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Integrated Blue Carbon Management On The Dutch Coast

“The development of saltmarsh-oyster reef management strategies and protocol for greenhouse gases measurement”

Htun Thiri Naing

HZ University of Applied Sciences , the Netherlands

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"The development of saltmarsh-oyster reef management strategies and protocol for greenhouse gases measurement"

Authored by:

Htun Thiri Naing

Student number - 74924

BSc (Aquatic Eco Technology)

Supervisors:

Dr. Anneke van den Brink (HZ University of Applied Sciences)

Dunia Rios Yunes (MSc Marine Science, Ph.D. candidate in NIOZ)

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Abstract

The Netherlands is a densely populated and economically developed country. Coastal areas are important for aquaculture, agriculture, harbors, and urban development. Coastal habitats mainly exist on the south Delta coast and the north Wadden sea, hosting a great biological diversity. The Netherlands had a historic tradition of land reclamation and conversion but now they are attempting to manage coastal ecosystems in an ecofriendly and sustainable way. The Dutch coastal defense vision shifted from “Hold the line” to “Building with Nature”, which involves replacing the use of artificial hard hydraulic structures with natural resources to strengthen coastal protection. Yet, little attention is given to carbon sequestration by coastal ecosystems as a means for climate change mitigation.

Dutch coastal regions are extensively urbanized and industrialized. As a result, space is needed in coastal areas for carbon sequestration. In this study, management of carbon sinks in coastal environment, renowned as blue carbon management activities, were integrated into Building with Nature projects aimed at decreasing spatial demand. We aim to strongly recommend the Integrated Blue Carbon Management as a national climate change mitigation plan. Different departments and organizations should work together to strengthen implementation and reporting measures. Raising public awareness about the consequences of blue carbon loss to climate change and the incentives acquired by managing blue carbon will make the project easier to implement.

Based on a Multi Criteria Analysis (MCA) of Building with Nature projects, the most effective blue carbon management initiative is saltmarsh conservation. Saltmarshes are combined with oyster reef-building. The reefs reduce erosion and increase carbon (C) stocks in saltmarshes. Management strategies of saltmarshes-oyster reefs are presented in this study. In addition, a protocol for the measurement of greenhouse gases emissions with gas monitors is one of the major conclusion of this research. The present thesis could assist decision makers and conservation activists in implementing blue carbon management activities and prioritizing coastal ecosystems in climate change mitigation plans and policies.

Keywords: Blue carbon, climate change mitigation, Building with Nature, ecosystem services, management strategies, greenhouse gases

Contents

Chapter 1 Introduction

Climate change over the last few decades has primarily been caused by human activities that have increased the concentration of greenhouse gasses (GHG) in the atmosphere (Johnson et al., 2016; Howard et al., 2017). The future impacts of climate change pose challenges to the world economy, such as a reduction in gross domestic product (GDP) and infrastructure damage. A climate-related economic crisis is a global problem specially for developing countries (Hof, 2015). A number of different approaches to reduce the concentration of carbon dioxide (CO_2) in the atmosphere are needed in order to mitigate the most extreme effects of climate change.

Coastal ecosystems regulate the climate by capturing carbon in coastal vegetation and sediments. These are known as “Blue Carbon ecosystems” (Howard et al., 2017). Blue carbon systems store a substantial amount of organic C (Pendleton et al., 2012). However, global blue carbon systems are vulnerable to human activities including land use change and coastal development work. Human activities caused significant blue carbon losses and C emissions in the coastal ecosystems (Lovelock et al., 2017). Lacking control of human disturbances can promote the continuous release of GHG from coastal environments and climate change effects (Pendleton et al., 2012). Avoiding emissions is a wise and promising concept to reduce climate change and its threats to the world's economy (Pendleton et al., 2012), and thus sustainable management and protection of coastal habitats should be encouraged.

Similar to global coastal ecosystems, the Dutch coastal habitats have been degraded. Much work on restoration of degraded ecosystems, such as Building with Nature (BwN) projects, has been put into practice (Ecoshape, 2020). Yet, to our knowledge no thorough study of C emissions and C storage in coastal habitats for climate change mitigation has been carried out. No action has been taken to promote coastal ecosystems C storage. As a result, C emissions and sequestration associated with coastal habitats are currently not included in national GHG inventories. Therefore, it is of national interest to investigate Dutch blue carbon ecosystems and develop management strategies for blue carbon projects. Since urban development and economic activities are very intense along the Dutch coast, tensions may arise between blue carbon conservation and economic development due to the spatial constraints. In this study, the integration of blue carbon projects into existing BwN projects is considered for efficient management and conservation of blue carbon.

The protection and conservation of Dutch blue carbon stocks can reduce national GHG emissions. The present study not only provides insight into various aspects of the Dutch blue carbon ecosystems approach and management, but it also provides a technical procedure for measuring GHG emissions from blue carbon projects and coastal ecosystems. The technical document would be useful for the investigation of C sinks and sources as well as monitoring which allows effective blue carbon management. Moreover, it can provide GHG emissions data which is needed for C accounting. The emissions data will be useful in managing country's climate change mitigation plans; thus, this study has both societal and scientific relevance.

This thesis addresses management strategies for Dutch blue carbon ecosystems while giving a comprehensive explanation of C emissions and sinks in coastal ecosystems. The main research question of the present study is: ***What management strategies can be suggested for Dutch blue carbon ecosystems?***

To answer the main question, the following issues were addressed:

- What are the blue carbon ecosystems in the Netherlands?
- How have the coastal habitats been degraded?
- What are the existing BwN projects and the potential of blue carbon management cooperation?
- How can BwN projects be managed for blue carbon management?

The outline of this thesis is that after Chapter 1 Introduction, Chapter 2 covers theories about the processes related to C sinks and sources from coastal environments. It contains background on potential economic impacts and blue carbon policies. In Chapter 3, methods of developing blue carbon management strategies are explained and motivated. The results of the eligible BwN projects and management strategies are presented in Chapter 4. Discussion about the results is provided in Chapter 5. Finally, in Chapter 6, conclusions are drawn, and research questions are answered. There is also a reflection that is crucial for further research.

Chapter 2 Theoretical background

2.1 Coastal habitats and climate change mitigation

Anthropogenic emissions of carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) from fossil fuel combustion and industrial activities promote the accumulation of these gases in the atmosphere (IPCC, 2018). The concentration of CO_2 in the atmosphere has increased from 280 parts per million (ppm) in the beginning of the industrial revolution (Richard et al., 2009) to around 411.76 ppm at present (NOAA, 2020). Current levels of CH_4 and N_2O are 1,870 ppb and 332 ppb respectively (NOAA, 2020). The concentration of GHG has increased by 146% for CO_2, 257% for CH_4 and 122% for N_2O from pre-industrial time to 2017 (WMO, 2019).

Increasing GHG concentrations in the atmosphere causes climate change (*e.g.* mean global temperature rise). The 2018 IPCC reported that the projected 1.5 degrees (Celsius) of warming would pose risks to human health, food security, water supply and economic growth. Reducing GHG emissions from fossil fuel combustion is a challenge for many countries (IPCC, 2018). The 2002 IPCC therefore introduced a mitigation strategy involving the reduction of climate change by both lowering emissions and amplifying sinks of GHG (IPCC 2002).

Owing to their long-term net carbon sinks, many coastal ecosystems are now considered large C sinks relative to rainforests (Pendleton et al., 2012). The term "Blue Carbon" is officially used when the carbon is sequestered in coastal and marine vegetated ecosystems namely salt marshes, mangrove forests and seagrass meadows (Figure 1) (Howard et al., 2017). The carbon sink in mangrove forests is in the range of 8,520 to 11,700 t C ha^{-1} yr^{-1} (Bouillon et al., 2008), which is greater than rainforests (4,030 t C ha^{-1} yr^{-1}) (Luyssaert et al., 2007). Unvegetated tidal flats (i.e. mudflats) should be officially referred to as blue carbon ecosystems since they are classified as wetland habitats (Mok, 2019), but they are currently not. Coastal vegetation captures CO_2 and traps organic substances in the sediment within their roots. Unlike terrestrial soils, coastal sediments are largely anaerobic which slows down decomposition. C storage in biomass can last from years to decades, whereas in sediment it can prevail over millions of years, making sediments more significant for long-term C storage. Despite their net C sink, blue carbon ecosystems have been largely ignored in international and national mitigation plans and carbon accounting (Johnson et al., 2016).

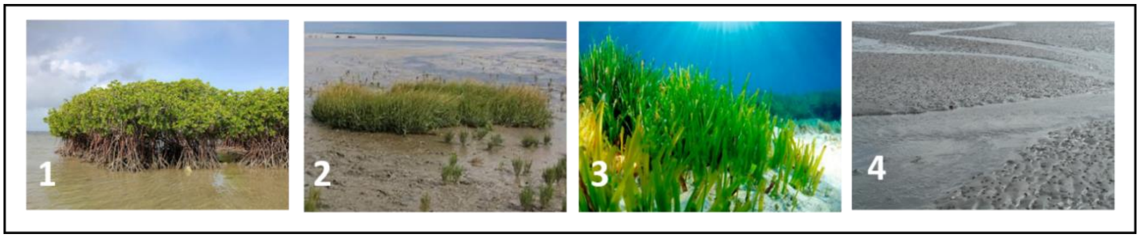

Figure 1: Coastal habitats: (1) mangroves; (2) salt marsh; (3) seagrass *(Source: IUCN)*; (4) tidal flat

The distribution of blue carbon ecosystems across the globe varies geographically. Mangroves can be found in tropical coastal areas and represent 13.8–15.2 million ha globally (Howard et al., 2017). Salt marshes are coastal wetland ecosystems with the presence of grass and shrub plant species and have an estimated global coverage of 40 million ha (Howard et al., 2017). Seagrasses are underwater plants that are found along the shore of worldwide except Antarctica and their distribution ranges from 17.7 to 60 million ha (Howard et al., 2017).

2.2 Greenhouse gases

CO_2, CH_4 and N_2O are potent GHG due to their capacity to absorb outgoing infrared radiation, trap heat in the lower layers of the atmosphere and increase the mean global temperature (Bertrand, 2014). The approximate atmospheric residence times are 4 years for CO_2, 10 years for methane (CH_4) and 123 years for N_2O (Bertrand, 2014; Kaiser et al. 2017). In some cases, CH_4 and N_2O emissions are coupled with the emission of CO_2 from coastal ecosystems. Since the global warming potential of CH_4 and N_2O is greater than that of CO_2 (25 and 310 times, respectively), CH_4 and N_2O emissions from blue carbon management projects can partially or fully negate C sequestration of the blue carbon project (Johnson et al., 2016). Understanding the sources and sinks of GHG is therefore essential for managing Blue Carbon.

Carbon dioxide (CO_2)

Atmospheric CO_2 is fixed by autotrophs and transformed into organic C which is consumed by heterotrophs (Bertrand, 2014). After consumption, CO_2 and organic waste are produced. Organic waste as well as dead organisms are bio-degraded by microorganisms, such as bacteria, through aerobic and anaerobic mineralization producing CO_2 as a byproduct. Under anaerobic conditions, bacteria use different electron acceptors; nitrate (NO_3^-), sulphate (SO_4^{-2}) or CH_4 to complete organic C mineralization (Bertrand, 2014). The electron acceptor is an oxidizing agent that is being reduced during the redox reactions (Nedwell, 1984). Furthermore, if organic C is not mineralized, it accumulates in the sediment and remains stored indefinitely thus reducing the release of CO_2 into the atmosphere. It is estimated that around 0.5% of C is permanently stored in sediments (Burdige, 2007).

Methane (CH_4)

CH_4 is a more potent GHG than CO_2. CH_4 is emitted from coastal environments during the mineralization of organic C by methanogens in anoxic sediments with low salinity (Bange, 2006). In areas with a salinity greater than 18 PSU, sulfate reducing bacteria inhibit CH_4 production, and thus its emission is negligible in these areas (Bange, 2006).

Nitrous oxide (N_2O)

N_2O is produced at an intermediate step during denitrification (Bange, 2006). Denitrification is an anaerobic process where nitrate is reduced to nitrous oxide and nitrogen gases. High inputs of nitrates in anoxic environments can result in an increase in N_2O emissions (Johnson et al., 2016).

2.3 GHG dynamics in coastal ecosystems

Coastal areas are transition zones from land to sea which are drained by channels that flow towards the sea. Tides and rivers deposit sediments with high content of organic C onto coastal areas and as a result its accumulation increases the coastal blue carbon pool (Pendleton et al., 2012). Marine organic C comprises detritus, phytobenthos, bacteria, macro fauna, and phytoplankton particles (Meziane et al., 1997). Terrestrial substances include plant litter, soil organic matter and minerals from mining and rock weathering (Burdige, 2007). The coastal environment is a dynamic system that influences the C sink of blue carbon ecosystems. Hence, environmental drivers controlling C sinks as well as human interferences with blue C storage need to be considered.

2.3.1 Environmental factors influencing carbon storage

Oxygen

Oxygen availability is one of the most important factors for organic C mineralization. Marine sediments are mostly reduced and anaerobic; the oxic layer only encompasses the top few millimeters (1-10 mm) (Revsbech et al., 1980). Microbes and macrofauna consume oxygen and organic C in sediments and emit CO_2. Suboxic and anoxic conditions lower microbial activities and increase long-term organic C storage (Pendleton, 2012; Lovelock et al., 2017).

Nutrients

Net C storage is obtained when nitrate concentration is low because nitrate is used for mineralization when oxygen is scarce (Andrews et al., 2006). Furthermore, the quality of organic material is relevant for microbes. Organic substrates with C:N ratio of above 10 are not suitable for microbial consumption (Kristensen et al., 2000). It is therefore clear that there is a link between nitrogen fluxes and C sinks. Moreover, high nitrate loads in anaerobic environments can increase N_2O emissions via denitrification; therefore, it is important to reduce nitrate loadings.

Salinity

In highly saline habitats, aerobic decomposition rates decrease by around 50% due to the oxygen levels decline, leading to increased C storage (Brouns et al., 2014). Moreover, nitrate reducers and methanogens decrease with increasing salinity because of competition with sulphate reducing bacteria (Seo et al., 2008). Therefore, in saltwater where sulphate reducing bacteria is more dominant, N_2O and CH_4 emissions are negligible (Andrews et al., 2006).

Calcification and dissolution

Seawater dissolved inorganic carbon contains $CO_{2(aq)}$ and H_2CO_3 (1%), HCO_3^- (89%), CO_3^{2-} (10%) (Barker & Ridgwell, 2012). Inorganic carbon species are formed when CO_2 dissolves in water. Dissolution of CO_2 is associated with hydrogen protons (H^+) release in the water. This lowers the pH of the water, but it is buffered by the total alkalinity which is the acid-buffering capacity of seawater. Total alkalinity comprises HCO_3^- and CO_3^{2-} (Barker & Ridgwell, 2012). Dissolution of CO_2 in the water first produces aqueous CO_2 ($CO_{2(aq)}$) and carbonic acid (H_2CO_3) (Barker & Ridgwell, 2012). Carbonic acid dissociates into bicarbonate (HCO_3^-) and hydrogen protons (H^+). Bicarbonate dissociates into carbonate (CO_3^{2-}) and hydrogen protons (H^+).These reactions are:

$$CO_{2\ (aq)} + H_2O \rightleftharpoons H_2CO_3 \rightleftharpoons HCO_3^- + H^+ \rightleftharpoons CO_3^{2-} + 2H^+ \qquad \text{Eq (1)}$$

During the biogenic calcification of corals and seashells, a large amount of carbon is incorporated into the corals and shells as $CaCO_3$ (Canon et al., 1994). This carbon is principally in the form of inorganic carbonates. Calcification requires bicarbonate (HCO_3^-) or carbonate ions (CO_3^{2-}):

$$Ca^{2+} + 2HCO_3^- \rightarrow CaCO_3 + CO_2 + H_2O \qquad \text{Eq (2)}$$

$$Ca^{2+} + CO_3^{2-} \rightarrow CaCO_3 \qquad \text{Eq (3)}$$

During calcification ($CaCO_3$), Eq (1) shifts from right to left and produces $CO_{2\,(aq)}$. In the equilibrium state, the atmospheric partial pressure of CO_2 ($pCO_{2(g)}$) is equal to seawater partial pressure ($pCO_{2(aq)}$) (Canon et al., 1994). Calcification causes elevations in seawater pCO_2 and transfers CO_2 from water to air (Canon et al., 1994).

Excess concentration of CO_2 in the atmosphere due to anthropogenic emissions imbalances the air-seawater pCO_2 equilibrium, causing the movement of CO_2 from air to the water (Feely et al., 2004). This leads to lowering the pH of the seawater and ocean acidification. Ocean acidification is a pressing matter, as it damages hard shell structures of calcifying organisms via $CaCO_3$ dissolution.$CaCO_3$ is dissolved to neutralize acidification by conversion to dissolved bicarbonate ions (Eq 4) (Barker & Ridgwell, 2012; Feely et al., 2004). $CaCO_3$ dissolution increases seawater pH and its capacity to absorb atmospheric CO_2 (Feely et al., 2004).

$$CaCO_3 + CO_2 + H_2O \rightarrow Ca^{2+} + 2HCO_3^- \qquad \text{Eq (4)}$$

Ocean acidification decreases the carbonate and bicarbonate (Feely et al., 2004). Carbonate or bicarbonate reacts with free H^+ protons and produces carbonic acid (H_2CO_3). Thus, ocean acidification reduces calcification rate (Feely et al., 2004). Decreased secretion of $CaCO_3$ and elevated $CaCO_3$ dissolution increase uptake of anthropogenic CO_2 by seawater. Nevertheless, this does not mean to promote the seawater uptake of anthropogenic CO_2 (Feely et al., 2004).

2.3.2 Carbon storage in coastal ecosystems

Blue carbon ecosystems are mainly found in intertidal areas and shallow coastal waters. Mangroves are coastal vegetated ecosystems holding the largest C stocks per hectare, while seagrasses have the lowest C stock (Table 1) (Pendleton et al., 2012). Salt marshes contain moderate to high C stocks, however, published data for C stocks in unvegetated tidal flats is limited (Pendleton et al., 2012). The seagrass species *Posidonia oceanica* accumulates high organic matter (Mateo et al., 1997 and 2006). Similarly, organic rich soils are found beneath mangroves in Australia, South East Asia, Mexico, and Belize (Giani et al., 1996). In nature, CO_2 is emitted from plants respiration and organic C mineralization. However, these emissions are likely to be outweighed by the accumulation of organic C via sedimentation and in situ production of organic C (*e.g.* plants) (Lovelock et al., 2017). Large blue carbon stocks in many coastal sediments have been accumulating since the mid Holocene period around 7,000 to 5,000 years ago (Andrew et al., 2000).

Similar to vegetated habitats, mudflats store organic C (Mok, 2019). C from adjacent sources such as salt marshes are deposited on unvegetated tidal flats particularly in muddy areas (Chmura et al., 2003).

Sediments in mudflats are made of small grains of clay, binding and holding organic matter for a long time (Mok, 2019).

Table 1: A summary of C storage capacity in blue carbon ecosystems

Ecosystem type	Carbon storage
Mangrove	High
Saltmarsh	Moderate to high
Seagrass	Low
Tidal flat (mud + sand)	?

2.3.3 Carbon losses and emissions from coastal ecosystems

Land conversion

When the stored carbon in the sediment is oxidized by natural disturbances (*e.g.* bioturbation or erosion) or human disturbances (*e.g.* land conversion), it is lost as CO_2 (Macreadie et al., 2019). Human disturbances of the coastal ecosystems have caused great blue carbon losses and C emissions. In many European countries, land reclamation and drainage were the main disturbances of coastal ecosystems (Pendleton et al., 2012). Land reclamation in the Humber estuary, UK has caused the loss of 40,000 ha of salt marshes (Andrews et al., 2006). Although there is no estimate of salt marsh losses worldwide, 67% of marshes in the world's 12 largest estuaries were reported to have been lost due to changes in land use (Pendleton et al., 2012). Coastal wetlands are drained to lower the groundwater table to make arable agricultural land. This consequently reduces C stocks and can potentially release ancient stored carbon by oxidation (Pendleton et al., 2012). It is estimated that 60% of near surface carbon (< 1m) is lost within 10 years after drainage (Huang et al., 2009). Nevertheless, worldwide CO_2 emissions from land use change are poorly documented and are not usually reported in national GHG inventories (Johnson et al., 2016).

Hydrological separation

Hydrological separation with tidal barriers and sluices influences blue carbon stocks by reducing sedimentation and organic C inputs (Pendleton et al., 2012). When building the sluice and flood barriers in the estuary, the flow of rivers to the estuary is hindered and sediments accumulate behind the sluices and barriers. The trapping of sediments can lead to CO_2 and CH_4 emissions behind the sluices (Pendleton et al., 2012). 20% of river-transported sediments are retained behind sluices worldwide (Syvitski et al., 2005). Flood barriers also reduce tidal currents and lead to a significant reduction in sedimentation rates (Troost et al., 2012). Furthermore, restriction of saline tidal flows caused a consequent change in blue carbon ecosystems shifting into brackish or freshwater (Troost et al., 2012). Changes in salinity reduce the domination of sulphate reducing microbes and switch the blue carbon systems from sinks to sources of C through CH_4 release (Pendleton et al., 2012).

Sea level rise

Coastal areas can maintain their surface elevation with sediment supply from hydrological flows (Macreadie et al., 2019). This vertical accretion helps them cope with sea level rise (Fujii et al., 2008) and thus make them resilient to sea level rise (Macreadie et al., 2019). Coastal habitats relocate landwards when storms become frequent in order to reestablish their original structure (Pethick, 1996). Meanwhile, such lateral movement is hindered by existing coastal hard defenses in a process called coastal squeeze (Figure 2) (Pethick, 1996). Coastal squeeze promotes the erosion of sediment as the sediments and vegetation become trapped between rising sea level and fixed sea defenses (Pethick, 1996). In the event of erosion, buried organic carbon will be eroded (Lovelock et al., 2017). There is, however, a wide gap in knowledge about whether eroded organic carbon is redeposited in anoxic areas or oxidized during erosion (Lovelock et al., 2017). A sea-level rise of 0.3 m can result in a 6.7% loss of the intertidal area (Fujii et al., 2008).

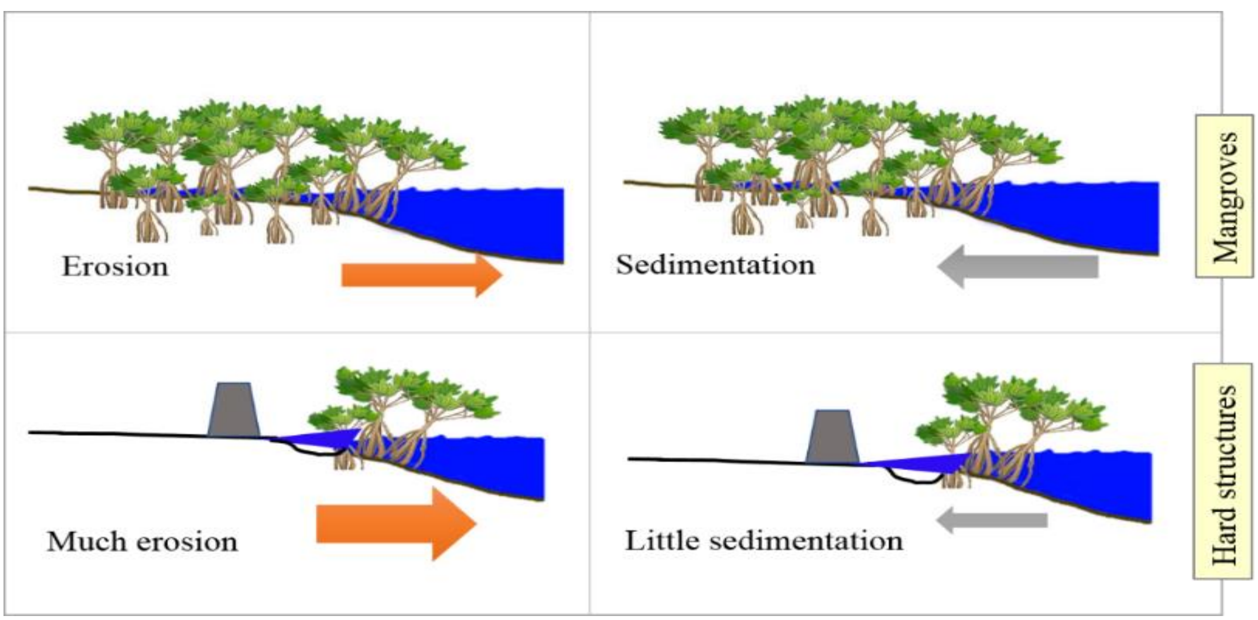

Figure 2: Illustration of the sediment balance. In mangroves ecosystem, sediment is less eroded (small orange arrow) and sedimentation is higher (big gray arrow) compared to hard structures *(Drawn by Thiri)*

2.4 Avoiding emissions from blue carbon ecosystems

GHG emissions from blue carbon ecosystems would have negative impacts on the global economy. This section provides an overview of the reasons to avoid emissions from coastal systems, projected economic impacts and benefits of managing blue carbon systems.

2.4.1 Avoiding emissions

The current annual loss rate of coastal habitats from land use conversion across the globe is estimated to be 1-2% for salt marshes, 0.7-3% for mangroves, and 0.4-2.6% for seagrasses (Pendleton et al., 2012). C from surface pools (< 1m deep of sediment) has been lost. A near surface sediment C pool contains roughly 250 Mg C ha^{-1} in salt marshes, 280 Mg C ha^{-1} in mangroves and 140 Mg C ha^{-1} in seagrass beds (Pendleton et al., 2012). Knowledge regarding the C loss from deep sediments, which contain more C per hectare than sediments from the top one meter, is missing (Pendleton et al., 2012). The depth of the sediment to be influenced depends on disturbance intensity. For example, diking and draining could affect several meters of sediment and expose carbon to oxygen (Pendleton et al., 2012).

2.4.2 Economic impacts

Releasing blue carbon to the atmosphere intensifies climate change, including rising mean sea level, escalating droughts, storms, and flooding (Pendleton et al., 2012). The potential impacts of climate change bring multiple challenges to the global economy, for example a decrease in productivity, a reduction in GDP and damages to household's assets and infrastructure. The economic crisis caused by climate change is a global challenge especially for developing countries that will experience an estimated 40% income reduction by the end of the century (Hof, 2015).

The impact of climate change on the economy is extremely complex with uncertainties concerning the degree of future global warming and the subsequent impact on GDPs, lower labor productivity and production of goods (Hof, 2015). To express these economic damages resulting from climate change, the social cost of carbon (SCC) is employed. SCC translates future damages into present monetary value and estimates the value of the impact of CO_2 emissions (Hof, 2015). Using SCC of \$41 per Mg CO_2(2007 value), the estimated annual economic damage cost for converting coastal ecosystems into other land use is in the range of \$6.1 and \$42 billion for the whole world (Pendleton et al., 2012). However, the actual damage costs will likely exceed this estimate (Pendleton et al., 2012).

Developing countries are particularly prone to climate change due to their low-incomes and naturally hotter climate. The effect of a 3°C global warming on countries' GDP can be seen in figure 3. Sub-Saharan Africa, South and South-Eastern Asia are the most vulnerable regions in the longer term, although many developed countries like the US and the EU are least affected. (Kompas et al., 2018).

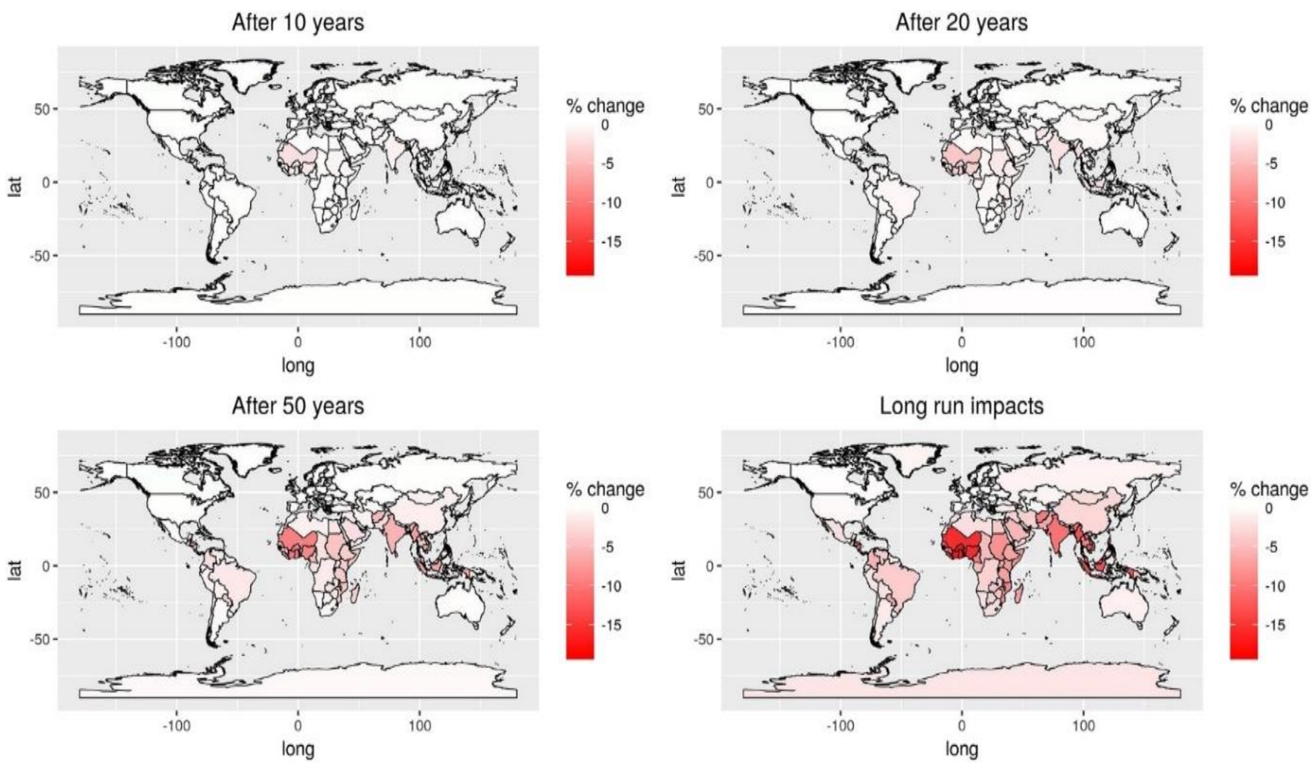

Figure 3: Impacts of global warming (3°C) on global GDP (Kompas et al., 2018)

An interesting concept, presented by Moore and Diaz (2015), is the economic resilience to climate change. It is assumed that economic damage can be lower at greater economic resilience which means that an economy can cope, recover, and reconstruct after natural disasters (Hallegatte, 2014). A resilient economy simply depends on the degree of losses, households' resilience to natural disasters, pre-disaster income and ability to reduce damages over time through savings, loans, insurance, and the social protection system (Figure 4) (Hallegatte, 2014). In developing countries, technologies that enhance food production are widely unavailable. In addition, low wages and a lack of livelihood insurance reduce their ability to reestablish businesses after natural disasters (Moore & Diaz, 2015).

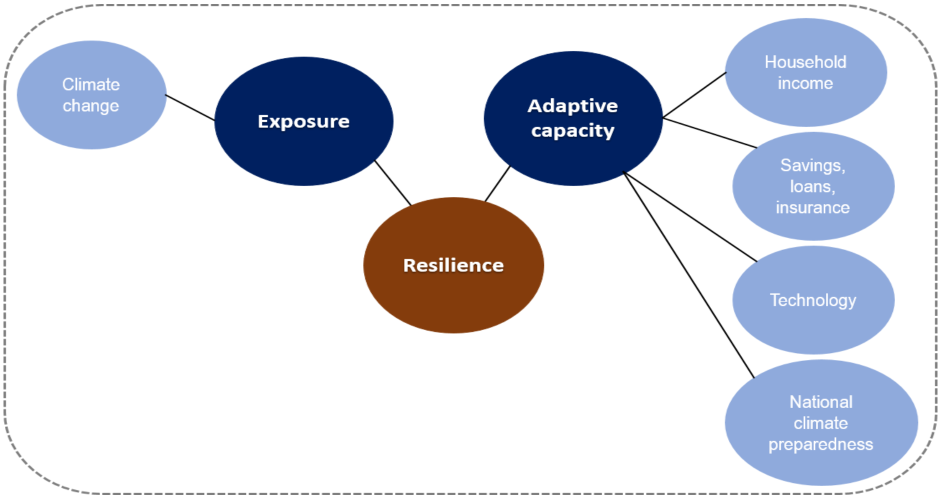

Figure 4: A conceptual framework of economic resilience to climate change

According to Mendelsohn (2013), inefficient climate change mitigation policies increase the threat of climate change to economic damage. The process of mitigation requires an economic transition from consumption to investment. This suggests that coastal ecosystems should be protected from disturbances such as land use change; this follows the argument that investing in mitigation actions is cheaper than the cost of inaction (Mendelsohn, 2013).

2.4.3 Co-benefits of managing blue carbon ecosystems

Apart from their role with GHG regulation, blue carbon ecosystems provide a wide variety of important resources and services to society and economy (Table 1, Appendix I). Vegetated habitats and unvegetated tidal flats act as natural barriers, serving as a flood defense from storms, stabilizing shorelines and reducing risk to coastal communities. As an example, mangrove forests provide timber and firewood. Pollutants such as heavy metals as well as nutrients are trapped in the sediment thus maintaining water quality and preventing eutrophication. Blue carbon ecosystems are biological hotspots with high productivity including nursery for fish and crustaceans, feeding grounds for birds as well as shelter for commercial species such as bivalves and worms (Frid et al., 2018). Around 15% of the world's population relies on seafood as their main source of animal protein. Fisheries therefore provide jobs to over 38 million people (UNEP, 2006). Besides, blue carbon ecosystems provide recreational opportunities such as snorkeling, recreational fishing and boating, and thus coastal ecotourism is one of the fastest growing sectors. Managing and protecting coastal ecosystems for their C sequestration value will generate significant co-benefits (Pendleton et al., 2012). This reinforces socio-ecological resilience and reduces vulnerability to climate change impacts.

2.5 Blue carbon policies and finance for better management

Working with nature is thought to be an approach to help address climate change and societal challenges with a sustainable use of ecosystem services. As coastal ecosystems play a central role in regulating GHG, managing and promoting carbon sinks in coastal ecosystems is a collaborative effort to work with nature. The United Nations Framework Convention on Climate Change (UNFCCC) and the Kyoto Protocol indicated blue carbon projects as an ecosystem based climate change mitigation project. The Paris Agreement described the promotion of sustainable management and enhancement of conservation of GHG sinks in coastal and marine ecosystems. Inclusion of international and national climate change mitigation plans in the blue carbon management with a focus on the conservation and restoration activities will combat climate risks effectively and adaptively.

The UNFCCC established commitments to restrict GHG emissions for industrialized nations, which are also known as Annex 1 countries (Arnoldus & Bymolt, 2011). These countries committed to reducing their emissions by an average of 5.2% compared to 1990 emission scales. In the agreement, countries were given emissions quotas (Arnoldus & Bymolt, 2011). Thereafter, the UNFCCC outlined recommendations for countries to integrate their carbon emissions reduction plans into coastal carbon management activities to meet their commitments (Arnoldus & Bymolt, 2011). A wide variety of policy frameworks were developed for countries interested to engage in managing carbon sinks and sources from coastal systems (Herr et al., 2016). Reduced Emissions from Deforestation and Degradation (REDD+) developed by the UNFCCC is a framework to finance the activities that reduce emissions from deforestation as well as the conservation of forest carbon stocks. REDD+ is relevant for mangroves, particularly if a country classifies them as forests. Meanwhile, Nationally Appropriate Mitigation Actions (NAMAs) is relevant for all activities that design coastal ecosystems to mitigate climate change (Herr et al., 2016). Furthermore, mitigation projects can be incorporated into two other work programs under the Kyoto Protocol namely the Clean Development Mechanisms (CDM) and Land Use, Land Use Change and Forestry (LULUCF) (Johnson et al., 2016). The Nationally Determined Contributions (NDCs) program, developed under the Paris Agreement, is also relevant for mitigation activities. These policy frameworks not only support to fulfill the commitments but also contribute to achieve the goals of conserving and enhancing natural carbon sinks by the UNFCCC and the Paris Agreement.

In addition to these frameworks and programs, blue carbon projects can be incorporated into Marine Spatial Planning or Integrated Coastal Zone Management Plans (Herr et al., 2016). National GHG emissions projects can be offset with its GHG sinks projects or do trading in international carbon markets. In short, a country can decide the policy framework and mechanisms for blue carbon projects based on its ambition and level including the national strategies (*e.g.* climate change strategy), market and non-market approaches or planning instruments (*e.g.* Marine Spatial Planning), goals (*e.g.* Sustainable Development Goals) and conditions (developed or developing) of the country (Herr et al., 2016).

The history of global carbon markets originated from the trading of carbon emission quotas among countries (Arnoldus & Bymolt., 2011). The countries that are able to meet their emissions quotas and have excess quotas can sell them to others that have not been able to meet or have exceeded their quotas. Such a trading marketplace is called the compliance market and only countries that are committed to reducing their emissions are eligible (Arnoldus & Bymolt., 2011). The CDM facilitates trading service to help countries achieve their national emission reduction targets. If countries want to trade their surplus emissions quotas, they must certify them as standard carbon credits at the CDM. In essence, carbon credits are authenticated for projects that remove GHG or reduce emissions and they can be sold to polluters who do not meet their emission quotas to offset their emissions in the carbon market (Arnoldus & Bymolt., 2011). In addition to selling their quotas, if countries have projects that reduce GHG emissions or sequester CO_2, carbon credits from those projects can be certified with the CDM and sold to other countries that need to achieve their emission reduction targets. However, the CDM is very strict with a very high administrative burden. It is therefore difficult for small scale carbon projects (GAO, 2008), seeking more flexibility, few costs, and a lower administrative burden (Wylie et al., 2016). Therefore, voluntary markets were formed due to their flexibility. Another compliance market is the European Emissions Trading Scheme (EU ETS) which is the largest carbon market; 81% of carbon credits around the world were traded in 2010 (Arnoldus & Bymolt., 2011).

In the voluntary market, companies and individuals buy carbon credits from carbon mitigation projects such as blue carbon conservation to offset their emission on a voluntary base (Arnoldus & Bymolt., 2011). While buyers in the compliance market are buying credits to meet their commitments, voluntary buyers offset their emission according to their motivations of cooperation to climate change mitigation and social responsibility. In voluntary markets, projects are not obliged to become certified to a standard, which makes it easier for small carbon emissions reduction projects (Arnoldus & Bymolt., 2011). The Verified Carbon Standard is also much easier to implement as it offers multiple voluntary standards with reduced costs for the required carbon accounting, verification, and certification processes. However, most project developers decide to get certified credits because buyers demand certification to make sure that the emissions reduction has been made, thereby causing higher prices for certified credits than non-certified ones (Arnoldus & Bymolt., 2011).

The voluntary market is smaller than the compliance market and carbon prices vary for each market (Arnoldus & Bymolt., 2011). In 2010, 131 Mt CO_2equivalents were traded on the voluntary market and 6,692 Mt CO_2 eq on the compliance market (Arnoldus & Bymolt., 2011). However, the voluntary market is fast growing. In 2018, voluntary carbon markets have been expanded to 83 countries around the world, mainly in Asia (51%), North America (18%), Latin America and the Caribbean (11%), Europe (11%) and Africa (11%). Some countries (*e.g.* South Korea) have government-operated domestic markets that encourage businesses and individuals to buy locally produced offsets (Arnoldus & Bymolt., 2011). Some airlines (*e.g.* DELTA airlines from the US) offer voluntary carbon offset options in their tickets and a person who flies frequently can buy those offers or offset in other voluntary markets to contribute to blue carbon conservation projects.

While many of the conservation and restoration efforts have been applied, blue carbon credits are rarely traded. Carbon credits trading has been undermined by the lack of methodologies regarding carbon accounting (Johnson et al., 2016). Carbon accounting is the estimation of carbon stock changes and it is based on two methods; (1) gain-loss method (estimating the net balance of additions and removals from a stock) and (2) stock difference method (estimating the difference in stocks between two time points) (Bird et al., 2010). Carbon accounting is used to restrict emissions, look for sinks and perform carbon credits trading.

In 2013, the IPCC issued guidelines for National GHG inventories for wetlands, providing GHG accounting methodologies for inland and coastal wetlands (IPCC, 2013). It encouraged all developed countries' parties to make use of it in countries' national GHG reports. However, coastal carbon systems have not been integrated into many countries' GHG inventory reports (Johnson et al., 2016). For example, the last Dutch National GHG Inventory in 2019 documents only GHG emissions from the energy sector, industrial processes, agriculture, land use and waste. Any emissions or sequestration related with human activities in coastal regions are not reported. Since an overview of sinks and sources is key for mitigation plans, more comprehensive and well-documented GHG inventory reports need to be produced (Johnson et al., 2016). Essentially, national GHG inventories should include the following information from an ecosystem: (1) carbon burial rate; (2) current carbon stocks, including the stability of those stocks and their potential loss under destruction; (3) the site area; (4) human activities which can lead to carbon emissions or habitat loss; and (5) emission rates from both degraded and undisturbed situations (Howard et al., 2017).

2.6 Environmental and socio-economic aspects of the Dutch coast

2.6.1 Dutch coastal geography

The Netherlands is situated in the north west of Europe, bordering the southern part of the North Sea with a total coastline of over 400 km. Approximately 27% of the land lies below sea level. Without coastal defense, at mean spring tide, about half of the country would flood (Stronkhorst et al., 2011). The Dutch coast is divided into three parts: the southern Delta coast, the central Holland coast and the northern Wadden coast (Figure 1, Appendix I) (Stronkhorst et al., 2011).

The Delta coast is a tidal dominated coast while the Holland coast presents storm dominance and is covered by aeolian sand dunes. The coast is strengthened by local hard structures (Stronkhorst et al., 2011). The Wadden sea is a tidal flat which is delimitated by the mainland and barrier islands. It is segregated from the North Sea by a number of barrier islands and is characterized by a large range of canals, sand and mud flats, gullies, and salt marshes (Lodder et al., 2019). Therefore, the Wadden sea is locked up by the islands and seawater comes in and out only through the gaps between the islands. Approximately 75% of the coast is covered by sand dunes (Stronkhorst et al., 2011). Beach flats are found around the ends of the Wadden Islands (Stronkhorst et al., 2011). The Wadden sea was enlisted to the UNESCO world heritage list in 2009.

2.6.2 Transformations of the Dutch coast

The central objective of the Dutch coastal policy is to protect from floods (Stronkhorst et al., 2011). Legislation has set the standard water level with the storm-surge water level, which will be returning in 10,000 years for the Holland coast, 4,000 years for the Delta and Texel coast and 2,000 years for the remaining Wadden islands (Stronkhorst et al., 2011).

The southwest part of the Netherlands is characterized by a constant war between man and sea (Smits et al., 2006). The salt-marsh areas were reclaimed and turned into agricultural land. However, storm floods have breached the man-built seawalls and destroyed the occupied land (Smits et al., 2006). After the 1953 storm, the Delta Project was formalized in 1957. Many tidal outlets to the North Sea, except the Westerschelde, were closed. New dikes were built along the Westerschelde to allow shipping access to the port of Antwerp (Smits et al., 2006).

Similarly, habitat conversions in the Wadden sea started 1,000 years ago (Reise, 2005). Land reclamation converted half of the near land marine ecosystems particularly saltmarshes and wetlands into arable land and freshwater lakes. Loss of saltmarshes weakened Wadden sea’s ability to weaken the tide and wave. Storm barriers were recruited to protect the hinterland (Reise, 2005).

2.6.3 Ecology

The Dutch coastal areas are of ecological importance and host a variety of habitats namely salt marshes, seagrasses, dunes, and tidal flats. They are home to a diversity of wildlife ranging from birds to marine mammals as well as macro fauna and fish. The Wadden sea is very important for migratory birds.

Each year millions of birds migrate from Siberia, Scandinavia, Greenland, and parts of Canada to the warmer areas of Europe and Africa to spend the winter (Baptist et al., 2007). Mammals such as seals and the bottlenose dolphins inhabit coastal waters (Baptist et al., 2007). The bottoms of the tidal flats are full of life with cockles, mussels, oysters, and worms. The environment is ideal as a nursery area for several species of fish (Berghahn, 1987). Some fish species live their entire life cycle in the Wadden sea while other species migrate there for access to food or to mate (Berghahn, 1987).

2.6.4 Socio-economic aspects

The Dutch coast is densely populated and about 9 million people, around 56% of the total population, currently live in regions below sea level (Stronkhorst et al., 2011). The coastal zone is utilized for many purposes. It is extensively urbanized and industrialized with ties to important harbors. Fishery is a growing sector along the coast (Stronkhorst et al., 2011). According to the Organization for Economic Co-operation and Development (OECD, 2019), the GDP per capita is US$ 59,420. Dunes are essential source of drinking water supply and it is also important for tourism. In the south Delta coast, estuaries to the North Sea are enclosed with tidal barriers. Figure 2 in Appendix I shows the land use in the Delta coast and Wadden coast in 2015.

2.6.5 Types of blue carbon ecosystems

Saltmarshes

Saltmarshes are found both on the Delta coast and the Wadden coast. On the Delta coast, saltmarshes are mainly located along the Westerschelde river and the Oosterschelde inlet (Bakker et al., 2002). There are three major types of saltmarshes in the Netherlands: (1) sandy back-barrier marshes which mainly occur on the islands of the Wadden Sea; (2) clayey estuarine saltmarshes on the Delta coast; (3) clayey artificial salt marshes formed from sedimentation works which are primarily located in the Wadden Sea along the Groningen and Friesland coasts (Bakker et al., 2002). The area of estuarine marshes in the Delta coast has increased significantly due to large scale plantation of *Spartina anglica* during the 1920s in order to increase sedimentation (Bakker et al., 2002). Marshes are also planted on the mainland of the Wadden coast and in the Dollard estuary. Marsh development requires a constant maintenance of the brushwood groynes, which improves sedimentation and prevents the marsh erosion (Bakker et al., 2002). Saltmarshes in the Wadden Sea cover almost 40,000 ha (Folmer et al., 2019).

Seagrasses

During the 1970s and 1980s the Delta coast had over 4,000 ha of common eelgrass (*Zostera marina*) and dwarf eelgrass (*Zostera noltii*). They are mainly located in the Oosterschelde estuary and in Lake Grevelingen (Troost et al., 2012). However, the area of seagrass decreased from 657 in 1984 to 63 ha in 1993 (90% reduction). The loss of seagrass was caused by changes in tidal currents and erosion of the tidal flats as a result of the Delta project (Troost et al., 2012). The seagrass beds in the Oosterschelde display a steady decline, however, both species are still present (Troost et al., 2012). The same species are found in the Wadden Sea (Folmer et al., 2017). The Wadden Sea is the largest intertidal seagrass area in Europe. Inventories in 1972 show that intertidal seagrass was much more abundant than at present (Folmer et al., 2017). While some areas of high seagrass density were still present in 2011, all of them disappeared by 2014 (Folmer et al., 2017). Current data shows that salt marshes in the Wadden Sea cover about 20,000 ha. Figure 3 in Appendix **I** shows the seagrass beds distribution along the Wadden coast in 2015.

Tidal flats

On the Delta coast, mud and sand flats exist along the Oosterschelde and Westerschelde estuaries (Troost et al., 2012). The Delta Works caused sand starvation problems in Oosterschelde estuary of the Delta coast because tidal currents were too weak to redeposit sediments (Troost et al., 2012). Nourishment works have been reinforced to limit erosion (Ysebaert et al., 2016). On the Wadden coast, the tidal flats are mostly sand (90%) and mud (10%) (Lodder et al., 2019). Tidal flats are disturbed in several ways: land reclamation, gas and salt mining that led to land subsidy, dredging, and dumping activities including developments of shipping channels and harbors (Lodder et al., 2019). Current total areas of tidal flats both on the Delta coast and Wadden coast have not been reported.

Table 2: A summary of the occurrence of Dutch blue carbon ecosystems

Ecosystem type	Location	Area
Salt marsh	Delta coast	Unavailable
	Wadden coast	40,000 ha
Seagrass	Delta coast	Unavailable
	Wadden coast	20,000 ha
Tidal flat (sand + mud)	Delta coast	Unavailable
	Wadden coast	Unavailable

Chapter 3 Methods

3.1 Methods for Multi Criteria Analysis

Section 2.6 justifies the great importance of the Dutch coast. Dense population and coastal developments, such as urbanization, tourism, agricultural uses, aquaculture, and harbors are contributing coastal ecosystem's pressure. Blue carbon ecosystems: saltmarshes, seagrasses, and mudflats are mainly present on the south Delta coast and the north Wadden Sea coast. However, there is a decreasing area on these ecosystems in the last decades, mainly related with land conversion and coastal protection work (*e.g.* Delta Work).

Protection of the blue carbon ecosystems requires legislation of protected areas and may raise conflicts between conservation and coastal development due to spatial need. Therefore, it was decided to integrate existing BwN projects, which are in the operating state, into managing blue carbon ecosystems. Regarding the development of management strategies, the following approach was employed. First, Dutch BwN projects are listed referring to the websites of Ecoshape 2020 and Deltares. After listing, potential collaboration of blue carbon projects with BwN projects was assessed with Multi Criteria Analysis (MCA). MCA is a tool that supports comparison of projects on the basis of a set of criteria. It is widely used in decision making processes and assessing complex issues (Silva et al., 2017; Youssef et al., 2019).

MCA helps to focus on the criteria and interests for the BwN alternatives and allows to select the most relevant BwN projects for the Blue Carbon Management project. First, a goal of finding a suitable BwN project for blue carbon management is set. Then, the criteria and interests considered for selecting the BwN project and available BwN alternatives are identified. The Criteria is divided into two categories: "Advantages" and "Sensitivity". Advantages criteria represent how the BwN project enhances the C stock and the potential of receiving carbon mitigation funds from conserving C stocks in BwN project. The Sensitivity criteria consider the potential response of BwN projects to climate change and thus to the potential C stock of the BwN project. After identifying the key criteria and alternatives, the criteria are graded for each alternative. For the analysis presented in this thesis, an ordinal 5-point scale was used to assign scores related to how well each alternative satisfies a particular criteria. Scales ratings include 5 (very high), 4 (high), 3 (moderate), 2 (low), 1 (very low) and 0 (unknown). Score assignment for each criteria in this MCA study were performed after reviewing many case studies and literature documents related with C stocks of the system, and climate change stresses on potential C storage. Scores of Advantages and Sensitivity for each criterion were summed up. Then, total scores of Sensitivity were subtracted from Advantages scores to select the projects with the highest positive outcomes or the most suitable for blue carbon project. After the MCA analysis step, management strategies for selected BwN projects are introduced for the launch of a blue carbon project.

3.2 Methods for the development of the protocol

The protocol had to be developed in order to measure the sediment GHG fluxes associated with the tidal cycle. Table 3 provides an overview of the GHG measurement experiment with a single tidal cycle. The experiment started with the exposed treatment as sediment cores were collected at low tide. After exposed treatment, semi-inundated (the test for incoming tide) and water-logged (fully flooded) were proceeded. Two gas analyzers, Innova 1312 photoacoustic infrared multi-gas monitor and EGM 5 gas analyzer were used. During the experiment, the system was placed in a climate room. GHG fluxes from sediment cores were measured in the closed system composed of a cylindrical incubation chamber (33cm, ⌀ 15 cm). Temperature was kept at ambient temperature by placing the chamber core in the water tank. Multiple tests of measuring the lab air, sediment gas fluxes and correcting devices' settings were conducted to develop the protocol. Sediment cores were collected from the Groot Buitenschoor mudflat, a brackish water-influenced intertidal area that is situated on the Scheldt river-bank, close to the Belgian-Dutch border.

Table 3: Summary of the experiment designs used in the protocol for one tidal cycle

Treatment	Measurement period	Condition	Replicates
Exposed	6 hours	Only sediment	2
Semi-inundated	3 hours	Sediment + 200 ml water	2
Waterlogged	70% O_2 saturation in the water	Sediment + water full of the core	2

Chapter 4 Results

4.1 Potential blue carbon projects

At present the Netherlands has not produced a scheme of action that focuses on C sinks of coastal ecosystems. Many of the programs, including restoration projects, aim to protect the coast against floods and rising sea level (Ecoshape, 2020; Deltares, 2020). These projects are known as Building with Nature (BwN), following the concept of Working with Nature. More specifically BwN replaced hydraulic engineering structures with ecosystem-based solutions. Examples include:

- oyster reef building
- salt marsh and seagrass restoration
- sand engine
- managed realignment
- dune strengthening
- mudflat conservation

Blue carbon managing activities can be incorporated into some BwN projects to reduce C emissions and improve C sequestration. The types of BwN projects and their potential for blue carbon projects will be evaluated.

Oyster reef building

Oyster reefs have been implemented worldwide as a wave barrier to protect the shoreline from erosion. In the Netherlands, oyster reefs were built in the Oosterschelde for sediment trapping, water filtration, habitat creation for fish juveniles and as a biodiversity hotspot.

Salt marsh and seagrass restoration

Restoration of damaged salt marsh and seagrass ecosystems has been undertaken due to their storm buffering characteristics and their ecological importance (Figure 5). The combination of blue carbon projects with saltmarsh and seagrass restoration or conservation is possible because the plants capture and stabilize the sediment with their root systems and preserve organic C below and above ground for extended periods of time.

 

Figure 5: Salt marshes in Rilland (left) and seedling quadrat (right) for restoration (*Photo by Thiri)*

Sand engine

The Directorate-General for Public Works and Water Management (Rijkswaterstaat) deposits about $12*10^6$ m^3 of sand annually along the sea to retain the coastline to the margin found in 1990 and to avoid coastal erosion (Wijnakker, 2015). Every 4 years, they review their coastal security plans and select which sites are vulnerable and should be nourished (Wijnakker, 2015). In 2011, a mega-nourishment, known as the Sand Engine, was initiated between Kijkduin and Ter Heijde where $21.5*10^6$ m^3 of sand were used to form the "Sand Engine" sand bank (Figure 6). The Sand Engine aims to deposit sand slowly along the coast by tidal flow, wind, and currents (Wijnakker, 2015). Therefore, it can be categorized as a mobile dune (Beaumont et al., 2014). The Sand Engine is estimated to be able to avoid erosion for at least 20 years on the nearby 10 km of shores (Wijnakker, 2015).

Sand Engine project is unable to trap CO_2 due to the lack of plant growth (Wijnakker, 2015). However, sand in the Sand Engine is calcium carbonate ($CaCO_3$) rich and contributes to carbonate sink (Wijnakker, 2015). The lifetime of the Sand system is expected to be 20 years (Wijnakker, 2015).

Figure 6: The Sand Motor *(Source: Ecoshape)*

Managed realignment

Managed realignment is locating a setback line with a rearranged defense to hinterland. It is a cost-effective and sustainable buffer zone to sea-level rise (Adam, 2019) which involves building a new parallel defense that allows the tide to flow freely in the new intertidal area between the two dikes when the sea defense is breached (Figure 7) (Adam, 2019). The aim is to create new intertidal habitats, salt marshes, increase biodiversity, and promote vertical sedimentation. In the Netherlands it is called "depoldering".

Rewetting the soil and restoring anaerobic conditions with tidal restoration can enhance net C stocks and lower CH_4 emissions (Pendleton et al., 2012). The inclusion of carbon storage goals in managed realignment projects could be a public choice since the depoldering can cause controversial matters regarding salinization of the surrounding agricultural land, as well as the costs of building a new dike.

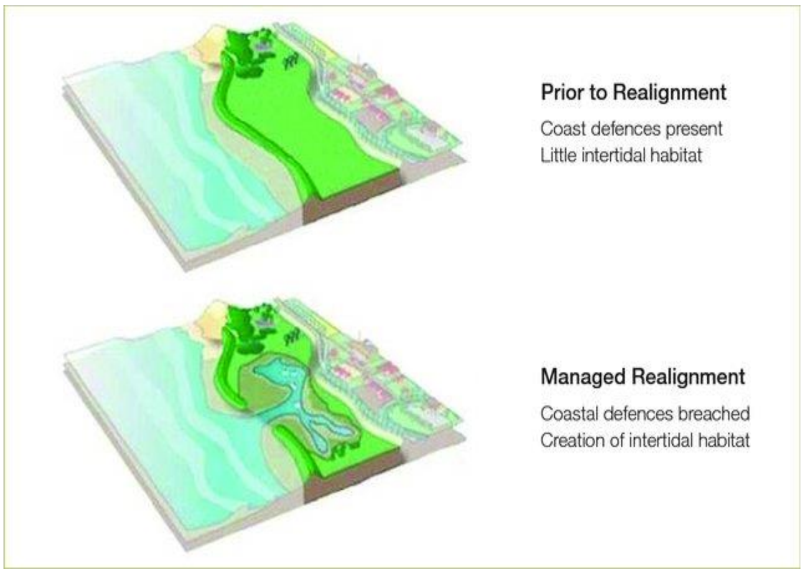

Figure 7: Creation of saltmarshes and intertidal habitat through managed realignment. Prior to managed realignment little intertidal habitat exists. In managed realignment, the coastal defense is breached and the intertidal area increased. (Nicholls et al., 2010)

Dune strengthening

Vegetated sand dunes can be found along the Dutch coastal margin especially above the beach to protect against flooding, store freshwater, create biodiversity islands and increase coastal tourism. Recent research has revealed the importance of sand dunes for nutrients and carbon cycling (Beaumont et al., 2014; Yang et al., 2014). Dune plants such as shrubs and grasses (Figure 8) sequester atmospheric carbon and store in their plant bodies and roots. Sand with vegetation increase the dune C stock within the biomass above and below ground (Yang et al., 2014). In the top 20 cm of soil greater organic C content contains, exceeding to 40 cm deep. Nitrous oxide and methane emissions in dune systems are not studied but are likely to be negligible in these dry habitats (Beaumont et al., 2014).

Figure 8: Vegetated dunes on Dutch (left) and Belgium coast (right) *(Photo by Thiri)*

Mudflat conservation

Under the UNESCO and Ramsar Convention, mudflats on the Wadden Coast and Delta Coast are protected (Figure 9). A number of studies about sediment dynamics on tidal flats, and benthic community structure have been carried out (Heip et al., 1995; Herman et al., 1999; Herman et al., 2001) although carbon burial rates and C stocks of tidal flats are understudied.

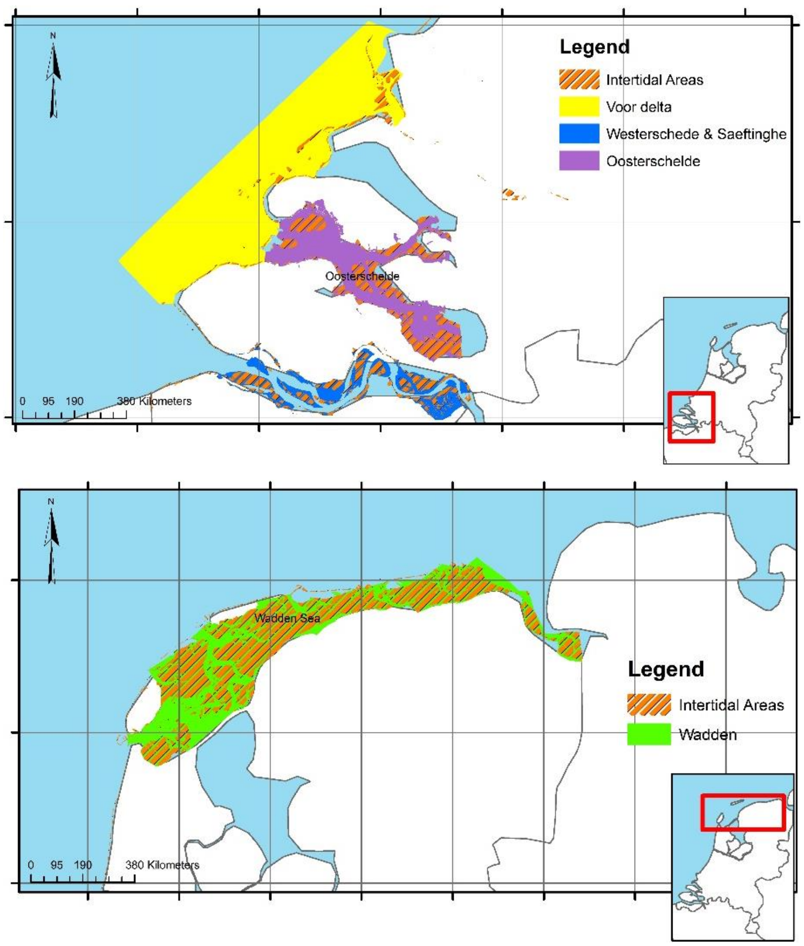

Figure 9: Intertidal areas including mudflats on the Delta coast (top) and the Wadden coast (below)

4.2 Analyzing BwN projects for blue carbon collaboration

The following explains scoring the criteria of the BwN alternative projects. Full MCA table can be viewed in Table 4 at the end of the explanation.

Sand engine

Of the BwN alternatives, the sand engine is not as efficient at sequestering carbon as vegetation, thus they were given "very low" scores for C stock per area. Sand Engine is a carbon sink as $CaCO_3$, but sand can be eroded during storms and aeolian transport. Due to their mobility, the long term C sink cannot be guaranteed. Besides, sea level rise can carry away the sand and erode the Sand Engine. The Sand Engine lifetime is expected to be 20 years. Therefore, managing erosion and carbonate in the sand engine is very low. In addition, the financial gain of blue carbon management cannot be reached.

Oyster reefs

There is disagreement among scientists regarding oyster reefs as a C sink (Ware et al., 1992; Munari et al., 2013; Fodrie et al., 2017). Oyster reefs were considered as C source due to their respiration activity and the emission of CO_2 during shell formation (Munari et al., 2013). However, inorganic carbon; bicarbonates or carbonates are sequestered in shells. Moreover, oyster reefs trap sediments and bury organic carbon (Fodrie et al., 2017), but high sedimentation rates can limit oyster survival and the reef growth (Housego & Rosman, 2016). Nonetheless, in decades-old reef structures, the sediment organic carbon burial rate is within range of 30 g C m^{-2} yr^{-1} to 270 g C m^{-2} yr^{-1} (Fodrie et al., 2017). Therefore, oyster reefs would be a big C sink in the decadal or centurial scale. For reefs to be credited as C sinks, it is important to notice the fixed organic carbon burial rates in reefs and not only the sequestered $CaCO_3$ ratio with CO_2 release from respiration and calcification (Fodrie et al., 2017). Ware et al. (1992) reported that CO_2 emissions of calcification accounts to 0.4% to 1.4% of anthropogenic CO_2 emissions from fossil fuel burning. It is for this reason that in our analysis, C stock per area in the reefs is scored as "high" and scored as "very high" in the long term. Oyster reefs can endure storms and sea level rise, but they present high sensitivity to temperature increases which could limit their survival (McCoy et al., 2017; Duarte et al., 2018). C stock management of the oyster reefs is high. There is growing evidence that the development of oyster reefs with saltmarsh and seagrasses enhances water quality and the growth of vegetation to sustain and promote C stocks (Sharma et al., 2016; Fodrie et al., 2017). Saltmarshes and seagrasses vegetation can compensate CO_2 release of calcification via photosynthesis (Canon et al., 1994). Blue carbon management funding for reef conservation cannot be achieved to date.

Salt marshes and seagrasses

Salt marshes and seagrasses hold the highest C stocks in their living biomass and sediment. C content in seagrass habitats is lower than saltmarshes. Thus, it is graded “high” for seagrasses while saltmarsh is graded “very high”. Long-term C conservation is assured in these ecosystems. Coastal squeeze, however, can damage and erode salt marshes as the sea level rises. In contrast, sea level rise does not affect seagrasses as long as turbidity is unaffected (Duarte et al., 2018). Some species can grow in water less than 10 m deep whilst species of the genus *Halophila* in Australia can grow at depths of 56m (Waycott et al., 2007). Seagrasses are highly sensitive to temperature rise whereas salt marshes are resilient to higher temperatures. However, warming can have positive or negative effects on saltmarsh productivity and species locally (Duarte et al., 2018). Both vegetation types are vulnerable to storms and storm effect is scored “high”. Seagrass beds in the more exposed south-western Wadden Sea are most likely to be affected (Folmer et al., 2017). Potential management strategies particularly in erosion control, eutrophication and bioturbation are extremely high while coastal squeeze management is controversial in political and socio-economic aspects since it includes shoreline retreat and land repurposing from agricultural to coastal. Therefore, management possibility obtained a “high” score. C stocks development and GHG emissions reduction of these ecosystems can also be financed through UNFCCC mechanisms and carbon markets.

Managed realignment

In managed realignment, the normal functioning of biogeochemical processes is difficult to recover since the restored situation does not completely equate to the functioning of a natural saltmarsh (Burden et al., 2013). For example, in the Blackwater estuary in the UK, the mineralization rate in restored sites is found to be the same as that of agricultural land after 15 years retreat. Thus, carbon accumulation rates of the restored sites are slow (92 g C m^{-2} yr^{-1}) and it is estimated to take around 100 years for newly formed marshes to reach the natural saltmarsh C stock (Burden et al., 2013). These results contrast with those of another realignment project on the Fundy Bay, Canada in which high C accumulation at a rate of 1,329 g C m^{-2} yr^{-1} was obvious within six years (Wollenberg et al., 2018). The deposition of labile sediment cannot lead to C accumulation due to its rapid degradation and thus translates into low and less effective C accumulation (Burden et al., 2013). It is therefore assumed that standing C stocks in managed realignment sites can be “moderate”, but the stock is expected to increase in the long term (Burden et al., 2013). Restoration of saltmarshes can be difficult as it depends on the successful growth and survival of the salt marsh vegetation. Overall, the practical management to improve C stock is given a “moderate” score. Blue carbon management funds for newly restored habitats are not yet eligible, and funding opportunity is considered to be “very low”. Sedimentation is enhanced after a saltmarsh establishes. Improved sediment catchment promotes vertical accretion thus making this type of vegetation resilient to sea level rise. Nevertheless, the sediment and the saltmarsh can be eroded by storms, but the erosion is expected to be limited due to sea defense barriers and storm effects are therefore scored "low". The effect of warming is expected not to be high in saltmarshes and thus it is graded as "very low".

Sand dunes

Sand dune systems are not widely studied and thus their C storage capacity is difficult to classify. Two studies of carbon stocks in dune systems in China and the UK have registered storage capacities ranging from 21.4 g C m^{-2} yr^{-1} in China (Yang et al., 2014) and 58.2 g C m^{-2} yr^{-1} in UK (Beaumont et al., 2014). In the UK sand system, C storage rate in saltmarshes ranges from 64 to 219 g C m^{-2} yr^{-1} (Beaumont et al., 2014). Since the C storage rate (58.2 g C m^{-2} yr^{-1}) in the UK dune system is close to the lowest C storage rate (64 g C m^{-2} yr^{-1}) of UK saltmarsh thus we classify it as "moderate" for the Dutch dunes C storage rate. It is important to mention that this classification is based on comparison of two systems with similar climate (UK and The Netherlands). In order to have an accurate value, more research on dunes systems in the Netherlands needs to be done. Long term C stocks cannot be estimated either due to an inadequate understanding of biogeochemical cycles in dunes (Beaumont et al., 2014). It is for this reason that the blue carbon management of the dune system is scored "unknown". Grading of the financing availability is very small since dunes are not officially classified as blue carbon ecosystems. Nonetheless, Beaumont et al. (2014) included dune C stock in the UK's coastal C stock quantification. Extensive sand dune studies are needed worldwide in order to expand our understanding of coastal dunes biogeochemical functioning and determine if they should be considered as blue carbon ecosystems. Dunes are located in an elevated position behind the beach which makes them less likely to be affected by sea level rise although, in some occasions, storms surges and waves strike them and cause erosion thus obtaining a "moderate" score. The temperature rise effect on dune systems, their plants and microbial community is unknown (Beaumont et al., 2014).

Mudflats

The C stocks and burial rates of mudflat ecosystems are not globally reported and therefore the ranking of mudflat C stocks is challenging. The value of C stocks in Korean mudflats (5,391 g C m^{-2}) from Mok's study (2019) is used as an example and graded Dutch mudflat C stocks as "very high". Mudflats C storage in the long term is likely to be compromised due to the effect of coastal squeeze under sea level rise scenarios (Wollenberg et al., 2018). The possibilities of management are also small as mudflats present very dynamic and regular erosion events that can reach depths of 20 cm or more. As a comparison, saltmarshes are more likely to retain C due to the stabilization effect of the vegetation roots (Wollenberg et al., 2018). Receiving funding might also be difficult because mudflats receive organic carbon from allochthonous sources (terrestrial or adjacent salt marshes) (Sasmito et al., 2020), and the Verified Carbon Standard does not apply to allochthonous C. The reason for this is to avoid doubling C stocks which have already been accounted for in neighboring ecosystems (Wollenberg et al., 2018; Macreadie et al., 2019).

Warming effects on sediment mineralization of BwN projects

Rates of temperature rise can vary regionally and will have different effects on saltmarshes, seagrasses, oysters, and dune plants (Macreadie et al., 2019). Thermal resistant plants will survive and maintain C stocks. In parallel to plants, thermal stress may also affect microbes in the sediment which has not been previously discussed. Temperature rise can increase microbial activity, thereby increasing mineralization rates of stored organic carbon (Macreadie et al., 2019). Yet, increased productivity of the vegetation can compensate or result in a net C accumulation if the vegetation productivity exceeds the mineralization of the soil organic matter (Macreadie et al., 2019). In a seven-month laboratory study with Mediterranean seagrass *Posidonia oceanica*, remineralization rates increased 4.5 times from 15°C to 25°C, suggesting that elevated temperatures increase the activity of the microbes. However, bacterial growth declined beyond 25°C, indicating a thermal optimum for an increased remineralization rate (Pederson et al., 2011). Contrary to this study, Macreadie & Hardy (2018) found no effect of increased water temperature on the loss of C stock in the top 10 cm of seagrass sediment over the six-month study in situ due to the sediment oxygen content whose solubility decreases in high seawater temperature (Macreadie & Hardy, 2018).

Together with all these studies, the response of saltmarsh sediment C to warming is expected not to be high due to the vegetation's thermal resistance. Increased vegetation productivity can compensate increased soil mineralization, and thus the score is unchanged. This also applies to managed realignment where saltmarsh will be grown. Seagrasses are highly susceptible to temperature changes and plant mortality can occur. The final score to warming is therefore assigned to "very high" due to loss of seagrass productivity and increased mineralization. In the case of mudflats, warming has a big effect on benthic organisms; not only microbes but also macrofauna such as bioturbators. The bioturbators' activities are high under high temperature and likely to increase sediment oxidation as well as sediment instability causing mudflats erosion when tidal current is strong (Martinetto et al., 2016). Therefore, warming effect on mudflats is scored as "very high". Similarly, organic carbon mineralization in oyster reefs can become increased thus final scoring to warming is "very high".

Table 4: MCA analysis of BwN alternatives for blue carbon cooperation (scoring: 5 = very high, 4 = high, 3 = moderate, 2 = low, 1 = very low 0 = unknown)

criteria	oyster reef	saltmarsh	seagrass restoration	sand engine	managed realignment	dune strengthening	mudflat
Advantages							
C stock per area	4	5	4	1	3	3	5
long term C storage (fixed CO2 and organic carbon burial)	5	5	5	1	5	0	1
management is possible to enhance C stocks and reduce GHG emissions	4	4	4	1	3	0	2
eligibility for funding	1	5	5	1	1	1	2
Total scores	14	19	18	4	12	4	10
Sensitivity							
sea level rise	1	4	1	4	2	1	4
warming	5	1	5	1	1	0	5
frequent storms	1	4	4	4	2	3	4
Total scores	7	9	10	9	5	4	13
End results	7	10	8	-5	7	0	-3

4.3 Selection of BwN projects for blue carbon collaboration

Saltmarshes and seagrasses present the highest Advantages scores. Regarding the Sensitivity scores, mudflats are the most vulnerable to climate change, and thus their potential capacity for C storage and other ecosystem services can be lost under future climate change scenarios. Saltmarshes, seagrasses, and sand engine are the second most vulnerable alternatives to climate change.

The total scores of Sensitivity criteria were subtracted from those of the Advantages criteria. The end outcomes of the MCA analysis in Table 3 in section 4.3 shows that saltmarshes and seagrasses received the highest positive score and therefore they are chosen as first priority projects for blue carbon management. Table 5 below summarizes the BwN projects which are eligible for collaboration of Blue Carbon project. In this study, saltmarshes were chosen. The second highest rating was oyster reefs and managed realignment. MCA results for oyster reef indicate that oyster reef alone cannot be a favorable Blue Carbon project. Nevertheless, there is mounting evidence of the tight coupling between oyster reefs and saltmarshes with respect to CO_2 fluxes and mutualistic benefits. Saltmarshes offset the reef induced CO_2 (Canon et al., 1994).

Ecological support of the reefs to saltmarsh vegetation with water filtration, organic C accumulation and erosion reduction are significant (Sharma et al., 2016; Fodrie et al., 2017). Thus, the combination of oyster reefs and salt marshes is proposed for Blue Carbon project. Such hybrid designs can also be particularly useful in managed realignment blue carbon projects. In the following section, management strategies linking saltmarshes and oyster reefs are recommended.

Table 5: MCA analysis outcomes of BwN projects integration into Blue Carbon project

BwN Project	*oyster reef building*	*salt marsh restoration/ conservation*	*seagrass restoration/ conservation*	*sand engine*	*managed realignment*	*dune*	*mudflat conservation*
integrating BwN into blue carbon project	no	yes	yes	no	no	no	no

4.4 Managing saltmarsh fringing oyster reefs

4.4.1 Constructing oyster reefs

To implement the hybrid creation of saltmarsh fringing oyster reefs, salt marsh sites need to be selected. Site selection falls beyond the scope of this study and will not be attempted here. Oyster reefs can be deployed in front of saltmarshes parallel to the sea. The reefs will act as breakwater to incoming waves and reduce erosion (Figure 10). The vertical accretion and stabilization of saltmarshes rises with the growth of oysters and their sedimentation.

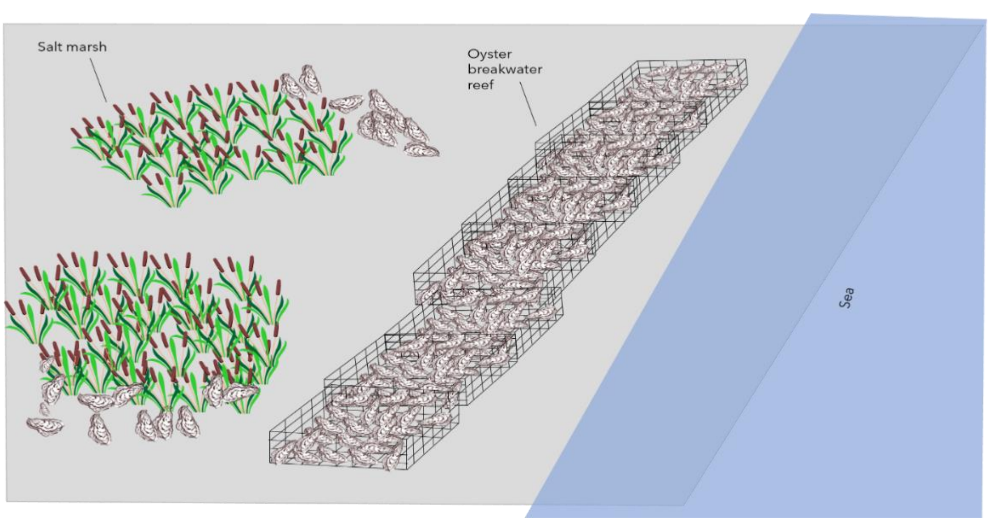

Figure 10: Ecological setting of saltmarshes with oyster reef

When construcing the reef, reef dimensions, particularly height above the sediment is an important factor since reefs height influences sedimentation patterns (Colden et al., 2017). The survival of oyster reefs depends on the balance of recruitment, growth, and sedimentation processes (Colden et al., 2017). Reefs height > 1 m is maximum oyster growth but lowest sedimentation. Sedimentation and mortality are highest on low reefs (0.1 m) (Colden et al., 2017). Therefore, 0.5 m height would be the optimum reef height to construct the reefs, which allows oysters to grow and facilitates optimum sedimentation. Furthermore, in the beginning of the construction, oysters need to be placed in boxes made of steel wire known as gabions to prevent them being washed away with the tide or during storms (Figure 11) (Colden et al., 2017). Once the oysters have established themselves, the steel wires corrode away, after which the reef will have to survive on its own, constantly renewing itself by attracting new oyster larvae and gradually building up a solid reef structure that is able to withstand winds and waves.

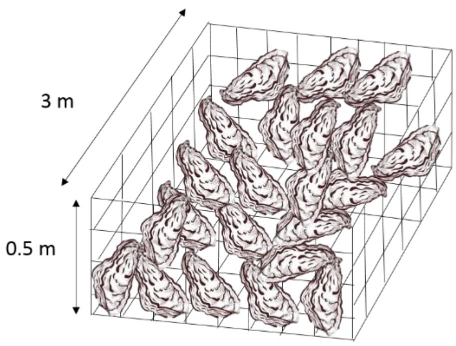

Figure 11: Optimum dimensions of a single oyster box to be used in oyster reef which will be constructed in the front line of saltmarshes *(Drawn by Thiri)*

4.4.2 Management strategies of saltmarsh-oyster reef

A range of strategies are needed to gain net C storage in saltmarsh fringing oyster reefs. Possible strategies which can increase vegetation growth and sediment C storage are (1) reducing anthropogenic nutrient inputs and (2) controlling bioturbation activities. Nutrients runoff from intensive agriculture and sewage discharge increases nutrient (N & P) inputs into coastal waters. Although there is a clear evidence that nitrate reduces C stock, the influence of phosphate is unclear yet (Macreadie et al., 2019). Increasing nitrate additionally increases N_2O emissions as denitrification increases in anaerobic situations. Managing bioturbation requires knowledge about food web structure of the site. Top down control of bioturbating populations could prevent losing sediment C stocks (Wilmers et al., 2012). When bioturbators are invasive and lack a native predator, bioturbator harvesting may be necessary in order to reduce their densities quickly (Malyshev and Quijon, 2011). Saltmarsh growth, seed recruitment, bioturbators and predator populations are necessary to monitor to track the changes of C stocks.

GHG emissions from saltmarsh-oyster reefs must be monitored to review high or low GHG emissions after restoration and to develop better management strategies. The protocol is developed for GHG measurements with gas monitors. This technical document is essentially developed to investigate the mudflats as C sink or source associated with one tidal cycle: exposed, semi-inundated and waterlogged. As the experiment was carried out in a non-ventilated climate room, our breathing contaminated the sediment core CO_2 concentration. It was optimized by flushing the core with the pump motor in order to have an ambient CO_2 concentration before the measurement started. Although it is in a developing and optimizing phase, it will be useful in further investigation of mudflats as C sink or source and GHG emissions after sea level rise which still needs to fill our knowledge gaps. The full description of protocol can be found in Appendix 2.

With regard to the financial value of the saltmarsh C credit, if the saltmarsh accumulates 2,500 t C ha^{-1} in six years and converts it from C to CO_2 with multiplication of 3.67, which is the molecular ratio weight ratio of CO_2 to C (Pendleton et al., 2012), 9,166.67 t CO_2 eq can be sold at the carbon market. Based on the EUETS 2019 average auction C price of € 24.72 t CO_2, the saltmarsh could produce € 226,600 ha^{-1} monetary value. C accumulation in oyster reefs are not eligible for carbon credits and thus monetary value cannot be determined.

4.5 Further guidance for climate change mitigation with blue carbon management

The goal of the guidance is to support an efficient start of blue carbon activities and priorities for working sectors regarding national climate change mitigation. The following sectors need to be involved in order to overcome existing gaps and achieve a specific blue carbon policy pathway. The guidance is briefly outlined in the table below.

Table 5: Guidance on specific sectors to start the Blue Carbon management for climate change mitigation

Scientific & technical progression:
○ Develop a comprehensive national coastal carbon inventory including existing carbon stocks and estimates of emissions if they are converted or degraded. ○ Develop a mapping of blue carbon distribution. ○ Identify C emissions and removals from human activities in coastal ecosystem that embody core categories for mitigating climate change. ○ Assess the types and rates of loss of coastal habitats using satellite, remote sensing, and field data. ○ Initiate pilot projects and develop management activities with baseline data and monitoring.

○ Fill knowledge gaps about the fate of eroded organic carbon (what percentages can be oxidized and redeposited in anoxic places), sea level rise effect on GHG emissions.
Stakeholder engagement:
○ Verify the departments to be involved in blue carbon management actions. ○ Build capacity at all stages of implementation to ensure participation and reporting. ○ Increase public attention to achieve their support and understanding of blue carbon activities. ○ Engage relevant coastal stakeholders and community to allow multi-stakeholder engagement. ○ Identify opportunities and risks for coastal communities.
Blue carbon financing:
○ Include blue carbon activities into national mitigation targets, *e.g*. REDD+ or emission reduction targets. ○ Trade blue carbon credits from conservation activities in international carbon markets. ○ Ensure transparency of carbon finance flows. ○ Conduct national cost-benefit analyses of blue carbon activities, together with a report of short and long-term benefits of blue carbon related activities and finance.

Chapter 5 Discussion

Over the next century, impacts of rising GHG will be a big challenge. Analogous to vegetated blue carbon systems, oyster reefs can act as large C sinks in decadal or centurial time scales. Oyster reefs are involved in two different processes of C sink and source. While oyster reef by itself represents a considerable C source in the short term, the C assimilation in carbonate shells act as a significant C sink in the long term. Furthermore, calcification generated CO_2 contributes 0.4-1.4% to the anthropogenic CO_2 emissions, which is quite small compared to anthropogenic production (Ware et al., 1992). Rather than exclusively arguing that the reef is a C source, the natural C cycle should be articulated here. Although total stoppage of $CaCO_3$ formation and $CaCO_3$ dissolution raises the seawater absorption of atmospheric CO_2, it jeopardizes the survival of calcifying organisms. Therefore, reefs-building is a valuable mean to raise seawater pCO_2 immediately. This reduces seawater uptake of anthropogenic CO_2, ocean acidification and potential harmful damages to calcifying organisms. The need to amend the international carbon trading law on the inclusion of reefs appears to be relevant given the broad perspective on inorganic carbonate sequestration and organic C burial by the reefs as well as their important ecosystem services.

While saltmarshes conservation is a final selection of the blue carbon project, other BwN projects should also be reviewed particularly in managing realignment. Sea level rise and storm surges impact on the saltmarshes are low in managed realignment as saltmarshes are surrounded by dikes. This leads to a reduced erosion and sustained C storage. Dunes, and mudflats can be investigated along with C accumulation rates, emissions, and potential C storage. According to MCA, mudflats are found to be the most vulnerable systems to climate change incidents. The ecosystem services of intertidal areas including mudflats are valued at approximately US$ 5.2 $\times 10^{12}$ yr^{-1} worldwide (Costanza et al., 2014). Efforts related to the protection of mudflats will need to increase. Nevertheless, no matter how much C is emitted or stored by mudflats, their destruction results in increase C emissions, and the loss of ecosystem services will occur. Future studies on searching mudflats with suitable hydrodynamic conditions or on building mudflats with managed realignment to regulate mudflat C stocks are needed. The Sand Engine is a C sink but its consideration in blue carbon managing is limited due to its mobility. The potential of the Sand Engine to act as C sink needs more scientific research in particular regarding the carbonate and C cycling.

Previous studies have found that an increase in nitrate concentration stimulates a decrease in C stock (Kristensen et al., 2000; Andrews et al., 2006). Therefore, controlling anthropogenic nutrient loads in coastal waters was mainly suggested for the management strategies of saltmarshes-oyster reefs. However, the effect of phosphate concentration on C stocks requires a comprehensive study. Modeling approaches are likely to give insights about the interactions of nutrients fluxes and organic C stocks.

The protocol for GHG measurement was developed with multiple tests and optimization. The measurement trends were similar using both gas monitors. Further statistical analysis is required to investigate if there is a significant difference between the trends of both devices. If no significant difference is found, research work can be rapidly performed by employing both devices. The protocol can be used in further investigation of the Dutch mudflats as C sink or source. In addition, it will assist monitor work that allows effective blue carbon management. It can also provide GHG emissions data required for C accounting. Emissions data would be useful in guiding the climate change mitigation plans of the country. Furthermore, the protocol can help demystifying the impact of sea level rise on sediment carbon mineralization and GHG emissions in Dutch blue carbon ecosystems. Sea level rise effect on carbon mineralization have been studied (Kathilankal et al., 2008; Krauss & Whitbeck, 2011; Conner et al., 2017), however, there is no conclusive agreement among previous studies. CO_2 emissions were reported as either lower or higher in flooding times. As sea level rise effect on C emissions is uncertain, research projects should address the extent to which these impacts are significant for C losses and provide new knowledge for future decisions and policies.

Chapter 6 Conclusion

Saltmarshes, seagrasses, and tidal flats are the main blue carbon ecosystems of the Dutch coast. These coastal habitats are not recognized as a mitigation strategy for climate change. Dutch coastal habitats were degraded from land reclamation, and construction of storm protection structures. Existing BwN projects are saltmarsh and seagrass restoration, oyster reef building, managed realignment, Sand Engine, dune strengthening and mudflat conservation.

In this dissertation, an integrated approach of BwN-Blue Carbon management is targeted to ensure a reduced spatial requirement and the sustainable blue carbon project. Findings of the MCA study on BwN alternatives demonstrate that saltmarsh conservation is an effective blue carbon management. Oysters are placed in front of saltmarsh lines and parallel to the sea, mimicking as a breakwater to efficiently conserve saltmarshes C stock from erosion. A hybrid ecological design of saltmarsh-oyster reefs could promote the saltmarsh growth, C accumulation rate and long term C storage in saltmarshes and the reef. Saltmarsh-oyster reefs management strategies were developed from different angles, taking into account requirements of reef-building, control on anthropogenic nutrients, and introducing the protocol for the GHG measurement with one tidal cycle. Saltmarshes are estimated to produce approximately € 226,600 ha^{-1} monetary value with the C accumulation rate of 2,500 t C ha^{-1} in six years. However, many sectors must be active to resolve current gaps and pursue a clear policy direction for Dutch blue carbon.

This study highlights the basis for the requirements of reef-building for saltmarsh-oyster reefs. Future research should focus on searching suitable sites. Andrews et al. (2006) suggested that choosing outer estuary sites for blue carbon storage can be beneficial and has fewer emissions of other GHG (N_2O and CH_4) because of the increased salinity. Accepting their suggestions, saltmarshes in outer estuary locations are reasonable locations for blue carbon projects. Spatial analysis can help to identify suitable sites with several data such as site area, salinity, shelter or hydrodynamic, existing C stocks, and C accumulation rate. Management strategies discussed in section 4.4 offer the ability to radically increase C accumulation of saltmarsh fringing oyster reefs. This ecological combination additionally provides a wide range of added value, including shoreline protection, biodiversity, and oyster harvesting, apart from C sequestration. These together strengthen the resilience of ecological and socio-economic structures to climate change effects.

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Appendix I

Table 1. Ecosystem services of blue carbon ecosystems (Adapted from Costanza et al., 1997)

No	Types of ecosystem services	Ecosystem services	Examples
1	Provisioning	Source of food	Fishing, seafood gathering by hand, aquaculture (oysters, mussels)
		Genetic resources	Genetic variability between individuals within population
		Other materials	Wood, jewelry
2	Regulating	Gas regulation	CO_2/O_2
		Climate regulation	Greenhouse gas regulation
		Disturbance regulation	Flood control, storm protection
		Water treatment and purification	Pollution control, detoxification
3	Cultural	Recreational activities	Eco-tourism, fishing, birdwatching, mud walking
		Cultural	Aesthetic, artistic, spiritual, education and research
4	Supporting	Erosion control and coastal protection	Benthic microalgae (diatoms)
		Primary production	Benthic microalgae (diatoms)
		Nutrient cycling	Nitrification, denitrification, sulphate reduction

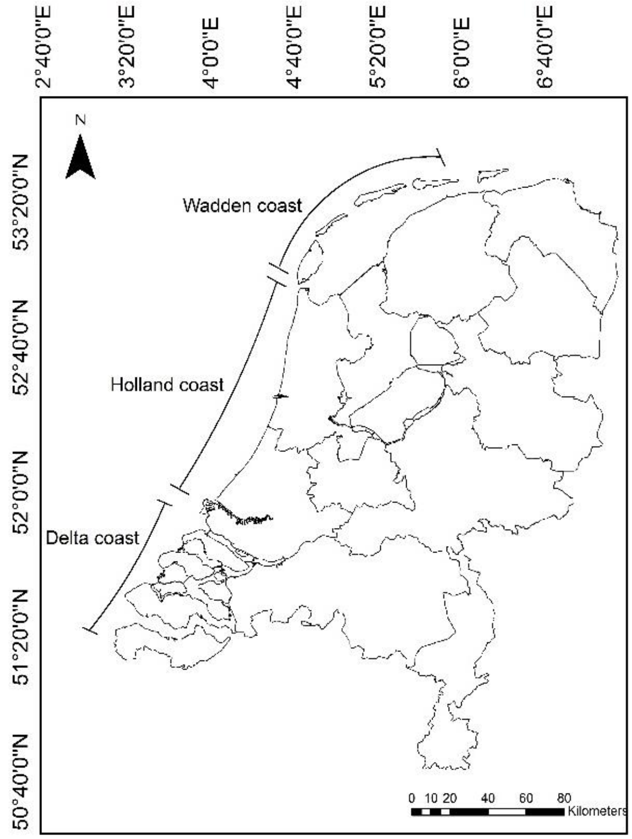


Figure 1: Map of the Dutch coast (Modified from Stronkhorst et al., 2011)

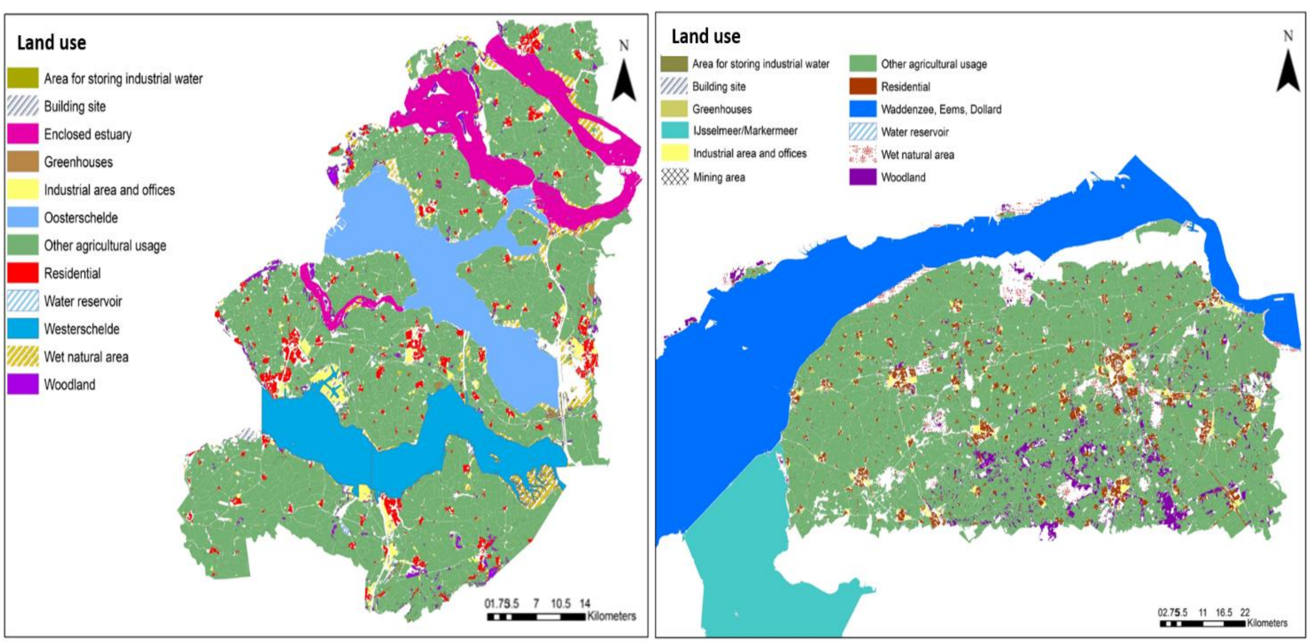


Figure 2: Maps showing 2015 Land use in the south Delta coast (left) and the north Wadden coast (right)

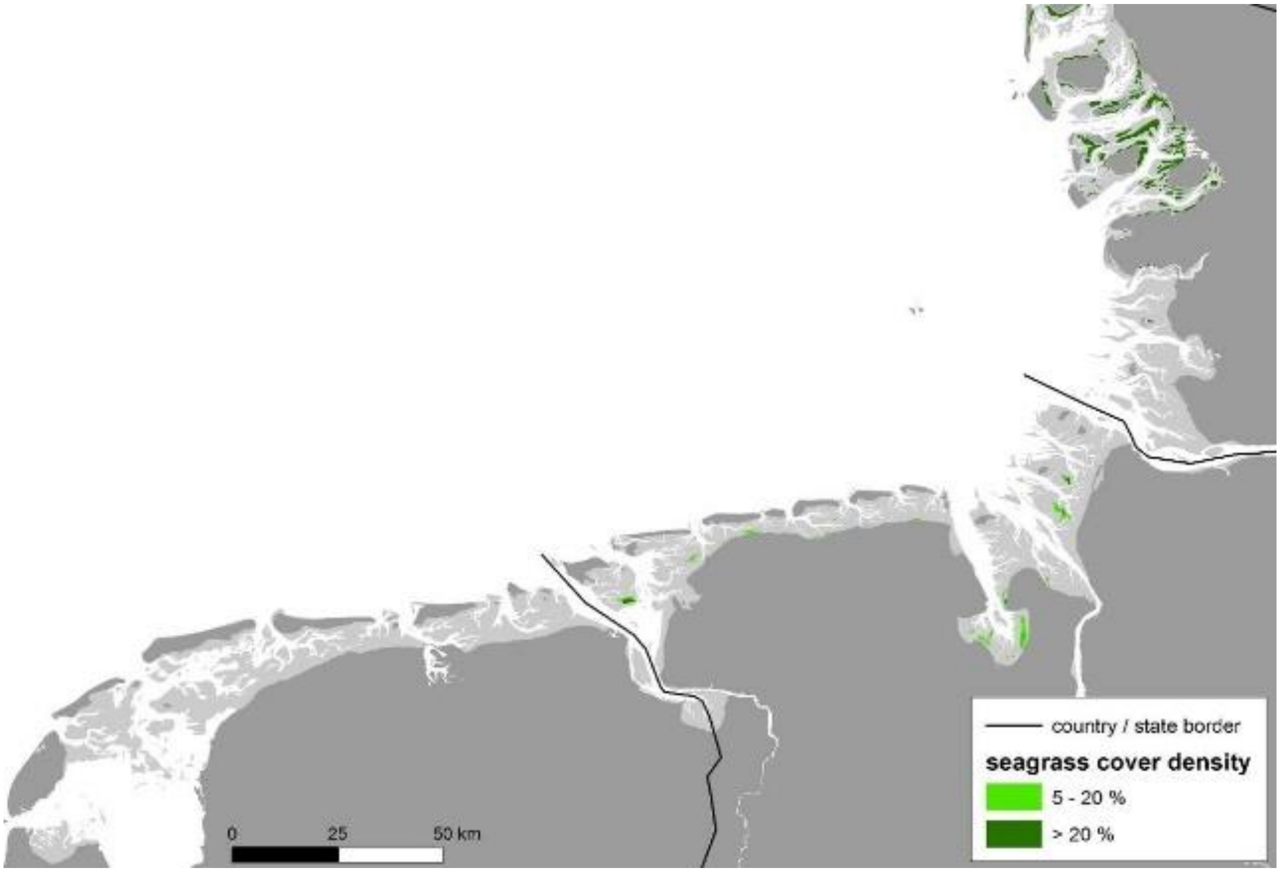


Figure 3: Spatial distribution of the seagrass beds in the Wadden intertidal area in 2015 (Folmer et al., 2017)

Appendix II

PROTOCOL FOR THE USE OF GREENHOUSE GASES MONITORS

Bookmark

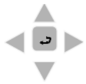
The protocol is primarily developed to investigate if the mudflats are C sink or source related with one tidal cycle. It is composed of three parts. Part I is about the familiarity of the Innova 1312 gas detector as well as the measurement procedures for greenhouse gas emissions from the sediment. Part II describes the settings and startup of EGM 5 gas analyzer for CO_2 gas measurement. Part III includes the methods of setting up the pump motor and preparing water samples for the DIC, alkalinity and pH analyses.

Part I

1.1 Innova 1312 infrared photoacoustic gas monitor

The infrared photoacoustic gas monitor measures the light absorption of gases by means of acoustic detection. It converts light absorbance (at characteristic wavelengths) to acoustic signals. The infrared light from a lamp is first modulated by a mechanical chopper and then passed through a narrow-band optical filter to remove all wavelengths except for the characteristic wavelength of a target gas. In the measurement cell, the target gas molecules absorb light, and the absorbed energy increases the temperature of the gas. Fluctuation of temperature causes an equivalent increase and decrease in the gas pressure by means of the ideal gas law, which creates sound or an acoustic signal. The acoustic signal is recorded by two microphones and converted to an electrical signal which is correlated to gas concentration. The device can measure almost any gas which absorbs infrared light. Five optical filters are installed so that the light transmitted by the optical filter is selectively absorbed by the gas.

1.2 Front panel



This group of 5 pushbuttons are direction buttons to **increase** and **decrease** numbers and to go to the **Previous** and **Next** displays.

This button functions as **Enter**.

1.3 Procedure for starting the gas monitor

i. Starting the gas monitor

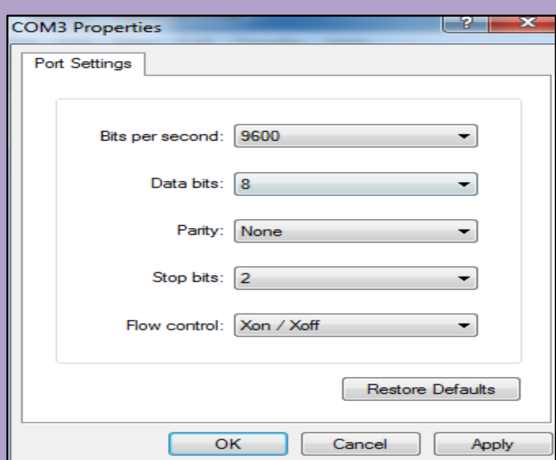
1. Turn on the gas monitor and warm it up for 15 mins.
2. Press ***Measure*** on the front panel. Press ***Start*** and ***Proceed***.
3. After measuring, press ***Measure*** and choose ***Stop measurement***.

ii. Transferring and saving the data

After the gas measurement, the data needs to be transferred to a PC. ***Do it immediately after measurement. Once the new measurement starts, the previous data will not be saved and cannot be recovered.

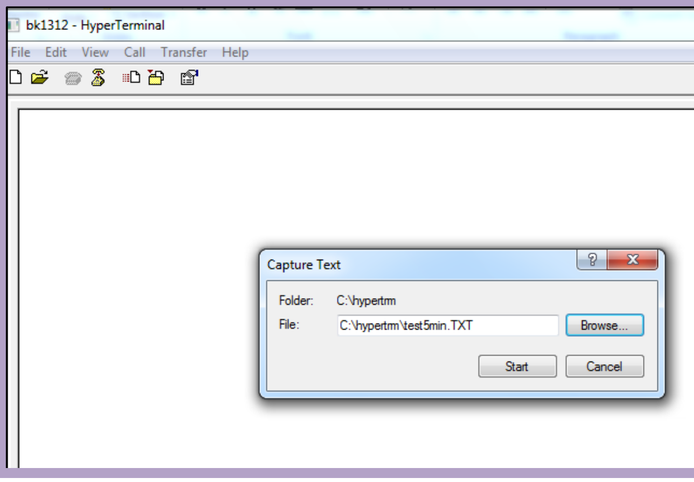
1. Click on ***Hypertherm*** icon on desktop.
2. A box will appear to fill ***Name***. Type ***bk1312*** and click ok.
3. ***COM3 Properties*** will appear to choose the ***settings***.
4. Adjust settings as the ones shown in Figure 1.

Figure 1



5. Click ***Apply*** and ***OK***.
6. Click ***Transfer*** on the menu tab.
7. Choose ***Capture text***. A box will drop to choose the folder to be saved (Figure 2), give the name.
8. Click ***Start*** after it.

Figure 2



9. Press ***Print*** on the front panel of the gas monitor. Now the data is transferring to PC.
10. After transferring, click ***Transfer*** again and click ***Capture text*** then press ***Stop***. Now the data is saved.

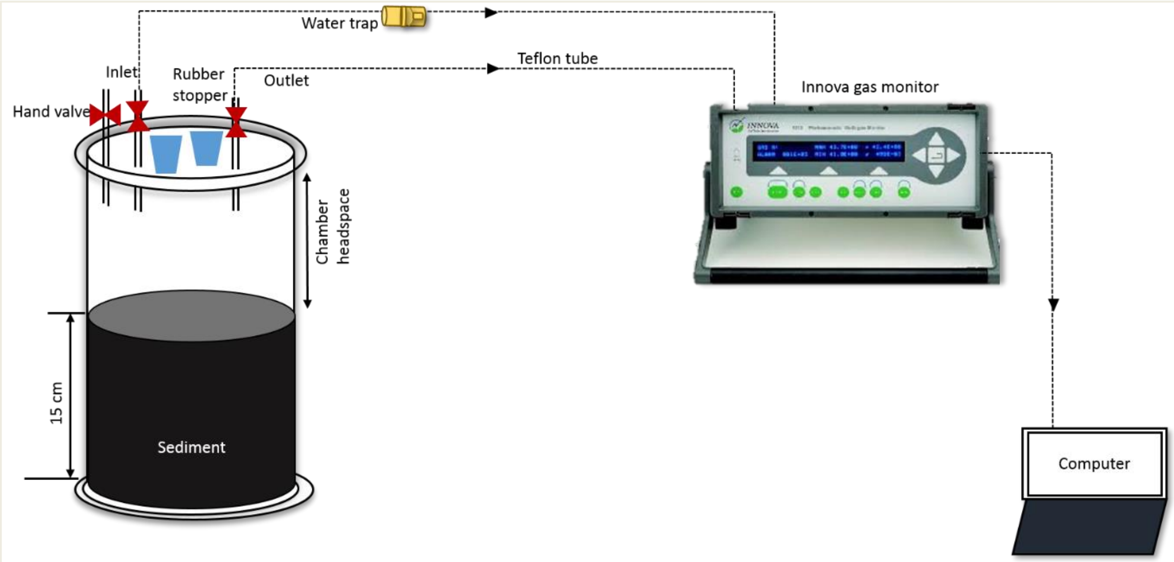
iii. Changing the sampling interval

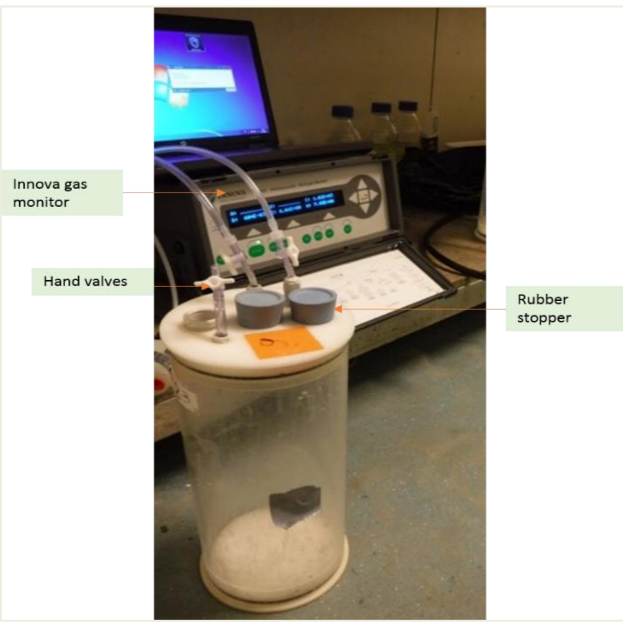
1. Press ***setup*** at the front panel of the gas monitor.
2. Press ***Measurement***
3. Then ***Monitoring task***.
4. Press ***Enter***, choose ***Yes***.

*** Double check with Peter for this method.

1.4 Gas measurement protocol for the dark tests in the climate room

Experiment set up of schematic drawing (top) and photo (below)





EXPOSED	
Procedures	**Materials**
1. Turn on and warm up the gas monitor for 15 mins. 2. Place the core with the sediment height of 15 cm in a bucket filled with water at room temperature. 3. Install the lid with 3 hand valves on top of the core by opening the rubber stoppers. If stuck, gently hit the lid with a hammer to push it down. Or slightly wet the black Ö¨ring around the lid. 4. Connect the Teflon tubes to hand valves.	1. Innova 1312 infrared photoacoustic gas monitor with 2 Teflon tube + water trap 2. bucket 3. perspex sampling core (33cm height x 14.5cm

5. Flush the headspace of the core with the pump motor to ensure that it is a homogenous mixture and not contaminated with CO_2 from our own breathing. This can be done from the open stopper holes. Stop flushing when the CO_2 value reaches ambient level (around 410 ppm). 6. Close the rubber stoppers after flushing. 7. Press ***Measure*** on the front panel. Press ***Start*** and ***Proceed.*** 8. Cover the core with the black garbage bag to prevent light from reaching the core. 9. Switch off the room light. 10. Measure for 6 hours. Every hour open the stoppers and ventilate the core with the pump motor. Stop when CO_2 value reaches around 410 ppm, or the CO_2 concentration registered inside the climate room. Record the flushing time so we can correct the time lag during data processing. 11. After 6 hours, stop measurement. Save the data. 12. Continue to semi-inundate test.	diameter) with 15 cm sediment length 4. core's top lid sealed with 3 hand valves 5. 2 rubber stoppers 6. hammer 7. pump motor (220 V) + 2 tubes (3 or 4 m length) 8. black garbage bag 9. laptop 10. climate room
SEMI INUNDATED	
Procedures	**Materials**
1. Open the lid. 2. Get the water samples in the tank collected from the site and save for DIC, pH, alkalinity, and salinity tests. For Alkalinity, the water is saved in Polypropylene centrifuge tube by filling the whole tube so little air space is made in the tube. DIC is saved in serum bottles closed with septum caps by using a crimping machine. pH and salinity are kept in sample bottles. ***Make sure the water samples are not turbid, contain particles, or have bubbles (in the case of DIC). 3. Add 200 ml of water from the site with a syringe. To prevent sediment resuspension, place a bubble wrap disc on the sediment surface and gently add the water on top of it. Remove the bubble wrap after the water addition has finished. 4. Close the lid. 5. Flush the headspace of the cores from open stopper holes. 6. Close the stoppers after flushing.	1. 1 plastic syringe (≥ 50ml) 2. septum caps (20 mm) 3. crimping machine 4. serum bottles (10 ml) 5. polypropylene centrifuge tube (50ml) 6. sample bottles 7. mercuric chloride ($HgCl_2$ (3% saturated)) 8. plastic bubble wrap cut in a circle of 15 cm diameter

7. Press ***Measure*** on the front panel. Press ***Start*** and ***Proceed.*** 8. Cover the core with the garbage bag. 9. Switch off the room light. 10. Measure for 3 hours. ***Open the stoppers and ventilate the core with the pump motor every hour. Stop when CO_2 value reaches around 410 ppm. Record this time. 11. After 3 hours, stop the measurement. Save the data. 12. Get water samples from the core for DIC, pH and alkalinity. ***Make sure the water samples are not turbid, contain particles or have bubbles. 13. Take out the remaining water in the core with the syringe. 14. Continue to the water-logged test.	9. water from the site
WATER-LOGGED	
Procedures	**Materials**
1. Open the lid. 2. Place the Firestring temperature sensor in the bucket. 3. Fill the core with new water from the site. ***Repeat the bubble wrap procedure to prevent sediment resuspension. 4. Close with the lid which is equipped with the mechanical stirrer. 5. Place one oxygen sensor into the core through one of the holes of the lid. The sensor should be held tight to prevent air exchange. 6. Make sure everything is enclosed again. 7. Open the Firestring program on the PC and record oxygen concentration. 8. Measure until 70% of oxygen saturation is reached. 9. Stop the measurement. 10. Save the Firestring file. 11. Take water samples for DIC, pH and alkalinity. 12. If needed subcore The sediment core 13. Clean everything.	1. Firestring oxygen and temperature sensors 2. mechanical stirrer equipped on top of the lid 3. water from the site

Part II

2.1 EGM 5 gas analyzer

EGM5 also functions as the light absorption of gases. Sample gases enter the collecting cell. The infrared (IR) source produces the IR wavelength and passes through the sample gas in the cell. When the cell fills with the sample gas, sample gases absorb the IR light energy. The optical filter narrows to particular wavelength absorbed by CO_2 and the reduction of IR energy that hits the detector is measured. The higher the CO_2 gas concentration, the lower the IR signal the detector receives that the Lambert-Beer Attenuation Law determines. CO_2 molecules have an absorption spectrum of 4.26 µm with very little overlap with the absorption spectrum of any other molecules, which offers good sensitivity and selectivity. The EGM 5 also includes the O_2 and H_2O sensors. For measuring the CO_2 fluxes from sediment core, the closed system a Canopy CPY-5 Assimilation Chamber is used. It is transparent and made from a strong, aluminum ring made of polycarbonate that gives the soil surface or soil collar a good seal.

2.2 Front panel

EGM5 does not have pushbuttons. It is a screen-touch design.

2.3 Procedure for starting the EGM5

i. Starting the gas monitor

1. Turn on the gas monitor and allow it to warm up for 15 mins. During warm-up, CO2 is displayed as 0 ppm. This will change when the machine starts measuring after 15 mins.
2. Connect it to the power supply for longer measurements. The flashing heartbeat in the upper left-hand corner of the display screen shows the battery life.
3. Connect the gas in and out cables of CPY to the respective probes of the gas monitor.

ii. Setting the flow rate

1. Click on ***Main.***
2. Go to ***Settings 1***.
3. Then ***Flow.***
4. Set the flow rate to be 300 cc/min which is in the optimal range of 280-340 cc/min.

iii. Checking a continuous stable measurement

If the Zero setting is not set as ***Manua***l, it should be done. This is because every 20 minutes the machine sets a zero and stops measuring for 1 minute. This has proven problematic during data analysis. To set Zero setting as ***Manual***,

1. Click on ***Main***.
2. Go to ***Settings 1.*** See Figure 3.
3. Choose ***Zero***. See Figure 4.
4. Choose ***Manual*** function.

Figure 3

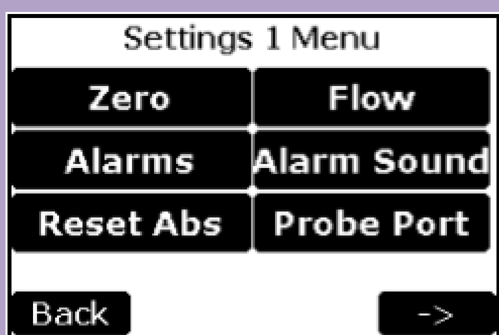
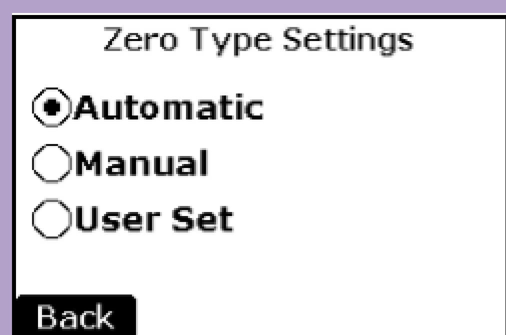


Figure 4



iv. Changing the sampling interval

1. Click on ***Main.***
2. Choose ***Settings 3***.
3. Then ***Memory***.
4. Set sampling interval to 60 seconds.
5. Format can be changed too. Choose ***M3*** which gives Date, Time, Record number, CO_2 value, Air pressure (mb), Flow rate, H_2O and O_2 reading.

v. Saving the data

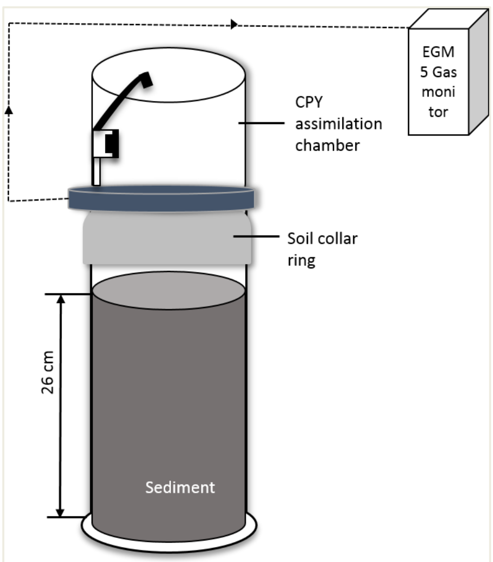
The data can be saved in different ways, but we recommend using a USB stick.

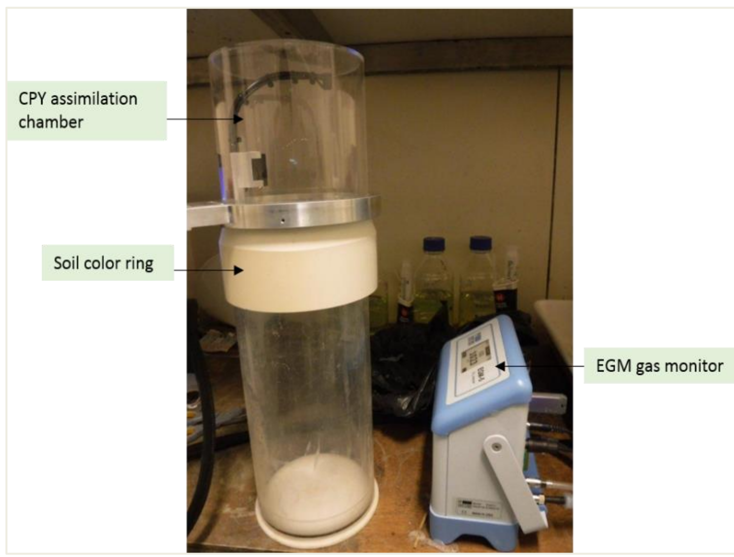
1. Install a USB drive at the USB port at the back of the machine.
2. Start the measurement.
3. Press ***Record*** on the front panel in order to save the measurement.

It is very important to press ***Record as the machine measures continuously but it doesn´t mean it is recording. The machine can take measurements without recording the data.

2.4 Gas measurement protocol for the dark tests inside the climate room

Experiment set up of schematic drawing (left) and photo (right)





EXPOSED	
Procedures	**Materials**
1. Turn on and warm up the gas monitor for 15 mins. 2. Place the core with the sediment of 26 cm height in the bucket filled with water at room temperature. 3. Join the assimilation CPY chamber with the shrinking part of the soil collar ring. Place this pair on top of the core. 4. Lift the pair a bit to flush the core.	1. EGM-5 portable gas analyzer + CPY assimilation chamber + Soil collar ring 2. bucket

5. Flush the headspace of the core with the pump motor to ensure that it is a homogenous mixture and not contaminated with CO_2 from our own breathing. Stop flushing when the CO_2 value reaches ambient level (around 410 ppm). 6. Close the pair after flushing. 7. Install the flash drive on the gas monitor and press ***Record*** to save measurement. 8. Cover the core with the black garbage bag to prevent light from reaching the core. 9. Switch off the room light. 10. Measure for 6 hours. Every hour open the pair and ventilate the core with the pump motor. Stop when CO_2 value reaches around 410 ppm, or the CO_2 concentration registered inside the climate room. Record the flushing time so we can correct the time lag during data processing. 11. After 6 hours, stop measurement. 12. Continue to semi-inundate test.	3. perspex sampling core (33cm height x 14.5cm diameter) with 26 cm sediment length 4. flash drive (≥ 32GB) 5. pump motor (220 V) + 2 tubes (3 or 4m length) 6. black garbage bag 7. laptop 8. climate room
SEMI INUNDATED	
Procedures	**Materials**
1. Open the CPY chamber pair. 2. Get the water samples in the tank collected from the site and save for DIC, pH, alkalinity, and salinity tests. For Alkalinity, the water is saved in Polypropylene centrifuge tube by filling the whole tube so little air space is made in the tube. DIC is saved in serum bottles closed with septum caps by using a crimping machine. pH and salinity are kept in sample bottles. ***Make sure the water samples are not turbid, contain particles, or have bubbles (in the case of DIC). 3. Add 200 ml of water from the site with a syringe. To prevent sediment resuspension, place a bubble wrap disc on the sediment surface and gently add the water on top of it. Remove the bubble wrap after the water addition has finished. 4. Close the CPY chamber pair. 5. Lift the pair a bit to flush the core.	1. 1 plastic syringe (≥ 50ml) 2. septum caps (20 mm) 3. crimping machine 4. serum bottles (10 ml) 5. polypropylene centrifuge tube (50ml) 6. sample bottles 7. mercuric chloride($HgCl_2$ (3% saturated))

6. Close the pair after flushing. 7. Install the flash drive and press ***Record***. 8. Cover the core with the garbage bag. 9. Switch off the room light. 10. Measure for 3 hours. *Open the CPY chamber pair and ventilate the core with the pump motor every hour. Stop when CO_2 value reaches around 410 ppm. Record this time. 11. After 3 hours, stop the measurement. 12. Get water samples from the core for DIC, pH and alkalinity. ***Make sure the water samples are not turbid, contain particles or have bubbles. 13. Take out the remaining water in the core with the syringe. 14. Continue to water-logged test.	8. plastic bubble wrap cut in a circle of 15 cm diameter 9. water from the site
WATER-LOGGED	
Procedures	**Materials**
1. Open the CPY chamber pair. 2. Place the Firestring temperature sensor in the bucket. 3. Cut the sediment. Take the top (15 cm) and dispose of the bottom half. 4. Fill the core with new water from the site. *Repeat the bubble wrap procedure to prevent sediment suspension. 5. Close with the lid which is equipped with the mechanical stirrer. 6. Place one oxygen sensor into the core through one of the holes of the lid. The sensor should be held tight to prevent air exchange. 7. Make sure everything is enclosed again. 8. Open the Firestring program on PC and record oxygen concentration. 9. Measure until 70% of oxygen saturation is reached. 10. Stop the measurement. 11. Save the Firestring file. 12. Take the water samples for DIC, pH and alkalinity. 13. At this point you can subcore the core if needed. 14. Clean everything.	1. Firestring oxygen and temperature sensors 2. mechanical stirrer equipped on top of the lid 3. water from the site

Part III

3.1 Setting up the pump motor

1. Set up the 2 pipes (3 or 4 m length); one at the inflow (which sucks in air) and the other at the outflow (which pumps air) head of the motor.
2. Plug the motor cable to the power.
3. Bring the outflow pipe into the climate room to flush the core.
4. Leave the inflow pipe outside the building, so it sucks in the outdoor atmospheric air and transports the air to the outflow pipe through the pump motor. (*We used air pumping in process because the air flow rate of pumping in was higher than that of sucking in the air out. If this method is used, test should be done to ensure that no contamination occurs from the air passed through the pump motor).

3.2 Safety for the gas monitors

The gas monitors are only designed to measure gases. They are not waterproof and thus water intrusion should be prevented in any way to prevent malfunction or total breakdown.

If one aims to perform a semi inundated test, there should be at least 5 cm of free space between the water level and the tubes on the lid which are connected to the gas monitors. For Innova, the water level should be 5 cm below the 3 hand valve tubes. For EGM 5, it should be below the bottom of the CPY chamber. In our experiments, we added 200 ml of water.

3.3 Water samples preparation

Water samples for the DIC and alkalinity tests are poisoned with $HgCl_2$ (3% saturated). The addition of $HgCl_2$ to the samples must be done in a laminar flow chamber. The use of lab coat, gloves and mask is mandatory due to the high toxicity of $HgCl_2$.

i. **Alkalinity samples preparation**

For the alkalinity water samples, add 40 µL of $HgCl_2$ into water samples with a micro syringe.

ii. **DIC samples preparation**

For DIC samples, add 10 ul of $HgCl_2$ with a micro syringe by inserting the needle into the septum caps. Care should be taken to avoid snapping the syringe tip.

Store the alkalinity and DIC in the fridge until analysis.

iii. pH samples preparation

pH samples were saved in the sample bottles and calibrated against standard buffer solutions (pH = 4, 7 and trim) at ambient temperature using a pH meter. The pH of the samples is computed in a formatted excel spreadsheet by providing the millivolt (mV) readings of buffer solutions and sample water.