Carbon-Smart Harvest and Carbon Sequestration in Tideland Oyster Aquaculture

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July 2025

Project supported by the Washington State Conservation Commission’s Sustainable Farms and Fields Program

Acknowledgements: We thank Francisco Meliton, Hector Meliton, Drummond Wengrove, Morgan Palmer, Clara Stanbury, Orin Beitz, and Kendall Fontenot for help with field work on this project.

Summary

In this report, we highlight measurements of sediment organic carbon in active oyster aquaculture tidelands in Willapa Bay, WA to demonstrate both the carbon value of these ecosystems and potential methods for minimizing carbon emissions during the harvesting process. We collected sediment samples before, immediately after, and several months after harvest to determine change over time at three sites with different harvest history. One site has been hand-harvested historically but was mechanically harvested during our study period. One site has been consistently mechanically harvested. The final site, which had been previously mechanically harvested, piloted a precision harvest method. A total of 27 sediment cores were taken on active aquaculture beds and analyzed for organic material. Our key results are:

- Unvegetated tidelands used in oyster aquaculture have carbon stocks and carbon accumulation rates that rival those from seagrass and marsh systems
- Mechanical harvest of oyster beds has a short-term impact on the surface (top 10 cm) of the flats. Following harvest, carbon is removed from the system. Within 4 months of harvest, the tidelands return to their state prior to harvest.
- When compared to mechanical harvest methods, precision harvest methods appear to minimize impacts on the bed and reduce the recovery time following harvest.
- Therefore, the assessments provided in this report underestimate carbon capture compared to vegetated tidelands.

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Background and Motivation

Coastal environments store disproportionately large amounts of carbon compared to terrestrial systems (Macreadie et al., 2021). Intertidal zones tend to accumulate sediment and organic matter over time at a rate related to sea level rise, continually adding to the carbon pool (Chen and Lee, 2022); this process does not occur in terrestrial ecosystems. Therefore, leveraging productive, economically-active intertidal areas' natural ability to continually store carbon is a smart solution to help mitigate climate impacts. In this way, we can harness the power of nature to maximize climate-smart efforts.

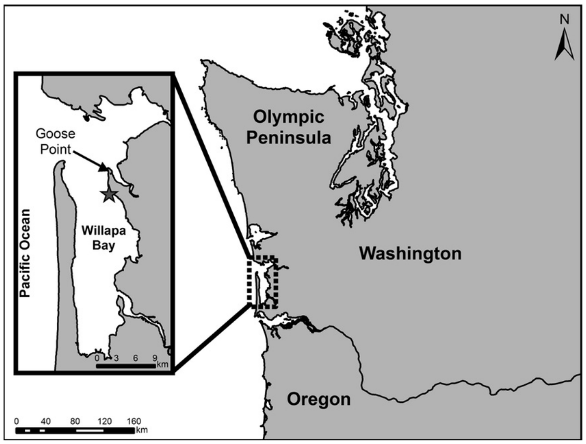

Figure 1. Map of Willapa Bay, WA. Samples were taken on tidelands of Goose Point Oyster Company. Figure from Lahane and Eckdale 2013.

In Pacific County, and other coastal communities across Washington and the world, on-bottom oyster aquaculture is a key economic driver. Shellfish aquaculture is the top employer in Pacific County and a top employer in Mason County, contributing $270 million annually to the economy (USDA, 2013). Many tidelands host vibrant aquaculture activities that support local economies and cultural traditions. For this report, we focused on on-bottom oyster aquaculture sites in Willapa Bay, WA managed by Goose Point Oysters (Figure 1). For on-bottom aquaculture, oysters are generally planted on tidelands and then harvested, sometimes years later, via several methods. The harvested oysters may be transplanted to other beds for further growth or put into food production and processing to be sold. On-bottom oyster culture employs two primary harvest methods: traditional hand harvest or mechanical harvest. Hand harvest requires low tides and large amounts of labor, meaning it is inefficient. This method has the least impact on the sediments, as each oyster is hand lifted from the bed. To overcome the challenges of hand harvest and to keep up with the extent of oyster farms and demand, many on-bottom oysters are harvested mechanically. This involves using dredge baskets attached to boats to lift oysters from the bed. This process can be done during a wider range of tides, harvesting at a much faster rate than hand harvest. However, this process disturbs the sediment, potentially releasing stored carbon and impacting the benthic ecosystem.

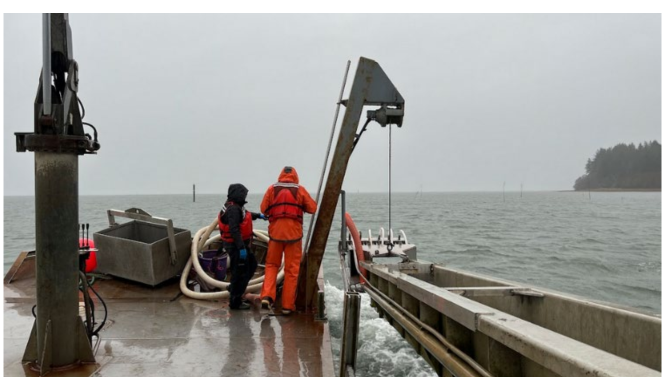
Figure 2. Prototype precision harvest arm mounted on the boat.

Here we report sediment carbon capture in tidelands actively farmed for on-bottom oyster aquaculture with the goal of testing the impacts of a precision mechanical harvest technique (Figure 2) that would maintain the flexibility and efficiency of mechanical harvest while reducing the impact to the bed sediment and potentially increasing carbon stock in the tidelands. We compare this to traditional mechanical harvest in Willapa Bay, WA.

Linking Tideland Aquaculture and Terrestrial Agriculture Practices

In this report, we are specifically quantifying both (1) the organic carbon stored in the sediments on active oyster beds and (2) the amount of carbon released following harvest of the oysters. For both tideland aquaculture and terrestrial (upland) agriculture, tilling and disturbance of the soils/sediments manually moves the carbon and introduces more oxygen, leading to faster rates of carbon decomposition. In terrestrial agriculture, carbon-smart farming practices have focused on maintaining carbon in soils (Maraseni et al., 2021; Bai et al., 2019). This includes the use of cover crops to reduce soil and associated carbon losses, as well as conservation tillage. For aquaculture, the same types of methods can be used to reduce greenhouse gas emissions. Through the precision harvest method we are testing here, this could be considered conservation tilling. Likewise, oysters shield the seabed, preventing erosion and soil loss (Dugan et al., 2017).

All production of food requires an input of carbon for transportation, machinery, and the like. The reduction of carbon emissions for food production has focused on this aspect. For example, irrigation significantly increases the carbon emissions from terrestrial farm fields (Qin et al., 2024). It is notable that in tideland aquaculture, carbon emissions from production are at a minimum; they require no irrigation, no fertilizer application, or many other carbon emission sources common to terrestrial agriculture (Ray et al., 2019; Barrett et al., 2022). The reduced nature of emissions from aquaculture compared to terrestrial agriculture means that for a "net-zero" goal, tidelands would be able to achieve this more easily. On the other hand, given that aquaculture practices are *a priori* more carbon-efficient compared to terrestrial agriculture, there is less opportunity to greatly reduce carbon emissions. As with terrestrial farming, aquatic farming has some impacts on the sediments, and therefore the carbon. Terrestrial soils can be rich in carbon, but have low to no accumulation, meaning that their carbon stocks are static over time (Schimel, 1995). Given that tidelands continue to accumulate carbon over time, this highlights the importance and value of intertidal zones for carbon-smart farming practices.

Literature Overview

Intertidal Carbon

Previous work has demonstrated that aquaculture beds can be significant carbon stores.
The primary components contributing to the organic carbon capture are (1) eelgrass (2) biofilms, and (3) organic particles adsorbed onto sediments.

Seagrass or eelgrass meadows have been heralded as ecosystems with high carbon stock potential (Fourqurean et al., 2012) and are currently considered a Blue Carbon ecosystem (Macreadie et al., 2021; Macreadie et al., 2019). Seagrasses are vascular submerged aquatic vegetation, meaning they have roots and a vascular system, more similar to terrestrial vegetation. This is markedly different from seaweeds, which have neither vascular systems nor roots. Seagrasses provide living above-ground and below-ground biomass. Additionally, the stems trap organic matter and muds, increasing accumulation rates and trapping carbon. The carbon from seagrasses is considered autochthonous, or locally-produced, a currently necessary metric for carbon crediting programs (James et al., 2024). This has been a relatively well-tested idea over the last decade but there are some concerns about long-term carbon capture in the Pacific Northwest (Prentice et al., 2020).

Figure 3. Example of (A) eelgrass and (B) biofilms in Willapa Bay, WA. Eelgrass photo by Kaylee Domzalski, OPB in Solomon 2019 on Goose Point Oyster tidelands. Biofilm photo by K. Valentine.

Beyond seagrasses, microbial mats or 'biofilms' are the other primary producers on tideflats that create autochthonous carbon. These mats, composed of photosynthetic cells and their secretions (Decho, 2000) play an important role on the tideland. Recent work has highlighted the potential for this carbon to contribute to sediment carbon stock (Valentine et al., 2022), as well as altering sediment transport. Biofilms are well-documented within Willapa Bay (Wiberg et al., 2013) and may be an important carbon source in the tidelands (Figure 3).

Organic particles attached to sediments, also known as mineral-associated organic carbon, create a form of carbon that is well-preserved and difficult to decompose. The chemical structure of the mineral-associated organic carbon provides protection to the organic matter. The amount of carbon attached to sediment particles is largely dependent on the surface area of the grains (Keil et al., 1994). The volume of sediment, including fine sediments, in Willapa Bay (Boldt et al., 2013) indicates a high potential for this type of carbon to dominate the system.

Oysters and Carbon Burial

It is notable that the carbon molecules used to create oyster shells do not further draw down carbon in most situations. Calcification of oyster shells occurs through the combination of calcium ions and carbonate ions in the water, where two dissolved carbon atoms are converted into calcium carbonate (the oyster shell) and carbon dioxide:

$$\mathrm{Ca^{2+}} + 2\mathrm{HCO_3^-} \leftrightarrow \mathrm{CaCO_3} \downarrow + \mathrm{CO_2} + \mathrm{H_2O}$$

Through this process, one atom of carbon is "sequestered" in the shell, while the other one is released as carbon dioxide and then exists as a species of carbon in the water or atmosphere depending on ambient conditions. However, the oyster animal itself also respires, releasing carbon dioxide as well. Therefore, the amount of carbon stored in the shells is offset by respiration of the animals, leading to no net carbon sequestration (Munari et al., 2013). This is true of the living oyster. There are other considerations here regarding the respiration rate of the oysters, and the full life cycle of the oyster versus the shell, but those will not be included in this report.

Although we are making the assumption for this report that the carbon in the oyster shells does contribute to carbon stock, the presence of the oysters alters the hydrodynamics, leading to changes in sedimentation rate and carbon capture. Roughness elements on the seabed, including oysters, interact with the flow, reducing the energy in the flow through friction (Reidenbach et al., 2010; Chatelain and Proust, 2021). As the flow slows, this reduces the capacity for the flow to carry sediment and can lead to increased sedimentation. Likewise, the rough elements of the bed provide protection from the flow, reducing resuspension. Previous work has documented increased sediment, and therefore carbon, trapping from oyster beds (Pietros and Rice 2003; Veenstra et al., 2021). Floating aquaculture has demonstrated varying responses to sedimentation, where high production of organic sediments from oysters deposited beneath the structures or were transported away, depending on local hydrodynamics (Forrest and Creese 2006; Everrett et al., 1995; Mitchell, 2006).

Methods

Figure 4. Site map of Willapa Bay, with inset images of the sites with property lines denoting private tidelands. Site 1 was hand harvested up until this experiment, at which time it was mechanically harvested. Site 2 is mechanically harvested. Site 3 has been mechanically harvested but then was harvesting using the precision arm during this study period. Images from OnX and Google Earth.

Here we specifically tested how carbon from biofilms and mineral-associated carbon was impacted by the oyster harvest method. This study was done over the wintertime period, during high oyster harvest, when eelgrass was not present. We sampled three locations within active beds in Willapa Bay, WA owned by Goose Point Oysters (Figure 4). Site "1" has been traditionally hand-harvested over the last decade and was subsequently mechanically harvested during our study period. Site "2" has been historically mechanically harvested and continues to be harvested in this manner. The final site, Site "3", is a location that has been historically mechanically harvested, but here we pilot the precision arm method of oyster harvest. Initial sampling occurred before harvest and the subsequent samples were taken 1-2- and 3-4-months post-harvest. Not all harvesting was done concurrently, which led to a range in post-harvest sampling timelines.

Field Sampling

Each site was sampled three times during low tide: October 2024, February 2025, and April 2025. October sampling took place when oysters were still on the beds, while February and April sampling occurred following harvest. Triplicate sediment cores (samples) were taken at each site using a Russian Peat corer (AMS) with a target depth of 50 cm (Figure 5). The specific location of the core was


Figure 5. Example sediment core. Metal plate is 50 cm long.

determined by selecting a spot with no visible eelgrass so that eelgrass would not be assessed and low cover of oyster shells so that the coring device would function. Cores were taken during low tide when the tidelands were exposed. Cores were sliced into 2-cm sections and bagged individually in the field and kept refrigerated until they were analyzed in the lab. Photographs of all cores are located in Appendix B.

Laboratory Procedures

Loss on ignition (LOI) procedure was based on previous methodologies (Craft et al., 1991, Dean 1974). The sediments were dried at 60 C, crushed, and redried to remove all moisture. Approximately 1 g of sediment was measured into a cleaned crucible and then was burned at 550 C for 4 hours in a muffle furnace. The final weight was then measured; the difference in weight is used as the amount of organic matter in the sample. When weighing samples, any large debris (a twig or a blade of seagrass) was removed to prevent significant bias; this occurred in a very small number of samples (less than 5 out of 600 samples). Total organic carbon was measured using a Costech 1040 CHNOS Elemental Combustion system. A total of 205 out of 600 samples were sent for analysis at the LSU Wetland Biogeochemistry Analytical Services to create a calibration curve between loss on ignition and total organic carbon. This was done because loss on ignition is inexpensive and can be done in-house, while total organic carbon is more costly and time consuming. Samples were fumigated, packed into capsules and run through the elemental combustion system. Samples with very low concentrations were run in duplicate to confirm the values.

Grain size was performed using an LS 30 320, an instrument that uses laser diffraction to determine the grain size distribution. Samples were mixed with sodium metaphosphate dispersant and then sonicated for 15 minutes. Then the samples were processed through the analyzer, which gave a complete grain size distribution. The samples were not pre-processed in any other way, so organic particles would have still been in the sample. Grain size statistics were calculated in the software native to the instrument and exported for analysis.

Calculations

To determine carbon stocks and fluxes, we use the information from grain size and organic matter content. Organic carbon was either calculated using the following equation (Craft et al., 1991):

$$\%C = 0.4LOI + 0.0025LOI^2$$

or from the direct percent carbon measurements, depending on the sample. Next, we determined total carbon stock according to:

$$C_{stock} = \%C \times depth \times bulk\ density$$

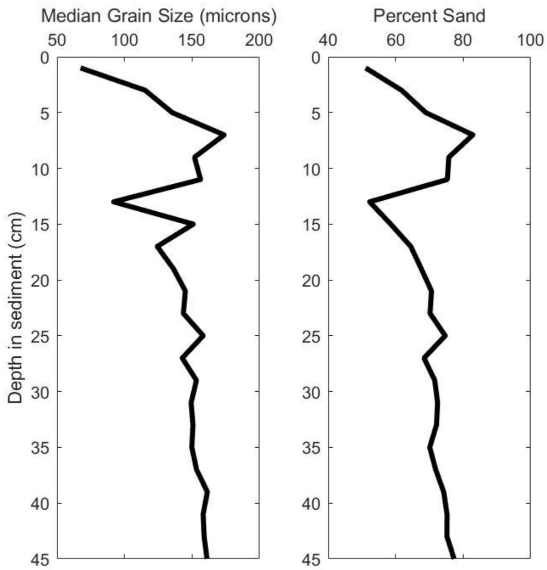

Figure 6. Example grain size distribution from a core at Site 1. All sites were dominated by sand at all depths. The left indicates median grain size (D50) for each depth, while the right indicates the percent sand in the sample at each depth.

To do this, we made several assumptions that are supported by the local data. First, we determined that organic content was constant with depth, meaning that we could linearly extrapolate our data to 1 m depth to be consistent with Blue Carbon datasets. Additionally, given that there was little variation in depth across all cores, we determined that an average organic matter percentage could be used to represent the entire sediment core. Lastly, we used grain size to determine a usable bulk density measurement. All sediments were dominated by sand (Figure 6), which allowed us to assume that the bulk density of sediment is 1990 kg/m^3 (Morris et al., 2016).

Finally, all calculations used dimensional analysis to transform the results to the correct units of MT carbon per hectare, consistent with terrestrial agriculture and blue carbon literature. To convert to CO_2 equivalents, the results were multiplied by 44/12, or the ratio of the atomic weight of carbon dioxide to carbon.

Results

Carbon Stock Assessment

We found that total organic matter in the sediments in the oyster beds was on average 2.43 +/- 0.35 % across all sites and harvest types, with very little variation in the vertical down to 50 cm (Figures 7-9). Site 1 had the highest organic content (3.75 +/- 0.42 %, Figure 7). Detailed data on the organic content for all sediment samples are found in Tables 1-3. In terms of carbon, this is 0.98 +/- 0.14 % Organic Carbon. Grain size results indicate that the sediments are primarily sandy across all sites and all depths, with a median grain size of 200 microns. The traditionally-hand harvested site had the smallest grain size, with a median of 140 microns.

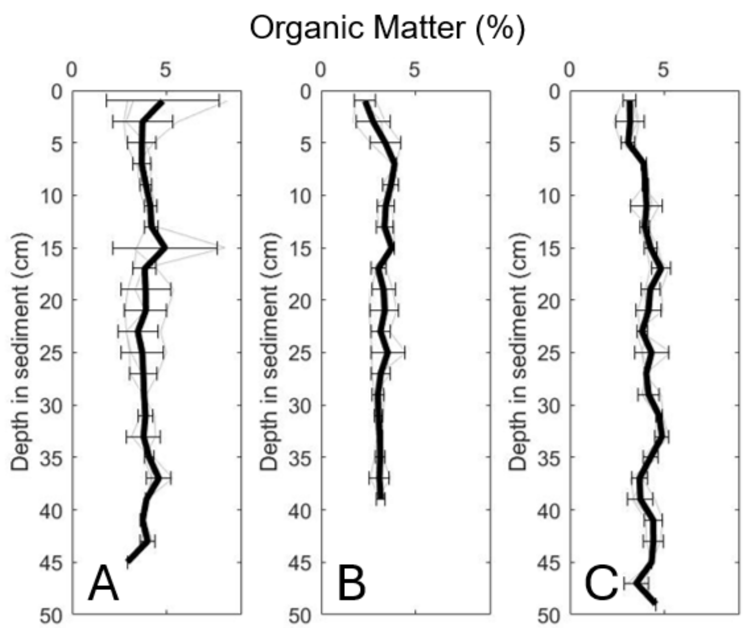

Figure 7. Site 1 organic matter profiles. Located at 46.70843, -123.90299 ("North River") in a location that has been traditionally hand harvested but then was mechanically harvested during the study period. (A) is pre-harvest, (B) is one-month post-harvest, and (C) is four months post-harvest. Error bars indicate standard deviation for the three triplicate samples at each depth bin.

Extrapolating the organic carbon measurements for all harvest types to a 1-meter depth, consistent with other calculations of carbon stock in coastal environments (standard for Blue Carbon metrics, Macreadie et al., 2019), we calculate a benthic carbon stock of 1965.1 +/- 279.2 kg C/m^2 of farmed oyster land, or 1.965x10^3 tons/ha. This highlights the carbon value of these tidelands, even when being actively farmed. Estimates from the bay indicate that sediment accumulates at 1-2 mm/yr, indicating that these areas continue to accumulate carbon over time (Sweet et al., 2022; Boldt et al., 2013). Assuming this range of sea level rise rates, this gives a carbon accumulation rate (CAR) of 0.196 - 0.392 kg C/m^2/yr. This value is on par with calculated CAR for known Blue Carbon systems such as salt marshes (~0.3 kg C/m^2/yr, Miller et al., 2022) and seagrasses (~0.1 kg C/m2/yr, Serrano et al., 2021).

The historically-hand harvested parcel started with the highest amount of organic matter and organic carbon, as well as the highest variability (Figure 7). The surface layer was particularly rich in organic carbon and had slightly finer grain sizes. This could be caused by the nature of the site location and elevation, as well as past harvest methods. Immediately following the mechanical harvest, the organic content dropped, but then recovered to pre-harvest values 4 months after harvest. It is noted that the mechanical harvest primarily impacted the top 10 cm of sediments and that there is relatively fast recovery time.

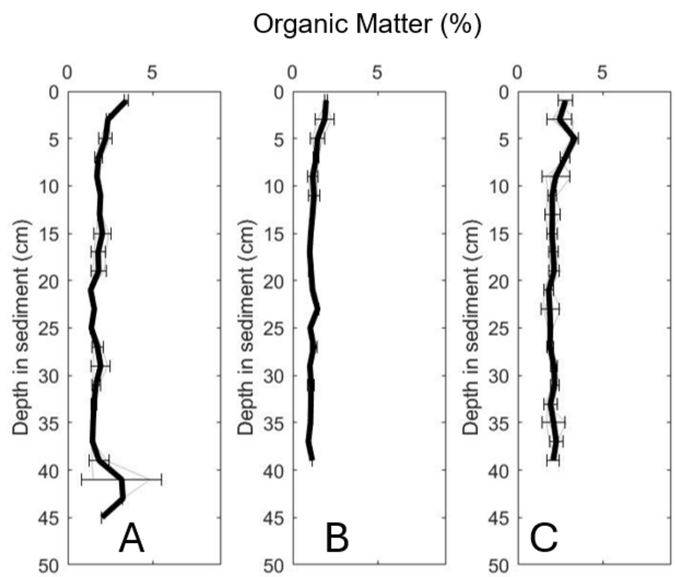

Figure 8. Organic matter profiles at Site 2. Located at 46.6871, -123.94312 ("Johnson Bed") in a location that has been traditionally mechanically harvested for oysters for many years. (A) is pre-harvest, (B) is one-month post-harvest, and (C) is four months post-harvest. Error bars indicate standard deviation for the three triplicate samples at each depth bin.

At Site 2, which continues to be harvested mechanically, the sediments and carbon did not change significantly over the course of a year (Figure 8). Organic carbon content at this site was less than half of that at the originally hand-harvested location. However, it remains unclear whether this difference is due to harvest intensity or underlying site characteristics (e.g., hydrodynamics, elevation, or grain size). Again, the only observation changes were in the surface of the sediments. There was one anomaly in measurements (Figure 8A) where there was one sample with high organic content that appears to be an outlier.

At the precision harvest test location, Site 3, organic matter profiles were low and consistent with depth, similar to the other locations (Figure 9). Total organic content between Sites 2 and 3 were similar (Table 2, 3) which can be partially explained by their close proximity and therefore likelihood of similar environmental conditions. While there was not much change in the organic content following harvest, there was a slight reduction in total carbon stock to depth, which is likely attributed to high oxygenation of the sandy sediments at this site. Notably, the surface sediments became more carbon rich through time following harvest.

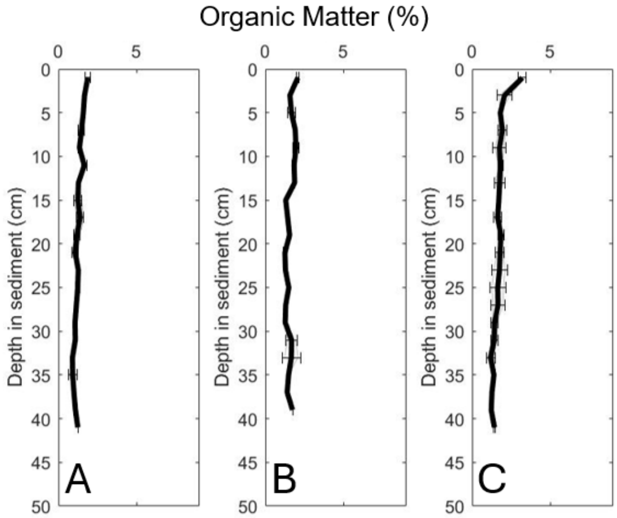

Figure 9. Organic matter profile at Site 3. Located at 46.68393, -123.9449 ("Johnson Bed") in a location that has been traditionally mechanically harvested but is now being harvested with the prototype precision arm. (A) is pre-harvest, (B) is one-month post-harvest, and (C) is four months post-harvest. Error bars indicate standard deviation for the three triplicate samples at each depth bin.

Table 1. Organic matter, organic carbon and carbon stock values for Site 1, which was historically hand-harvested and was then mechanically harvested in this study.

Hand Harvest	Organic Matter (%)	Organic Carbon (%)	MT C/ha	MT CO2 eq/ha
Pre	3.93±0.42	1.61±0.17	32100 ±3340	118000±12300
1 month post	3.24±0.35	1.32±0.14	26300±2800	96500±10300
4 months post	4.07±0.48	1.67±0.19	33200±3870	122000±14200
Average	3.75±0.42	1.53±0.17	30500±3340	112000±12200

Table 2. Organic matter, organic carbon and carbon stock values for Site 2, which is mechanically harvested.

Mechanical Harvest	Organic Matter (%)	Organic Carbon (%)	MT C/ha	MT CO2 eq/ha
Pre	1.27±0.26	0.511±0.104	10200±2070	37300±7600
1 month post	1.59±0.25	0.642±0.101	12800±2010	46800±7370
4 months post	1.70±0.42	0.686±0.168	13600±3350	50000±12300
Average	1.52±0.31	0.613±0.124	12200±2480	44700±9080

Table 3. Organic matter, organic carbon and carbon stock values for Site 3, which was historically mechanically harvested and is now being harvested with the prototype precision harvest method.

Precision Harvest	Organic Matter (%)	Organic Carbon (%)	MT C/ha	MT CO2 eq/ha
Pre	1.97±0.30	0.798±0.121	15900±2400	58300±8820
1 month post	1.23±0.14	0.494±0.055	9830±1090	36000±4000
4 months post	2.20±0.37	0.892±0.148	17700±2950	65100±10800
Average	1.80±0.27	0.728±0.108	14500±2150	53100±7890

Changes in Organic Carbon: Source versus Sink

Differences in carbon content between pre- and post- harvest vary depending on the ecological/hydrodynamic conditions, the harvest type, and the amount of time since harvest. For carbon emissions (source) or sequestration (sink), we focus on only the top 10 cm of the sediment, as this is where most change was observed in the samples; below this the harvest appeared to have little impact.

Immediately post-harvest, carbon was removed from the sediments with both Site 1 (previous hand-harvest, mechanically harvested during the experiment) and Site 3 (precision harvest) (Figure 10). This indicates that these locations emitted of carbon out of the sedimentary system after harvest. The effect with mechanical harvest was only measured at the site that had been previously hand-harvested; the site that has routinely been mechanically harvested saw a modest increase in carbon content in the surface sediments. However, four months post-harvest, all sites had significant recovery of carbon with the precision harvest location accumulating far more carbon that had been initially present.

The site that has been, and continues to be, mechanically harvested is composed of well-sorted sand and low carbon content as a whole (Figure 10). This site saw no reduction in carbon content following harvest; in fact, we measured an increase in carbon content following harvest at this location. This increase was not statistically significant, but demonstrates that the mechanical harvest at this site was relatively carbon neutral. In the mechanically harvested site that had been previously hand-harvested, total carbon contents were higher (Table 1). Approximately 2265 MT CO_2 equivalents were emitted from the sediments following mechanical harvest at this site based on soil carbon content. Similarly, 2217 MT CO_2 equivalents were emitted following precision harvest. It is important to note that the period between the pre- and post- harvest measurements covered winter (November-January) when the largest storms are present and therefore could have contributed to carbon losses from the surface sediments. Of note is that, although the sites both lost similar amounts of carbon from the sediments, the precision harvest site recovered more quickly compared to the newly-mechanically-harvested site. The fast recovery time indicates that the precision, lighter-touch method may increase resilience of the site, leading to neutral carbon emissions during the harvest timeline.

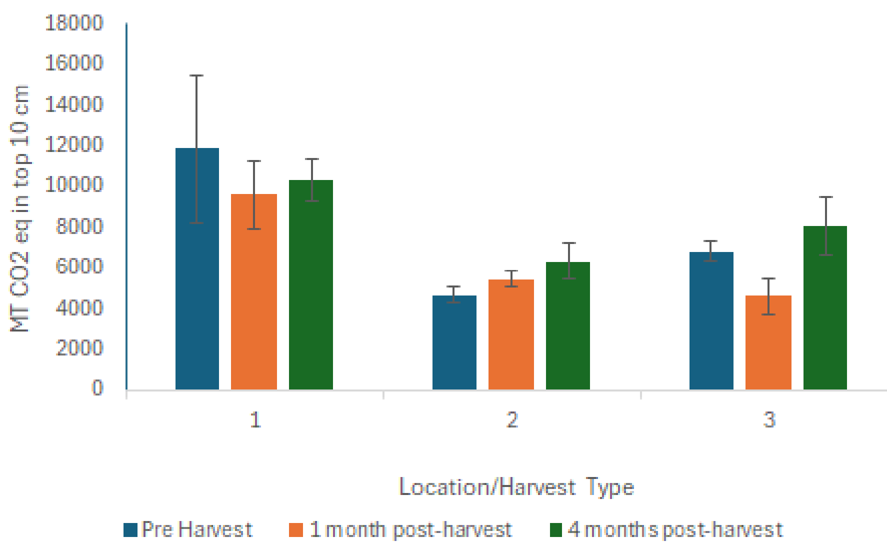

Figure 10. Change in CO_2 equivalents in the top 10 cm of the sediments at the three sites over time.

Discussion and Conclusions

Comparison across Aquaculture Harvest Methods

In summary, historically hand-harvested tidelands had a higher amount of soil organic carbon compared to the sites that were mechanically-harvested or precision harvested. This largely reflects the different mud content of the sites, and likely affects the harvest type. In other words, muddy sites are often prioritized for hand-harvest; the combination of mud, which has strong affinity for organic matter, and the use of light-touch hand harvest combined increase carbon stock. There was no statistical difference in the carbon lost from mechanical harvest versus the light-touch harvest, and both sites had relatively low carbon concentrations. However, it is worth noting that the large area occupied by sandy tidal flats results in a large stock even though per area concentrations are low. Although harvest of oyster beds mobilizes some of this carbon, recovery occurs quickly with even more short-term rapid rates of deposition. Our experiments indicated that harvest methods with lighter impact on sediments led to faster recovery of organic carbon in the surface sediments than harvest techniques with greater impact on sediments. This finding highlights the high carbon capture capacity of these systems.

Comparison of Tideland Aquaculture to Terrestrial Agriculture

In these experiments, we find that overall carbon capture – averaged across all harvest methods – occurs across the oyster aquaculture tidelands at a rate of ~7 MT CO_2 equivalents/ha/year, assuming an accumulation rate of 1-2 mm/year. This is compared to reduced tillage in terrestrial agriculture, which found that an average of 0.175 MT CO_2 equivalents/ha/year are stored (Tambet et al., 2025). Beyond our findings that aquaculture tidelands are efficient at carbon capture, oyster bed and other aquaculture provide additional benefits. Aquaculture provides a low-carbon-cost food source, with limited carbon inputs compared to terrestrial agriculture (Schoor et al., 2023).

Limitations

This work was done over the winter during a time when eelgrass was not present. Eelgrass significantly influences carbon cycling in coastal environments (Fourqurean et al., 2012) and likely enhances carbon stock. Therefore, the assessments provided in this report underestimate carbon capture compared to vegetated tidelands. Overall, standard deviations were small, and triplicate samples were done for each location and sampling time period, indicating that the data themselves are strong and should not be considered a limitation. However, there are limitations in sampling in that we were unable to sample all environmental conditions (sediment types, hydrodynamic conditions) that a tideland may experience; this fact makes it difficult to separate environmental factors from harvest type completely. However, Sites 2 and 3 were extremely comparable, as they were located within 500 m of each other. We also lack the comparison to hand harvest, as the sampling scheme had to be altered to fit with the business model for Goose Point Oysters. This added comparison would provide greater context for how oyster aquaculture interacts with sediment and carbon.

Appendices

Appendix A: References

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Appendix B: Photographs

Cores 1-3: Site 1, October 2024

Cores 7-9: Site 2 October 2024

Cores 4-6: Site 3 October 2024

Cores 10-12: Site 1 February 2025

Cores 14-16: Site 2 February 2025

Cores 17-19: Site 3 February 2025

Cores 20-22: Site 1 April 2025

Cores 23-25: Site 2 April 2025

Cores 25-28: Site 3 April 2025