ÖSTERSJÖSTIFTELSEN
THE FOUNDATION FOR BALTIC AND EAST EUROPEAN STUDIES

SCIENTIFIC FINAL REPORT
Two- and three-year projects and postdoctoral projects

Registration number, Östersjöstiftelsen: 21-PD2-0002

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Project title: Unravelling the relative influence of climate and land-use change on nitrogen retention in Baltic Sea coastal sediments over the last 300 years

1. The three most important results of the project and what conclusions can be drawn from them

1. Seagrass meadows in the Baltic Sea can constitute large and old carbon and nitrogen sinks if the environmental and geomorphological conditions are favourable.

In the project we found that seagrass carbon and nitrogen stocks in the Baltic Sea were considerably higher than previous publication with equal storage levels as the high seagrass carbon and nitrogen stocks on the Swedish west coast (Dahl 2024; Dahl et al. manuscript). We also found that the short-term accumulation rates of the carbon and nitrogen sinks over the last 100 years were similar. However, the seagrass meadows in the Baltic Sea showed difference in carbon and nitrogen storage permanence as one studied seagrass meadow was established not more than a century ago (marking the starting point of the carbon and nitrogen accumulation) while another was at least 1,700 years old, and that a mixed seagrass meadow (with other rooted vegetation) was likely established 4,000 years ago (Dahl et al. manuscript). This difference in seagrass colonization time is likely driven by the geomorphological setting as the older seagrass meadows were growing in hydrodynamically sheltered areas, which favours seagrass growth, while the more recent seagrass meadows was growing in a more exposed location leading to sediment erosion and less organic matter input from surrounding habitats.

2. The main environmental factor for seagrass carbon and nitrogen accumulation is likely the colonization of the seagrass meadows rather than land use- and climate change.

We found on the Swedish west coast that the main factor for changes in carbon and nitrogen accumulation was the establishment of the seagrass meadow rather than changes in climate. Once the seagrass started to colonize the study area, the carbon and nitrogen content of the sediment increased 20 to 24-fold (Dahl et al. 2024). However, climatic changes could still play a role in creating a favourable environment for the seagrass to establish (e.g. increasing temperature). Furthermore, there were no indication of seagrass decline when assessing future regional climate scenarios in relation to known seagrass tolerance levels. In the study by Dahl et al. (2024) we found that the reason for seagrass colonization was likely due to land-up lift following the last glacial period and the colonization time was estimate to around 2,000 years ago when the study area became sheltered and shallow enough for the seagrass to establish.

In the Baltic proper, preliminary results show similar patterns to that on the Swedish west coast and identified the colonization of the seagrass meadow as the main driver for carbon and nitrogen stock increase and not change in land use or climate. However, there are some

indications that land-use over the last 3000 years could have a minor influence when correlating the sediment characteristics with land use change models (Vinogradova et al. 2024; Dahl et al. manuscript). More clearly were changes observed in more recent (the last 100 years) sediment deposits, which showed signs of anthropogenic activities and industrialized agriculture leading to increased terrestrial run-off and mobilization of organic matter (Dahl et al. unpublished). This observation was also seen in Andrén et al. (2024) from a nearby location, which further strengthens this finding.

3. Other coastal ecosystems in the Baltic Sea besides seagrass meadows can also be important carbon and nitrogen sinks.

In several of the studies we found that other coastal ecosystems, such as shallow unvegetated bottoms, deeper accumulation bottoms, had comparable or higher carbon and nitrogen stocks to seagrass meadows in the same area (Wikström et al. 2025; Andrén et al. 2024; Gubri et al. in press). The results showed that the vegetation had a minor role in the carbon and nitrogen sink function and that level of enclosure and protection of wind and wave forces were of most important for the accumulation of organic matter, which leads to greater accumulation rates and trapping of organically-rich particles (Wikström et al. 2025; Gubri et al. in press). This highlight that the Baltic Sea coast as a whole can serve as a sink for carbon and nitrogen to mitigate climate change and eutrophication.

2. The project's contribution to the international research frontline

There has been an ongoing debate during the last years weather to expand the coastal habitats defined as important carbon and nitrogen sinks. Previous research has focused mainly on seagrass meadows, salt marshes and mangrove forest. This project adds to this discussion by providing data on other habitats with equal high accumulation rates. Therefore, the findings from this project can contribute to expanding the current view and definition of what is considered an important carbon and nitrogen sink.

This project also demonstrates co-benefits of the accumulation of organic matter in coastal habitats by not only storing nitrogen but also carbon and phosphorous, which show that restoration and conservation of these ecosystems provide multiple ecosystem services for people and the environment.

The longevity and permeance of the carbon and nitrogen sinks is important for their capacity to mitigate mitigate climate change and excess nutrient loads. The findings show that some seagrass meadows (eelgrass) have existed and functioned as carbon and nitrogen sinks for thousands of years, which has not been documented before. This shows that coastal ecosystems do not only continuously sequester carbon and nitrogen but also that the sink function can be maintained on millennial time scales. Therefore, the conservation and protection of these ecosystems is of high importance as disturbance, such as dredging, increased sedimentation, coastal constructions or boating activities, can lead to degraded ecosystems and release of buried carbon and nitrogen though sediment erosion. These human activities can therefore turn the ecosystems from a sink to a source of greenhouse gas emissions and nutrient leakage, which again highlight the importance of conservation and protection of coastal ecosystems.

3. The contribution of the research to the knowledge of the Baltic Sea Region and Eastern Europe

The Baltic Sea region is clearly lacking data on coastal carbon and nitrogen sinks. This project adds carbon and nitrogen data on both temporal and spatial scales as well as on less studied coastal ecosystems. For example, data on accumulation rates of carbon and nitrogen in Baltic Sea coastal ecosystems was previously very sparse with only a handful of studies (and completely lacking in a Swedish context). Furthermore, the project contributed to the first known age determination of historical establishment of eelgrass meadows in the Baltic Sea and demonstrated that they can act as carbon and nitrogen sinks over millennia. Findings from this project also gained insights into Baltic Sea seagrass meadows as indictors for environmental change over thousands of years and especially recent anthropogenic activities. Although other ecosystems, such as deeper accumulation bottoms, might be more suitable as paleo-archives due to the generally slow sediment accumulation rate (leading to poorer age resolution) in the studied seagrass meadows, coastal ecosystems may still serve as an important indicator for environmental change as they generally are the habitats being first affected by land-based human activities due to their close proximity to land.

The understanding on the carbon and nitrogen sink function in Baltic Sea coastal habitats has therefore greatly expanded through the studies generated by the project. This information can guide management of coastal ecosystems in the Baltic Sea region to improve conservation and restoration efforts where one key aspect is to protect the coastal ecosystems and maintain ecosystem health to avoid release of historically accumulated carbon and nitrogen.

4. New research questions that the project has led to

There are several new research questions generated by the project. One key aspect of understanding seagrass carbon and nitrogen sinks is the time and age of the accumulation. This was estimated in only two locations (Västervik and Bråviken) in the Baltic Sea but to understand this on a regional scale, research should be conducted in several seagrass meadows (in a gradient from Kattegat to the Bothnian Bay, to capture the spatial variability and to understand natural seagrass colonization across time. Another research topic is to understand the drivers of coastal carbon and nitrogen storage (e.g. vegetation type, geomorphological setting or climate- and environmental changes). Furthermore, to increase the knowledge on Baltic Sea coastal carbon and nitrogen sinks, research needs to be expanded to include other types of habitats besides seagrass meadows (such as other rooted vegetation, unvegetated sediments and reed beds). Not only do we need to understand the quantity of the carbon and nitrogen storage functions in terms of mapping and stocks and accumulation rates but also the longevity and permanence of the sink.

5. Dissemination of the results of the project within and outside the research community

Published scientific articles (all are published as open access):

1. Wikström SA, Gubri B, Asplund ME, **Dahl M**, Gullström M, Hansen JP, Kumblad L, Rydin E, Garbaras A, Björk M. (2025). Influence of landscape characteristics and submerged aquatic vegetation on sediment carbon and nitrogen storage in shallow brackish water habitats. Scientific Reports, 15(1), 7808. https://www.nature.com/articles/s41598-025-92217-z
2. **Dahl M**, Lavery PS, Mazarrasa I, Samper-Villarreal, J, Adame MF, Crooks S, Duarte CM, Friess DA, Krause-Jensen D, Leiva-Dueñas C, Lovelock CE, Macreadie PI, Masqué P, Mateo MA, Oscar Serrano (2025). Recommendation for strengthening blue carbon science. One Earth, 8, 101175. https://www.cell.com/one-earth/fulltext/S2590-3322(25)00001-6
3. **Dahl M**, Asplund ME, Björk M, Bergman S, Braun S, Forsberg SC, Hällberg P, Löfgren E, Smittenberg R, Svensson JR, Gullström, M (2025). Evaluating seagrass lipid biomarkers as indicator for organic carbon provenance and storage capacity in *Zostera marina* (L.) sediments. Science of The Total Environment, 959, 178324. https://www.sciencedirect.com/science/article/pii/S0048969724084821
4. Katrantsiotis C, Vinogradova O, **Dahl M**, Palm V, Rönnby J, Gaillard, M-J, Andrén T, Andrén E. (2025). Holocene shoreline displacement, land-cover change and human settlement distribution on the southeast coast of Sweden. Journal of Quaternary Science, 40, 124-140. https://onlinelibrary.wiley.com/doi/full/10.1002/jqs.3666
5. Andrén, E, Vinogradova O, Lönn M, Belle S, **Dahl M**, Palm V. Nielsen A-B, Jakobsson M, Rönnby J, Andrén T. (2024). Modern land use changes drive shifts in nutrient cycling and diatom assemblages in the Baltic Sea coastal zone: A millennial perspective with a case study from Gamlebyviken, Swedish east coast. Quaternary Science Reviews, 346, 109058. https://www.sciencedirect.com/science/article/pii/S0277379124005602
6. **Dahl M**, Gullström M, Bernabeu I, Serrano O, Dueñas CL, Linderholm HW, Asplund ME, Björk M, Ou T, Svensson JR, Andrén E, Andrén T, Bergman S, Braun S, Eklöf A, Ežerinskis Z, Garbaras A, Hällberg P, Löfgren E, Kylander ME, Masqué P, Sapolaite J, Smittenberg R, Mateo MA (2024) A 2,000 - year record of eelgrass (*Zostera marina* L .) colonization shows substantial gains in blue carbon storage and nutrient retention. Global Biogeochem Cycles 38:e2023GB008039. https://agupubs.onlinelibrary.wiley.com/doi/pdf/10.1029/2018GB005941
7. Vinogradova O, Gaillard MJ, Andrén E, Palm V, Rönnby J, **Dahl M**, Almgren E, Karlsson J, Nielsen AB, Åkesson C, Andrén, T. (2024). 3000 Years of past regional and local land-use and land-cover change in the southeastern Swedish coastal area: Early human-induced increases in landscape openness as a potential nutrient source to the Baltic Sea coastal waters. The Holocene, 34, 56-73. https://journals.sagepub.com/doi/full/10.1177/09596836231200433

8. **Dahl M**, Asplund ME, Bergman S, Björk M, Braun S, Löfgren E, Martí E, Masqué P, Svensson R, Gullström M. (2023). First assessment of seagrass carbon accumulation rates in Sweden: a field study from a fjord system at the Skagerrak coast. Plos Climate 2, e0000099. https://journals.plos.org/climate/article?id=10.1371/journal.pclm.0000099
9. **Dahl M**, McMahon K, Lavery, PS., Hamilton, SH, Lovelock, CE, Serrano, O. (2023). Ranking the risk of CO_2 emissions from seagrass soil carbon stocks under global change threats. Global Environmental Change 78, 102632. https://www.sciencedirect.com/science/article/pii/S0959378022001704
10. Katrantsiotis C, **Dahl M**, Palm V, Rönnby J, Andrén T, Andrén E. (2023). Holocene relative sea level changes in the Vastervik-Gamlebyviken region on the southeast coast of Sweden, southern Baltic Sea. Boreas, 52, 206-222. https://onlinelibrary.wiley.com/doi/full/10.1111/bor.12605

On going manuscripts:

1. **Dahl M**, Braun S, Asplund ME, Forsberg SC, Andrén T, Andrén E, Björk M, Svensson JR, Kylander M, Faizal MV, Kaal J, Garbaras A, Ežerinskis Z, Šapolaitė J, Mateo MA, Serrano O, Masqué P, Gullström M. Influence of past and future climate and land-use change on carbon and nitrogen accumulation in Baltic Sea seagrass meadows. (manuscript)

Popular science articles:

1. **Dahl M**, Gullström M, Asplund ME, Björk M. Våra viktiga sjögräsängar – tusenåriga kolsänkor. Havsutsikt nr. 2 2024.

Conferences (presenter are bolded):

1. Dahl M, **Braun S**, Asplund ME, Forsberg SC, Andrén T, Andrén E, Björk M, Svensson JR, Kylander M, Faizal MV, Kaal J, Garbaras A, Ežerinskis Z, Šapolaitė J, Mateo MA, Serrano O, Masqué P, Gullström M. Influence of past and future climate and land-use change on carbon and nitrogen accumulation in Baltic Sea seagrass meadows. EGU, Vienna, 2025.
2. **Dahl M**, Lavery PS, Mazarrasa I, Samper-Villarreal, J, Adame MF, Crooks S, Duarte CM, Friess DA, Krause-Jensen D, Leiva-Dueñas C, Lovelock CE, Macreadie PI, Masqué P, Mateo MA, Oscar Serrano. Recommendation for strengthening blue carbon science. ASLO, Mallorca 2024.