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Diving into Blue Carbon: A Review on Carbon Sequestration by Mangrove Forests, Seagrass Meadows and Salt Marshes, and Their Capacity to Act as Global Carbon Sinks

Neddykning i Blue Carbon: en litteraturstudie över mangroveskogars, sjögräsbäddars och salttrasks kolfixering, samt deras kapacitet att agera som globala kolsänkor

Hugo George

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Abstract

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Hugo George

During the last decade, the academic interest for Earth's natural carbon sinks and their role concerning climate change has increased. Today, many scientists around the world are trying to calculate different ecosystem's potential to sequester and store carbon dioxide from the atmosphere.

As a newcomer to the scientific arena, the term 'blue carbon' has been well received by scientists in the field. 'Blue carbon' highlights the carbon captured and stored by productive ecosystems along the world's coasts. The term refers to coastal wetlands – such as mangrove forests, salt marshes and seagrass meadows – and it came to life as the scientific community recognized these ecosystems' significant potential as effective carbon sinks.

New research indicates that these ecosystems' complex and vertical root systems can store much larger amounts of carbon in the soil than any other terrestrial ecosystem. By studying this subject, scientists are trying to understand how these ecosystems can help us in the quest of removing excessive carbon dioxide from the atmosphere.

The goal of this thesis is to conduct a literature review, aiming to analyse and compile the new research on 'blue carbon' that has been published during the last 10 years. The paper aims to investigate whether the ecosystem's potential as carbon sinks differ from each other, and what threats they will face in the future. It will additionally review if scientists have been able to unite around any predictions about what the future for 'blue carbon' – and its role in mitigating climate change – will look like.

Key words: carbon sinks, coastal ecosystems, carbon sequestering, blue carbon

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Supervisor: Marcus Wallin
Department of Earth Sciences, Uppsala University, Villavägen 16, SE-752 36 Uppsala (www.geo.uu.se)

Sammanfattning

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Under det senaste decenniet har intresset kring naturliga kolsänkors potential och roll i att mildra klimatförändringar ökat. Idag är det många forskare som arbetar med att beräkna mängden kol som olika ekosystem runt om världen kan lagra i sin biomassa och i jorden under dess rötter.

Som en nykomling på den vetenskapliga arenan, har termen ’blue carbon’ blivit väl mottaget av forskare inom området. ’Blue carbon’ syftar på det kol som fixeras och lagras av de produktiva ekosystemen längs världens kuster. Termen refererar till kustbelägna våtmarker – så som mangroveskogar, saltträsk och sjögräsbäddar – och introducerades efter att den vetenskapliga världen erkänt deras imponerande potential som kolsänkor.

Ny forskning tyder på att deras avancerade och vertikala rotsystem kan lagra mer koldioxid i marken än vad vanliga terrestra skogar kan. Genom att studera detta ämne försöker forskare att förstå hur dessa ekosystem kan hjälpa oss att avlägsna överskottet av koldioxid från atmosfären.

Målet med denna uppsats är att utföra en litteraturstudie och analysera, samt sammanställa den nya forskningen om ’blue carbon’ som publicerats de senaste 10 åren. Uppsatsen kommer undersöka hur stor skillnad det är mellan de olika ekosystemen och vilka hot de står inför i framtiden. Dessutom kommer den undersöka ifall forskare kommit närmre i att enas kring förutsägelser om framtiden för ’blue carbon’, och hur dess roll i att mildra klimatförändringarna kommer se ut.

Nyckelord: kolsänkor, kustbelägna ekosystem, kolfixering, blue carbon

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Handledare: Marcus Wallin
Institutionen för geovetenskaper, Uppsala universitet, Villavägen 16, 752 36 Uppsala (www.geo.uu.se)

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1. Introduction

Since the Intergovernmental Panel on Climate Change (IPCC) published their Fourth Assessment Report in 2007, where they estimated that global CO_2 emissions must be reduced by 85% until the year 2050 – if we want to keep the global mean temperature increase under 2°C (IPCC, 2007) – the interest for global natural carbon sinks has increased. The activities and interactions we humans have with the major carbon pools of today – the atmosphere, fossil fuel reservoirs, oceans, and – collectively – vegetation, soils, and detritus – will define the increasing rates and future paths of CO_2 concentrations in our atmosphere (Nellemann *et al*., 2009).

One year after IPCC's report, Canadell and Raupach (2008) issued the novel statement and approach that sought to see a single emissions reduction strategy (to lower anthropogenic sources of CO_2) combined with a subsidizing of the conservation of ecosystems that support high rates of CO_2 sequestering and organic carbon storage (Thomas, 2014).

In order to keep track of the different sorts of carbon and make them easier to distinguish from each other, an illustrative colour has been related to each type of carbon. 'Black carbon' is the pollutants from incomplete combustion of fuels, like coal, biomass, dung and diesel. 'Green carbon' is the carbon stored in terrestrial ecosystems – more correctly, in their biomass and soils. 'Blue carbon' is the carbon that is stored in our oceans and their coastal ecosystems. This is a huge reservoir. In fact, marine organisms capture over half (55 %) of all the biological carbon captured around the world (UNEP, 2010).

Unfortunately, the oceans that have worked to absorb the bulk of the historical carbon emissions are now being saturated by the amounts of it. However, even though the oceans' waters are being saturated with carbon, their ecosystems are not (UNEP, 2010). Scientists have generally overlooked the important role of these vegetated coastal ecosystems, since their area coverage (and impact) seemed minor in comparison to terrestrial forests, where the main focus of research previously have been (Nellemann *et al*., 2009).

Even though this was the case, in 2008-2009, a number of new reports surfaced that emphasized these ecosystems' natural capacities for sequestering CO_2, which catalysed new research among conservation organizations and academic institutions – owing to the issue's increased popularity.

Due to 'blue carbon ecosystems' – mangroves, salt marshes and seagrass meadows – efficiency in trapping suspended matter and their accompanied organic carbon during tidal insulation, their contribution to long-term carbon sequestration per unit area is much greater than terrestrial forests'. In fact, while terrestrial ecosystems are able to store 'green carbon' at the time scale of decades or even centuries, coastal ecosystems are able to store ' blue carbon' on a time scale up to millennia's (Thomas, 2014).

Since the subject of 'blue carbon' is reasonably new, the aim of this study is to conduct a literature review and investigate the novel research on 'blue carbon' that has been published the last 10 years. The study will strive to analyse new findings that might shed a light on how these coastal ecosystems work with their environment, to investigate whether the ecosystem's potential as carbon sinks differ from each other, and to examine what threats they will face in the future. It will additionally review if scientists have been able to unite around any predictions about what the future for 'blue carbon' – and its role in mitigating climate change – will look like.

1.1 Background of ”Blue Carbon”

When addressing these ecosystems, one could argue that the specific term ‘coastal blue carbon’ is the most correct way to refer to them – because of the fact that they are restricted to the world’s coastal areas – but since the general term ‘blue carbon’ is the most well recognized and received while addressing this issue, this is the term that will be used in this study.

The idea that terrestrial forests have been replaced from the top – as the most effective carbon sinks in the biosphere – might feel like a sudden move, but scientists in the field have been waiting – and working – for the rest of the scientific community to recognize this fact. The United Nations Environment Program (UNEP) published a significant report in a special issue in November 2009 that lead to the establishment of the term ‘blue carbon’. The report was titled *Blue Carbon: A rapid response assessment* (Nellemann *et al*., 2009).

The publication did not only complete the IPCC’s process of a global carbon accounting (which started with the atmosphere and moved on to terrestrial biomes), it also called for awareness of these vital coastal and marine ecosystems by underlining their worth in ecosystem services and their significance to sequester, cycle and store carbon (Thomas, 2014).

The rapid response assessment additionally made five key policy recommendations, the first one being an instalment of a global blue carbon fund for international protection and management. Besides their capacities of handling carbon, mangroves, seagrasses and salt marshes provide coastal hazard- and erosion protection, waste processing, food, fuel, energy, recreational opportunities and cultural values to coastal communities (Thomas, 2014).

2. Method

The aim of this study was to obtain an updated view of the certain capacities the 'blue carbon ecosystems' has when it comes to carbon sequestration and carbon storage. To reach this objective, as told earlier, a literature review was conducted that examined the recent research that has been published the last decade.

In order to identify relevant research papers and technical or policy-angled reports about 'blue carbon', the online database for natural sciences GeoDatabase was used. This database covers the biological, geographical, chemical and earth scientific spectrum that was needed for this research. The primary keyword used in the search was 'blue carbon'. However, that simple search term resulted in 4 270 hits that dated back to the 1960's.

To narrow the search results, unnecessary words that automatically were placed in the search vocabulary were excluded. Geologic terms like "Sedimentary rocks", "Carbonate rocks", "Clastic rocks", "Metamorphic rocks", "Igneous rocks", "Limestone", "Paleozoic", "Cenozoic", "Ordovician" and "Mesozoic" were removed, since the field of 'blue carbon' mostly focus on the soil science of the different ecosystems, rather than considering the underlying bedrock.

After removing these unfitting words from the search vocabulary, the article count landed on 2702 hits. After further removal of the words "Dye" and "Adsorption", which relates to articles about colouring, the article count dropped to 1312 hits.

From the 1312 papers that appeared among the results, 194 were relevant for this paper's intentions. After examining these 194 papers, by reading the abstracts, deleting duplicates, sifting out the most relevant (papers that contained keywords like *carbon, sequestration, storage, blue carbon*) and placing them in groups of special topics – mangroves, salt marshes and seagrasses – only 55 papers were left in order to form the basis of this literary study. Due to the short timespan of this project though, only roughly 20 papers would actually be used, and the rest would function as a back up if some special facts/topics were needed.

One of the methods for acquiring a grasp of how the research have advanced the recent decade, was by conducting the selection of literature by reading the papers in a sequence from 'oldest to newest'. By doing so, it was evident that more and more relevant papers surfaced as the selection went on. In the years 2014-2016 the articles about 'blue carbon' certainly caught speed, and there were less and less articles irrelevant to this study in the result field.

In 2017, nearly all of the papers among the results were connected to 'blue carbon', whether they referred the mangrove forests, salt marshes or seagrass meadows, or simply 'blue carbon' as a concept. Case studies from around the world began to appear, concerning the different ecosystems and their ability to sequester and store carbon in their soils.

Many of the articles found, that discussed 'blue carbon', originated from different branches amongst the natural sciences, indicating a broad interest from multiple disciplines. This fact strengthens the recognition of 'blue carbon' as an important factor in the climate change mitigation toolbox, and its vital role in a future sustainable and rich environment. The extensive new research that is conducted by scientists around the world, with different backgrounds, shows that it might be a topic too interesting (and crucial) not to look into.

3. Results and Discussion

3.1 Mangrove Forests

Mangroves are situated on the edge of the land and the sea, which has given these forests components of both marine and terrestrial biomes. This makes them true ecotones, with unique adaptations (Alongi, 2012). They have, for example, developed physiological instruments to tolerate living in saltwater, aerial roots that enables its plants to respire in an anaerobic environment and even viviparous embryos (production of living offspring) (Alongi, 2012).

Mangrove forests' high rates of productivity, combined with their anaerobic and waterlogged soils – that generate a slow decomposition – results in sizeable long-term carbon storages along the Earths' tropical and sub-tropical coasts (Murdiyarso *et al*., 2015). Due to the fact that a substantial section of mangrove's soil carbon is acquired from plants, it is essential to evaluate the rates of net primary productivity (NPP) of mangroves and its related plants, in order to produce correct estimates of the potential to store 'blue carbon' in these ecosystems (Alongi, 2012).

3.1.1 Sequestration and Storage of Carbon

Of all the coastal wetlands that support and store 'blue carbon', mangroves are pondered to be the most productive ones, with a gross primary production (GPP) up to fivefold higher than the other ecosystems. Although mangroves only cover less than 1% of the global coastal areas, they embody up to 15% of all the organic carbon stored in these sediments (Pérez *et al*., 2018).

The factors affecting the rates of carbon sequestration – and therefore the ecosystem's potential as a carbon sink – has for a long time been unclear. However, researchers are now closer to understanding these ecosystems' dynamics than ever before.

The complexity of mangroves is what makes them so hard to fully understand. Ultimately, the temperature is the limiting factor, but it is the local and regional variations in tides, precipitation, waves, salinity, geomorphology and river flow that really define the ecosystem's biomass and expansion (Alongi, 2012). It is also these complexities that complicate the mapping and measurement of different variations of mangrove forests. Most countries do not have the necessary information available in order to generate country-specific data on mangroves' carbon stocks, which preferably should be included in a country's national reporting to the United Nations (Murdiyarso *et al*., 2015).

However, in a recent study, André S. Rovai *et al*. (2018) presented a new "ecogeomorphology framework" that linked distinct coastal environmental settings (CES) to global varieties in mangrove's soil organic carbon (SOC) stocks. With this framework, the authors were finally set to develop a global model that could correlate the variation in mangrove SOC stocks with different CES across the globe. Due to this framework, the authors were also able to provide 57 nations with SOC data, which they previously lacked- and needed to be able to evaluate their own blue carbon inventories.

The development of this new framework made Rovai *et al*. (2018) realise that mangrove SOC stocks in carbonate settings had been underestimated by up to 50% and SOC stocks in deltaic settings had been overestimated by up to 86%. The over- and underestimations had been made due to omission of geophysical and geomorphological drivers that explains large-scale variability of mangrove SOC stocks (Rovai *et al*., 2018).

3.2 Seagrass Meadows

Of all the coastal ecosystems that handle ‘blue carbon’, seagrasses were the last whose organic carbon stocks got assessed and calculated. Fourqurean *et al*. (2012) argued that seagrass meadows are among the most productive ecosystems on Earth. But they further reasoned that due to the large uncertainties that exists concerning their extent and carbon sequestration capacity hinder the necessary claims of marine carbon conservation schemes to unprotected seagrass meadows.

The knowledge of how much carbon an ecosystem sustain seems to be required in order to properly understand the serious impact that degradation has to the release of the stored CO_2. However, the estimation is that seagrass meadows, which cover less than 0,2% of the area of Earth’s oceans, could represent roughly 10% of the oceans yearly organic carbon burial (Fourqurean *et al*., 2012).

Núria Marbà *et al*. (2015) argued that uncertainties among seagrass meadows still hampered with the implementations of ‘blue carbon strategies’ that could help to mitigate climate change. Nevertheless, these uncertainties concern the fate of carbon stocks after a loss or restoration of a seagrass ecosystem.

The authors’ reasoned in their paper that they could demonstrate – with a combined carbon chronosequence and a ^{210}Pb dating of seagrass sediments – that a loss of vegetation would in fact erode the organic carbon stock, while the restoration of a seagrass meadow would restore its carbon sequestration capacity (Marbà *et al*., 2015).

3.2.1 Sequestering and Storage of Carbon

In a review paper, Johannessen and Macdonald (2016), compared restoration of seagrasses with other geoengineering technologies, such as iron fertilization of the oceans and sulphide injection in the stratosphere.

However, comparing restoration of seagrasses with other geoengineering technologies seems unsuitable, since seagrass restoration just enhances a natural carbon sink and does not bring any serious side effects. Simultaneously, they argued that the carbon sequestration rates of seagrass meadows have been overestimated.

The authors claimed that previous calculations had not been made properly. After a close examination of the paper and its related- and concerned responses from the ‘blue carbon community’, it seems that Johannessen and Macdonald (2016) had the adequate proof to back up their claims of an overestimation of seagrasses carbon sequestration and storage potential.

In a reply to one of the concerned responses, Johannessen and Macdonald (2018) listed multiple problems they found in methods that tend to overestimate carbon sequestration in seagrass sediments, such as for example; confusing carbon inventories with carbon fluxes, extrapolating from Posidonia beds (a certain species of seagrass) to all seagrass meadows globally, neglecting mixing in surface sediments (e.g. bioturbation), and neglecting organic carbon export resulting from the high energy of the shallow ocean environment (Johannessen & Macdonald, 2018).

This belief was also shared by Howard *et al.* (2016), where the authors argued that the amount of organic carbon hidden in seagrass meadows is large enough to be regarded into the global carbon budget, but they additionally admitted that a thorough understanding of the SOC of seagrasses was lacking and that the methods currently used to estimate these values were inadequate (Howard *et al.,* 2016).

3.3 Salt Marshes

Historically, salt marshes have been an underestimated and, in fact, neglected landform in general. Human's primary interaction with these ecosystems has been "reclamation" of the salt marsh land and conversion to agricultural land. Later in history, port development has claimed significant salt marsh areas around the world. It has been estimated that 25% of Earth's salt marshes has been lost due to human land claiming (Burden *et al.,* 2013).

Today we know that salt marshes can provide a variety of ecosystem services, such as, a reservoir for biodiversity, immobilisation of pollutants (which get fixed in accumulating sediments), shoreline erosion control and flood defence – as well as carbon sequestration (Burden *et al.,* 2013).

Burden *et al.* (2013) argued that previous research has been focused on restoring peat-lands rather than salt marshes, but that this is in need of a change. The authors claimed that – due to the fact that peat-lands emit increasing rates of methane (CH_4) after they have been re-wetted and that salt marshes do not – restoration of salt marshes would, per unit area, contribute more to carbon sequestration and climate mitigation, than peat-lands.

3.3.1 Sequestering and Storage of Carbon

Nai-Shun Bu *et al.* (2015) have contributed with empirical evidence on how a reclaimed salt marsh loses its previously sequestered and stored carbon under a nine-year period that followed the reclamation.

The authors found that the soil microbial activity increased while the soil moisture declined, which resulted in a three-fold higher soil respiration in reclaimed lands compared to untouched salt marshes. This lead to a 60% decline in the soil organic carbon pool in the top layer (0-20 cm) and a 79% decline lower down in the sediments (0-100 cm) (Bu *et al.,* 2015).

Kelleway *et al.* (2016) investigated the spatial variability of salt marshes in southeast Australia and analysed what sedimentary factors that are key predictions for 'blue carbon' hotspots. In this way the authors could recommend targeting of specific areas for conservation and management activities, and hopefully reverse the trend of habitat loss and re-emissions of stored CO_2.

It turned out that the geomorphic setting of the salt marshes was a major factor that clarified depth-integrated carbon stocks and carbon density across depth intervals, and that, in fluvial settings, the mean stocks were more than twice as high relative to marine settings (Kelleway *et al.,* 2016).

This conclusion contradicts the preceding belief that vegetation was the key predictor to salt marshes carbon stocks on the southeast coast of Australia. Another finding was that sediment grain size was a key factor indicating the carbon density of a site, with a higher carbon density in finer sediments (Kelleway *et al.,* 2016).

However, the same year, Macreadie *et al.* (2016) also wrote a paper regarding Australia's salt marshes, where they pointed out- and recommended that new research on salt marshes vegetation's effect on organic carbon storage should be focused on the refractory tissues of different plant communities. This recommendation was done even though Macreadie *et al*. (2016) cited the conclusion made by Kelleway *et al*. (2016) and agreed with it. It seems like there is always need for more comprehensive research to be done in these new and complex fields of science.

3.4 A Blueprint for Blue Carbon

In the popular review paper *A blueprint for blue carbon: toward an improved understanding of the role of vegetated coastal habitats in sequestering CO_2,* written by Mcleod et al. (2011), the authors gathered data from several other scientists and publications and compiled a table with estimations of salt marshes, mangroves and seagrasses carbon burial rates, global area and global carbon burial. The following figure – which the authors produced in their paper – shows the carbon burial rates (g C m^{-2} yr^{-1}) of terrestrial forests compared to the coastal vegetated ecosystems of salt marshes, mangroves and seagrasses, and indicates their potential for long-term carbon sequestration.

As shown in the figure, the impressive ‘blue carbon ecosystems’ carbon sequestration potential is evident. The figure does not take into consideration the global spatial extent of the several ecosystems, but focuses on the carbon burial rates they are capable of. Mcleod *et al.* (2011) claimed that the phenomenon that is shown is due to the fact that sediments of healthy salt marshes, mangroves and seagrasses do not become saturated with carbon because of the sediments’ capacity to accrete vertically in response to a rising sea level – unlike terrestrial soils.

However, the sources and data used to make these estimations were published in the years ranging from 1990-2010 – which could contain some out-dated numbers, if the new findings of the last decade are considered. But the striking work of Mcleod *et al. (*2011) still shows the major differences between terrestrial and coastal ecosystems, in terms of carbon sequestration, and inspires to discover more about these coastal ecosystems and their potential in mitigating climate change.

A blueprint for blue carbon

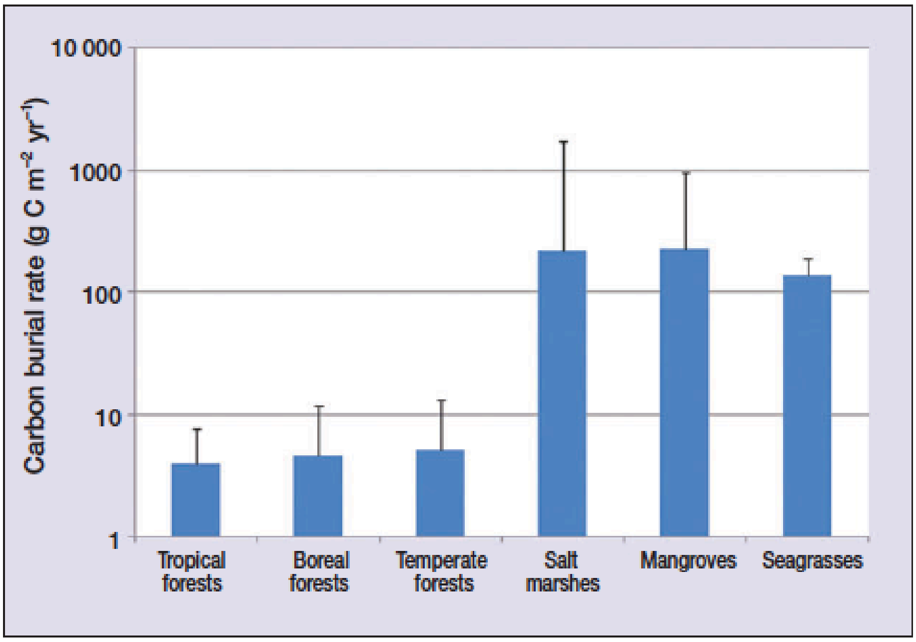

Figure 5. *Mean long-term rates of C sequestration (g C m^{-2} yr^{-1}) in soils in terrestrial forests and sediments in vegetated coastal ecosystems. Error bars indicate maximum rates of accumulation. Note the logarithmic scale of the y axis. Data sources are included in Tables 1 and 2.*

Source: A blueprint for blue carbon: toward an improved understanding of the role of vegetated coastal habitats in sequestering CO2 (Mcleod et al., 2011).

3.5 Anthropogenic Threats to Blue Carbon

The loss of these healthy and important ecosystems is happening at critically and unprecedentedly high rates. This diminishes the sequestering of carbon and its mitigating effect on climate change, since once these ecosystems are degraded; they switch from being a net carbon sink, to a net carbon source (Mcleod *et al.,* 2011).

The 'blue carbon ecosystems' will then start to release the carbon they have been storing for centuries or millennia's back to the atmosphere, involuntarily contributing to more greenhouse gas emissions and induced climate change.

Mcleod *et al.* (2011) pointed out that – at the time the paper was written – one third of the mangroves, sea grasses and salt marshes had been lost during the past decades, due to deforestation, urbanization, reclamation and transformation to aquaculture ponds.

Apart from the threats that land claiming, degradation and deforestation pose, Mcleod *et al*. (2011) argued that human-induced climate change would bring new critical pressures to 'blue carbon ecosystems' in the near future. Climate change – with rising sea levels and temperatures – will affect the coastal wetlands negatively, due to stronger coastal erosion, temperature stress and a "coastal squeeze" for ecosystems that fails to migrate inland as the rising sea levels draw closer.

A "coastal squeeze" happens when an ecosystem gets trapped between a rising sea-level and a developing coastal community, which often fails to leave a buffer zone for their coastal wetlands, which is needed for them to migrate inland and survive (Mcleod *et al.,* 2011).

3.6 Hopes of the Future

During the research of 'blue carbon conservation', it was inevitable to come across Worldview International Foundation (WIF), a non-profit organization, founded by, among others, Thor Heyerdahl – who was also the foundation's first vice president. WIF focuses on restoration of 'blue carbon', and especially mangrove forests, in order to support the UN Paris Climate Agreement and UN Sustainable Development Goals (WIF, 2019).

WIF has taken the pledge to plant one billion mangrove trees, which they assess will mitigate 500 million tonnes of CO_2 (WIF, 2019). The foundation builds its estimations on the Verified Carbon Standard (VCS) methodology – that each mangrove tree has the capacity to mitigate 500 kg of CO_2 during a timespan of 25 years (WIF, 2019).

The project of mangrove restoration started in 2012 and has already come a long way in the construction of their restoration parks (commonly called Thor Heyerdahl Climate Parks) in Myanmar – which is one of the countries with the greatest need of mangrove restoration. The first phase of the park contained 2,200 hectares for mangrove restoration, while the second phase, planned to occur during 2019-2023, will contain additional 2,100 hectares. Another larger project is also planned in Myanmar, which will stretch over 75,000 hectares (WIF, 2019).

The foundation also claimed to plan on construct new Thor Heyerdahl Climate Parks in India, Indonesia and Bangladesh – in order to meet their goal of planting one billion mangrove trees (WIF, 2019). These pioneering projects show that it is possible to create practical solutions to mitigate climate change, with both local and global impacts.

4. Conclusions

We now know one thing; 'blue carbon ecosystems' are important- and very much relevant for human's capacity to mitigate the on-going climate change. The dangers to these coastal ecosystems are comprehensive and future climate-mitigation work should incorporate protection and restoration of these vital carbon sinks. Not only for their carbon sequestration- and burial potential, but also for the ecosystem services they provide for nearby coastal communities, which additionally are among the most vulnerable and exposed of the consequences climate change will bring.

Through this literature review, it has been – to some extent – clearer what factors that actually determine 'blue carbon ecosystems' capacity to sequester and bury carbon in their sediments, and therefore determine their capacity to act as global carbon sinks and help humanity in the strive to mitigate and adapt to climate change.

The development of Rovai *et al.'s* (2018) new ecogeomorphology framework has contributed immensely to the understanding of how certain coastal environmental settings (CES) correlate to its relating soil organic carbon (SOC) stocks. The intertwining of geomorphology, and variations of tides, temperature, salinity, river flow and precipitation seems to be the factors most important to these coastal 'blue carbon ecosystems', since they fixate carbon from both allochthonous (outside boundaries) and autochthonous (inside boundaries) sources.

4.1 Comparing the 'Blue Carbon Ecosystems'

When it comes to "ranking" these ecosystems based on their 'carbon sink potential' it appears that mangroves are at the top of the list. They are not only the most productive of the three ecosystems; they are also able to store additional CO_2 due to the fact that they produce larger amounts of biomass than seagrasses and salt marshes, in which more CO_2 is stored – just as in terrestrial forests. They are therefore able to store significant amounts of carbon in both the soil and the biomass.

Concerning seagrasses, it seems that the enthusiasm and urgency to install 'blue carbon strategies' might have rushed the process of its carbon stock estimations, which resulted in calculation flaws. Johannessen and Macdonald recognized this fact and rightly pointed it out. It is crucial that restoration and protection of blue carbon ecosystems takes place, but it is even more important that the estimations are made right, in order to know what we are working with.

It is a frustrating process, especially since the window for climate change mitigation diminishes every year, but if the process is rushed and becomes incomprehensive, the credibility of the 'blue carbon community' is weakened. Due to the calculations flaws, it seems like seagrass meadows are the least effective carbon sinks among the 'blue carbon ecosystems' and is placed third on the list. However, this does not mean that they are unimportant; they are just least efficient of the three ecosystems investigated.

This leaves salt marshes – a previously neglected landform – between mangroves and seagrasses in 'carbon sink potential'. The great distribution of salt marshes across the world contributes a lot to its high capacity to act as a global carbon sink. Salt marshes in fluvial settings are especially efficient in sequestering carbon, since rivers help the ecosystem with capturing more carbon that they would have in a more static marine environment.

However, this is not a comparison of 'blue carbons' ecosystem services, which might yield different results due to their abilities in promoting, for instance, biodiversity, coastal protection, filtering of water- and nutrients and commercial fisheries.

4.2 Final Note

The fact that ‘blue carbon ecosystems’ are able to sequester and store more carbon than previously thought means that these coastal wetlands at the same time can release more carbon than previously thought – if they are poorly managed and continues to be degraded.

Therefore, ‘blue carbon’ is a double-edged sword; its ecosystems can sequester and store unprecedented large amounts of carbon, but they can also release the amounts they have stored for thousand of years, if they are claimed for other land-uses instead of being restored and protected. This is commonly called a negative double-whammy for climate mitigation, when valuable carbon sinks are lost at the same time as they emit huge amounts of carbon to the atmosphere that previously has been safely stored in the soil.

In the future, it is important to continue the measuring of the SOC stocks of mangroves, seagrasses and salt marshes, in order to quantify carbon stocks of different regions, thus identify ‘blue carbon sinks’ that are priority areas for protection – based on conservation and social benefits, carbon sequestration potential, and prospects for surviving the impacts of climate change, with particular emphasis on sea-level rise.

Since different methodologies tend to end up with varying results, more research is also needed in this field to reach a common understanding of how to calculate an ecosystem’s carbon stock in the best possible way.

To conclude, I reason that if we want to maximize the potential for natural carbon sequestration, it is essential that we gather around the evidence base, listen to the strong arguments and protect these valuable coastal ecosystems as an additional option to add to our portfolio for mitigating climate change.

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References

Alongi, D. M. (2012). Carbon sequestration in mangrove forests. *Carbon Management,* **3**, pp. 313-322

Burden, A., R.A. Garbutt, C.D. Evans, D.L. Jones, D.M. Cooper. (2013. Carbon sequestration and biogeochemical cycling in a saltmarsh subject to coastal managed realignment. *Estuarine, Coastal and Shelf Science,* **120**, pp. 12-20

Bu N., Jun-Feng Qu, Gang Li, Bin Zhao, Rong-Juan Zhang, Chang-Ming Fang. (2015). Reclamation of coastal salt marshes promoted carbon loss from previously-sequestered soil carbon pool. *Ecological Engineering,* **81**, pp. 335–339

Canadell, J.G. and Raupach, M.R. (2008). Managing Forests for Climate Change Mitigation. *Science,* **320**, pp. 1456-1457

Fourqurean W. J., Carlos M. Duarte, Hilary Kennedy, Núria Marbà, Marianne Holmer, Miguel Angel Mateo, Eugenia T. Apostolaki, Gary A. Kendrick, Dorte Krause-Jensen, Karen J. McGlathery and Oscar Serrano. (2012). Seagrass ecosystems as a globally significant carbon stock. *Nature Geoscience,* **5**, pp. 505-509

Howard L. J., Alex Perez, Christian C. Lopes and James W. Fourqurean. (2016). Fertilization Changes Seagrass Community Structure but not Blue Carbon Storage: Results from a 30-Year Field Experiment. *Estuaries and Coasts,* **39**, pp. 1422–1434

IPCC, 2007: *Climate Change 2007: Impacts, Adaptation and Vulnerability.* Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, M.L. Parry, O.F. Canziani, J.P. Palutikof, P.J. van der Linden and C.E. Hanson, Eds, Cambridge University Press, Cambridge, UK

Johannessen, S and Macdonald, R. (2016). Geoengineering with seagrasses: is credit due where credit is given? *Environmental Research Letters,* **11**, 11301

Johannessen, S and Macdonald, R. (2018). Reply to Oreska et al 'Comment on Geoengineering with seagrasses: is credit due where credit is given?' *Environmental Research Letters,* **13**, 038002

Kelleway, J. J., Neil Saintilan, Peter I. Macreadie and Peter J. Ralph. (2016). Sedimentary Factors are Key Predictors of Carbon Storage in SE Australian Saltmarshes. *Ecosystems,* **19**, pp. 865-880

Macreadie, P. I., Q. R. Ollivier, J. J. Kelleway, O. Serrano, P. E. Carnell, C. J. Ewers Lewis, T. B. Atwood, J. Sanderman, J. Baldock, R. M. Connolly, C. M. Duarte, P. S. Lavery, A. Steven and C. E. Lovelock. (2017). Carbon sequestration by Australian tidal marshes. *Scientific Reports*, **7**, 44071

Marbà, N., Ariane Arias-Ortiz, Pere Masqué, Gary A. Kendrick, Inés Mazarrasa, Geoff R. Bastyan, Jordi Garcia-Orellana and Carlos M. Duarte. (2015). Impact of seagrass loss and subsequent revegetation on carbon sequestration and stocks. *Journal of Ecology,* **103**, pp. 296–302

Mcleod, E., Chmura, G.L., Bouillon, S., Salm, R., Björk, M., Duarte, C.M., Lovelock, C.E., Schlesinger, W.H., Silliman, B.R., 2011. A blueprint for blue carbon: toward an improved understanding of the role of vegetated coastal habitats in sequestering CO2. *Front. Ecol. Environ.* **9 (10)**, pp. 552–560

Murdiyarso, D., Joko Purbopuspito, J. Boone Kauffman, Matthew W. Warren, Sigit D. Sasmito, Daniel C. Donato, Solichin Manuri, Haruni Krisnawati, Sartji Taberima and Sofyan Kurnianto. (2015). The potential of Indonesian mangrove

forests for global climate change mitigation. *Nature Climate Change,* **5**, 10891092
Nellemann, C., Corcoran, E., Duarte, C.M., Valdés, L., DeYoung, C., Fonseca, L., Grimsditch, G. (2009). Blue Carbon. A Rapid Response Assessment. *United Nations Environment Programme*
Pérez, A., Libardoni BG, Sanders CJ. (2018). Factors influencing organic carbon accumulation in mangrove ecosystems. *Biology Letters,* **14**, 20180237
Rovai, A., Robert R. Twilley, Edward Castañeda-Moya, Pablo Riul, Miguel Cifuentes-Jara, Marilyn Manrow-Villalobos, Paulo A. Horta, José C. Simonassi, Alessandra L. Fonseca and Paulo R. Pagliosa. (2018). *Nature Climate Change,* **8**, pp. 534-538
Thomas, S. (2014). Blue carbon: Knowledge gaps, critical issues, and novel approaches. *Ecological Economics,* **107**, pp. 22-38
UNEP. (2009). Annual Report 2009: Seizing the Green Opportunity. *United Nations Environment Programme*

Internet Sources

Worldview International Foundation, (2019). *https://wif.foundation/* [2019-04-24]

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