; Breithaupt et al., 2012; Chmura et al., 2003; Hutchison et al., 2014; Mcleod et al., 2011). The reuse of primary sources makes it extremely difficult to determine the number of unique primary sources contributing to our estimate. This difficulty applies to other climate variables, below. Here, the number of values averaged together for input to the Drawdown model are presented. These “numbers of data points” are likely one to two orders of magnitude smaller than the number of primary observations that they are derived from. Additionally, six regional data points that were published after the global studies, were used and weighted by the areal distribution of mangroves (Bianchi et al., 2013; Ha et al., 2018; Sasmito et al., 2020; Serrano et al., 2019). Emissions from degraded or deforested mangroves are set at 29.88 tons of carbon dioxide-equivalent per hectare per year, based on meta-analysis of 21 data points from 10 sources. 18 data points are global estimates coming from metanalysis (Bulmer et al., 2015; Cahoon et al., 2003; Donato et al., 2011; Kauffman et al., 2014; Lang’at et al., 2014; Lovelock et al., 2011, 2017; Mcleod et al., 2011; Sidik & Lovelock, 2013; Siikamäki et al., 2012), while 3 data points are regional estimates not included in the global estimates weighted by the areal distribution of mangroves (Cameron et al., 2019). Mangrove carbon storage is set to 553.31 tons of carbon per hectare based on 18 data points from 8 sources. 11 data points are global estimates from metanalysis (Donato et al., 2011; Hamilton & Friess, 2018; Hutchison et al., 2014; Jardine & Siikamäki, 2014; Sanderman et al., 2018), while 7 data points are regional estimates weighted by the areal distribution of mangroves (Cameron et al., 2019; Ha et al., 2018; Sasmito et al., 2020). Salt marsh sequestration rates are 1.82 tons of carbon per hectare per year, based on 28 data points from 12 sources of which 5 data points are global estimates (Alongi, 2012; Crooks et al., 2011; Mcleod et al., 2011; Ouyang & Lee, 2014) and 23 data points are regional estimates weighted by areal distribution of salt marshes (Bianchi et al., 2013; Connor et al., 2001; DeLaune & White, 2012; Drake et al., 2015; Kathilankal et al., 2008; Loomis & Craft, 2010; Macreadie et al., 2017; Ouyang & Lee, 2014; Ruiz-Fernández et al., 2018). Emissions from degraded salt marshes are 14.29 tons of carbon dioxide-equivalent per hectare per year, based on 8 data points from 5 sources. Salt marsh carbon storage is estimated at 204.17 tons of carbon per hectare based on 7 data points from 7 sources of which 3 data points are global estimates (Alongi, 2020b; B. J. Johnson et al., 2016; Pendleton et al., 2012) and 4 data points are regional estimates weighted by areal distribution of salt marshes (Brown et al., 2016; Cacho et al., 2021; Ruiz-Fernández et al., 2018; Sousa et al., 2017). Seagrass sequestration is set at 1.34 tons of carbon per hectare per year, based on 31 data points from 7 source of which one is a meta-analysis of 155 different sites (Duarte et al., 2010) and the other sources are field

measurements that were done after 2010 (Arias-Ortiz et al., 2018; Bedulli et al., 2020; Poppe & Rybczyk, 2018; Salinas et al., 2020; Serrano et al., 2021; Wahyudi et al., 2020). Emissions from degraded seagrass beds are set at 3.68 tons of carbon dioxide-equivalent per hectare per year, based on 11 data points from 7 sources, where 8 data points are global estimates (Lovelock et al., 2017; Macreadie et al., 2014b; Marbà et al., 2015; Pendleton et al., 2012; Serrano et al., 2016) and 3 data point are regional estimates weighted by areal distribution of seagrass (Arias-Ortiz et al., 2018; Greiner et al., 2013). Seagrass carbon storage is estimated at 224.47 tons of carbon per hectare based on 12 data points from 9 source, of which one is a meta-analysis of 3,640 observations at 946 different locations globally (Fourqurean et al., 2012) and the other sources are field measurements of 1 m depth sediment profile that were done after 2012 (Arias-Ortiz et al., 2018; Belshe et al., 2018; Campbell et al., 2015; A. Green et al., 2018; Phang et al., 2015; Salinas et al., 2020; Serrano et al., 2021; Stankovic et al., 2021).

Table 2.1 Climate Inputs

	Units	Project Drawdown Data Set Range	Model Input	Data Points (#)	Sources (#)
Emissions from degraded/deforested mangroves	<i>tCO₂-eq/ha/yr</i>	4.13-55.64	29.88	21	10
Biosequestration from mangroves	<i>tC/ha/yr</i>	1.13-2.52	1.82	12	11
Storage in mangroves	<i>tC/ha</i>	169.84-936.78	553.31	18	8
Emissions from degraded salt marshes	<i>tCO₂-eq/ha/yr</i>	-1.31-29.87	14.29	8	5
Biosequestration from salt marshes	<i>tC/ha/yr</i>	0.92-2.73	1.82	28	12
Storage in salt marshes	<i>tC/ha</i>	41.89-366.44	204.17	7	7

	Units	Project Drawdown Data Set Range	Model Input	Data Points (#)	Sources (#)
Emissions from degraded seagrass	$tCO_2\text{-eq/ha/yr}$	0.10-6.36	3.68	11	7
Biosequestration from seagrass	$tC/ha/yr$	0.06-2.61	1.34	31	7
Storage in seagrass	tC/ha	123.11-224.47	224.47	12	9

Note: the Project Drawdown data set range is defined by the low and high boundaries which are respectively 1 standard deviation below and above the mean of the collected data points².

Modeling Saturation

Biosequestration does not have limitless potential. In most cases, there is a maximum amount of carbon that can be stored in soils and aboveground perennial biomass before they become saturated. Biosequestration continues after saturation but is offset by more or less equal emissions. In most cases soils, and biomass can return to their approximate pre-agricultural or pre-degradation levels of carbon. This takes anywhere between 10-50 years in agricultural cases, and sometimes somewhat longer in the case of ecosystems like forests. Data about saturation time is very limited.

The Drawdown land model takes the conservative approach that all land units currently adopted for agricultural solutions (including multistrata agroforestry) have already achieved saturation and will not be contributing additional sequestration. New adopted land is assumed to sequester for at least 30 years before achieving saturation. Note that there are some important exceptions to saturation. Certain ecosystems continue to sequester soil carbon for centuries, notably peatlands and coastal wetlands. Some scientists argue that tropical forests can continue to sequester carbon at a slower rate after saturation. The addition of biochar to saturated soils may be able to overcome this constraint, as does the use of biomass from bamboo or afforestation in long-term products like buildings.

² In some cases, the low boundary is negative for a variable that can only be positive, and in these cases the lowest collected data point is used as the “low” boundary.

Coastal wetlands are an exception to saturation because they can continue to accumulate soil and carbon as sea level rises (Laffoley & Grimsditch, 2009) and wetlands have been shown to be capable of generating exceptionally deep (10 m), carbon rich soils over hundreds of years (Brevik & Homburg, 2004; McKee et al., 2007). Furthermore, vertical carbon gradients within wetland soils are close to uniform so the older, deep soil is just as carbon-rich as the younger, shallower soil (Nahlik & Fennessy, 2016) suggesting continual sequestration potential. The Drawdown model assumes sequestration continues indefinitely for both current and future adoption areas.

2.4.2 Financial Inputs

It is assumed that any costs for *coastal wetlands protection* (e.g. carbon payments or payment for ecosystem services) are borne at a government or NGO level. Drawdown land solutions only model costs that are incurred at the landowner or manager level.

2.5 ASSUMPTIONS

Assumption 1: Six overarching assumptions have been made for Project Drawdown models to enable the development and integration of individual model solutions. These are that infrastructure required for the solution is available and in-place, policies required are already in-place, no carbon price is modeled, all costs accrue at the level of agency modeled, improvements in technology are not modeled, and that first costs may change according to learning. Full details of core assumptions and methodology will be available at www.drawdown.org. Beyond these core assumptions, there are other important assumptions made for the modeling of this specific solution. These are detailed below. Coastal wetland degradation will continue with the current rate of degradation under the conventional case and either the current rate of degradation or a reduced rate of degradation will apply to the solution case.

Assumption 2: Efforts will be made at the national and international level to protect coastal wetlands on an urgency basis, considering the high carbon stock in the coastal wetland areas and their limited availability.

Assumption 3: The leakage effect can be accounted for by delaying the carbon benefits of protecting coastal wetlands by one year. The leakage effect is defined as “the unanticipated decrease or increase in GHG benefits outside of the project's accounting boundary” (IPCC, 2013). For example, protecting a wetland may displace wetland disturbance activities to another location. The leakage related degradation is a time bound phenomenon and will stabilize after some time; here we assume that time scale is one year.

Assumption 4: It is assumed that the re-growth of the degraded coastal wetland area will start one year after the coastal wetlands will be brought under protection.

Assumption 5: It is assumed that the required agency level legalities to bring coastal wetlands under protection will be in place by the year of adoption. Thus, there will be no delay in the climate benefits as a result of delay in agency level efforts to bring a coastal wetland area under protection. The "year of protection" is assumed to be the "year of implementation".

2.6 INTEGRATION

The complete Project Drawdown integration documentation (will be available at www.drawdown.org) details how all solution models in each sector are integrated, and how sectors are integrated to form a complete system. Those general notes are excluded from this document but should be referenced for a complete understanding of the integration process. Only key elements of the integration process that are needed to understand how this solution fits into the entire system are described here.

The Agroecological Zone model

Drawdown's approach seeks to model integration between and within sectors and avoid double counting. Several tools were developed to assist in this effort. The Agroecological Zone (AEZ) model categorizes the world's land by: current cover (e.g. forest, grassland, cropland), thermal climate, moisture regime, soil quality, slope, and state of degradation. Both Food (supply-side) and Land Use solutions were assigned to AEZs based on suitability. Once current solution adoption was allocated for each zone (e.g. semi-arid cropland of minimal slopes), zone priorities were generated and available land was allocated for new adoption. Priorities were determined based on an evaluation of suitability, consideration of social and ecological co-benefits, mitigation impact, yield impact, etc. For example, *Indigenous peoples' land management* is given a higher priority than *forest protection* for AEZs with forest cover, in recognition of indigenous peoples' rights and livelihoods. *Multistrata agroforestry* is highly prioritized in tropical humid climates due to its high sequestration rate, food production, and highly limited climate constraints.

Each unit of land was allocated to a separate solution to avoid overlap between practices. The exceptions to this are *farmland irrigation*, *nutrient management*, and *women smallholders*, which can be implemented in addition to other practices. The constraint of limited available land meant that many solutions could not reach their technical adoption potential. The AEZ model thus prevents double-counting for adoption of agricultural and land use solutions.

Drawdown’s agricultural production and land use model approach defines the Total Land Area as the area of land (in million hectares) suitable for adoption a given solution. Data on global land is acquired from Global Agro-Ecological Zones database, developed by the Food and Agriculture Organization of the United Nations (FAO) and the International Institute for Applied Systems Analysis (IIASA). The Drawdown Land-Use Model categorizes and allocates land according to agro-ecological zones based on the following factors: thermal climate, moisture regimes, soil quality, slope, cover type, and degradation status. These characteristics influence the suitability of different practices, and solution adoption scenarios are restricted by one or more of these factors.

Determining the total available land for a solution is a two-part process. The technical potential is based on: current land cover or land use; the suitability of climate, soils, and slopes; and on degraded or non-degraded status. In the second stage, land is allocated using the Drawdown Agro-Ecological Zone model, based on priorities for each class of land. The total land allocated for each solution is capped at the solution’s maximum adoption in the *Maximum* Scenario. Thus, in most cases the total available land is less than the technical potential. The *coastal wetlands* solution was not affected by integration with other solutions, as coastal wetlands are largely distinct from terrestrial land uses. An exception is mangroves, which were included in the “forest” land use model but were given highest priority and were therefore not limited by any other forest land use.

2.7 LIMITATIONS/FURTHER DEVELOPMENT

The impacts of climate change on coastal wetlands, particularly sea level rise, are not modeled. If the accumulation of sediment and biomass in coastal wetlands is sufficient for the wetland to rise in step with sea level, then coastal wetlands can continue to store and sequester carbon (Laffoley & Grimsditch, 2009). On the other hand, if sea level rise is sufficiently fast that wetlands cannot keep up with it, they will cease to function as wetlands. The large number of factors, acting at both local and large scales, places modeling the response of wetlands to sea level rise outside the scope of Project Drawdown. Recently published research on this question is divergent; some studies conclude that 20-90% of wetland area may be lost due to sea level rise while another study suggests that coastal wetlands can gain up to 60% more area provided that they are allowed enough accommodation space and there is no change in sediment supply (Schuerch et al., 2018). Our assumption that only degradation rates impact the total available wetland area fits within this broad uncertainty range.

2.8 SECTOR OF OCEAN-BASED SOLUTIONS

Project Drawdown has investigated eight ocean-based solutions and their potential to avoid GHG emissions or sequester carbon. The ocean-based solutions form two main groups: a group of protection and restoration solutions and a group of approaches to improving fisheries and aquaculture operation.

The protection and restoration solutions focus on blue carbon sinks, and their potential to sequester carbon. They include protection and restoration of coastal wetlands and macroalgae ecosystems, as well as seafloor protection from bottom trawling activities (Fig. 2-1). The adoption of protection solutions involves the expansion of marine protected areas and other conservation tools such as bottom trawling bans. The adoption of solutions focusing on restoration additionally requires active restoration programs. The climate impact of solutions from this sector, include avoiding carbon emissions or enhanced carbon sequestration and are designated for the government agency level.

The second group of solutions explores the potential of improving fisheries, improving aquaculture and seaweed farming. The fisheries can be improved by reducing fishing effort and restoring large fish biomass. The climate impact, therefore, includes avoiding carbon emissions from fuel usage and enhanced carbon sequestration in sunken large fish biomass and the implementation of this solution involve governments. Improving aquaculture solution assumes shifting from fuel-based energy systems to hybrid systems partly based on renewables, thus includes the climate impact based on avoiding GHG emissions. The seaweed farming solution explores the potential of expanding seaweed production and its climate effect on the enhancement of carbon sequestration in the deep sea together with unharvested biomass (Fig. 2-1). The agency-level for the two last solutions involves farmers.

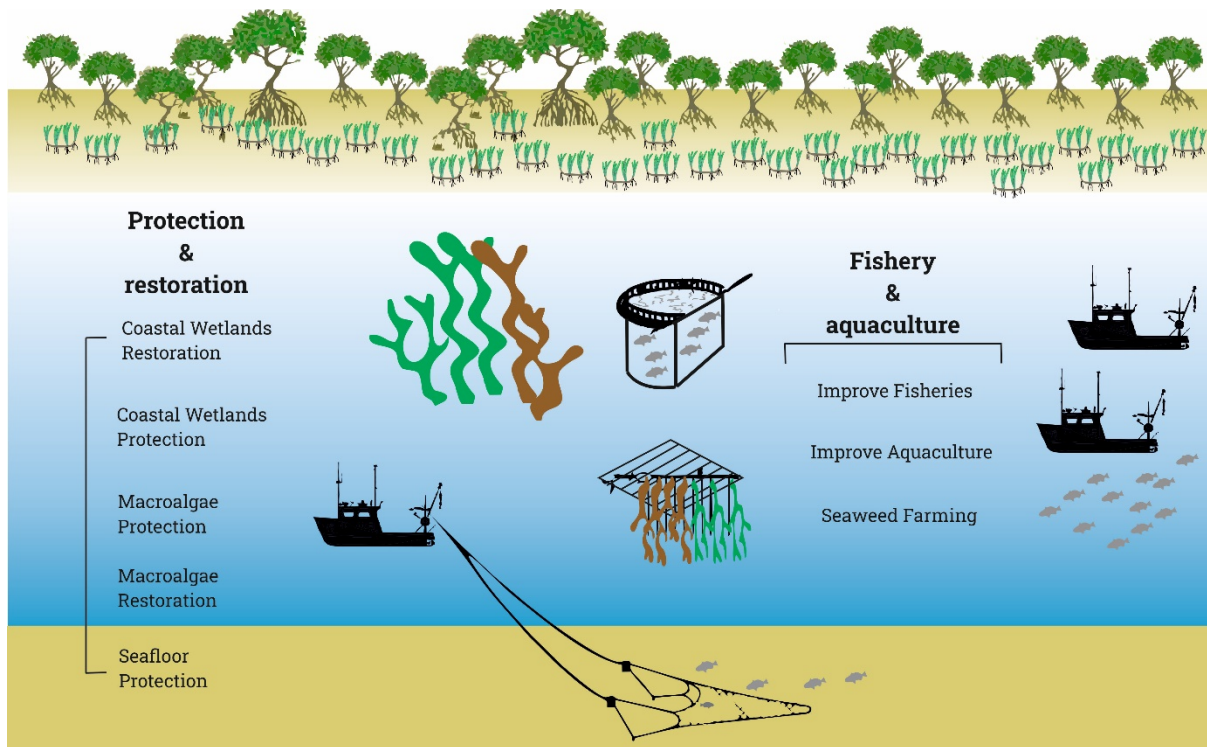


Figure 2.1 Schematic of Drawdown ocean-based solutions.

3 RESULTS

3.2 ADOPTION

Below are shown the world adoptions of the solution in some key years of analysis in functional units and percent for the three Project Drawdown scenarios. In Table 3.1, the percentages of the new adoption up to 2050 of the total land available are presented for each wetland type and then aggregated over all three wetland types.

Total adoption in the *Plausible* Scenario is 28.58 million hectares in 2050, representing 64.30 percent of the total suitable land. Of this, 15.39 million hectares are adopted from 2020-2050.

Total adoption in the *Ambitious* Scenario is 31.95 million hectares in 2050, representing 71.85 percent of the total suitable land. Of this, 17.87 million hectares are adopted from 2020-2050.

Total adoption in the *Maximum* Scenario is 35.1 million hectares in 2050, representing 78.96% of the total suitable land. Of this, 20.10 million hectares are adopted from 2020-2050.

Table 3.1 World Adoption of the Solution.

Solution	Units	Base Year (2018)	New Adoption 2020- 2050		
			Plausible	Ambitious	Maximum
Mangrove forest protection	Mha	3.22	5.76	6.70	7.65
	% TLA	24.36	43.54	50.72	57.90
Seagrass meadow protection	Mha	5.95	7.76	8.90	9.80
	% TLA	23.09	30.17	34.61	38.09
Saltmarsh protection	Mha	1.49	1.87	2.26	2.64
	% TLA	27.05	34.07	41.07	48.07
All Coastal Wetlands' Protection	Mha	10.65	15.39	17.87	20.10
	% Total Land Available	23.95	34.63	40.20	45.22

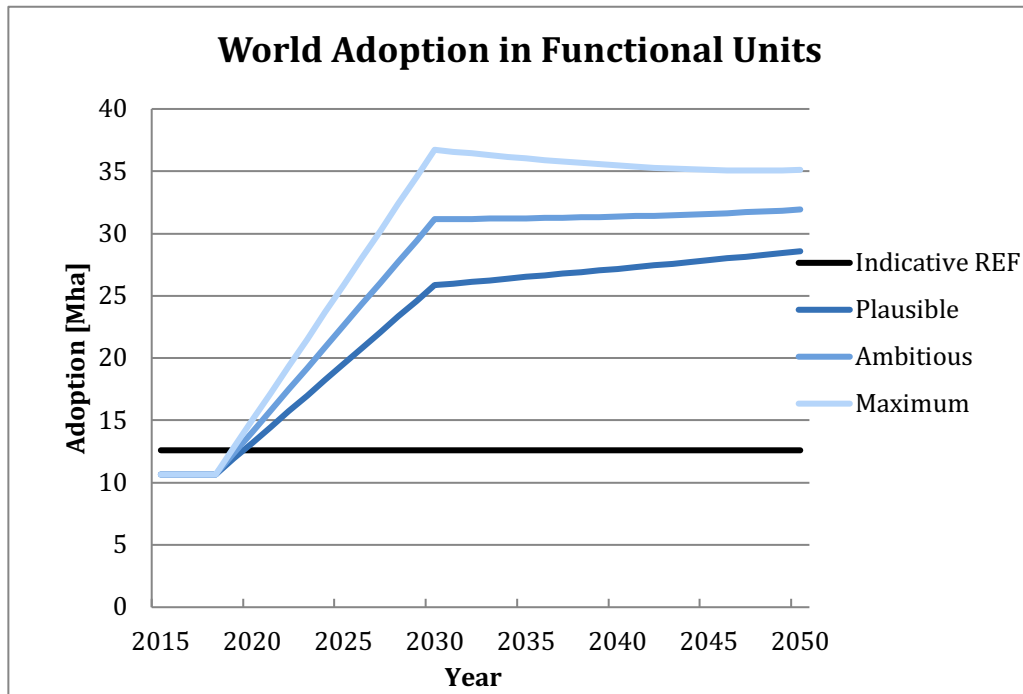


Figure 3.1 World Annual Adoption 2020-2050.

3.3 CLIMATE IMPACTS

Below are the emissions results of the analysis for each scenario which include total emissions reduction, atmospheric concentration changes, and sequestration where relevant. For a detailed explanation of each result, please see the glossary (Section 6).

Total impact is 1.60, 2.15, and 2.70 gigatons of carbon-dioxide equivalent in the *Plausible*, *Ambitious*, and *Maximum* Scenarios respectively in the period 2020-2050. Protected carbon stocks are 37.25, 41.95, and 45.90 gigatons of carbon dioxide equivalent in the *Plausible*, *Ambitious*, and *Maximum* Scenarios respectively. Each wetland type contributes differently to the total protected carbon stocks. Mangroves protect 19.78, 22.58 and 25.38 gigatons of carbon dioxide equivalent for *Plausible*, *Ambitious*, and *Maximum* Scenarios, respectively. Seagrass meadows protect 12.50, 13.68, and 14.69 gigatons of carbon dioxide equivalent for *Plausible*, *Ambitious*, and *Maximum* Scenarios, respectively. Salt marshes protect 4.97, 5.69, and 5.83 gigatons of carbon dioxide equivalent for *Plausible*, *Ambitious*, and *Maximum* Scenarios, respectively. Mangrove forests make the greatest contribution, followed by seagrass meadows and then salt marshes.

Table 3.2 Climate Impacts.

Scenario	Maximum Annual Emissions Reduction	Total Emissions Reduction	Max Annual CO ₂ Sequestered	Total Additional CO ₂ Sequestered	Total Atmospheric CO ₂ -eq Reduction	Emissions Reduction in 2030	Emissions Reduction in 2050
	(Gt CO ₂ -eq/yr.)	Gt CO ₂ -eq/yr. (2020-2050)	(Gt CO ₂ -eq/yr.)	Gt CO ₂ -eq/yr. (2020-2050)	Gt CO ₂ -eq (2020-2050)	(Gt CO ₂ -eq/year)	(Gt CO ₂ -eq/year)
<i>Plausible Mangroves</i>	0.036	0.473	0.008	0.098	0.571	0.007	0.036
<i>Plausible Seagrasses</i>	0.014	0.208	0.018	0.258	0.466	0.004	0.014
<i>Plausible Salt Marsh</i>	0.008	0.110	0.004	0.048	0.157	0.002	0.008
<i>Plausible Total</i>	0.059	0.791	0.030	0.404	1.195	0.013	0.059

Scenario	Maximum Annual Emissions Reduction	Total Emissions Reduction	Max Annual CO ₂ Sequestered	Total Additional CO ₂ Sequestered	Total Atmospheric CO ₂ -eq Reduction	Emissions Reduction in 2030	Emissions Reduction in 2050
	(Gt CO ₂ -eq/yr.)	Gt CO ₂ -eq/yr. (2020-2050)	(Gt CO ₂ -eq/yr.)	Gt CO ₂ -eq/yr. (2020-2050)	Gt CO ₂ -eq (2020-2050)	(Gt CO ₂ -eq/year)	(Gt CO ₂ -eq/year)
<i>Ambitious Mangroves</i>	0.050	0.689	0.011	0.143	0.832	0.011	0.050
<i>Ambitious Seagrasses</i>	0.017	0.247	0.022	0.307	0.553	0.004	0.017
<i>Ambitious Salt Marsh</i>	0.012	0.166	0.005	0.072	0.238	0.003	0.012
<i>Ambitious Total</i>	0.078	1.102	0.038	0.522	1.623	0.019	0.078
<i>Maximum Mangroves</i>	0.063	0.904	0.014	0.188	1.093	0.016	0.063
<i>Maximum Seagrasses</i>	0.019	0.289	0.025	0.360	0.648	0.005	0.019
<i>Maximum Salt Marsh</i>	0.015	0.222	0.007	0.097	0.319	0.004	0.015
<i>Maximum Total</i>	0.098	1.415	0.046	0.645	2.060	0.025	0.098

The solution was integrated with all other Project Drawdown solutions and may have different emissions results from the models. This is due to adjustments caused by interactions among solutions that limit full adoption (such as by feedstock or demand limits) or that limit the full benefit of some solutions (such as reduced individual solution impact when technologies are combined).

Table 3.3 Impacts on Atmospheric Concentrations of CO₂-eq.

Scenario	GHG Concentration Change in 2050	GHG Concentration Rate of Change in 2050
	<i>PPM CO₂-eq (2050)</i>	<i>PPM CO₂-eq change from 2049-2050</i>
Mangroves Plausible	0.050	0.004
Seagrasses Plausible	0.046	0.003
Salt Marsh Plausible	0.014	0.001
All Plausible	0.110	0.007
Mangroves Ambitious	0.072	0.005
Seagrasses Ambitious	0.073	0.004
Salt Marsh Ambitious	0.021	0.001
All Ambitious	0.166	0.011
Mangroves Maximum	0.094	0.006
Seagrasses Maximum	0.084	0.005
Salt Marsh Maximum	0.027	0.002
All Maximum	0.205	0.013

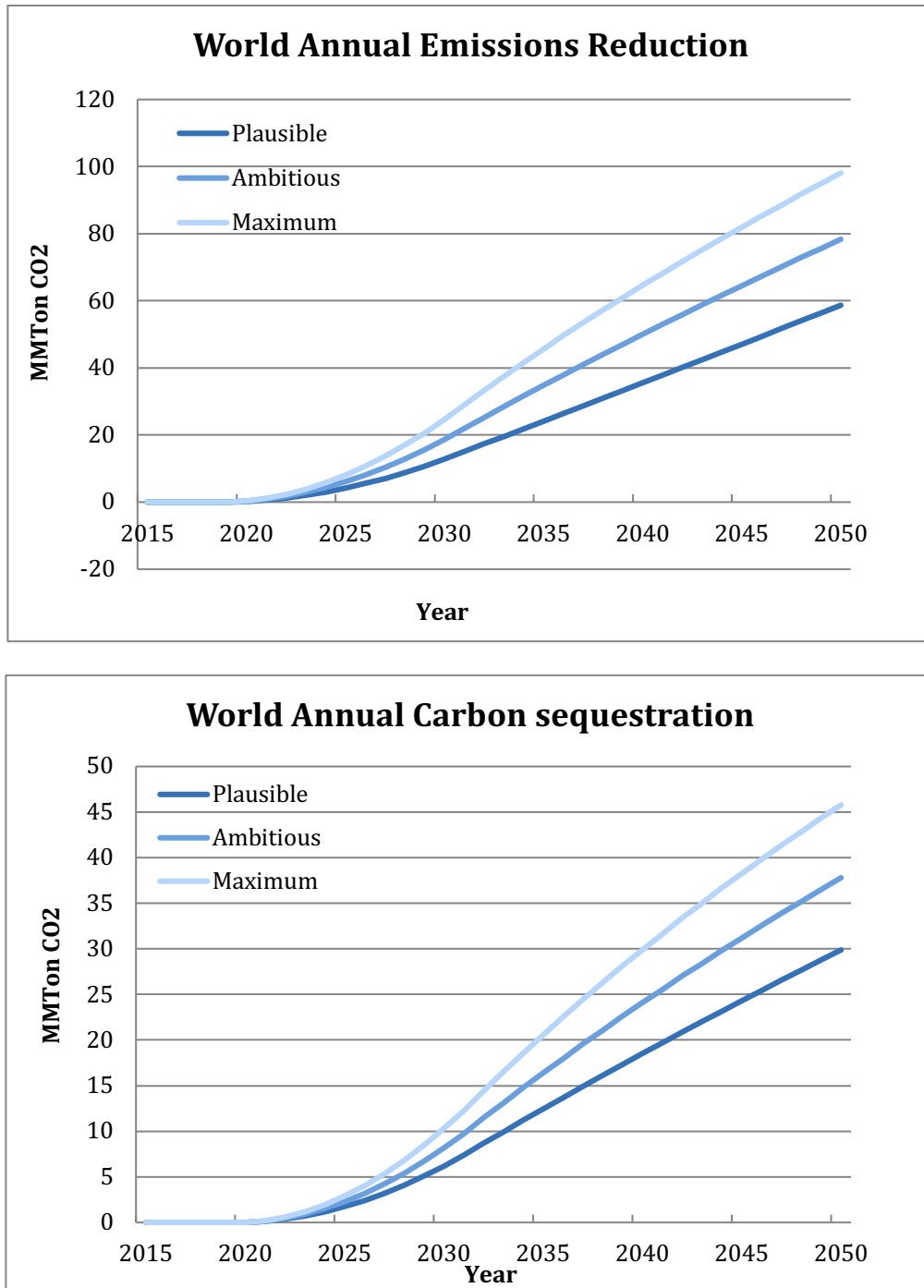


Figure 3.2 World Annual Greenhouse Gas Emissions Reduction and Additional Carbon Sequestration from implementation of Coastal wetlands protection between 2020-2050.

3.4 FINANCIAL IMPACTS

Due to the complexity of valuing ecosystem services, the financial impacts of coastal wetlands protection are not modeled here.

4 DISCUSSION

Like peatlands, coastal wetlands harbor a disproportionate share of the world's stored carbon. They also provide critical ecosystem services. Thus aggressive efforts to protect these ecosystems are an important component of climate change mitigation efforts. This model suggests that the coastal wetlands are an important carbon sink. Their protection (and restoration, though this was not modeled) make a modest contribution to climate change mitigation, which is rather impressive given the relatively tiny area of coastal wetlands.

Coastal ecosystems also deliver a significant amount of ecosystem services. The economic evaluation of those ecosystem services is much higher than the benefits accrued by the conversion of coastal wetlands to other land uses. Moreover, the degradation of coastal wetlands curtails further carbon sequestration and emits significant amounts of stored carbon to the atmosphere. Thus, greater the degradation, the greater will be the CO₂ emissions (Moritsch et al., 2021). Degradation of coastal wetlands emits globally significant amounts of carbon, although the input data vary widely. Thus, this study strongly advocates the protection of coastal wetlands.

The climate outcomes of the study clearly support the need for coastal wetlands protection. In recent years, scientists and policy makers have increased their awareness of benefits of coastal wetlands, for animal habitats, disaster mitigation, and carbon sequestration. The current national and international initiatives, in terms of long-term commitments for the protection of coastal wetlands, provide a greater feasibility for the adoption percentages considered in the study. Coastal wetlands protection is likely to be included as a part of mitigation strategy during upcoming COP26 (Earth Security, 2020).

Here it was argued that without active protection, the degradation of coastal wetlands will have negative impacts which will further accentuate with climate change, including sea level rise and increased storm intensity. Furthermore, increased damage to coastal wetlands will emit even more carbon. Protecting and restoring coastal wetlands can mitigate negative climate impacts, reducing emissions and increasing carbon sequestration. Healthy coastal wetlands also help communities adapt to the effects of climate change as well as mitigating these effects. In addition to providing habitat for many species of birds and fish, coastal wetlands offer many ecosystem services, including reduced storm damage, erosion mitigation, and nutrient filtration. Communities that note the many benefits of coastal wetlands are more likely to protect these ecosystems. Thus, combined efforts, both at the local level by the communities and at the national and international level by the government bodies are required to take necessary steps towards the protection of coastal wetlands.

4.2 LIMITATIONS

Net costs and savings should be calculated for future upgrades of this solution.

4.3 BENCHMARKS

An initial estimate for the climate impact of coastal wetland destruction is 0.45 gigatons of carbon dioxide per year with an uncertainty range of 0.15 – 1.02 gigatons of carbon dioxide per year (Pendleton et al., 2012). A more recent, cross-sectorial study calculates an annual impact of 0.30 ± 0.16 gigatons of carbon dioxide equivalent per year in 2030 with 0.130, 0.042, and 0.132 gigatons of carbon dioxide equivalent per year for mangroves, saltmarshes, and seagrasses, respectively (Griscom et al., 2017). The Drawdown Scenario for the model presented here results in a maximum annual reduction of about 0.14 gigatons of carbon dioxide per year, somewhat more conservative than both benchmarks. There are some key differences in the data used by Pendleton et al. (2012) and the data used in this study. Since the analysis of Griscom et al. (2017) closely parallels the Pendleton et al. (2012) estimates for mangroves and is a duplicate for saltmarshes and seagrasses, we do not discuss it separately here. First, Pendleton et al. (2012) used degradation rates based on older sources that can be up to twice as much as the degradation rates used here. The climate impacts of coastal wetlands protection will be greater if the degradation rates are higher. Secondly, the older sources feeding into the Pendleton et al. (2012) estimate overestimated the area of mangroves by about 10%. Finally, the Pendleton et al. (2012) calculation used higher values for coastal wetland carbon storage, in particular nearly double the values used here for mangroves and saltmarshes.

The most recent investigation of coastal wetlands protection mitigation potential shows even higher impact by 2030 than previous sources, between 0.25-0.76 gigatons of carbon dioxide equivalent per year (Hoegh-Guldberg O. et al., 2019). The authors used higher area of mangroves and seagrasses and calculated the climate impact using IPCC 2013 guidelines that does not provide carbon sequestration and emission methodology for seagrasses. No further explanation on the methodology is given by the authors, therefore it is impossible to evaluate and compare their results to Project Drawdown results.

Although this study suggests a reduced climate impact of coastal wetlands protection compared to previous studies based on update data, there is still an incontrovertible, significant, and positive climate impact of coastal wetlands protection in addition to many other co-benefits.

Table 4.1 Benchmarks.

Source and Scenario	New Adoption	Mitigation Impact Gt CO ₂ -eq in 2030
(Pendleton et al., 2012)	Coastal wetlands protection	0.45
(Griscom et al., 2017)	Coastal wetlands protection	0.18-0.30
(Gao et al., 2016)	Global sequestration potential	0.32
(Hoegh-Guldberg O. et al., 2019)	Coastal wetlands protection	0.25-0.76
<i>Plausible</i> Scenario	Coastal wetlands protection	0.019
<i>Ambitious</i> Scenario	Coastal wetlands protection	0.027
<i>Maximum</i> Scenario	Coastal wetlands protection	0.035

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6 GLOSSARY

Adoption Scenario – the predicted annual adoption over the period 2015 to 2060, which is usually measured in **Functional Units**. For the coastal wetlands protection, the functional units are millions of hectares, Mha. A range of scenarios is programmed in the model, but the user may enter her own. Note that the assumption behind most scenarios is one of growth. If for instance a solution is one of reduced heating energy usage due to better insulation, then the solution adoption is translated into an increase in use of insulation. There are two types of adoption scenarios in use: **Reference (REF)** where global adoption (i.e. the area of coastal wetlands protected) remains mostly constant, and **Project Drawdown Scenarios (PDS)** which illustrate high growth of the solution.

Approximate PPM Equivalent – the reduction in atmospheric concentration of CO₂ (in **PPM**) that is expected to result if the **PDS Scenario** occurs. This assumes a discrete avoided pulse model based on the Bern Carbon Cycle model.

Average Abatement Cost – the ratio of the present value of the solution (**Net Operating Savings** minus **Marginal First Costs**) and the **Total Emissions Reduction**. This is a single value for each solution for each **PDS Scenario**, and is used to build the characteristic “*Marginal Abatement Cost*” curves when Average Abatement Cost values for each solution are ordered and graphed.

Average Annual Use – the average number of functional units that a single implementation unit typically provides in one year. This is usually a weighted average for all users according to the data available. For instance, total number of passenger-km driven by a hybrid vehicle in a year depends on country and typical number of occupants. We take global weighted averages for this input. This is used to estimate the **Replacement Time**.

Cumulative First Cost – the total **First Cost** of solution **Implementation Units** purchased in the **PDS Scenario** in the analysis period. The number of solution implementation units that are available to provide emissions reduction during the analysis period is dependent on the units installed prior to the analysis period, and hence all implementation units installed after the base year are included in the cumulative first costing (that is 2015-2050).

Direct Emissions – emissions caused by the operation of the solution, which are typically caused over the lifetime of the solution. They should be entered into the model normalized per functional unit.

Discount Rate- the interest rate used in discounted cash flow (DCF) analysis to determine the present value of future cash flows. The discount rate in DCF analysis takes into account not just the time value of money, but also the risk or uncertainty of future cash flows; the greater the uncertainty of future cash flows, the higher the discount rate. Most importantly, the greater the discount rate, the more the future savings are devalued (which impacts the financial but not the climate impacts of the solution).

Emissions Factor– the average normalized emissions resulting from consumption of a unit of electricity across the global grid. Typical units are kg CO₂e/kWh.

First Cost- the investment cost per **Implementation Unit** which is essentially the full cost of establishing or implementing the solution. This value, measured in 2014\$US, is only accurate to the extent that the cost-based analysis is accurate. The financial model assumes that the first cost is made entirely in the first year of establishment and none thereafter (that is, no amortization is included). Thus, both the first cost and operating cost are factored in the financial model for the first year of implementation, all years thereafter simply reflect the operating cost until replacement of the solution at its end of life.

Functional Unit – a measurement unit that represents the value, provided to the world, of the function that the solution performs. This depends on the solution. Therefore, LED Lighting provides petalumen-hours of light, Biomass provides tera-watt-hours of electricity and high speed rail provides billions of passenger-km of mobility.

Grid Emissions – emissions caused by use of the electricity grid in supplying power to any operation associated with a solution. They should be in the units described below each variable entry cell. Drawdown

models assume that the global electric grid, even in a Reference Scenario, is slowly getting cleaner, and that emissions factors fall over time resulting in lower grid emissions for the same electricity demand.

Implementation Unit – a measurement unit that represents how the solution practice or technology will be installed/setup and priced. The implementation unit depends on the solution. For instance, implementing electric vehicles (EV) is measured according to the number of actual EV's in use, and adoption of Onshore Wind power is measured according to the total terawatts (TW) of capacity installed worldwide.

Indirect Emissions – emissions caused by the production or delivery or setup or establishment of the solution in a specified area. These are NOT caused by day to day operations or growth over time, but they should be entered into the model normalized on a per functional unit or per implementation unit basis.

Learning Rate/Learning Curve - Learning curves (sometimes called experience curves) are used to analyze a well-known and easily observed phenomenon: humans become increasingly efficient with experience. The first time a product is manufactured, or a service provided, costs are high, work is inefficient, quality is marginal, and time is wasted. As experienced is acquired, costs decline, efficiency and quality improve, and waste is reduced. The model has a tool for calculating how costs change due to learning. A 2% learning rate means that the cost of producing a *good* drops by 2% every time total production doubles.

Lifetime Capacity – this is the total average functional units that one implementation unit of the solution or conventional technology or practice can provide before replacement is needed. All technologies have an average lifetime usage potential, even considering regular maintenance. This is used to estimate the **Replacement Time**, and has a direct impact on the cost to install/acquire technologies/practices over time. E.g. solar panels generate, on average, a limited amount of electricity (in TWh) per installed capacity (in TW) before a new solar panel must be purchased. Electric vehicles can travel a limited number of passenger kilometers over its lifetime before needing to be replaced.

Lifetime Operating Savings—the operating cost in the PDS versus the REF scenarios over the lifetime of the implementation units purchased during the model period regardless of when their useful life ends.

Lifetime Cashflow NPV—the present value (PV) of the net cash flows (PDS versus REF) in each year of the model period (2015-2060). The net cash flows include net operating costs and first costs. There are two results in the model: Lifetime Cashflow NPV for a Single **Implementation Unit**, which refers to the installation of one **Implementation Unit**, and Lifetime Cashflow NPV of All Units, which refers to all **Implementation Units** installed in a particular scenario. These calculations are also available using profit inputs instead of operating costs.

Marginal First Cost – the difference between the **First Cost** of all units (solution and conventional) installed in the **PDS Scenario** and the **First Cost** of all units installed in the **REF Scenario** during the analysis period. No discounting is performed. The number of solution implementation units that are available to provide emissions reduction during the analysis period is dependent on the units installed prior to the analysis period, and hence all implementation units installed after the base year are included in the cumulative first costing (that is 2015-2050).

Net Annual Functional Units (NAFU) – the adoption in the PDS minus the adoption in the REF in each year of analysis. In the model, this represents the additional annual functional demand captured either by the solution in the **PDS Scenario** or the conventional in the **REF Scenario**.

Net Annual Implementation Units (NAIU) – the number of **Implementation Units** of the solution that are needed in the PDS to supply the **Net Annual Functional Units (NAFU)**. This equals the adoption in the PDS minus the adoption in the REF in each year of analysis divided by the average annual use.

Net Operating Savings – The undiscounted difference between the operating cost of all units (solution and conventional) in the **PDS Scenario** minus that of all units in the **REF Scenario**.

Operating Costs – the average cost to ensure operation of an activity (conventional or solution) which is measured in 2014\$US/**Functional Unit**. This is needed to estimate how much it would cost to achieve the adoption projected when compared to the **REF Case**. Note that this excludes **First Costs** for implementing the solution.

Payback Period – the number of years required to pay all the **First Costs** of the solution using **Net Operating Savings**. There are four specific metrics each with one of **Marginal First Costs** or **First Costs** of the solution only combined with either discounted or non-discounted values. All four are in the model. Additionally, the four outputs are calculated using the increased profit estimation instead of **Net Operating Savings**.

PDS/ Project Drawdown Scenario – this is the high growth scenario for adoption of the solution

PPB/ Parts per Billion – a measure of concentration for atmospheric gases. 10 million PPB = 1%.

PPM/ Parts per Million – a measure of concentration for atmospheric gases. 10 thousand PPM = 1%.

REF/ Reference Scenario – this is the low growth scenario for adoption of the solution against which all **PDS scenarios** are compared.

Regrets solution has a positive impact on overall carbon emissions being therefore considered in some scenarios; however, the social and environmental costs could be harmful and high.

Replacement Time- the length of time in years, from installation/acquisition/setup of the solution through usage until a new installation/acquisition/setup is required to replace the earlier one. This is calculated as the ratio of **Lifetime Capacity** and the **Average Annual Use**.

Total Emissions Reduction – the sum of grid, fuel, indirect, and other direct emissions reductions over the analysis period. The emissions reduction of each of these is the difference between the emissions that would have resulted in the **REF Scenario** (from both solution and conventional) and the emissions that would result in the **PDS Scenario**. These may also be considered as “emissions avoided” as they may have occurred in the REF Scenario, but not in the PDS Scenario.

Transition solutions are considered till better technologies and less impactful are more cost effective and mature.

TWh/ Terawatt-hour – A unit of energy equal to 1 billion kilowatt-hours