An aerial view of a salt marsh in low sunlight. © Janis Meyer/Waddenagenda.

Workshop report

CO_2 Sequestration in the Wadden Sea - State of knowledge and open questions

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Content

1. Introduction

The Wadden Sea is expected to have a high potential to sequester and store carbon, but the rate at which specific habitats may contribute to the reduction of greenhouse gases has not yet been quantified at the trilateral level. Still, much knowledge exists at the national or local level, providing an opportunity to scale up estimates to the ecosystem level. Given the accelerating impact of climate change, there is increasing interest in assessing the potential for CO2 sequestration in the Wadden Sea. As a first knowledge exchange about carbon sequestration by salt marshes, sea grass, sediments, as well as mussel beds, more than 50 experts from the three Wadden Sea countries and beyond responded to the invitation from the Common Wadden Sea Secretariat and participated in the trilateral workshop "CO_2 Sequestration in the Wadden Sea-State of knowledge and open questions".

The workshop began with a series of presentations about recent findings regarding carbon cycling and carbon storage in the Wadden Sea. The findings highlighted the need to carefully assess carbon sequestration not only in different habitats, but also in different regions, while also pointing out specific knowledge gaps, especially with regard to the human use of the Wadden Sea as well as different management regimes. These points were taken up in the subsequent discussion on 1) knowledge gaps and opportunities for a trilateral assessment of CO_2 sequestration as well as 2) potential impact of management actions and anthropogenic activities on CO_2 sequestration in the Wadden Sea.

This report provides a short summary of the presentations, followed by the outcomes of the discussions and an outline of the next steps.

2. Summaries of workshop presentations

Keynote: Wadden Sea Blue Carbon – An Introduction.

Peter Müller, University of Münster

Salt marshes, mangroves, and seagrass beds, known as coastal blue carbon ecosystems, have some of the highest rates of long-term carbon sequestration. They rapidly generate new soil volume, allowing their organic carbon stocks to increase linearly, potentially for millennia. In contrast, upland terrestrial ecosystems reach a carbon saturation point, balancing carbon uptake and output through primary production and decomposition.

In coastal wetlands, soil volume increases through mineral accretion (sediment trapping by vegetation) or organic accretion (peat formation from partially decomposed plant remains, which constitute most of the soil volume). In the Wadden Sea's blue carbon ecosystems, including seagrass beds and salt marshes, mineral accretion is the primary driver.

Recently, the number of projects and studies assessing organic carbon stocks and sequestration rates has increased, enhancing our understanding of soil organic carbon balances in Wadden Sea salt marshes and seagrass beds. However, recent studies have highlighted the significant role of allochthonous (external) organic carbon contributions to salt marsh carbon stocks in the Wadden Sea, as well as substantial contributions of particulate inorganic carbon. The implications of allochthonous organic and inorganic carbon for carbon crediting are complex and require considering carbon sequestration at the seascape scale and studying vertical carbon exchange processes between coastal ecosystems.

Carbon sequestration in Dutch Wadden Sea salt marshes and the effects of grazing.

Kelly Elschot, Wageningen Environmental Research

In the Netherlands awareness is growing that natural habitats can provide important ecosystem services, e.g. the blue carbon potential of coastal habitats. Therefore, several studies estimating carbon stocks in Dutch marshes have been done in the past decade. As part of a European H2020 project called Rest-coast, sediment samples were collected at 137 locations divided over 7 marshes along the Dutch mainland coast in 2023. Permanent plots located in 5 marsh zones were selected that were already part of a large salt marsh monitoring project for the Dutch government. Vegetation composition and surface elevation change has already been monitored in these plots for multiple years, ranging between 4 and 30 years. Preliminary results showed that the carbon sequestration is driven for a large part by the surface elevation change. High sedimentation rates were measured in the most western marshes and it reduced eastwards. Another study on Schiermonnikoog showed that carbon stocks in the marsh soil stabilise with increasing age of the marsh. Carbon sequestration rates were highest in the youngest marshes, but this stabilised in mature marshes, unless livestock was introduced which increased the carbon stock significantly.

Carbon retention in Danish eelgrass habitats.

Dorte Krause-Jensen, University of Aarhus

The ability of seagrass meadows to filter nutrients and capture and store CO_2 and nutrients in the form of organic carbon (OC) and nitrogen (N) in their sediments may help to mitigate local eutrophication as well as climate change via meadow restoration and protection. This study assesses OC and N sediment stocks (top 50 cm) and sequestration rates within Danish eelgrass meadows. At four locations, eelgrass-vegetated and nearby unvegetated plots were studied in protected and exposed areas. The average OC and N sediment 50 cm stocks were 2.6 ± 0.3 kg OC m^{-2} and 0.23 ± 0.01 kg N m^{-2}, including vegetated and unvegetated plots. In general, OC and N stocks did not differ significantly between eelgrass meadows and unvegetated sediments. Lack of accumulation of excess ^{210}Pb suggested sediment erosion or low rates of sediment accumulation at most sites. OC accumulation rates ranged from 6 to 134 g m^{-2} yr^{-1} and N from 0.7 to 14 g m^{-2} yr^{-1}. Generalised additive models showed that ≥ 80% of the variation in sediment OC and N stocks was explained by sediment grain size, organic matter source, and hydrodynamic exposure. Long cores, dated with ^{210}Pb, showed declining OC and N densities toward present time, suggesting long-term declines in eelgrass OC and N pools. Estimates of potential nation-wide OC and N accumulation in eelgrass sediments show that they could annually capture up to 0.7% ± 0.5% of CO_2 emissions and 6.9% ± 5.2% of the total terrestrial N load.

Potential climate change effects on coastal ecosystems and their ability to sequester carbon.

Svenja Reents, Alfred Wegner Institute

Although coastal vegetated ecosystems such as seagrass meadows and salt marshes play an essential part in the provision of many ecosystem services (e.g. carbon sequestration), their area is declining worldwide. This negative trend is mainly driven by anthropogenic impacts such as land-use, eutrophication and climate change. Climate change effects that are most threatening for the persistence of coastal vegetated ecosystems are accelerated rates of sea level rise, rising temperatures and an increased storminess resulting in higher hydrodynamic forces acting on the coastline. How these particular climate change effects influence the vegetation and sediments of seagrass meadows or salt marshes, and thereby their ability to sequester carbon, is diverse and complex.

For example, higher temperatures can on the one hand increase plant productivity and thereby enhancing the accumulation of soil organic matter while on the other hand it might increase microbial activity within the sediment leading to an accelerated organic matter breakdown and eventually release of CO_2 back into the atmosphere. Whether one pathway dominates over the other under warming is dependent on the environmental conditions of an ecosystem and the species community (vegetation and microorganisms) within. Similarly, accelerated sea level rise and an increased storminess can have positive as well as negative effects on plant productivity, species composition or microbial activity and thus carbon sequestration.

The influence of climate change on specific local drivers of carbon sequestration has drawn increasing interest by the scientific community. However, linking climate change and blue carbon research on a regional level is challenging. It is important to further promote interdisciplinary research, including in-situ experiments and measurements to address these challenges. Further, it will improve current evaluations of the CO_2 sequestration potential of coastal vegetated ecosystems worldwide as well as in the Wadden Sea region.

Carbon effects of nature-based solutions.

Wouter van der Star, Deltares-EcoShape

Nature based solutions are aimed at restoring nature and creating a natural link between the dike and the water line. Three different examples of nature-based solutions were presented that make use of sediments extracted from the Wadden Sea: mud ripener, markerwadden, and the growing dike. To assess the effects on CO2 sequestration a system approach is needed, and assessments need to be made on different time scales, comparing the results to a business-as-usual scenario. Ripening and dredging can have strong GHG impacts, especially linked with methane emission.

Benthic-pelagic coupling impacts on the carbon system in the Wadden Sea.

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Reduced organic carbon as DOC or methane can be oxidized in intertidal sediments forming carbon dioxide (DIC), and both carbon dioxide and methane, that are strong green-house gases, and may be released from intertidal surface sediments into the bottom waters and/or directly to the atmosphere. Detailed investigations of the pelagic North Sea carbon system clearly demonstrate that benthic-pelagic coupling in the tidal areas of the southern and northern Wadden Sea impact the tidal surface waters and, therefore, the ability to interact with atmospheric CO_2.

Coastal intertidal sediments with reduced surfaces are formed when the typical balance of the biogeochemical processes is disturbed due to event-type burial of reactive organic matter, and or methane fluxes due to an upward flow of pore waters. These areas may act as windows for the liberation of reduced substances, DIC and TA. The most important anaerobic oxidation process of DOM/CH_4 is microbial sulfate reduction which is accompanied by the release of DIC. The isotopic composition of DIC, methane and acetate are necessary to characterize the different C sources and to identify the key reactions in the carbon cycle of tidal systems. Besides this, the close and dominant link to the isotope biogeochemistry of the sulfur cycle must be considered.

Due to the closeness to the coastal catchment areas, submarine groundwater discharge further impacts the coastal hydrology and associated element cycles, including carbon, to a still to be explored magnitude, that requires further isotope tracers (water and Ra isotopes) to be included.

The role of shellfish in carbon sequestration.

Henrice Jansen, Wageningen University - Aquaculture and Fisheries Group

Bivalves store carbon in tissue and shell material, and unlike any other animal the structural biomass of the shell is often larger than the meat product itself

(50-85%). The contribution of bivalves in carbon sequestration is debated in literature, and different approaches are used to quantify carbon capture. Some argue that harvesting shells from the marine system is an option for long term carbon sequestration as it locks away dissolved inorganic carbon (DIC) into a solid mineral form. Others argue that CO_2 released through respiration and biocalcification and (pseudo) faeces production and mineralisation should also be included, while others stress the importance of an ecosystem approaches (reviewed in Jansen & vd Bogaart 2020). The Wadden Sea hosts large populations of shellfish, of which part is harvested each year and could thus potentially remove carbon from the ecosystem. It is estimated that only in the shells a minimum of 65-70 thousand tons carbon is locked away in cultivated and wild shellfish in The Wadden Sea. None of the above-mentioned approaches does however account for changes in seawater chemistry, such as alkalinity. Recent studies (Morris & Humphreys 2019) highlight the importance of these processes and suggest that while calcification (shell formation) does remove DIC from seawater, it also removes alkalinity, which is capacity to store DIC. It turns out that the DIC storage capacity is reduced more than the DIC that is removed. So yet more DIC (CO_2) must be removed to return to the original $p\mathrm{CO}_2^{sw}$. To conclude, shellfish interact with carbon cycling and remove DIC from the water column, but shell formation does not contribute to CO_2 sequestration owing to simultaneous changes in the alkalinity.

What is the blue carbon potential of the German Bight? An update from the NABU WATTRenature project

Irini Brauer, NABU

Healthy seas can store enormous amounts of carbon and protect the climate. A NABU study has calculated the carbon storage potential of salt marshes, seagrass, kelp forests and the seabed in the North Sea for the first time. The salt marshes of the German North Sea coast alone already store 6.64 million tons of carbon - enough to drive a car around the world seven times! Almost 40,000 tons of carbon are stored in the soil of the salt marshes every year. The study shows: In total, the four biotopes studied store over 250,000 tons of carbon dioxide per year. The restoration and protection of seagrass and salt marshes are therefore promising and necessary means of protecting our climate.

Many marine ecosystems have been destroyed by human intervention in the past. Drained salt marshes, for example, have lost much of their carbon storage because they have been converted for agricultural purposes. Seagrass meadows on the coast of Lower Saxony have also declined sharply. 97 percent of the areas have disappeared due to poor water quality caused by excessive nutrient pollution. From a nature conservation and climate protection perspective, there is therefore a need to restore these habitats to their original state.

3. Summary of workshop discussions

3.1 What are necessary steps to assess the CO2 sequestration potential for the entire Wadden Sea?

Participants of this breakout group discussed the next steps for the assessment of carbon sequestration potential in the Wadden Sea. Overarching is the need collaborate in a trilateral approach to assess which data are currently available and how to make best use of it and identify what is missing. There was strong interest in continuing this exchange.

This includes an overview on on-going projects and who is working on what, for which this workshop provided a first effort. Also, recommendations for regular monitoring would be welcome.

Questions raised and comments included:

- Do we have spatial data for Wadden Sea habitat types and dynamics? For which do we have carbon content and sequestration data?
- Seascape scale investigations – lateral carbon fluxes
- Include old datasets, e.g., previous studies (from 80s), also to add to the exchange of inorganic and organic carbon with the wider North Sea and from terrestrial origin (catchment area)
- Investigate the contribution/role of ground water flow/ pore water in the carbon system,
- Investigate feasibility of extrapolation of information from specific sites to the entire Wadden Sea
- Parameters to investigate are e.g., allochthonous content, grain size, water content, carbon accumulation, rates, isotopes (specific interest for trilateral meeting on parameters was raised)
- To account for the difference of sites, investigate alternative parameters, such as habitat characteristics, species composition, pore size for better comparability of sites
- Budgeting and quantification of carbon needs a wider view
- How deep into the ground do we need to investigate (does a restriction to the upper meter make sense)?

- Trilateral discussions should be on best methods and best practices for monitoring and an agreement what we need to know in future.
- What is the role and scale of methane?
- Investigations of carbon fluxes in different tidal basins
- Inclusions on summer polders, also in terms of restoration
- Last but not least, the ecosystem service of carbon sequestration should be seen holistically, also in context with biodiversity, coastal protection, etc.

Key outcomes of discussion 1

➔ To get a holistic view on the carbon sequestration potential of the Wadden Sea, a trilateral approach needs to be taken.

➔ Gather information on past, present and future projects.

➔ Gain an overview on the availability of data on carbon sequestration and carbon flux in the Wadden Sea, but also similar habitats outside the area.

➔ Determine if data are comparable through assessment of methods used.

➔ Assess whether an extrapolation of information from specific sites to the entire Wadden Sea is feasible.

➔ Conduct more research into specific aspects of carbon sequestration such as allochthonous carbon, grain size, pore water content.

➔ Develop best-practice guidelines for carbon sequestration projects in the Wadden Sea.

➔ Consider the establishment of a blue carbon forum for the Wadden Sea, where carbon experts can share their knowledge with managers and policy makers, following the example from the UK.

3.2 Which management measures and other human activities may reduce the CO2 sequestration potential of the Wadden Sea?

There is a shift in the baseline of the carbon sequestration potential in the Wadden Sea, mainly due to increasing human activities, in particular bottom trawling and dredging. The main activities discussed in this group are briefly summarised below.

A recent assessment of the carbon sequestration potential of benthic habitats in the North Sea shows that bottom trawling has a significant impact. This is particularly relevant as the intensity of bottom trawling in the Wadden Sea (at least the Dutch part) is even higher than in the North Sea. Turbidity is high throughout the Wadden Sea and further increased by bottom trawling, limiting primary production. This in turn limits the restoration potential of subtidal *Zostera marina* habitats, which are important blue carbon habitats. In addition, most of the primary production in the Wadden Sea comes from benthic diatoms and much less from phytoplankton which again has an impact on carbon sequestration. Besides release of carbon from sediments, bottom trawling may also contribute to the reduction of the carbon sequestration potential of the Wadden Sea by increasing turbidity. In this context, the impact of dredging should also be considered.

The areas between the coast and the dikes have a high restoration potential. However, it is important to also consider areas behind the dikes, which are no longer wet but have good drainage, in discussions on greenhouse gas emissions as it is possible that much carbon and methane is released from these old salt marsh soils. This could mean that there is a significant restoration potential in these areas, which goes hand in hand with a significant emission reduction potential. Rewetting of old marshes with salt water could reduce methane emission. Therefore, creating brackish or saline habitats behind and between dikes in areas that were once extensive salt marshes occurred could lead to immediate reductions in methane emissions. The concept of 'Saline agriculture' should be discussed in this context.

A study from the US shows that shellfish reefs can make a positive contribution to blue carbon and carbon sequestration in nearby salt marshes. By changing water flow and speed, these reefs can increase sedimentation and accretion rates, an important aspect of carbon sequestration in salt marshes. Further monitoring and research are needed to better understand the positive interaction between natural shellfish beds (such as mussel beds and Pacific oyster reefs) and salt marshes in terms of carbon sequestration potential. This may provide additional motivation to combine the restoration of these two important habitats at the same time.

Another US study on eutrophication shows that nitrate inputs reduce the carbon sequestration potential of salt marshes. Two mechanisms have been observed: 1) Salt marsh plants don't grow their roots as deep as before, leading to increased erosion of the entire soil profile and therefore less carbon is sequestered in the soil. 2) Nitrate acts as an electron acceptor for microbial decomposition (stimulates microbial decomposition), which has been shown to mobilise old organic carbon from deep in the soil profile.

Key outcomes of discussion 2

- ➔ It was recognised that human interventions caused a shift in baseline of the carbon storage potential in the Wadden Sea.
- ➔ Bottom trawling and dredging are likely to have a strong impact on carbon sequestration potential and storage due to the release of organic carbon stored in sediments and the resuspension of fine sediments into the water column, further increasing turbidity.
- ➔ Sediment resuspended by bottom trawling and dredging may deposit elsewhere, but knowledge on mud-deposition centres in the North Sea/Wadden Sea, potentially storing the released carbon, are missing.
- ➔ Increased turbidity affects primary production of macroalgae and creates a bottleneck for subtidal seagrass beds.
- ➔ While shellfish itself do not significantly contribute to carbon sequestration, their reef structures could alter water flow and contribute to deposition of sediment on nearby salt marshes (thereby potentially partly altering negative effects of dredging).
- ➔ Eutrophication: Nitrate inputs lower carbon sequestration potential in salt marshes due to lower development of root system (increasing erosion) and stimulation of the microbial decomposition which mobilise organic carbon from the soil in decomposition by the microbial community.
- ➔ Hot potato: Methane emission behind the dikes could be significantly reduced by creating brackish or saline habitats, that is where is a lot of potential to restore.

4. Summary and next steps

During the discussion important knowledge gaps (Discussion 1) and possible threats, but also opportunities (Discussion 2) related to carbon sequestration in the Wadden Sea were identified. It was frequently pointed out that a holistic view is needed, as carbon sequestration is only one of several ecosystem services provided by Wadden Sea habitats and management for increased carbon storage should not have negative effects on other aspects such as biodiversity conservation or coastal protection. In this regard, consideration should also be given to the new Nature Restoration Law. Furthermore, it was pointed out that the rate at which Wadden Sea habitats can sequester carbon is much lower than the current rate at which the Wadden Sea countries emit carbon, highlighting the urgent need for the reduction of carbon emissions. In this respect, the prevention of old carbon being mobilised from natural sources (e.g. old salt marshes behind the dyke, degraded seagrass beds) was highlighted. Besides, an ethical question was raised related to the carbon balance of restoration projects which use heavy machinery that contributes to carbon emission.

To advance the understanding of carbon sequestration in the Wadden Sea, a few immediate steps can and shall be taken:

1) Trilateral exchange on latest findings should be further strengthened.
CWSS established a working group on the Wadden Sea Exchange Platform as an opportunity for experts to share information on projects, reports, papers or events linked to carbon sequestration in the Wadden Sea. Experts interested to join the group and not yet registered on the exchange platform are asked to contact CWSS for registration.

2) Collate information on past, present and future projects that (at least partly) deal with sequestration and storage of carbon and other greenhouse gases in the Wadden Sea.
CWSS prepared a survey to gather information on carbon projects from all relevant stakeholders in the Wadden Sea countries.

3) Provide an overview of data availabilities and methodologies of ongoing projects.
A study shall be commissioned to collate information on data availabilities and methodologies for future discussions of Wadden Sea experts regarding a trilateral assessment of carbon sequestration and storage of different Wadden Sea habitats.