Mangrove forests, salt marshes and seagrass beds; the blue carbon potential under climate change

A study on how the blue carbon potential changes and can be preserved under different future atmospheric CO2 levels

Picture 1: Blue carbon system

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Contents

1. Abstract

This thesis aimed to identify how the blue carbon potential of mangrove forests, salt marshes and seagrass beds will change under RCP2.6, RCP4.5 and RCP8.5 scenarios by analyzing the threats posed to these marine ecosystems under each scenario, the potential responses and the measures that can be implemented to preserve their blue carbon potential. This was done by performing a meta-analysis and expert interviews. Human physical activity is the biggest threat all three ecosystems are facing, since it does not only lead to the loss of these systems but also lowers their resilience to climate change pressures. The main climate change stressor mangroves and salt marshes are facing under future climate change is sea level rise, whereas seagrasses are mainly at risk of degradation due to ocean warming and changes in water quality. Regionally blue carbon sinks are expected to respond differently. Some regions of seagrasses and most of salt marshes and mangroves will benefit from warming. In addition some regions and species will be less sensitive to sea level rise, namely high sediment regions and seagrasses. These factors will likely promote an expansion of these systems in those regions and thus an increase of blue carbon potential in some areas of the world. An RCP8.5 scenario would most likely lead to a net decrease of the blue carbon potential, but this is partly contingent on the impacts of human physical activity. Whether the global blue carbon potential will decrease, be a zero net gain, or increase under scenarios RCP2.6 and RCP4.5 strongly relies on whether human physical activity will be decreased in the next few decades. A combination of measures, with a focus on conservation, restoration and adaptation, are important to not only preserve these marine ecosystems under these future climate change scenarios but also enhance their blue carbon potential to make sure they can play a mitigating role.

2. Introduction

For decades now the rise of CO_2 levels in the atmosphere has been an urgent topic among scientists (Leslie Hook, 2020). Due to the continuous emission of carbon, CO_2 has been piling up in the atmosphere. Last year in May the CO_2 levels hit a record peak of 417 parts per million. According to Pieter Tans, a scientist at the NOAA, it would take thousands of years for the CO_2 emissions to be absorbed in the ocean and return back to the levels of CO_2 before industrial times even if humans were to stop emitting carbon (Leslie Hook, 2020).

The reason for the steep rise in CO_2 levels are the anthropogenic influences on the carbon cycle. Pre-industrial levels of CO_2 lie around 260-280 ppm (Hofman et al., 2009). The enormous rise in these levels over the past few decades is fossil fuel induced due to the rise of the industry and economic growth (Hendry & Pretis, 2013).

Several RCP scenarios have been created that outline different future atmospheric CO_2 level scenarios. These scenarios focus on the greenhouse gas emissions and concentrations in the next 100 years. Based on the amount of emissions one of the four possible RCP scenarios is likely to happen (Rogelj et al., 2012). These RCP scenarios give an estimate of the increase in atmospheric temperature and sea level rise based on the projected amount of emissions (Rogelj et al., 2012). Researchers have now been looking for ways to help mitigate climate change caused by the rise of atmospheric CO_2 levels. More recently research has emphasized the valuable role of blue carbon systems (McLeod et al., 2011). Blue carbon systems are coastal and marine ecosystems, specifically mangrove forests, seagrass beds and salt marshes. They sequester carbon. Even though there are less of these coastal ecosystems than terrestrial forests, which are mainly known for sequestering carbon dioxide, the contribution of these coastal vegetations to long-term carbon sequestration is much larger than that of terrestrial forests. These coastal ecosystems are however being lost at high rates worldwide as a result of coastal development and anthropogenic induced climate change (McLeod et al., 2011). While the CO_2 levels are increasing, so are the global temperatures. Atmospheric warming due to the rise in carbon emissions could lead to negative consequences for these marine ecosystems and is linked to changes in precipitation which affect their water supply. Anthropogenic carbon dioxide has already been causing sea level rise and will continue to do so (Hendry & Pretis, 2013). Recent research has shown that at current rates of loss nearly all mangrove forests and 30-40% of salt marshes and seagrass beds could be gone in the next 100 years. The loss of these marine ecosystems would not only cause a release of blue carbon into the atmosphere but would also affect the efficiency of long-term carbon sequestration of the marine environment (Pendleton et al., 2012). Therefore there is a global value to preserve these coastal wetlands as blue carbon sinks and make sure they will not contribute to the rising atmospheric CO_2 levels. The importance of protecting these blue carbon systems is being underlined by the increase of preservation measures worldwide (McLeod et al., 2011). This research paper therefore answers the following research question:

How will the blue carbon sink potential of mangrove forests, salt marshes and seagrass beds change under the RCP2.6, RCP4.5 and RCP8.5 scenarios?

To answer the main research question these sub questions were answered:

- What are the threats posed to mangrove forests, salt marshes and seagrass beds under the scenarios RCP2.6, RCP4.5 and RCP8.5?
- Do mangrove forests, salt marshes and seagrass beds respond differently under the scenarios RCP2.6, RCP4.5 and RCP8.5?
- Are there regional differences regarding the threats posed to and responses of mangrove forests, salt marshes and seagrass beds under the RCP2.6, RCP4.5 and RCP8.5 scenarios?
- What measures can be applied to make sure that the blue carbon potential of mangrove forests, salt marshes and seagrass beds are preserved?

3. Research aim

The importance of finding solutions to help mitigate climate change caused by the anthropogenic emission of CO_2 is rapidly increasing. This thesis aims to create a deeper understanding of the response of blue carbon systems under the scenarios RCP2.6, RCP4.5 and RCP8.5 and how these marine ecosystems can be preserved as blue carbon sinks. This thesis focusses on three RCP scenarios to illustrate the range of possible effects of anthropogenic influences on blue carbon sinks.

4. Theoretical background

4.1 Carbon cycle

The carbon cycle, as seen in figure 1, plays an important role in the sequestration of carbon. The global carbon cycle shows surface-atmosphere exchanges of CO_2 by the ocean and land. This includes natural processes, such as photosynthesis, respiration and decomposition, and anthropogenic activities such as the emission of fossil fuel and land use changes (Ito et al., 2020). There is a steady state of fluxes between the atmosphere and the two reservoirs, the biosphere and oceans. The increase of atmospheric CO_2 does not equal the rates of emissions caused by anthropogenic activities, which is due to two factors. First there is the uptake of carbon by the terrestrial biosphere. Vegetation, such as forests, act as a carbon sink. This means they take up CO_2 via photosynthesis and hold onto it until they decay, also known as carbon sequestration. After decay the CO_2 returns to the atmosphere. In addition there is the uptake of carbon by the ocean. Due to changes in atmospheric pressure and the partial carbon pressure in the ocean there is a flux from either the ocean to the atmosphere or from the atmosphere to the ocean (Smithson et al., 2013). There are three pumps that contribute to the uptake of carbon in the ocean, namely a solubility pump and two biological pumps that export inorganic and organic carbon to the deep ocean (Schlunegger et al., 2019).

The terrestrial biosphere is assumed to be the biggest contributor when it comes to the uptake of carbon. However recent research highlighted the importance of wetlands as carbon dioxide sinks (Battin et al., 2009). Even though only up to 1% of the world is covered by wetlands their contribution to the global carbon cycle is significant compared to that of terrestrial ecosystems and the ocean (Battin et al., 2009). They contribute for up to 70% of the carbon storage in all ocean sediments (Saderne et al., 2019).

Blue carbon systems such as mangrove forests, salt marshes and seagrass beds are vegetation. They can thus take up carbon from the atmosphere via photosynthesis and store this carbon in their underlying sediments (Saderne et al., 2019). Blue carbon can be stored for thousands to millions of years in these underlying plant sediments, making them efficient carbon sinks.

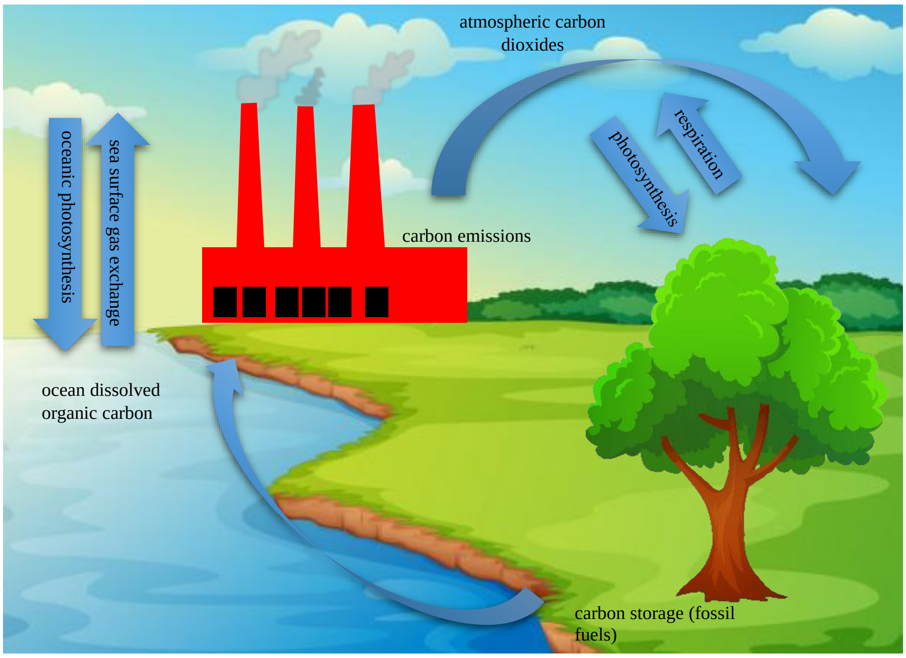


Figure 1: Carbon cycle

4.2 Blue Carbon Systems

4.2.1 Mangrove forests

Mangroves are the only woody plants taking up coastal ecosystems. They cover about 138.000 km² of the earth's surface and can be found in subtropical and tropical coastlines. Like tropical forests mangroves assimilate CO2 into organic compounds for nutrition. The mean global carbon burial rates are 24 Tg carbon per year (Alongi, 2012). As coastal habitats they comprise for 14% of carbon sequestration by the global ocean (Alongi, 2012). Even though the soil respiration rates of mangrove forests are similar to those of tropical forests they store their carbon more efficiently and thus are more effective in sequestering carbon (Lovelock, 2008). They store carbon for longer periods of time due to the high carbon deposition and the low rates of carbon oxidation, caused by anaerobic conditions, in mangrove soils. These factors cause mangrove forests to allocate a big portion of their fixed carbon to their roots (Lovelock, 2008).

Due to coastal development, tourism and over-harvesting these marine ecosystems have declined by 30-50%. Mangroves are the most carbon-rich forests in the tropics. Deforestation of them accounts for around 10% of the global carbon emissions caused by land use change (Donato et al., 2011). Mangrove ecosystem services, such as carbon sequestration, depend on the size of forest patches. Land use changes have caused mangrove forests to be fragmentated and lost. Small mangrove forests are particularly affected by this land use change. Their capacity to sequester carbon becomes way smaller due to this fragmentation, causing them to work less efficiently (Bryan- Brown et al., 2020).

4.2.2 Salt marshes

Salt marshes are intertidal ecosystems that can sequester carbon as they accumulate and bury sediments rich in organic matter (Kathilankal et al., 2008). The global area of marshes is estimated to be around 54950 km² (Mcowen et al., 2017). Rates of carbon sequestration are an order of a magnitude higher than those of tropical forests. Salt marshes are storing up to 87.2 Tg of carbon per year (Chmura, 2013). These rates of carbon sequestration are high due to both autochthonous primary production and import of allochthonous matter. This means that the rates of deposition of organic matter are slow while the rates of input of organic matter are high (Mueller et al., 2019). They also store up carbon for millennia's whereas forests usually only store carbon for decades (Macreadie et al., 2013).

Due to landscape conversion salt marshes have undergone a decline of 25% (Macreadie et al., 2013). This raises concerns since there are large amounts of carbon buried in these sediments. Disturbance is likely to affect salt marshes in several ways. First off it could reduce the carbon stocking capacity, causing a reduction in the accumulation of carbon. In addition the overall plant biomass is reduced leading to a decrease in photosynthesis. The plant dying off as well could lead to the release of buried carbon (Macreadie et al., 2013).

Sea level rise might be the most significant concern for salt marshes. In order for these intertidal ecosystems to persevere their surface elevations must increase with rising sea levels. If this does not occur, the carbon stored in these sinks might be exposed to conditions that cause decomposition and thus a release of carbon (Ruiz-Fernández et al., 2018).

4.2.3 Seagrass beds

Seagrass beds grow in meadows along all continents, except Antarctica. They form beds between the water column and sediment in tidal or subtidal environments (Marba, 2007). They can form in depths up to 50 meters. These meadows cover 170.000 to 600.000 km². Like other plants seagrasses use carbon dioxide to synthesize their own food. Research has shown that seagrass beds increase their primary productivity under elevated CO_2 concentrations (Russell et al., 2013). They bury up to 27.4 Tg carbon per year and thus account for 10% of oceanic carbon burial. The anaerobic conditions of seagrass meadows halt the decomposition of carbon and therefore make efficient carbon sinks by promoting long-term carbon sequestration (Campbell et al., 2015).

Many seagrass meadows are dealing with pressures from anthropogenic disturbances, such as sewage disposal, construction works and destructive fishing. These disturbances lead to damages and losses of seagrass beds. Research has shown that about a third to half of seagrasses have already been lost worldwide (Lyimo, 2016). Disturbance of seagrass beds lowers the capacity of retention of carbon. This is due to loss of photosynthetic capacity (Rozaimi et al., 2017). In addition the filtering capacity of seagrass beds is lowered meaning that the flux to the below-ground carbon stock will be reduced thus lowering the long-term carbon sequestration. The decay of seagrass beds in response to anthropogenic activities could lead to the release of buried carbon through mineralization, erosion and leaching (Lyimo, 2016).

<u>4.3 RCP scenarios</u>

4.3.1 Background

Four RCP scenarios have been developed by the Intergovernmental Panel on Climate Change (IPCC). These scenarios describe four potential futures (RCP1.9; RCP2.6; RCP4.5; RCP8.5) that are projected to happen based on the amount of greenhouse gas emissions in the next years. They are named after a possible range of radiative forcing values projected to occur in 2100, as seen in figure 2 (Pachauri et al., 2014).

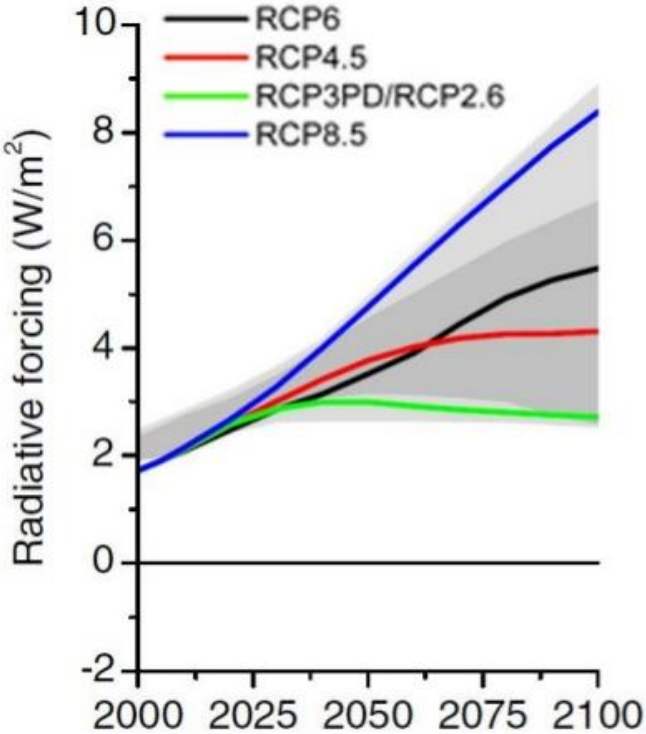


Figure 2: RCP pathways (Van Vuuren et al., 2011)

4.3.2 RCP2.6

The RCP2.6 scenario aims for CO2 emissions to start declining by 2020 and go down to zero by 2100. This requires negative emissions, such as CO2 absorption by blue carbon systems. This scenario would most likely be able to keep the global temperature rise below two degrees Celsius and the sea level rise below 0.4 meters in the next hundred years (Van Vuuren et al., 2011).

4.3.3 RCP4.5

The RCP4.5 scenario is a stabilization scenario. Under this scenario CO2 levels in the atmosphere should start declining by 2045 and they should be roughly half the levels of what they were by 2100. This scenario would keep the global temperature rise just below two degrees and the sea level rise just below 0.5 meters in the next hundred years (Thomson et al., 2011).

4.3.4 RCP8.5

The RCP8.5 scenario is the most aggressive scenario in that it is the worst-case scenario. This scenario is also described as the 'business as usual' scenario meaning that the CO2 emissions would continue rising throughout the 21st century. Under this scenario the global temperature is expected to rise 3.7 degrees Celsius and the sea level up to 0.82 meters in the next hundred years (Schwalm et al., 2020).

4.5 DPSIR framework

To make sense of the response of blue carbon systems under the scenarios RCP2.6, RCP4.5 and RCP8.5 an analytical framework can be used. The Driver-Pressure-State-Impact-Response framework is a tool developed by the EEA and OECD for the management of interactions between society and the environment (Kristensen, 2004). The approach can be used for all ecosystems but is mainly used to describe social and ecological interactions of aquatic systems, as shown for blue carbon systems in figure 3.

The "Drivers", as well known as driving forces, are human activities and processes that control the "Pressures" on the environment (Kristensen, 2004). In this context the "Drivers" are land use change and climate change. Land use change promotes the disturbance and loss of blue carbon systems. Climate change causes the rise of sea levels and atmospheric warming, therefore also leading to disturbance of blue carbon systems. These are the "Pressures". The co-occurrence of these "Pressures" leads to a change in the "State" of the blue carbon systems, namely the increased risk of the loss of blue carbon systems. This change in "State" results in "Impacts" on the environment in the form of the release of blue carbon and a lower capacity of long-term carbon sequestration. "Responses", assessed in this thesis, are measures to preserve the blue carbon potential. This paper examined how mangrove forests, salt marshes and seagrass beds can be preserved as blue carbon sinks under the scenarios RCP2.6, RCP4.5 and RCP8.5 using the DPSIR framework.

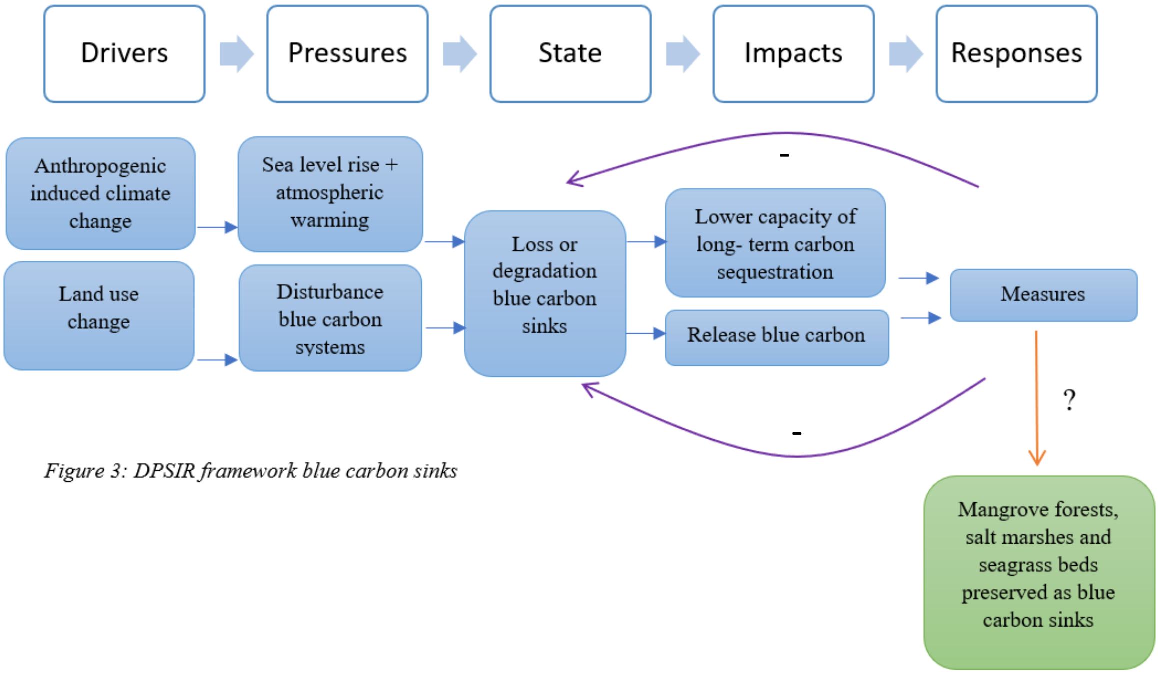


Figure 3: DPSIR framework blue carbon sinks

5. Methodology

In the following section the mixed method that was used to gather and analyze data for this research is given. To answer the research question a meta-analysis and expert interviews were performed.

5.1 Systematic literature review

The systematic literature review focused on three types of blue carbon systems namely mangrove forests, seagrass beds and salt marshes. The responses of these blue carbon systems under the scenarios RCP2.6, RCP4.5 and RCP8.5 were assessed. In addition it was examined how these marine ecosystems can be preserved as blue carbon sinks.

5.1.1 Primary selection

Academic papers were selected from ‘Google Scholar’ based on their relevance and applicability to the posed research question. To acquire relevant literature the terms in the table below were used.

	RCP2.6	RCP4.5	RCP8.5
Mangrove forests	Search term: "Mangrove forests AND blue carbon AND preservation AND RCP2.6" Articles found: 209	Search term: "Mangrove forests AND blue carbon AND preservation AND RCP4.5" Articles found: 83	Search term: "Mangrove forests AND blue carbon AND preservation AND RCP8.5" Articles found: 312
Seagrass beds	Search term: "Seagrass beds AND blue carbon AND preservation AND RCP2.6" Articles found: 88	Search term: "Seagrass beds AND blue carbon AND preservation AND RCP4.5" Articles found: 77	Search term: "Seagrass beds AND blue carbon AND preservation AND RCP8.5" Articles found: 135
Salt marshes	Search term: "Salt marshes AND blue carbon AND preservation AND RCP2.6" Articles found: 189	Search term: "Salt marshes AND blue carbon AND preservation AND RCP4.5" Articles found: 46	Search term: "Salt marshes AND blue carbon AND preservation AND RCP8.5" Articles found: 285

Figure 4: Search terms used to require relevant literature for the meta-analysis

5.1.2 Secondary selection

After the search engine yielded the number of papers per search term as indicated in the table, relevant papers were selected according to these secondary selection criteria:

- Reading the abstract needs to give the impression that the paper's results will show answers to the posed research question and the sub questions.
- The research papers need to be linked explicitly to one or more of the blue carbon systems used for this research.

- The research papers need to state something about blue carbon. They also need to state something about preservation measures. In addition they should state something about either RCP2.6, RCP4.5 RCP8.5 or all three.

5.2 Meta-analysis

31 papers were selected for the meta-analysis (appendix I). The literature selected for the meta-analysis was assessed. The advantage of using a meta-analysis is that this type of study is more precise than a normal literature review and is an excellent tool for finding patterns across different papers. The findings of each individual paper were examined. In a table, using excel, the findings of the papers were linked to the posed sub questions. The sub questions were answered by searching for patterns in the results extracted from the papers. The meta-analysis also provided the data to assess which measures could be used to preserve mangrove forests, salt marshes and seagrass beds as blue carbon sinks. In addition qualitative data was extracted from the papers used for the meta-analysis to create a deeper understanding of the results found in the meta-analysis.

5.3 Expert interviews

To gain more insight from the field into the challenges and opportunities that come with the preservation of blue carbon systems under different RCP scenarios experts were interviewed to enhance the findings derived from the systematic literature review. Topics for the interview were based on the sub questions and their results. The interviews were used to validate and/or contrast the results found in the meta-analysis. Unstructured interviews are a good way of gaining information about a topic through experiences and perspectives of the interviewee. They are useful for finding patterns and generating in-depth understanding of a phenomenon (Zhang & Wildemuth, 2009). Six unstructured interviews were therefore conducted and the ethical principles were considered before, during and after the interview. Meaning the interviewee was asked for consent regarding the recording of the interview and the use of their knowledge in this thesis, see consent form (appendix II). They were given the opportunity to withdraw from the interview at any time and after the interview all records and transcripts were saved carefully where only I could access them.

The first expert interviewed, Patrick Megonigal, is a deputy director and senior scientist at Smithsonian Environmental Research Center. He is a biogeochemist who studies the soil ecology of tidal wetlands. Expert 2, Jos Verhoeven, works at Utrecht University and has focused his career around the diversity and functioning of wetland ecosystems. Expert 3, Yadav Sapkota, is a PhD student who has done research on marsh edge erosion and its implications for coastal wetland restoration and conservation. Expert 4, Ed Sherwood, is executive director at the Tampa Bay Estuary Program that focuses on the bay's science-based restoration and recovery strategies. Expert 5, Carlos Duarte, is a marine ecologist and distinguished professor at the King Abdullah University of Science and Technology. Expert 6, Aurora Martinez Ricart, is a postdoctoral researcher at the Bigelow Laboratory for Ocean Sciences and marine ecologist studying global change in coastal ecosystems.

6. Results

These results first show the regions studied across papers and what kind of assessment was performed in the studies used for the meta-analysis. Then they show the results found in the meta-analysis per ecosystem. A map of the threats, a figure of the responses and a diagram of recommended preservation measures were created based on those results. This is supported by qualitative information extracted from the papers used for the meta-analysis. Lastly expert opinions from the interviews are discussed to enhance the findings.

6.1 Type of studies

Region	*Mangrove forests*	*Salt marshes*	*Seagrass beds*
Africa	0 (0%)	0 (0%)	0 (0%)
Asia	6 (30%)	2 (11%)	2 (18%)
Australia and South Pacific	5 (25%)	3 (17%)	2 (18%)
South-America	2 (10%)	2 (11%)	1 (9%)
North-America	0 (0%)	0 (0%)	1 (9%)
Middle East	1 (5%)	0 (0%)	0 (0%)
Europe	0 (0%)	4 (22%)	0 (0%)
Mid-latitudes	0 (0%)	0 (0%)	2 (18%)
Global	6 (30%)	7 (39%)	3 (27%)
Total	20 (100%)	18 (100%)	11 (100%)

Figure 5: regions studied across papers

Most papers studied the effects of climate change on these three blue carbon sinks globally, as seen in figure 5. Papers also covered mangrove forests in Asia and salt marshes in Europe to a large extent. In addition a large part of the studies were done in Australia and the South Pacific.

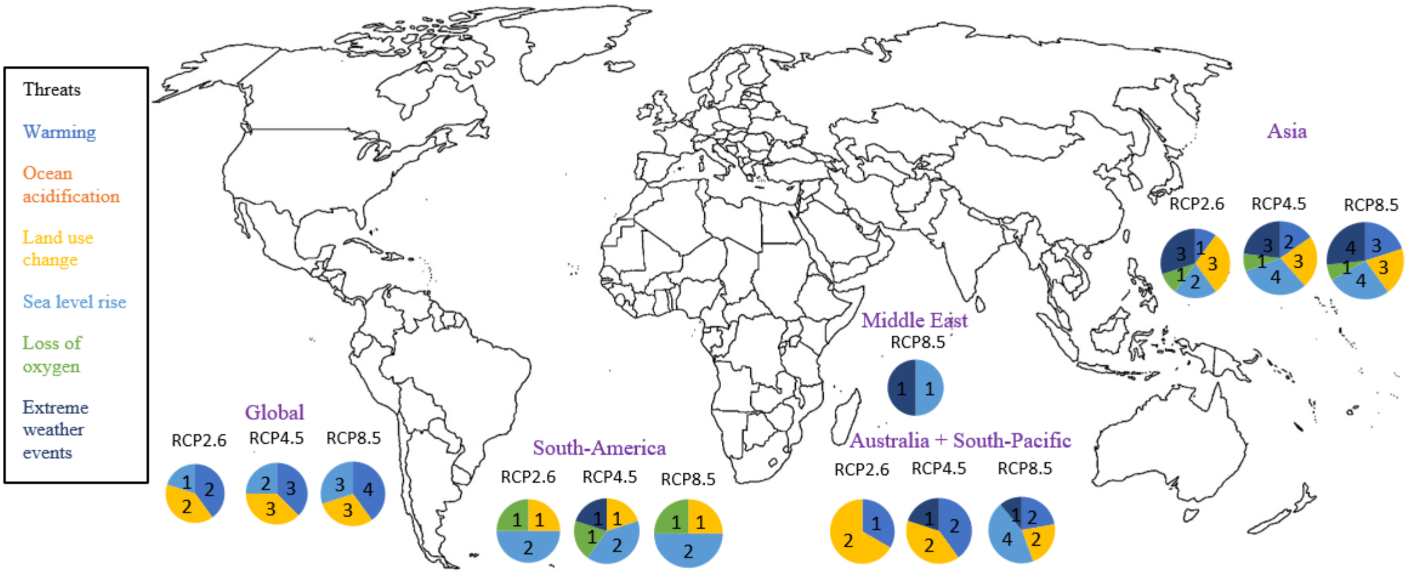
Type of study	*Mangrove forests*		*Salt marshes*		*Seagrass beds*	
	Case study	Global	Case study	Global	Case study	Global
Risk evaluation	0 (0%)	3 (15%)	1 (6%)	2 (11%)	0 (0%)	2 (18%)
Sensitivity analysis	0 (0%)	1 (5%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)
Spatial modeling	2 (10%)	0 (0%)	1 (6%)	1 (6%)	1 (9%)	0 (0%)
Management assessment	1 (5%)	1 (5%)	1 (6%)	1 (6%)	0 (0%)	1 (9%)
Climate change impact assessment	7 (35%)	1 (5%)	5 (28%)	1 (6%)	4 (36%)	1 (9%)
Climate change & management assessment	1 (5%)	1 (5%)	1 (6%)	0 (0%)	0 (0%)	0 (0%)
SLR assessment	2 (10%)	0 (0%)	2 (11%)	1 (6%)	1 (9%)	0 (0%)
Systematic literature review	0 (0%)	0 (0%)	0 (0%)	1 (6%)	0 (0%)	1 (9%)
Total papers	20 (100%)		18 (100%)		11 (100%)	

Figure 6: type of study

Most studies were climate change impact assessments, risk evaluations and sea level rise assessments (figure 6). Of these studies most were case studies of regions or countries.

6.2 Mangrove forests

6.2.1 Results meta-analysis



Map 1: distribution of number of studies projecting threats to mangrove forests under different RCP scenarios

From map 1 it seems that sea level rise, warming and land use change are the three most significant threats to mangrove forests in all three RCP scenarios. Extreme weather events were also mentioned as a threat to mangroves in some studies, especially under extremer RCP scenarios. In the Middle East lack of precipitation seems to be a stressor that could affect mangroves negatively whereas in Asia extreme weather events such as storms seem to form a bigger threat to mangrove ecosystems (Mafi-Gholami et al., 2020; Jennerjahn et al., 2017; Sorn & Veth, 2019). Loss of oxygen is mentioned as a threat to mangroves in studies in South-America and Asia (Mairi, 2019; Mairi, 2020)

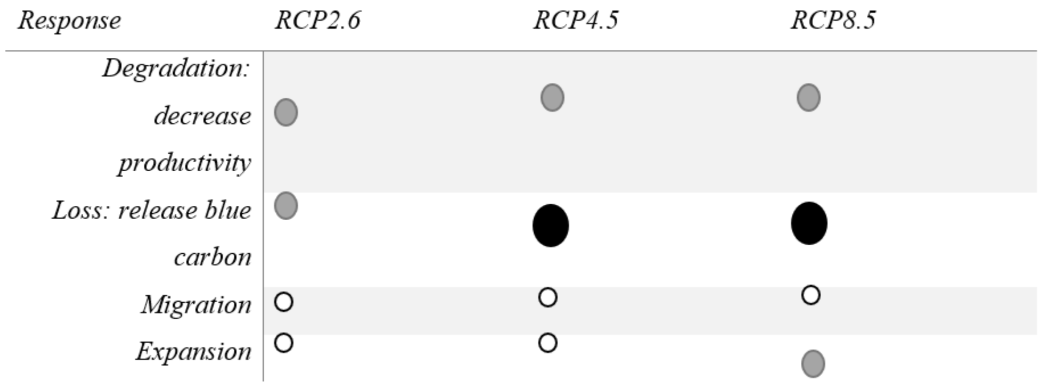
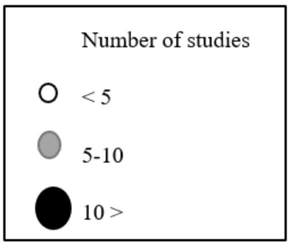


Figure 7: projected responses of mangrove forests under different RCP scenarios



It becomes evident in figure 7 that with increasing atmospheric CO_2 levels the risk of degradation and loss of blue carbon systems becomes larger. To a smaller extent mangrove forests also seem to expand and/or migrate, especially under scenario RCP8.5 (Wang, 2014; Bowie, 2015; Dittman et al., 2019; Osland et al, 2018).

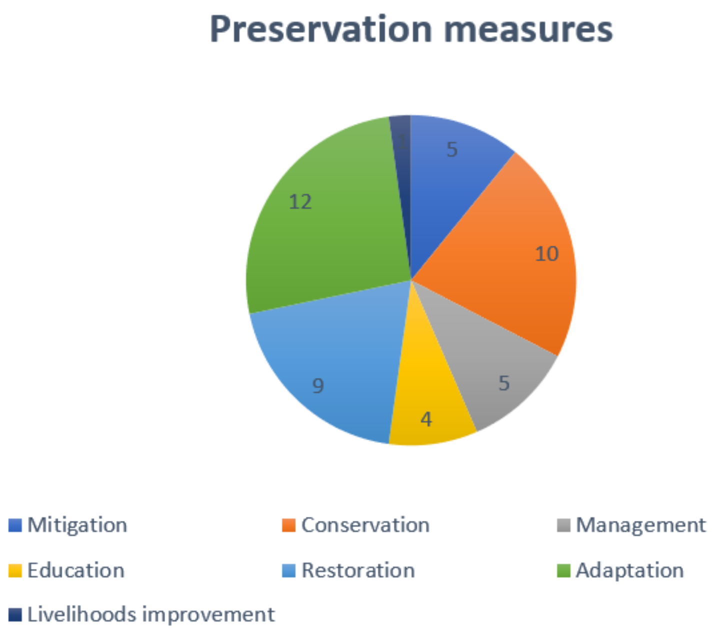


Figure 8: frequency of preservation measures in studies recommended to protect and enhance the blue carbon potential of mangroves

Most papers highlight the importance of adaptation, conservation and restoration to reduce the threats posed on mangrove forests by land use change and sea level rise, as seen in figure 8. Overall a majority of the papers underlined that a combination of preservation measures will be most effective, by also improving management, raising awareness and decreasing CO2 emissions (Gattuso et al., 2018; Bowie, 2015; Steven et al., 2020; Ellison, 2018; Sorn & Veth, 2019; Sandi et al, 2018; Osland et al, 2018; Maggini et al, 2013).

6.2.2 Qualitative information papers

Even though warming is mentioned as a threat in some studies, a majority of the papers stated that warming on its own is usually a benefit for mangrove forests, because it increases their primary productivity (Mairi, 2019; Mairi, 2020; Sorn & Veth, 2019; Gattuso et al, 2015). This explains why in some areas mangrove forests are projected to expand (Wang, 2014). This seems to especially be the case in the tropics where drought plays less of a role than in the Middle East or Australia (Mafi-Gholami et al., 2020; Jennerjahn et al., 2017).

Studies that did mention warming as a threat linked this to indirect effects caused by warming. A study in Cambodia linked warming to an increase in extreme weather events (Sorn & Veth, 2019). A paper in Australia linked warming to the lack of precipitation, which could be a stressor for mangroves (Maggini et al., 2013). In addition, papers mentioned loss of oxygen, which is a result from ocean warming, as a threat in South-America and Asia (Mairi, 2019; Mairi, 2020). So while the direct effects of warming will benefit mangroves, the indirect effects like sea level rise, increase in extreme weather events and loss of oxygen may not.

Coastal development enhances the risks posed by sea level rise by creating what is mentioned in most studies as coastal squeeze (Mairi, 2019; Mairi, 2020; Lovelock & Reef, 2020; Dittman et al., 2019; Osland et al., 2018; Payo et al., 2016; Jiao et al., 2015). Mangroves are prevented from expanding and/or migrating due to coastal settlement, thus increasing their risk of being exposed to sea level conditions that would degrade them.

Even though the risk of loss and degradation of mangrove forests increases with increasing atmospheric CO2 levels, these can be prevented if mangrove forests are given the option to migrate inward, expand and are restored where they have been lost by implementing preservation measures (Gattuso et al., 2015; Gattuso et al., 2018; Dittman et al., 2019; Oslan et al, 2018).

6.2.3 Expert opinions

The experts interviewed in regards to mangroves all shared the opinion that sea level rise is the biggest threat mangroves are facing under climate change. According to Verhoeven (personal communication, December 23, 2020) the only thing that is certain about the impacts of climate change is that highly elevated levels of the sea will negatively impact mangrove forests. They only thrive in shallow coastal waters and the very gradual sloping beaches and deltas will slowly drown, causing the mangrove zones to narrow. He expects a large part of the mangrove losses to be caused by human physical activity in the first half of this century and in the second half of this century sea level rise to narrow the coastal zones that provide habitat to mangroves. Sherwood (personal communication, January 5, 2021) tied into that in his interview by explaining that coastal areas with an urbanized environment will probably experience upslope boundaries so that mangroves cannot continue to march upslope with rising sea levels.

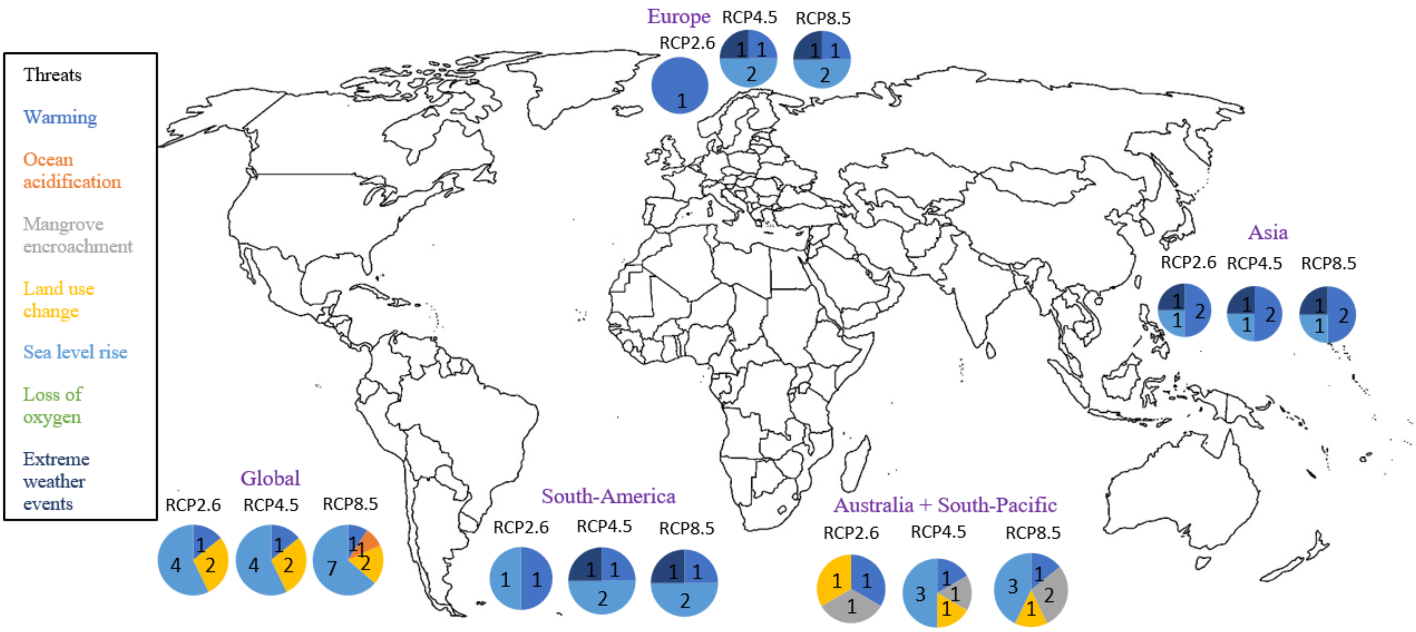
According to Verhoeven (personal communication, 2020) extreme RCP scenarios are more likely to lead to losses of mangrove coverage worldwide, which will lead to the release of carbon and a decrease of carbon storage. Megonigal (personal communication, December 21, 2020) explained that even though mangroves are projected to degrade, they are also expected to expand and migrate because just focusing on accelerated sea level rise, which could be seen as the biggest existential threat, these mangrove systems have a higher capacity to build elevation. This is partly to do with their crude architecture and the chemistry of their tissue which does not break down very quickly. The mangroves, once they are established, are pretty hardy, can survive a great deal of sea level rise and warming itself benefits them in a lot of ways. Regional differences will influence whether mangroves will degrade or expand. Megonigal (personal communication, 2020) highlighted that it is important to focus conservation efforts in the southern hemisphere. Research that he was involved in about a year ago showed that there are certain parts of the world where the rate of sea level rise has historically been slow, namely the southern hemisphere. The stability of these systems depend partly on their historical rate of sea level rise. Mangroves in the southern hemisphere have elevation capital. This means that they sit relatively high in the tidal frame and can therefore absorb more accelerated sea level rise than areas in the northern hemisphere which have had very high sea level rise already and have sunk down into the tidal frame.

According to Megonigal (personal communication, 2020) allowing adaptation in the form of landward migration is very important, because for these systems to maintain their area and their footprint, they do have to be able to migrate inland. He believes that overall climate change under any scenario will not have huge negative impacts on mangrove forests if losses due to land use change are limited, lost mangroves are restored and adaptation measures are implemented to make sure these ecosystems can continue to thrive and grow.

According to both Verhoeven (personal communication, 2020) and Megonigal (personal communication, 2020) most losses of mangroves, especially in Asia and Africa, are caused by the removal of mangroves to use the ground for shrimp pawns, for economic benefits. This makes it hard to protect mangrove areas. Therefore conservation is usually only successful if it is also focused on its other ecosystem services. These mangrove systems are habitat for fish and wildlife, important for clean water and the livelihood of a lot of subsistent communities around the world. Both Verhoeven (personal communication, 2020) and Megonigal (personal communication, 2020) mentioned that the biggest challenges will be motivating people and politicians to reserve these areas.

6.3 Salt marshes

6.3.1 Results meta-analysis



Map 2: distribution of number of studies projecting threats to salt marshes under different RCP scenarios

A significant part of the papers focused on sea level rise when assessing the impact climate change would have on salt marshes. From map 2 sea level rise overall seems to pose the biggest threat to salt marshes, especially under scenarios RCP4.5 and RCP8.5. In addition land use change is considered a threat, mainly in studies assessing impacts on salt marshes worldwide. Mangrove encroachment and extreme weather events also seem to form a threat to salt marshes. Mangrove encroachment was mentioned in studies in Australia and the South-Pacific.

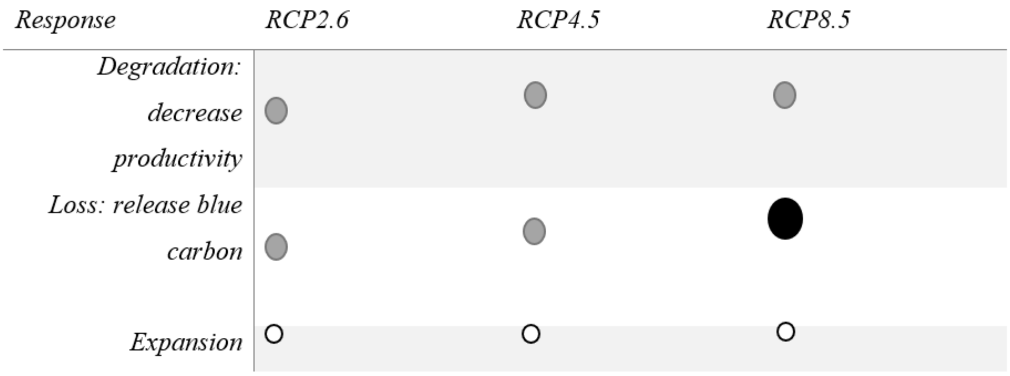
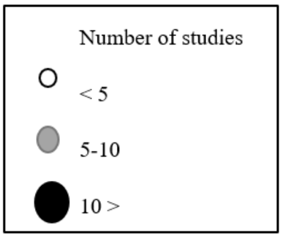


Figure 9: projected responses of salt marshes under different RCP scenarios



Some papers stated that sea level rise will overwhelm salt marshes and that they will not be able to keep up with the speed at which the sea level is increasing, especially under scenario RCP8.5 (Steven et al., 2020; Mairi, 2019; Mairi, 2020; Lovelock & Reef, 2020, Fitzgerald & Hughes, 2017). Other papers, to a smaller extent, however stated that salt marshes seem to be more resilient than other studies have shown and that they will be able to elevate with rising sea levels (Ratliff et al, 2015; Bitoun et al., 2018; Heron et al, 2020; Bowie, 2015), as seen in figure 9.

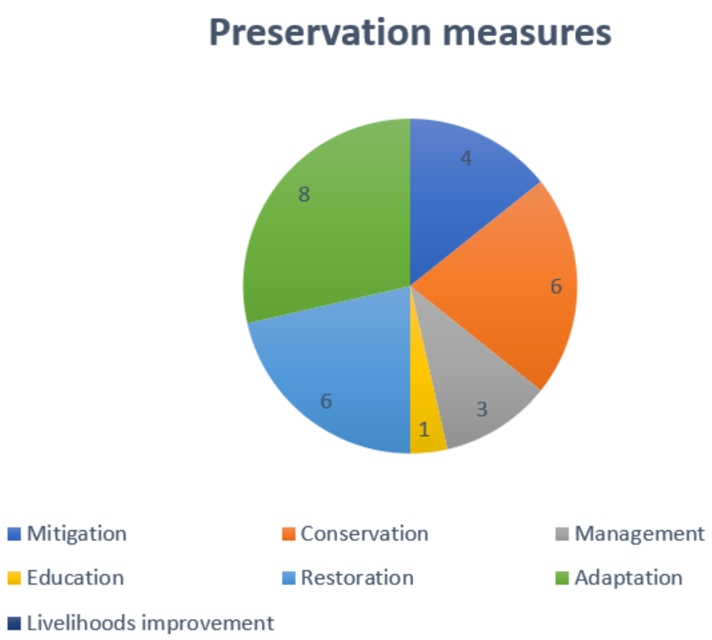


Figure 10: frequency of preservation measures in studies recommended to protect and enhance the blue carbon potential of salt marshes

Almost all papers underline the importance of not only using conservation as a strategy but also implementing proper management measures and restoration and adaptation measures, as seen in figure 10. Most papers deemed adaptation to be the most important preservation measure to protect the blue carbon potential of salt marshes.

6.3.2 Qualitative information papers

Mangrove encroachment forms a threat where wetlands are a combination of salt marshes and mangrove forests, which is the case in the regions studied in Australia (Bowie, 2015; Sandi et al., 2018).

Especially in Europe the studies predict that salt marshes will be able to keep up with rising sea levels and one study deemed that their growth will be promoted by warming (Bitoun et al., 2018), explaining why a small number of studies projected salt marshes to expand, as seen in figure 10. Another study highlighted that elevated CO2 levels will increase the primary productivity of salt marshes which will benefit salt marshes (Ratliff et al., 2015).

Adaptation is seen as a very important preservation measure, because in order for salt marshes to survive they need to build elevation and/or be able to migrate inwards (Steven et al., 2020).

6.3.3 Expert opinions

Megonigal (personal communication, 2020) mentioned that salt marshes are more sensitive to sea level rise because they do not have the capacity to build elevation as quickly as for example mangrove forests despite them being very productive. In the Caribbean the ecosystems are entirely built on plant productivity. The soils are peat and they are very sensitive to accelerated sea level rise. Sapkota (personal communication, January 4, 2021) tied into that by explaining that edge erosion driven by relative sea level rise is the major cause of land loss. As sea level comes up, water will come close to the edge of the marsh and wind waves will cause edge erosion. Especially in delta systems, that have been heavily affected by land use change, local subsidence is a big threat. The land is sinking and the sea level is also rising, causing the relative sea level rise to be larger than actual sea level rise.

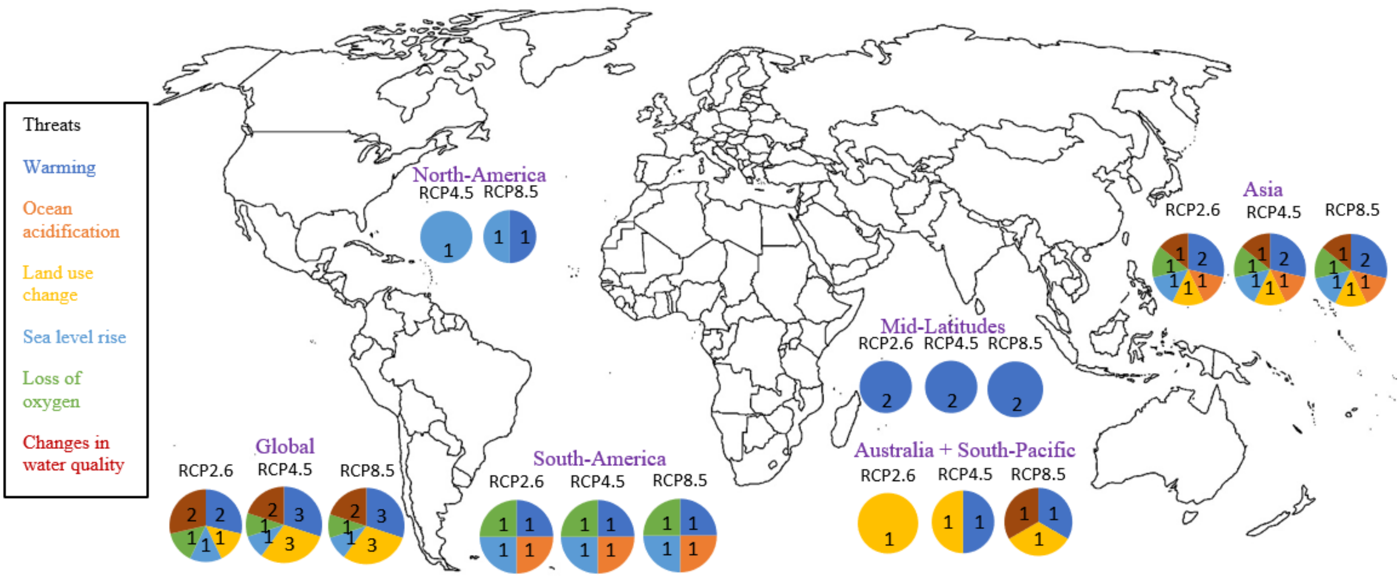
According to Megonigal (personal communication, 2020) the reason salt marshes in Europe are more stable is because in Europe there are some very high sediment systems and increased flooding leads to a lot of increased sediment deposition. As a result a lot of new area is created for plants to colonize and salt marshes to form. Keeping up with sea level rise is all about adding elevation and if there is a lot of sediment in the system then there is the capacity to add elevation very quickly. Sapkota (personal communication, 2021) tied into this in his interview by explaining that especially in delta systems the salt marshes are not receiving sediment due to constructions such as dams and thus the sediment flows directly into the ocean. It is very hard for systems like that to keep pace with sea level rise. This puts salt marshes in delta systems at risk in future scenarios such as RCP4.5 and RCP8.5, where sea level rise is more significant. Sapkota (personal communication, 2021) mentioned that restoration is therefore very important for salt marshes, especially in delta systems. They have projects like marsh excretion to raise the sand from the river. They have created barriers so that the wind waves can no longer erode the marshes.

According to Megonigal (personal communication, 2020) allowing landward migration of these salt marshes is important, because for these systems to maintain their area and their footprint, they have to be able to migrate inland. Sapkota (personal communication, 2021) called this the accommodational space. If there is more of that space, salt marshes can keep up with sea level rise. Megonigal also underlined the importance of restoration (personal communication, 2020). From a climate perspective the most exciting restorations are places that were historically diked, so tidal marshes that have had impoundments built across them. Due to these impoundments they turned from tidal to not tidal which made them fresher and thus less salty. That means that their methane emissions are much higher than in the past. To restore them they have to be made tidal again. This increases carbon being sequestered in the soil but also decreases the methane that is being emitted. From a climate perspective that methane benefit vastly outfits the soil carbon benefit.

Both Sapkota (personal communication, 2021) and Megonigal (personal communication, 2020) mentioned that the biggest challenges in preserving salt marshes will be human development. It has played a huge role in land loss and will continue to do so.

6.4 Seagrass beds

6.4.1 Threats



Map 3: distribution of number of studies projecting threats to seagrass beds under different RCP scenarios

From map 3 it appears that warming and land use change are the biggest threats seagrasses will be facing under climate change. Changes in water quality are also mentioned as a concern for seagrasses in a majority of the papers, namely in global assessments and studies in the Pacific and Asia (Bates et al., 2019; Steven et al., 2020; Sorn & Veth, 2019; Brodie & Antoine de Ramon, 2018). Some papers also claimed that ocean acidification can form a threat for seagrasses in the future (Mairi, 2019; Mairi, 2020) as well as a loss of oxygen (Mairi, 2019; Mairi, 2020; Steven et al., 2020) and sea level rise (Mairi, 2019; Mairi, 2020; Scalpone et al., 2020; Steven et al., 2020). All three of these are mentioned as threats in studies done in Asia and South-America.

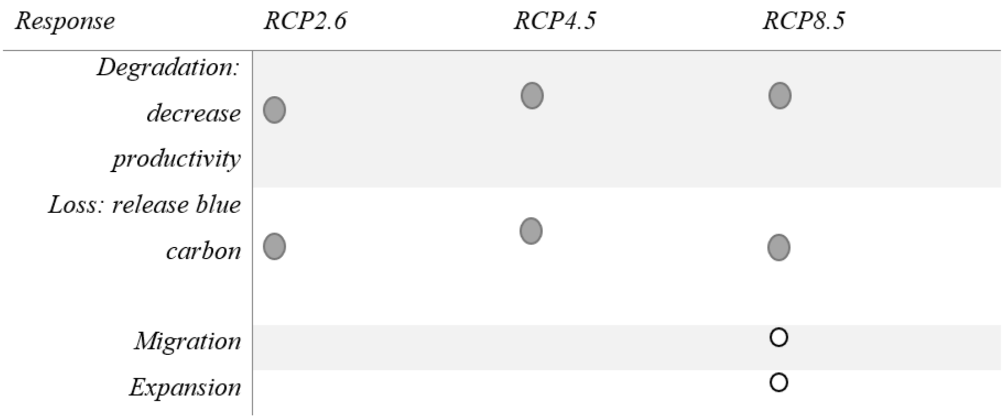
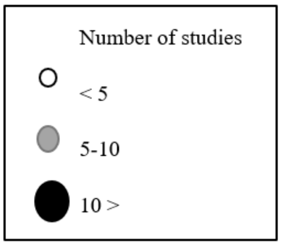


Figure 11: projected responses of seagrass beds under different RCP scenarios



Less papers covered seagrass beds, but most papers claimed that in all scenarios climate change affects seagrass beds negatively, thus causing a high risk of degradation and loss, as seen in figure 11. In the South-Pacific and Australia seagrass beds are projected to migrate landward with rising sea levels and expand (Dittman et al., 2019; Brodie & Antoine de Ramon, 2018).

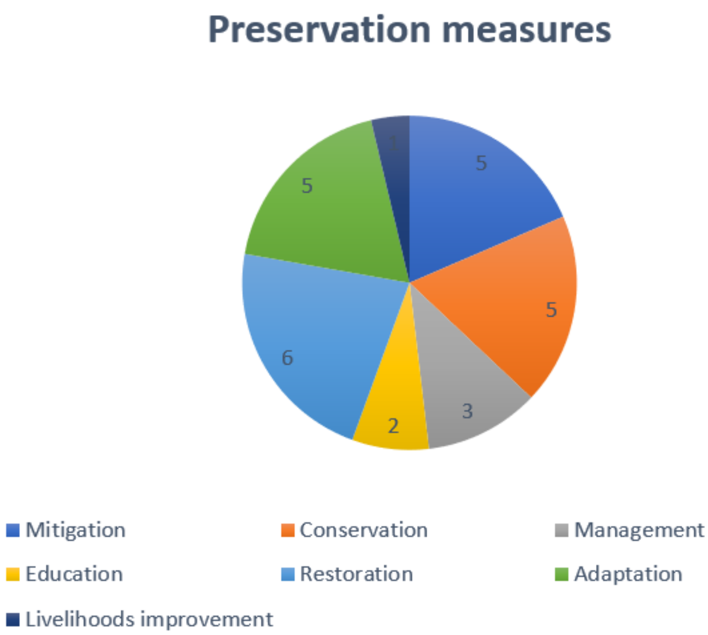


Figure 12: frequency of preservation measures in studies recommended to protect and enhance the blue carbon potential of seagrasses

A majority of the papers that included seagrasses underlined the importance of using several measures to preserve and enhance the blue carbon potential of seagrass beds, as seen in figure 12. Conservation was deemed important to remove pressures from human physical activity in coastal areas. In addition restoration and adaptation are mentioned as methods to increase the blue carbon potential of seagrasses.

6.4.2 Qualitative data meta-analysis

A majority of the papers that covered all three ecosystems, namely mangrove forests, salt marshes and seagrass beds, mentioned that seagrasses seem to be the most sensitive to the impacts of climate change (Gattuso et al, 2015; Mairi, 2019; Mairi, 2020). The main threat is considered to be warming when focusing on climate change scenarios. (Gattuso et al, 2015; Gattuso et al, 2018; Steven et al, 2020; Mairi, 2019; Mairi, 2020; Sorn & Veth, 2019; Bates et al, 2019). A majority of the papers make it evident that pollution and land use changes can lead to changes in water quality which causes seagrass losses (Bates et al, 2019; Sorn & Veth, 2019; Steven et al, 2020; Brodie & Antoine de Ramon, 2018).

Conservation should be supported by adaptation and restoration measures, because with increasing sea level rise more areas will be inundated, giving seagrasses the opportunity to migrate and expand there and thus enhance their blue carbon potential (Dittman et al., 2019; Gattuso et al., 2018; Steven et al., 2020).

6.4.3 Expert opinions

According to Ricart (personal communication, January 6, 2021) there is a lot of variability within all these ecosystems. Both region and habitat will factor into whether species are vulnerable to climate change. Some seagrasses are very sensitive to warming, because it attacks the metabolism (Ricart, personal communication, 2021). Like with all other species, if the temperature is changed, the comfortability of that species is changed and they need to do more effort to resist that change. Duarte (personal communication, January 6, 2021) tied into this by explaining that the seagrass species that are most vulnerable to climate change, mainly ocean warming, will be those that are located at the edge of their distribution. Most of them are located in the Mediterranean sea, Posidonia Oceanica, where the geographical range does not make it possible for them to adapt to climate change and they cannot displace their range forward due to the presence of landmass. Additionally, some species in the Indian Ocean are deemed to be more sensitive because the Asian continent is preventing the distribution from migrating forward as well. He is not aware that other species are equally sensitive. Therefore he thinks it is premature to conclude that seagrasses are more vulnerable. Increasing CO_2 levels will increase CO_2 productivity. Research that he has been involved in is projecting a massive expansion of seagrass in the Arctic with warming. So globally there may be losses in some areas but those losses might be compensated by increases elsewhere. Warming might not be a global driver of the decline of seagrass. It might be a zero net gain. Ricart (personal communication, 2021) tied into this by explaining that ocean acidification, caused by elevated CO_2 levels, will act as a benefit, because it is providing more carbon dioxide into the water. Seagrasses use this for their benefit by photosynthesizing. However, water quality and impacts of human activities on the coastal zone will likely continue to be the major sources of loss. Sherwood (personal communication, 2021) also highlighted this. There are exasperated water quality conditions that prevent seagrasses from proliferating in deepening water. Meaning that a majority of that is contingent on maintaining water quality or improving it at what it is now. Although the research he has been involved in has projected that seagrasses might increase for Tampa Bay due to newly inundated shorelines, it is uncertain whether they can maintain water quality to support that increase. Duarte, too, mentioned that the main driver of seagrass losses is eutrophication (personal communication, 2021). Impacts of human input of nutrients, water quality, light penetration and also organic loads into the sediments are the number one driver of seagrass losses followed by physical disturbance by coastal development such as dredging and other human physical activities.

Sherwood explained that the biggest challenges in protecting these environments is therefore coastal urbanization (personal communication, 2021). The human population continues to expand around population centers that these habitats exist in. If regions do not live in the coastal environment more sustainably in the future then a lot more of these habitats will be lost from continuing urbanization in the coastal environment. Duarte (personal communication, 2021) thinks that it is therefore important that seagrasses are given the opportunity to migrate. There has been a trajectory of global loss of seagrasses during much of the 20th century but now they have documented a trend reversal where seagrasses are expanding in Europe, North-America and other regions. It shows that conservation and legislation to mitigate impacts is effective in reversing losses and changing the trajectory from one of loss to one of gains. He underlines the importance of increasing their chances to mitigate. He does not think the ambition is to conserve what is currently present but actually to rebuild seagrass habitats to their historical abundance which requires active restoration measures.

According to Ricart (personal communication, 2021) conservation will be the first priority, especially because the habitats are very complex and they need years, sometimes even hundreds of years or thousands of years, to be at the climax point of their habitat. Restoration would additionally work very well in places where seagrasses had been present and then were lost and the stressor has disappeared. Solely focusing on blue carbon potential there are some species in temperate regions that are highly effective in storing carbon, like the Posidonia Oceanica. In terms of carbon mitigation that is a high priority in temperate sub-tropical areas. Seagrasses however also provide many other ecosystem services like habitat for other species, coastal protection from wave action and erosion. Conservation in all coastal areas is therefore important. It is impossible to conserve all seagrasses in the world because there are other activities that need to be done, but she thinks it can be managed at local levels in every country by applying conservation actions.

Ricart (personal communication, 2021) also mentioned that climate change as a whole is a tricky problem that seagrasses are facing. It is still not known how all these multi-stressors will act together on the long term. There are some ideas because there are many studies trying to predict what will happen in the future, but in the long term it is just a guess, causing a lot of uncertainty.

7. Discussion

7.1 Responses

The meta-analysis indicates that extremer climate change scenarios will lead to an increase in the loss of blue carbon sinks globally, which has been shown in earlier studies (Ruiz-Fernández et al., 2018; Bryan- Brown et al., 2020; Lyimo, 2016). There was an overall consensus that human physical activity is one of the biggest threats all three ecosystems are facing. Given that RCP8.5 is a “business as usual” scenario, it is very likely that human physical activity will not be limited on these systems in such a scenario, exposing them to stressors of coastal development as well as climate change. However there were some papers that deemed blue carbon sinks to be more resilient to the pressures of climate change than originally thought and actually projected an expansion of these systems, even under extremer climate change scenarios. For mangroves and salt marshes warming was deemed to increase the primary productivity leading to the expansion of these systems (Jennerjahn et al., 2017; Wang, 2014; Bitoun et al., 2018; Ratliff et al., 2015). A majority of these studies were performed in areas where drought is not a limiting factor for these systems, explaining why they were projected to expand. This ties into what has been stated in earlier studies, namely that the main threat of warming is a change in precipitation which affects water supply (McLeod et al., 2011). In addition to that one of these papers, which assessed climate change impacts globally, stated that expansions will mainly occur towards the poles, whereas decreases will occur in arid regions (Jennerjahn et al., 2017).

Further the impact of sea level rise was also not seen as a negative stressor in every study (Heron et al., 2020; Bitoun et al., 2018; Ratliff et al., 2015; Jennerjahn et al., 2017; Dittman et al., 2019). Especially salt marshes in Europe were projected to elevate with rising sea levels, which according to Megonigal (personal communication, 2020) is consistent because of the high sediment systems present in Europe. Additionally, some studies projected mangroves to migrate inward with rising sea levels (Jennerjahn et al., 2017; Dittman et al., 2019). Lastly, seagrasses were expected to profit from newly inundated areas, because they can migrate into those areas and expand there (Dittman et al., 2019; personal communication, Duarte, 2021; personal communication, Sherwood, 2021).

Whereas the analysis indicated that ocean warming will form a major threat to seagrasses, interviews with experts showed that this is place- and species-dependent. Duarte (personal communication, 2021) has been involved in research showing a massive expansion of seagrasses in the Arctic due to warming. He deemed the Posidonia Oceanica sensitive to warming because it cannot place its range forward due to land mass. However he believes that with newly inundated areas most seagrasses will be able to do very well and expand into those regions.

These, sometimes, contrasting results make it evident that there is a lot of variability in species, habitats and regions. This means that certain species might respond very differently to certain pressures than other species. On top of that certain regions might experience climate change on a different level than other regions, meaning that these marine ecosystems will respond differently regionally. The DPSIR-framework proposed earlier in this thesis thus changes based on threats species and regions are facing. Additionally, some studies used for the meta-analysis only focused on one stressor, namely sea level rise (Payo et al., 2016; Crosby et al., 2016; Ivajnšič et al., 2018; Fitzgerald & Hughes, 2017). This means that the short-term effects of one stressor can be projected, but the long-term effects and how several multi-stressors will act together have not been projected yet. While the exact trajectories of these systems cannot be determined, it is likely that arid regions and regions, that due to coastal development or land mass prevent these blue carbon systems from migrating, will probably face bigger pressures of climate change in the future than other regions, leading to a decrease in their blue carbon potential. Species in colder or high-sediment regions, or regions with elevation capital and/or accommodational space will most likely experience an increase of primary productivity with warming which will give them the opportunity to expand, leading to an increase in their blue carbon potential. Therefore changes of the blue carbon potential of these marine ecosystems under future climate scenarios cannot necessarily be deemed as a zero net loss.

In addition blue carbon systems offer many other ecosystem services than just the sequestration of carbon. Therefore when looking at what areas to preserve, all ecosystem services should be considered and not just the carbon storage benefit these marine ecosystems provide.

7.2 Relevance

The increase of atmospheric CO2 levels is a serious concern for ecosystems and species worldwide. In order to halt and decrease these levels, carbon offset strategies need to be implemented. Additionally, coastal wetland loss is not only threatening to reduce carbon storage but also enhance carbon emissions into the atmosphere. The findings in this thesis allow for a better insight into the blue carbon potential of mangrove forests, salt marshes and seagrass beds under future climate scenarios. The results show that these systems can be useful as carbon offset strategies, especially if preservation efforts are focused on enhancing their blue carbon potential in addition to conserving the blue carbon potential already present. Blue carbon systems can thus add a significant contribution to long term carbon sequestration, but this is contingent on decreasing human physical activity. This thesis showed that not only does coastal development degrade blue carbon sinks, it also hinders them from elevating and/or expanding. If coastal development is not limited these systems will degrade which will decrease their blue carbon potential and lead to these systems enhancing carbon emissions by releasing CO2 into the atmosphere. Legislation to decrease human physical activity is required to create an opportunity to enhance the blue carbon potential of these systems and incorporate them in projects to mitigate climate change. Based on these findings future research should focus on the long-term effects of anthropogenic-induced stressors and identify how species and regions will react differently. It is important that future research is extended over disciplines to tackle this issue. Research needs to focus on an integration of several disciplines to make sure that policies and plans can be developed to set aside preservation areas for these marine ecosystems as well as developing adaptation and restoration projects to enhance the blue carbon potential of these systems.

8. Conclusion

This thesis aimed to identify the blue carbon potential of mangrove forests, salt marshes and seagrass beds under future atmospheric CO2 concentrations and what measures can be implemented to preserve their blue carbon potential. Based on a meta-analysis and expert interviews threats were analyzed, potential responses were identified and measures were examined. The results indicate that the blue carbon potential of these marine ecosystems will decrease in some regions, whereas it will increase in other regions, depending on the species and habitats. An RCP8.5 scenario will most likely lead to a net loss of these systems if coastal development is not limited. An RCP2.6 or RCP4.5 scenario on the other hand does not necessarily have to be detrimental to these systems. Even though it is hard to project a trajectory, it is likely that if preservation measures are implemented and human physical activity is limited, the blue carbon potential of these systems can be enhanced under these future climate change scenarios.

Overall sea level rise, in addition to coastal development, appears to be the biggest climate change induced threat that mangrove forests and salt marshes will be facing in the future. Mangroves in the southern hemisphere will potentially be more hardy due to sea level rise historically being slower there than in the northern hemisphere. Mangroves in Asia and Africa are expected to be more sensitive because they have already been heavily impacted by human physical activities and weather events are expected to become extremer in those regions. Salt marshes in Europe are projected to keep up with rising sea levels due to their higher tidal frame, whereas marshes that have their habitat in delta systems or the Caribbean are likely to be very sensitive to sea level rise. Seagrass beds appear to not be that sensitive to sea level rise but mainly to warming and changes in water quality, caused by human physical activity. Especially seagrasses in the Mediterranean, Posidonia Oceanica, and the Indian Ocean are projected to be sensitive to climate change because land mass is preventing them from migrating. If all three ecosystems are given the opportunity to migrate inward and elevate with rising sea levels, in addition to being monitored and restored in areas where they have historically been lost, these blue carbon sinks will likely be able to be preserved and used for carbon offset strategies. All in all it is important that coastal development is limited as much as possible and an RCP8.5 scenario is avoided to enhance the blue carbon potential of these marine ecosystems.

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11. Appendix I

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12. Appendix II

CONSENT FORM

Bachelor's Thesis Blue Carbon Systems

Researcher: Marlien Nooren

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• I voluntarily agree to participate in this research.

• I understand that even if I agree to participate now, I can withdraw this at any time and/or refuse to answer any questions without any consequences of any kind at any time.

• I understand that I can withdraw my permission to use data from my interview within a week after the interview, in which case the material will be deleted.

• I have had the aims of the research explained to me in writing and I have had the opportunity to ask questions about the research.

• I understand that participation involves an interview of about 20 minutes.

• I agree to my interview being audio recorded.

• I understand that all information I provide for this research will be treated confidentially.

• I understand that the results of this research will be published in the bachelor's thesis.

• I understand that in this research my personal identity will be disclosed.

• I understand that extracts from my interview might be quoted in this research.

• I understand that signed consent forms and original audio recordings will be retained on a password protected laptop and in an online storage space which is only accessible by the researcher until the examination board confirms the results of the researcher's bachelor's thesis.

• I understand that a transcript of my interview in which my personal identity has been disclosed will be retained until the examination board confirms the results of the researcher's bachelor's thesis.

• I understand that under freedom of information legalization I am entitled to access the information I have provided at any time while it is in storage as specified above.

• I understand that I am free to contact any of the people involved in the research to seek further clarification and information.

I have read the foregoing information. I have had the opportunity to ask questions about it and any questions I have asked have been answered to my satisfaction. I consent voluntarily to be a participant in this study and

- **The interview being audio recorded** Yes / No
- **Having my personal identity disclosed in the research** Yes / No
- **Being quoted in the research** Yes / No

Print Name of Participant___________________

Signature of Participant ___________________

Date _____________________________