Climate Change Will Create Regional Dependencies for The Blue Carbon Potential of Mangroves

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ABSTRACT

Mangroves are viewed as effective blue carbon solutions due to their substantial carbon stock and sequestration capacity. However, there remains uncertainty as to whether mangroves as nature-based solutions will be resilient under climate change. To assess the future viability of mangroves as part of a larger portfolio of nature-based climate solutions, I first identify the fundamental characteristics of effective blue carbon systems. Second, I assess and predict the impact of climate change on mangroves. Finally, I draw conclusions about the carbon sequestration capacity of mangroves under climate change and offer future directions for both research and mitigation. In sum, the blue carbon potential of mangrove forests in the face of climate change will be highly variable, depending on geographic region, local positioning, and ecological characteristics. Moving forward, it will be critical to not treat mangrove forests as a monolith when incorporating them into a climate portfolio. This paper is the first of its kind to evaluate the effectiveness of mangroves as blue carbon solutions under climate change. As such it will help inform both mangrove conservation and restoration efforts, and mangrove carbon pricing.

Background

Mangroves

Mangroves are a unique plant and a prime candidate for blue carbon as they possess several characteristics that maximize carbon storage and sequestration. Due to their dynamic coastal environment (C. Woodroffe, 1992), mangroves are highly resilient and can adapt faster than other tree species (Kathiresan & Bingham, 2001). Occupying a total area of 18.1 million ha (Nyanga, 2020) across 5 continents, mangrove forests are concentrated in the tropics and found primarily in Asia (Jia et al., 2023). Two-thirds of the total area of mangrove forests is located in 18 countries (Barbier, 2016; Kathiresan & Bingham, 2001), meaning a wide variety of communities are dependent on them. Not only are mangrove forests found in a range of locations, but there are also 80 different mangrove species.

All mangrove species possess several traits that make them uniquely adapted to coastal environments. The root structure of mangroves is optimized for gas exchange under semi-aquatic and anoxic conditions. Such adaptations vary among taxa, but notable structures include the stilt roots of Rhizophora which raise the trees above the water level, and pneumatophores of Avicennia, Sonneratia, and Lumnitzera which emerge laterally from the soil (Kathiresan & Bingham, 2001). Despite variation amongst species, the root structure of mangroves serves the common function of increasing exposure to oxygen. Furthermore, lenticels, loose porous tissue found on exposed root surfaces, enable the transfer of gas between the atmosphere and interior tissues of the root. Beyond adaptations in root structure, the wood of most mangroves is diffuse-porous which helps slow down water conduction despite periodic flooding (Kathiresan & Bingham, 2001; Das & Ghose, 1988). During periods of flooding, mangroves are submerged under brackish water–a combination of fresh water and salt water found in coastal ecosystems. To tolerate this prolonged exposure to salinity, mangroves have the ability to exclude, excrete, and accumulate salt.

Despite occupying a range of regions, mangroves have a higher net primary productivity in warmer, tropical areas. Their high overall productivity leads to more leaf and stem production which results in larger amounts of dead organic matter known as litter. The decomposition of mangrove litter in situ leads to tighter cycling of energy and nutrients which benefits the ecosystem (Kathiresan & Bingham, 2001).

Beyond playing a vital ecological role, mangroves provide substantial benefits to several human communities. Mangrove forests, along with all ecosystems, have four primary ecosystem services: provisioning services, regulating services, cultural services, and supporting services. Provisioning services are defined as any type of material good that can be extracted from the ecosystem. For mangrove forests, this includes timber, fuelwood, medicinal, and food resources. In terms of regulating services, mangroves can sequester carbon and provide erosion and flood control. Furthermore, mangroves have significant cultural services as they play an important role in the tourism industry and are tied to the culture of local communities. Finally, mangroves provide the supporting services of acting as a nursery for juvenile marine organisms as well as a feeding and breeding site for a host of animals (WRI, 2005).

Climate Change

Climate change is defined as long-term shifts in temperature and weather patterns—notably the anthropogenically-caused rapid warming of Earth's climate. Significant causes include the burning of fossil fuels and the subsequent release of greenhouse gases. Increased concentrations of greenhouse gasses (namely carbon dioxide) cause more heat to be trapped in the atmosphere giving rise to a host of global impacts. The main effects of climate change analyzed in this paper are rising sea levels, rising temperatures, and variations in precipitation. Note that this paper focuses on climate change, not global change. Global change includes any anthropogenically caused natural phenomenon (e.g., increased siltation and runoff, pollutants, habitat loss, etc.), whereas climate change comprises the secondary effects of releasing greenhouse gasses.

Blue Carbon

Blue carbon is a label given to marine ecosystems that have the potential to contribute to the mitigation of climate change when managed strategically (Howard et al., 2023). To be a viable blue carbon solution, an ecosystem must display evidence of long-term carbon storage. This entails that their capacity to store carbon, when optimized through protection, restoration, and management, should have the capability to reduce atmospheric greenhouse gasses and influence the climate (Howard et al., 2023). Coastal ecosystems, such as seagrasses, saltmarshes, and mangrove forests, are experiencing increasing attention as natural climate solutions. Out of these ecosystems, the potential of mangroves has been most comprehensively researched (Macreadie et al., 2019; Vanderklift et al., 2019; Zeng et al., 2021).

The voluntary carbon market plays a critical role in the valuation of mangrove ecosystems. The carbon market is built on the idea of carbon credits: each carbon credit represents the removal of one ton of carbon dioxide from the atmosphere. After a carbon sequestration project is certified by a certification body (either government or independent), external organizations can purchase carbon credits. The global carbon market has experienced a significant expansion in the last decade with trade volume increasing by 170% (USD 109 million) between 2017 and 2018 (Donofrio et al., 2019; Griscom et al., 2017; Zeng et al., 2021). Around 20% of the 18.1 Mha of mangrove forests worldwide are viable to be invested in as nature-based solutions. This total area has the potential to sequester the equivalent of 0.13% of global carbon dioxide emissions (3.8 ± 5.1 $MtCO_2e$) per year (IPCC 2014; Zeng et al., 2021).

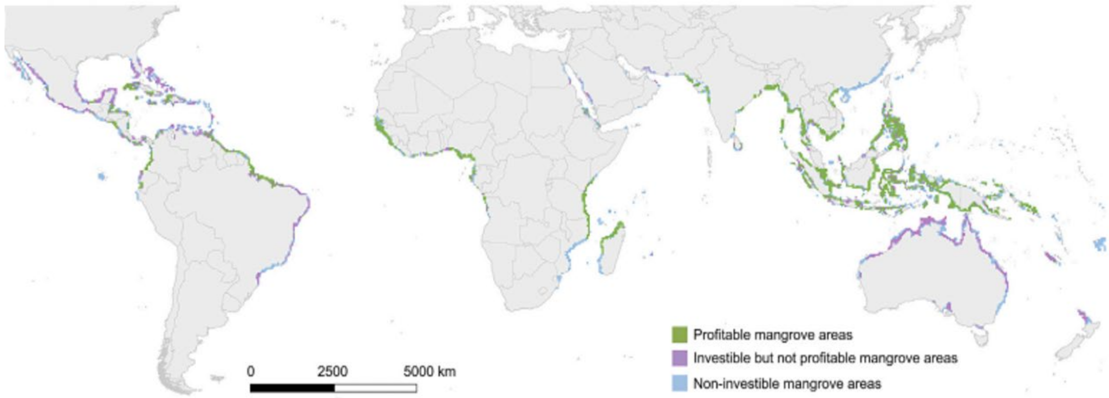

Figure 1. Global map of mangrove areas from Zeng et al. (2021, Figure 1 Panel A), categorized as profitable, investible, and non-investible sites. The majority of mangrove forests are potentially profitable as blue carbon solutions, however, there is significant variation. Of the profitable sites, most are located in Southeast Asia.

The relative profitability of investment in mangrove forests was modeled based on an average cost of project establishment (US$232 ha^{-1}) and variable yearly maintenance cost. A constant carbon price of US$5 per ton of CO_2e was assumed (based on the average prices between 2006–2018) for the first 5 years with a price appreciation of 5% per year over a 30-year time frame (Butler et al., 2009; Donofrio et al., 2019; Siikamäki et al., 2012; Zeng et al., 2021) (Fig 1). However, carbon pricing is highly variable, with the current range between $20 USD and $162 USD per metric ton (Bloomberg NEF, 2024). The viability of mangrove blue carbon projects is sensitive to this pricing, with higher viability as the price increases (Butler et al., 2009; Donofrio et al., 2019; Siikamäki et al., 2012; Zeng et al., 2021).

Mangrove Carbon Stock and Sequestration

The impressive capability of mangroves to store and sequester carbon is explained by several biological and ecological characteristics.

Mangrove storage or stock refers to carbon stored in the aboveground biomass of mangroves. Greater biomass means greater capacity for carbon storage. Aboveground biomass is roughly negatively correlated with increasing latitude as lower temperatures decrease the productivity of mangrove ecosystems (Hutchison et al., 2013).

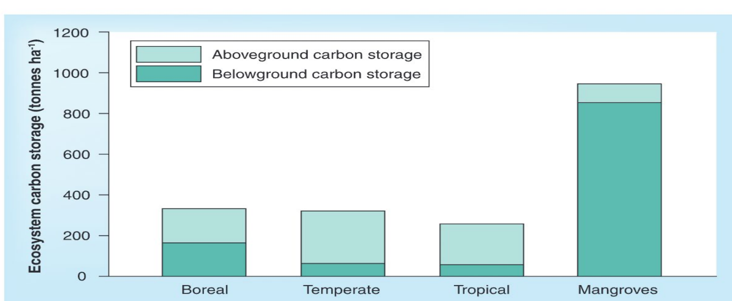

Figure 2. Visualization of aboveground and belowground carbon storage across four ecosystems from Alongi (2012, Figure 1). Mangroves store substantially more carbon compared to other ecosystems. While the ratio of

aboveground carbon storage to belowground carbon storage varies amongst ecosystems, Mangroves store carbon primarily in belowground biomass.

Carbon sequestration refers to the long-term storage of carbon below ground. Mangroves can sequester twice as much carbon as they can store in their biomass (Fig 2; Kaul et al., 2010; Swangjang & Panishkan, 2021). Tree carbon belowground is vested in dead, rather than live, roots and the amount of soil carbon increases with forest age as the soil and dead root carbon pools increase in size (Alongi, 2012; Alongi et al., 2003, 2004).

Mangrove carbon sequestration is facilitated, in part, by mangrove ecosystems' slow rate of decomposition. This slow decomposition is primarily due to their low oxygen conditions, which limits the breakdown of phenolic compounds (Alongi, 2012; Chapman et al., 2019; Freeman et al., 2001; Simpson et al., 2023). Mangrove forest decomposition ranges from 0.07% to 0.17% (Alongi, 2012; Zhang et al., 2008). This slow rate of decomposition reduces the turnover of carbon by microbial communities and allows carbon to be buried in sediments.

The input of carbon in the soil pool of mangroves combined with sediment accumulation enables the accretion of carbon. The rate of this accretion is controlled by tidal inundation as inundation causes the input of sediment and, therefore, contributes to sediment accumulation (Alongi, 2012). Additionally, the sedimentation rate is affected by upstream human activity, such as the creation of dams and excessive groundwater depletion.

Clay, a common component of mangrove sediment, is positively correlated with bulk density and therefore increases carbon stocks (Srivastava et al., 2020; Swangjang & Panishkan, 2021). Because clay is a fine particle that binds effectively to organic matter, mangrove sediments with higher clay content can store more carbon.

Furthermore, mangroves have an extensive root system with their roots being both abundant and extremely thin. This enables the tighter aggregation of soil and binding of organic matter, which increases carbon sequestration capacity. Additionally, their root structure slows down wave action which leads to reduced overturn of carbon.

It is important to note that the factors that influence mangrove stock and sequestration are highly site-specific. For example, stock and sequestration are dependent on how much protection the mangrove gets on the coast and its position in relation to human development, as mangrove deforestation causes a permanent loss of below-ground carbon (Swangjang & Panishkan, 2021). Additionally, nitrogen from upstream anthropogenic inputs drives up the rate of decomposition and drives down carbon sequestration. As a result of this variability, the capacity of mangrove soils for carbon storage ranges from less than 0.1% to over 40% of soil dry weight (Alongi, 2012; Kristensen et al., 2008).

Due to their higher net primary productivity and slow rates of decomposition, mangroves have higher carbon storage and sequestration capacity relative to other ecosystems (Fig 2) (McKee et al., 2007; Twilley et al., 1986); the amount of carbon stored in mangrove soils is 3.5 times greater than the amount of carbon stored in tropical forest soil (Mcleod et al., 2011; Swangjang & Panishkan, 2021). Furthermore, when compared to other coastal ecosystems, the carbon storage and sequestration capacity of mangroves has been most extensively validated, which is a primary advantage in legitimizing investments in mangrove ecosystems. As a result, the use of mangroves as a blue carbon solution is becoming increasingly widespread.

Incorporating Climate Change

With the expansion of the carbon market, mangroves are prime targets for incorporation as blue carbon solutions. Subsequently, the planting and upkeep of mangrove forests is used as a method to offset carbon emissions. However, an effective blue carbon solution needs to be sustainable. Climate change has the potential to threaten the longevity of mangrove forests, and therefore, their viability as a blue carbon solution comes into question.

To date, this has not been considered and may be a key determinant of mangrove restoration efforts in the next several decades.

Climate Change Impacts on Mangroves

Historical Evidence of Mangrove Resiliency

Ecological resilience is defined as the ability to recover from disturbances to a persistent state. Mangroves possess ecological resilience as they are well adapted to the change and instability of their coastal environment. Even under normal environmental conditions, mangroves experience frequent changes in water temperature, wave action, salinity, and oxygen levels due to their unique positioning at the interface of land and ocean. Characteristics such as large reservoirs of below-ground nutrients, efficient biotic turnover, and effective biotic controls enable mangrove forests to maintain resilience whilst facing variable environmental conditions (Alongi, 2008; Duke, 1992). Despite the ecological resilience of mangroves, climate change has been predicted to lead to a loss of 10-15% of mangrove forests by 2100 (Alongi, 2008). The next sections assess the impact of sea level rise, temperature increase, and precipitation changes on mangroves and the subsequent impact on C stock and sequestration. While there are other components of climate change to consider, these three will have an outsized effect on mangroves.

Sea Level Rise

Mangroves have experienced changes in sea level throughout history. The general pattern for the last interglacial glacial cycle is one of overall sea level fall. Since then, the sea level has risen at an average rate of 5-15 mm per year (Alongi, 2008; Woodroffe, 1990). Furthermore, analysis of stratigraphic sequences in mangrove peat deposits suggests that mangroves experienced a global trend of landward migration as a result of sea level rise during the Holocene (Alongi, 2008; Kim et al., 2005; Plaziat, 1995; Woodroffe, 1990). This previous example of mangrove resiliency to sea level rise indicates the potential that mangroves could be resilient to the rate of sea level rise under climate change.

Impacts

The mean sea level is predicted to rise between 0.43 m and 0.84 m by 2100, which would amount to an annual rate of 5.5 mm-11 mm. Mangroves will likely experience sea level rise differently, with an expected regional variation of 1.65 mm - 3.3 mm due to changing oceanic thermal dynamics (IPCC., 2022). Mangrove responses to increased sea level rise vary depending on region-explicit circumstances.

Responses

The rate of sea level rise can be directly countered by sediment accrual and landward migration, which elevates mangroves above the water level. This leads to likely differences in mangrove resiliency due to variability in sediment availability and transport. Mangrove communities rich in sediment have a greater potential for sediment accretion and can keep pace with sea level rise. Macro tidal coastlines—coastlines that experience tides greater than 4 meters—receive more sediment deposits. Therefore, mangroves in mainland estuaries and deltas (ecosystems with macro tidal coastlines) are least vulnerable due to extensive sediment supply.

However, mangrove communities in carbonate islands are extremely vulnerable as landward migration and sediment accretion are often not possible (Alongi, 2008). Landscape type may also play a role in sediment availability. For example, low-lying islands between 30°N and 30°S may not be able to keep pace with sea level rise due to limited sediment availability (Ellison & Stoddart, 1991). In contrast, mangroves on high islands will be relatively more resilient and are predicted to keep up with sea level rise at a rate of 4.5 mm per year, or 80% of the sea level rise anticipated by 2100 (Ashrafuzzaman, 2023).

Finally, vulnerability is caused by the anthropogenic restriction of sediment supply. The rate of sediment accretion on a coast is determined by delivery from rivers. The rate of river flow is reduced by human activity, such as the damming of rivers as well as excessive groundwater extraction(Milliman & Farnsworth, 2011; Sippo et al., 2018; Wong et al, 2014; Woodroffe et al., 2016).

Effect on Blue Carbon

Historically mangroves have been able to keep pace with sea level rise by migrating landward. Historic rates of sea level rise are similar to current rates with historic rates being 5-15 mm and the current rate being 5.5-11mm. Therefore, it can be assumed that landward migration can keep pace with the current rate of sea level rise. However, many mangrove forests are surrounded by human communities, which would limit landward migration. In areas with high human population density, mangroves will experience a loss of forest area. Resultantly, the aboveground biomass of mangroves will decrease immediately, causing decreased C stocks. While sequestered carbon will remain trapped in the sediment, active sequestration will no longer occur.

Currently, sediment accretion is occurring at a rate comparable to sea level rise. However, in areas with low sediment availability, the rate of sedimentation may not be able to keep pace with sea level rise. In this scenario, mangroves would essentially be slowly drowning, causing total loss of aboveground C stocks and a slow loss of sequestered C in sediment as roots die and sediment is washed away into the ocean. There would be no more active sequestration. In the scenario where sediment availability is sufficient to keep pace with sea level rise, C stocks will be maintained. It is vital in this situation that mangrove root growth is plastic and is able to keep pace with sedimentation. Furthermore, the total amount of C sequestered has the potential to increase due to more available sediment. In the scenario where there is excess sediment available, sedimentation would cause mangroves to gain elevation. Consequently, due to decreased access to water, mangroves could experience desiccation and subsequent loss of C stock and C sequestration due to decreased biomass.

Rise in Temperature

Impact

The earth has experienced warming in the range of 0.65 - 1.06 degrees Celsius between the years 1880 and 2012. By 2081 - 2100, the earth has been predicted to warm another 1.4 - 4.4 degrees Celsius (IPCC, 2023).

Responses

Mangroves in different locations will be impacted differently depending on their current local temperatures. In mangrove forests with local temperatures less than 30-33°C, temperature changes will likely amount to a marginal increase in rates of photosynthesis, reproduction, and growth. However, mangrove forests with local temperatures greater than 33°C will experience a decline in photosynthetic rates (Alongi, 2015; Cheeseman, 1994; Lovelock et al., 2022) dependent on water availability. Precipitation will be a key lever of how increased temperature affects mangroves, which is explored in more detail below while this section will focus on responses to temperature increase independent of precipitation changes.

Mangroves will likely experience a tipping point between temperature and productivity, where productivity will increase with temperature before plateauing and eventually declining. This means that at an extreme mean temperature increase, mangroves will die, while a marginal mean temperature increase will likely increase productivity. This specific tipping point will depend on the mangrove species and its historical experiences with temperature. For example, species in the tropics, with the evolutionary experience of warmer temperatures, may fare better under warming conditions and eventually migrate to temperate regions as those areas are also warm.

Effect on Blue Carbon

Mangrove forests with lower local temperatures will experience increased photosynthesis, or increased productivity, with rising temperatures until a 'tipping point' is reached. Increased productivity would cause increased aboveground biomass and therefore higher C stock. Additionally, due to increased root biomass, the amount of C sequestered would increase in parallel.

However, it is important to note that higher temperatures impact the entire ecosystem. Rising temperatures could cause an increase in microbial activity and consequently speed up rates of decomposition. Resultantly, the mangrove forest could experience either slowed sequestration or a transformation into a C source instead of a C sink.

Decreased productivity in areas with high local temperatures would experience the opposite effect with less aboveground and belowground biomass causing a decrease in C stocks and sequestration.

Precipitation Changes

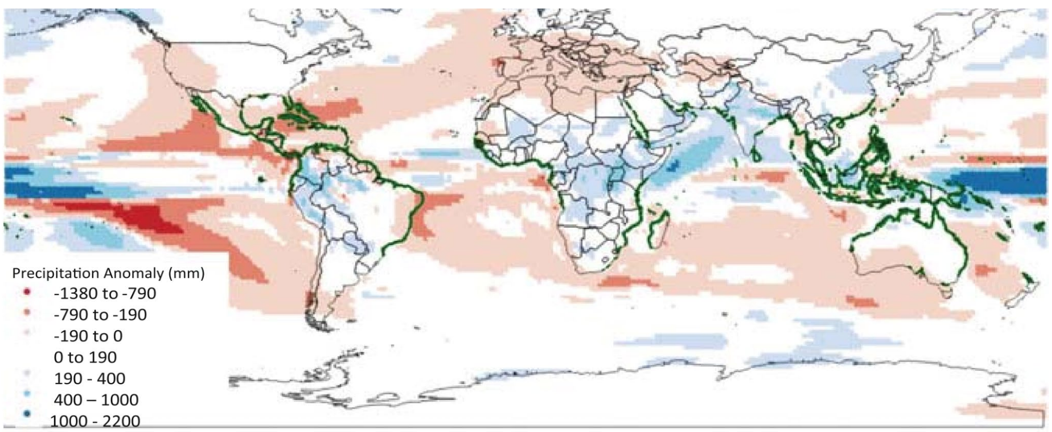

Figure 3. Global map depicting predicted changes in precipitation due to climate change from Lovelock et al. (2016, Figure 5, Panel B). Despite variation, decreased rates of precipitation are predicted to be experienced by non-equatorial mangrove forests. In contrast, mangrove forests along the equator are expected to experience more increased rates of precipitation.

Impact

Changes in precipitation caused by climate change are variable with some regions experiencing a net increase in precipitation while others face a net decrease (Fig 5; Ashrafuzzaman, 2023; Chow, 2017). Increased precipitation is predicted to affect equatorial regions whereas non-equatorial areas are expected to experience decreased precipitation.

Responses

Mangroves are adapted to a certain equilibrium of fresh and saline water, therefore changes in mean precipitation threaten to disrupt this balance (Ashrafuzzaman, 2023; Ward, 2016.; Jia et al., 2018).

Reduced precipitation would increase soil salinity, reduce productivity, growth, and seed emergence, and prompt a shift toward more salt-tolerant species. It would also decrease freshwater surface runoff and groundwater supply to mangroves (Ashrafuzzaman, 2023; Chow, 2017; Ward et al., 2016). Non-equatorial mangrove forests are especially vulnerable to less water availability. Mangroves in North Western Australia, the Caribbean, and Central America have been predicted to experience and suffer from increased aridity (Fig 3; Alongi, 2015; Record et al., 2013).

Further, increased precipitation can also result in increased siltation and sedimentation (Ashrafuzzaman, 2023; Ellison & Stoddart, 1991; Ward et al., 2016), potentially causing negative consequences. Depending on upstream anthropogenic activities in the watershed, chemicals, fertilizers, and heavy metals found in runoff could harm mangroves. However, without anthropogenic effects, increased sedimentation can allow mangroves to keep pace with sea level rise as detailed in the section above.

Effect on Blue Carbon

Due to decreased precipitation in some regions, the salinity of water will increase. In response, mangroves are likely to create extensive root systems (Alongi, 2012). These large-scale root systems have the potential to increase C sequestration capacity as more sediment is being trapped by the roots. However, mangroves can only tolerate salinity to a certain extent. Beyond a point, increasing salinity would pose a threat to mangroves.

Mangroves in non-equatorial regions will experience increased aridity. As a result, mangrove mortality rates would rise in such regions causing a decline in aboveground biomass and thus decreased C stock. While C would remain sequestered in sediment, active sequestration would stop.

Solutions

Evolution

The typical lifespan of mangrove species ranges from 20 to 40 years. However, certain species, such as the red mangrove (*Rhizophora mangle*), are more likely to live to be older than 50. Red mangroves that are over a century old have been documented. Both the white mangrove (*Laguncularia racemosa*) and black mangrove (*Avicennia germinans*) commonly have lifespans of more than 50 years.

Mangrove lifespans are too long relative to the pace of climate change to allow for feasible adaptation. It is therefore improbable that mangroves will keep pace with climate change without facilitated evolution, artificial selection, or plasticity.

Plasticity

Phenotypic plasticity is defined as the potential of organisms to alter their phenotype as a response to changes in their environment, independent of their genotype. Phenotypic variation may arise due to variation in either biotic or abiotic factors. This phenomenon enables populations to increase their survival and fitness without evolutionary change (Vovides et al., 2021). Some mangroves have been observed to exhibit high levels of trait plasticity, which could potentially facilitate adaptation to climate change (Lovelock et al., 2016). Factors that cause mangroves to display plastic responses include both environmental variability (eg. salinity and soil anoxia) (Ball, 1988; Feller et al., 2010; Tomlinson, 2016; Vovides et al., 2021) and coastal processes (eg. erosion and sedimentation) (Balke et al., 2013; Dahdouh-Guebas et al., 2004, 2007; Vovides et al., 2018; Vovides et al., 2021). While phenotypic plasticity has not been specifically demonstrated to mitigate the impact of climate change on mangroves, the concept of plastic rescue holds potential and requires further research.

Human Intervention

Since the potential of plastic rescue as a solution to climate change has not yet been solidified, options involving human intervention must be assessed as well.

Using Specific Species

An avenue for intervention is the artificial selection of mangrove species with greater C sequestration and stock capacity. The ability of mangroves to store and sequester carbon has been shown to vary amongst species (Table 1). For example, the rate of carbon sequestration was found to be 96.8% higher in *Rhizophora mucronata* than in *Avicennia marina* (Kathiresan et al., 2018). Additionally, carbon stock capacity was found to be positively correlated with chlorophyll (a, b, total), flavonoids, and leaf surface wax (Kathiresan et al., 2018). These biochemical markers can be taken into account when selecting species for mangrove planting programs to optimize for carbon stock capacity.

Table 1. Table showing variation in biochemical markers amongst *Avicennia marina* and *Rhizophora mucronta* from Kathiresan (2018, Table 1). *Avicennia marina* and *Rhizophora mucronta* are mangrove species with varying geographical distribution and morphology. The annual carbon sequestration per kilogram of tree of *Rhizophora mucronta* is almost double that of *Avicennia marina.*

Species	Carbon sequestration (kg/tree/year)	Carotenoids (umol/g)	Anthocyanin OD 530nm	Flavonoids OD 315 nm	Phenols (mg/g)	Tannins (mg/g)
Avicennia marina	6.12 +3.36[a]	585.21 ± 87.03[a]	0.36+0.17[a]	1.04+0.31[a]	0.49+0.07[a]	0.20+0.01[a]
Rhizophora mucronata	12.05+3.55[b]	472.09 ± 129.16[a]	1.19 +0.19[a]	1.20 0.40[b]	0.54+0.10[a]	0.86+0.16[b]

Genetic Engineering

While mangroves themselves have not been genetically engineered, genetic engineering of other coastal plants has been previously successful. Wetland grass has been genetically engineered for the purpose of improving phytoremediation capacity (Czakó et al., 2005). If the genetic engineering of mangroves were to be made possible, immediate traits that should be considered include above and below-ground biomass. Mangroves with larger trunks and more expansive pools of below-ground biomass have the capability to store and sequester greater amounts of carbon. Furthermore, mangroves with more extensive root structures are able to trap more sediment and have a greater carbon sequestration capacity as a result. With increasing levels of salinity due to decreasing rates of precipitation in some regions, another consideration could be improving the tolerance of mangroves to salinity to increase their resilience to climate change. This could include improving the efficiency of root filtration systems or increasing the concentration of salt-excreting glands found on mangrove leaves.

Restoration Using Ecological Engineering

Beyond human intervention through facilitated evolution, mangrove restoration efforts must utilize ecological engineering principles to optimize for success and longevity.

Ecological engineering can be broadly defined as methods that optimize self-sustaining ecosystems or restore anthropogenically degraded ecosystems (Lewis, 2005). While most restoration efforts immediately focus on active restoration, such as planting, it may be more efficient to prioritize assessing and removing exogenous stressors (Clintron-Molero, 1992; Hamilton & Snedaker, 1984; Lewis, 2005), such as upstream pollution or blocked tidal inundation. After the stressor has been removed through the installation of defense structures such as tidal gates or weirs, the potential for natural propagule recruitment needs to be determined. If natural restoration is not possible, assisted restoration should be pursued.

Assisted restoration will include key activities including planting propagules, facilitating the establishment of seedlings, and modifying hydrology (Lewis, 2005; Lewis & Marshall, 1997). The potential of assisted restoration is evidenced by a study conducted on the coastline of Demak district, Java, Indonesia which found that mangrove restoration in the coastal zone may be facilitated by combining assisted restoration with the planting of pioneer species. This study additionally indicates that a combination of both assisted and active restoration could be required depending on site-explicit circumstances.

Conclusion and Recommendations

The impacts of climate change will affect mangroves disproportionately depending on their geographic region, local positioning, and ecological characteristics. This context-dependency has important ramifications for how mangrove blue carbon is assessed and implemented in carbon markets. Critically, mangrove forests cannot be treated as a monolith—the specific situation of each mangrove forest will need to be considered.

In this paper, I explored three predominant components of climate change, and have identified unifying considerations for making more accurate assessments of the blue carbon potential of mangroves. With the threat of sea level rise, mangrove forests with high availability of sediment are best equipped to keep pace with the rising sea level and mangroves in remote regions have the greatest potential for landward migration due to a lack of anthropogenic activity. Furthermore, when facing rising temperatures, mangroves in regions with lower local temperatures (<33°C) will be substantially more resilient.

In contrast, mangroves will be highly vulnerable in regions such as carbonate islands and low-relief islands, which have limited capacity to adapt to sea level rise. Additionally, mangrove forests in arid regions with higher local temperatures (>33°C) are vulnerable to both increased temperature and decreased precipitation caused by climate change.

As such, the vulnerability of mangrove forests under the threat of climate change will vary substantially from region to region, and this variability should be considered when involving mangroves in carbon accounting as a blue carbon solution. Mangroves still have a high potential to be included in a wider portfolio of natural climate solutions; however, they are under threat from climate change and particular measures need to be taken to safeguard their future capacity.

It is vital to invest in the protection of mangrove ecosystems with pre-existing resilience to climate change. Preservation could include establishing protected areas such as natural reserves or World Heritage Sites. Furthermore, there are specific, immediate interventions that could increase the ecological resilience of mangrove forests in the face of climate change. These suggested interventions can be costly in both time and financial investment but may pay off in the long run. To keep pace with sea level rise, it is necessary to prevent groundwater depletion, stop the creation of new dams, and remove existing dams, all of which would increase sediment availability and enable sediment accretion. In order to reduce downstream pollution and improve mangrove health, upstream activities could be tightly regulated whilst natural filters can be added to filter pollutants. Under the threat of increased storm surges, the creation of seawalls could protect mangrove forests during extreme events exacerbated by climate change. Finally, conducting further research on mangrove plasticity and evolution would open doors to more potential solutions.

Although it is important to exercise caution when involving mangroves in carbon accounting as blue carbon solutions, mangroves are a vital resource and should be invested in as such. By taking deliberate steps to improve their resilience, the position of mangroves as a promising and viable blue carbon solution can be secured.

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