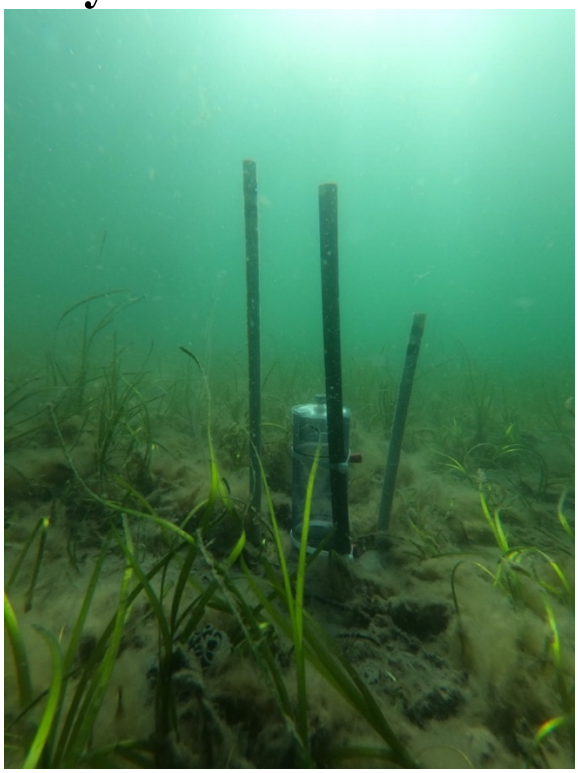
GÖTEBORGS UNIVERSITET

INSTITUTIONEN FÖR BIOLOGI OCH MILJÖVETENSKAP

Influence of different carbon sources on methane fluxes in sediments of eelgrass beds and unvegetated areas: a case study on the Swedish west coast



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Abstract

One of the best ways to mitigate climate change is through natural carbon sequestration. An efficient way to mitigate climate change is through carbon sequestration from coastal habitats. Seagrass meadows, for example, store up to ten times more carbon per square meter than terrestrial forests and are therefore of great importance as so called blue carbon sinks. However, the anoxic marine sediments can contain methanogenetic archaea that emits methane. Methane is a greenhouse gas that is 28-34 times as potent as carbon dioxide. These emissions threaten to undo part of the carbon sink potential of these ecosystems. It is yet not known how different sources of carbon from different types of vegetation influence these emissions. This study aims to investigate how methane emissions vary between different types of carbon sources by using teabags filled with different organic materials and measuring the methane emissions during decomposition using static gas chambers. This was tested *in situ* in "Potätabukten" in the Gullmar Fjord on the Swedish west coast. It was tested both in an eelgrass (*Zostera marina*) bed and in bare sediment in order to find any differences between the two habitats. Methane emissions were relatively low in the area (0.39 ± 0.67 CH_4 $\mu g\ m^{-2}\ h^{-1}$). The amount of sedimentary carbon around the teabags was also measured and found to be relatively high ($0.70 \pm 0.20\%$). Sedimentary carbon content was significantly higher in the eelgrass bed ($0.82 \pm 0.14\%$) than the bare sediments ($0.56 \pm 0.17\%$). This in combination with the low methane emissions indicates that the seagrass meadow is a potential blue carbon hotspot. Decomposition rate was measured for the different carbon sources and filamentous macro algae were found to decompose significantly faster than non-filamentous macro algae, indicating that filamentous algae are a more labile source of carbon. No significant difference in methane production was found between carbon sources nor habitats. The low levels of methane and non-significant differences between the carbon substrates are theorized to be due to the relatively short time of exposure (5 weeks) in combination with low water temperatures during this spring which slows the degradation processes. This conforms to earlier studies where methane emissions have been found to be lower during colder periods of the year.

Sammanfattning

Ett av de mest effektiva sätten att hindra klimatförändringar på är genom naturlig kolinlagring som i t.ex. kustnära habitat. Sjögräsängar kan lagra upp till tio gånger så mycket kol per kvadratmeter som skogar på land och är därför av stor betydelse som kolsänkor. Men i syrefria marina sediment kan det finnas metanogena arkéer som släpper ut metan, en växthusgas som är 28–34 gånger mer potent än koldioxid. Dessa utsläpp riskerar att motverka den positiva effekten sjögräsängar har för klimatet. Man vet ännu inte hur olika sorters kol från olika växter och alger påverkar produktionen av metan i marina sediment. Denna studie syftar därför till att undersöka hur metanutsläpp varierar mellan olika kolkällor genom att använda tepåsar fyllda med olika sorters organiskt material och mäta metanutsläppen under nedbrytning med hjälp av gaskammare. Detta experiment utfördes i fält i Potätabukten i Gullmarsfjorden på den svenska västkusten. Tester genomfördes både i en ålgräsäng och i bart sediment för att urskilja skillnader mellan de båda habitaten. Metanutsläppen var relativt låga i försöket (0.39 ± 0.67 CH_4 µg m^{-2} tim^{-1}). Mängden kol i sedimentet mättes också kring tepåsarna och visades vara relativt högt (0.70 ± 0.20%). Mängden sedimentärt kol var signifikant högre i ålgräsängen (0.82 ± 0.14%) jämfört med i det bara sedimentet (0.56 ± 0.17%). Detta, i kombination med de låga metanutsläppen indikerar att ålgräsängen är en effektiv kolsänka. Ingen signifikant skillnad i metanproduktion upptäcktes mellan de olika kolkällorna. De låga nivåerna av metan och icke signifikanta skillnaderna mellan kolkällorna tros bero på den korta nedbrytningstiden (5 veckor) i kombination med låga vattentemperaturer som minskar nedbrytningshastigheten. Detta stämmer överens med tidigare forskning som har visat på att metanproduktion är lägre vid kallare årstider.

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1. Introduction

1.1 Carbon storage

One of the biggest threats humanities faces today is climate change. Anthropogenic activities have already caused rising temperatures that have devastating impacts on our planet (IPCC, 2022). It is hence of great importance for the environment to mitigate climate change. One of the best ways to protect our nature is to utilize it, for instance, by using its potential for carbon sequestration (IPCC, 2022). This can be done on land by e.g. planting trees and rewetting peatlands (Lal, 2008), but marine coastal vegetation habitats are particularly efficient regarding carbon sequestration (Mcleod et al., 2011; Duarte, 2017). In comparison, marine sediments store carbon for hundreds to thousands of years whereas land ecosystems tend to only hold carbon for tens or hundreds of years (Mcleod et al., 2011). This so-called blue carbon in costal marine sediment is, therefore, of great importance to mitigate the effects of climate change. However, there is a great variability in the carbon sink capacity both within and between different coastal blue carbon habitats. How these marine blue carbon sinks function is not yet fully known and something that needs to be better understood.

Both globally and in Sweden, one of the marine coastal habitats with the best carbon storage potential is seagrass meadows. They are capable of storing 83-138g of carbon per square meter each year (Duarte et al., 2005; Mcleod et al., 2011). That is more than ten times as much as temperate forests and rain forests per surface area (Mcleod et al., 2011). Seagrasses are thought to account for 15% of all carbon storage in the ocean worldwide (Kennedy & Björk, 2009). The most abundant seagrass species in Sweden is *Zostera marina* (eelgrass). In Swedish waters, based on data from the Gullmar Fjord area on the Swedish Skagerrak coast, *Z. marina* meadows have been reported to store 14 ± 3 g organic carbon per square meter per year (Dahl et al., 2023). On the Swedish west coast, the cover of eelgrass has declined since the 1980s with more than 60% gone already about 20 years ago (Baden et al., 2003). The reasons for this decline are thought to be anthropogenic activities such as eutrophication, overfishing, dredging and other marine exploitation (Borum et al., 2004; Orth et al., 2006, Moksnes et al., 2008). Eelgrass meadows are not only important for carbon sequestration, but they also provide habitat for a large number of different species including many key commercial species (Adams, 1976; Bertelli & Unsworth, 2014) and provides many other

ecosystem services (Schmidt et al., 2011; Namba et al., 2018). It is therefore of great importance to protect these areas.

1.2 Methane emissions

In the sediment of both seagrass meadows and unvegetated areas, decomposition occurs. This causes greenhouse gases (GHGs) to be reemitted to the water column, and by extension, to the atmosphere. Only up to one centimeter of marine sediments are oxygenated (Revsbech et al., 1980). This means that decomposition occurs in an anoxic environment. Much of this decomposition is done by sulphate reducing bacteria (Jørgensen 1982). However, some of the decomposition is also done by methanogenetic archaea (Oremland & Taylor, 1978; Bakker et al., 2014). Instead of O_2 methanogenetic archaea use different carbon sources such as carbon dioxide and acetic acid as electron acceptors, resulting in the formation of methane (Bakker et al., 2014). This methane is then emitted to the water column. Because of the oxygen in the water, much of the methane is oxidized, meaning that not all methane created reaches the surface (Saunois et al., 2020). Some of it however reaches the atmosphere where it acts as a greenhouse gas. Methane is 28-34 times more potent as a greenhouse gas than carbon dioxide over a 100-year span (Myhre et al., 2013). Studies have shown that as much as half of all global methane emissions come from aquatic sources (Rosentreter et al., 2021). Coastal ecosystems only account for a small part of the ocean but as much as 75% of marine methane emissions are thought to originate from these areas (Bange et al., 1994). Part of the reason for this is that the water-column is so much shorter, meaning that less of the methane gets oxidized before being emitted to the atmosphere (Weber et al., 2019). In fact, the emissions of methane and other greenhouse gases from the sediment lessen the carbon sink capacity of seagrass meadows and other coastal blue carbon sinks and must therefore be included when estimating the carbon sink potential of coastal blue carbon habitats.

The level of methane production in seagrass meadows was until recently unknown. A recent study by Asplund et al. (2022) assessed the methane production of *Z. marina* meadows in Nordic waters. They found a relatively low methane production when compared to other seagrass meadows globally. When compared to the carbon storage potential of these seagrass meadows the methane emissions are 12-78 times lower in (CO_2-equivalents) than their carbon accumulation rates (Asplund et al., 2022). The ratio observed is hence comparably

lower than global averages, were 6-9 times lower methane emissions than carbon storage levels have been suggested (Al-Haj & Fulweiler, 2020).

It has been shown that methane emissions from seagrass meadows increase with an increase in anthropogenic disturbance (Lyimo et al., 2018; Rosentreter et al., 2021). Warmer temperatures have also been proven to increase the methane production of seagrass meadows (Burkholz et al., 2020; George et al., 2020). It is therefore likely that methane emissions from seagrass meadows will increase in the future due to climate change, urbanization and eutrophication (Rosentreter et al., 2021)

It is of great importance to understand what other factors affect how much methane is released from marine sediments. For instance, Asplund et al. (2022) observed a positive significant relationship between amount of organic carbon (C_{org}) and methane production in Nordic seagrass meadow sediment. However, less than half of the carbon stored in the sediment in these areas originates from the seagrass itself (Röhr et al., 2018). It is yet unknown how different carbon sources influence GHG fluxes in the sediment and it would therefore be of high importance to study if different carbon sources contribute to different levels of methane emissions.

1.3 Aims

The main aim of this study was to investigate methane fluxes during decomposition of various carbon sources from different vegetation types, in marine sediments. A second aim was to compare the amount of carbon in the sediment around these carbon sources. A third aim was to compare decomposition rates in sediments of different carbon sources. Finally, a fourth aim was to compare the outcome of the first three aims between bare sediments and eelgrass meadows in order to evaluate how effective these two habitats are as carbon sinks.

2. Method

2.1 Field experiment

This research experiment was conducted in a shallow bay ("Potätabukten") of the Gullmar Fjord near Kristineberg Research Center in Fiskebäckskil on Swedish west coast (Figure 1). Coordinates for the study site were N5824865 E01144763. The field efforts were carried out between the 4th of April and the 11th of May 2023.

Figure 1 *Map of the study area near Kristineberg Research Center, Fiskebäckskil, Sweden. Each spot represents a block within the study area. The inner four blocks were located in bare sediment, whereas the outer four blocks were located in an eelgrass bed. The coordinates for the study site were N5824865 E01144763. The map was created in Google Earth (version 7.3.2.5776).*

Six different plant species were selected and used as carbon sources, including *Zostera marina* (seagrass), *Fucus serratus* (non-filamentous brown macroalgae), *Ectocarpales* spp. (filamentous brown macroalgae), *Furcellaria lumbricalis* (non-filamentous red macroalgae), *Polysiphonia* spp. (filamentous red macroalgae) and *Phragmites australis* (reed). These plant species were chosen due to their relatively high abundance in the coastal zone of this region and to be able to compare different types of carbon sources. Methane production and decomposition rates of these different types of vegetation were studied in both seagrass meadows and unvegetated sediment. This was done in order to know how methane production varies in different areas, including meadows that are heavily overgrown with

filamentous algae, meadows that only consist of *Z. marina*, sediment areas without vegetation, and meadows near a water outlet with a higher input of terrestrial carbon.

The biological material was collected within a maximum of two days before being used. The collected material was cleaned of any biofouling, dried of any excess water and cut into small pieces with a maximum length of 2 cm. Each carbon source was placed in 8 teabags, all containing 5 g of wet material (Figure 2). After this, the teabags were melted shut and replaced in cold seawater. This was based on a previous method by Keuskamp et al. (2013).

Figure 2 *Teabags filled with different plant species prior to the experiment. From left to right: Phragmites australis, Zostera marina, Ectocarpales spp., Fucus serratus, Furcellaria lumbricalis and Polysiphonia spp.*
Photo: Hampus Holmberg

The teabags were then buried at roughly 2-7 cm depth in the sediment of an eelgrass meadow and an unvegetated area. The teabags were buried in a manner that disturbed the sediment as little as possible. The bags were placed in seven treatments (six plant treatments and one control) in each of eight blocks (i.e. n = 8) using stratified random block design. Four blocks were located in bare sediment and four in an adjacent eelgrass meadow, all within the same bay. The bags were buried with at least 1 m in-between each other within the blocks and the blocks were at least 5 m away from each other. Each sample was clearly marked with one

stick on either side with markings on them, indicating the sample name. The area was then clearly marked with buoys.

In order to capture and measure the greenhouse gas emissions from the decomposition, static gas chambers were used (Figure 3) (Al-Haj et al., 2022; Asplund et al., 2022). The gas chambers were built from a 310 mm long PVC pipe with an inner diameter of 68 mm and outer diameter of 74 mm. They were fitted with a 3 mm thick lid with a 7 mm wide hole in the middle. Through this hole a 20 mm long tube was placed with an inner diameter of 5 mm and outer diameter of 7 mm. Both the lid and the tube were sealed using a glue gun and marine sealant. The tube was then fitted with a gastight septum, allowing samples to be taken through it. Halfway through the experiment the chambers were strapped to poles as a way of better securing them in the sediment. Before the final sampling, the chambers were also fitted with two plugged holes used to drain them from water without removing the sediment.

Figure 3 *Static gas chamber used in the study.*
Photo: Hampus Holmberg

The static gas chambers were put down between 10 and 15 cm into the sediment with a 5 cm air pocket (at atmospheric pressure) (Figure 4). The chambers were placed in the mornings, between 07:30 and 11:00, and an initial sample was taken from each chamber. In the afternoon, between 16:45 and 18:15, a second sample was taken, covering the majority of the productive phase of the day. Next morning, between 07:30 and 09:30, a final sample was

taken to capture the night phase. The exact time for each sampling occasion was noted. Samples were extracted from the chambers using a syringe. Before each sample was taken, the air within the chamber was mixed by pulling 22 ml air in and out of the syringe three times. Subsequently, a 22 mL sample was collected. After all samples had been taken, the chamber was removed, which sometimes led to that the teabags came up. When so, the teabag was reburied in the same spot. This procedure was done four times over a five-week period to capture the difference in methane production between the samples.

Figure 4 *Static gas chambers placed over the teabags in bare sediment (left) and an eelgrass bed (right). Photo: Hampus Holmberg*

2.2 Laboratory analysis

In the laboratory, 18 mL of each sample was transferred from the syringes into glass vials filled with 58.3 mM zinc chloride for storage. The vials were stored in a refrigerator until taken for analysis. A gas chromatograph (GC 8A Schimadzu Corporation) was used to analyze the samples for methane. 1 mL of each sample was injected into the gas chromatograph. From the output, methane concentration was calculated.

The carbon content of the sediment was calculated using loss of ignition (LOI%). After the final sample, the water was drained from the chambers and the sediment within the chambers

were emptied into plastic bags. Some of the sediment was then placed in cups and dried at 60 ºC. After being dried, it was weighed in pre-burnt cups and set in an oven at 550 ºC for 24 hours. It was then reweighed, and the difference was used to estimate carbon content.

The teabags were also collected and dried at 60 ºC and the dry weight was compared to the initial weight and used to calculate decomposition rate. The control treatment showed no decrease in weight and teabags were therefore assumed to not have decomposed. All broken teabags (n=15) were excluded from the decomposition calculations. All but one of the *P. australis* teabags broke (n=7) and *P. australis* was therefore also excluded from the calculations.

2.3 Environmental characterization

As a way of characterizing the environment and to correlate results to the surroundings, different environmental factors were measured. Temperature was measured constantly throughout the experiment at half hour intervals using HOBO-loggers. Each block was fitted with a separate HOBO-logger as a way to notice environmental differences between the blocks. Salinity, pH and dissolved oxygen concentration were measured a few times during the experiment using a salinity measurer and a multimeter. This was done to characterize the area and to notice any abnormalities.

Two different habitats – unvegetated sediment and a vegetated *Z. marina* meadow – were compared in the experiment. Biometrics were taken in order to characterize the seagrass meadow. For each block within the eelgrass bed, the average *Z. marina* shoot density and shoot length as well as overall biomass were measured. Shoot density of the different eelgrass blocks was estimated by counting shoots in ten randomly placed 19 cm * 19 cm squares per block. Shoot length was measured for twenty randomly selected shoots per block. For each block, three core samples were taken, containing all biomass within a 36 cm^2 circle. Biomass was divided into three subcategories, including non-seagrass vegetation, aboveground seagrass and belowground seagrass. The seagrass and other vegetation were taken to laboratory where they were dried and weighed.

2.4 Statistical analysis

All data were prepared and modified in Microsoft Excel (16.72). SPSS (29.0.0.0) was then used to perform all statistical analyses. Graphs were created using R-studios (4.3.0). A map of the area was created using Google Earth (v. 7.3.2.5776).

2.4.1 Methane and sedimentary carbon content

Initially, a Levene's test was used to test for homogeneity of variance. Homogeneity of variance was not achieved (even after $\log_{10}(x+1)$-transformation) ($p > 0.05$). A non-parametric Kruskal-Wallis test was therefore used to compare differences in methane production between the carbon sources as well as sedimentary carbon content between the different carbon sources. To compare differences in methane production and sedimentary carbon content between the two habitats one-way ANOVA´s were used. In order to find out how the different treatments varied amongst each other, Tukey's post hoc tests were performed. Bonferroni corrections were used when calculating the significance.

2.4.3 Decomposition rate

Initially, a Levene's test was used to test for homogeneity of variance. The test showed that the data was homogenously distributed ($p > 0.05$). Therefore, a two-way ANOVA was used to compare differences in decomposition rate between the carbon sources and between habitats. In order to find out how the different treatments varied amongst each other, a Tukey's post hoc test was used.

3. Results

3.1 Methane production rate

Average methane production rate was found to be 0.39 ± 0.67 CH_4 µg m^{-2} h^{-1} over the full experimental period and all treatments. No significant difference in methane production was found between the different carbon sources within the two habitats (Table 1), seagrass (Figure 5a) and bare sediment (Figure 5b) throughout the experiment. Pairwise comparisons between carbon sources showed no significant correlations after Bonferroni correction in either of the two habitats throughout the entire test period. Table 2 shows an increase in

average methane production throughout the experiment. No significant relationship between habitat and methane production was found throughout the experiment (P=0.373) (Figure 6).

Table 1 *Significance summary for independent samples Kruskal-Wallis test on carbon source´s effect on methane production during a five week period in two different habitats.*

Sample time and habitat	Asymptotic sig. (2-sided test)
Week1	
Bare sediment	0.421
Seagrass meadow	0.653
Week 2	
Bare sediment	0.83
Seagrass meadow	0.287
Week 3	
Bare sediment	0.634
Seagrass meadow	0.238
Week 5	
Bare sediment	0.86
Seagrass meadow	0.065

Table 2 *Average methane production (including standard deviations) through the different weeks.*

	Average methane production (CH_4 µg m^{-2} h^{-1})	Standard deviation (CH_4 µg m^{-2} h^{-1})
Week 1	0.15	0.16
Week 2	0.18	0.83
Week 3	0.56	0.62
Week 5	0.69	0.68

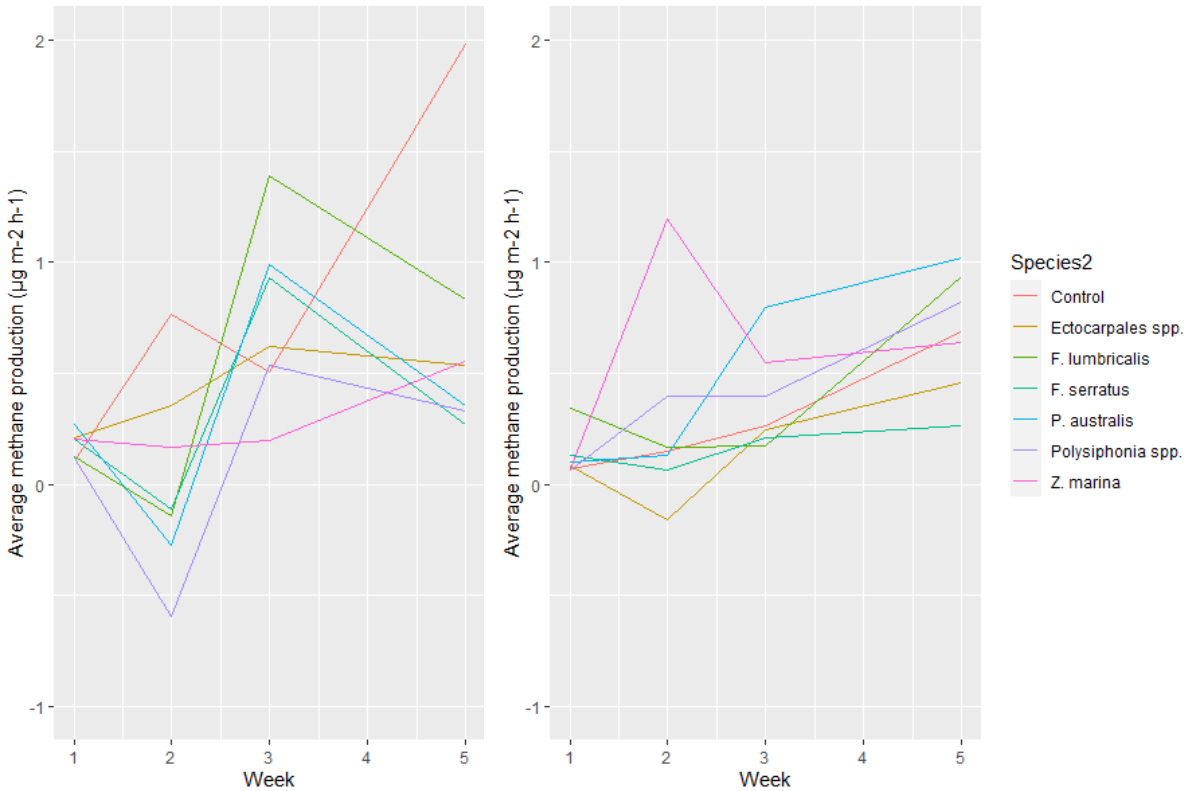

Figure 5a *Graph showing average methane production (µg m^{-2} h^{-1}) in an eelgrass bed over a five-week period for seven different treatments (Control, Ectocarpales spp, F. lumbricalis, F. serratus, P. australis, Polysiphonia spp. and Z. marina)*

Figure 5b *Graph showing average methane production (µg m^{-2} h^{-1}) in bare sediment over a five-week period for seven different treatments (Control, Ectocarpales spp., F. lumbricalis, F. serratus, P. australis, Polysiphonia spp. and Z. marina).*

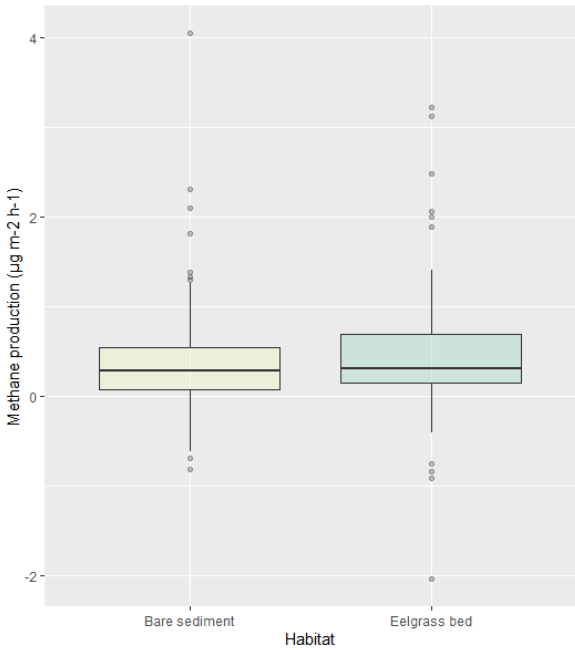

Figure 6 *Boxplot displaying methane production (µg m^{-2} h^{-1}) in the studied bare sediment and eelgrass bed throughout the entire experiment and including all treatments.*

3.2 Sedimentary carbon content

The average carbon content in the sediment surrounding the teabags after five weeks of decomposition was found to be 0.70 ± 0.20%. No statistically significant difference in sedimentary carbon content (based on LOI as a proxy) was found between the different treatments in neither bare sediment ($p = 0.065$) nor in eelgrass beds ($p = 0.660$). A significant difference was, however, found in sedimentary carbon content between habitat types ($p < 0.001$) with the eelgrass meadow having higher average carbon content (0.82 ± 0.14%) than the bare sediments (0.56 ± 0.17%) (Figure 7).

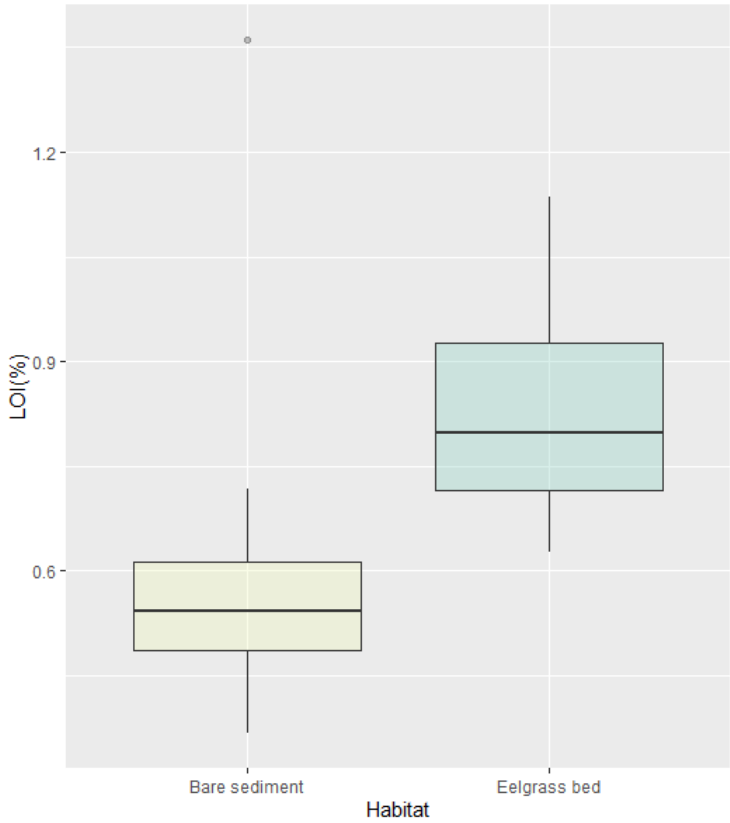

Figure 7 *Boxplot displaying carbon content in the sediment surrounding the teabags (based on percental LOI as a proxy) in the studied bare sediment and eelgrass bed.*

3.3 Decomposition rate

The average decomposition rate was found to be 32.20 ± 13.62% over the five-week study period. A significant difference in decomposition rate was discovered both between the different carbon sources ($p < 0.001$) (Figure 8) and between habitats ($p = 0.018$) (Figure 9), while there was no interaction between carbon source and habitat ($p = 0.626$). Pairwise comparisons showed which carbon sources that had a significant difference from each other

(Table 3). *Ectocarples* spp. showed a higher decomposition rate than *F. serratus* and *F. lumbricalis*. *Polysiphonia* spp. showed a higher decomposition rate than *F. serratus*, whereas no other pairwise comparison showed any significance. Amongst the habitats, there was a significantly higher average decomposition rate in the bare sediment (35.60 ± 14.44%) than in the seagrass meadow (28.35 ± 11.97%) (p =0.018) (Figure 9).

Table 3 *Pairwise post hoc comparisons between carbon sources regarding decomposition rate. Significant values are*

Species 1 - Species 2	Sig.
Z. marina - *Polysiphonia* spp.	0.739
Z. marina - *F. serratus*	0.313
Z. marina - *Ectocarpales* spp.	0.054
Z. marina - *F. lumbricalis*	0.652
Polysiphonia spp. - *F. serratus*	**0.019**
Polysiphonia spp. - *Ectocarpales* spp.	0.370
Polysiphonia spp. - *F. lumbricalis*	0.087
F. serratus - *Ectocarpales* spp.	**<0.001**
F. serratus - *F. lumbricalis*	0.982
Ectocarpales spp. - *F. lumbricalis*	**0.002**

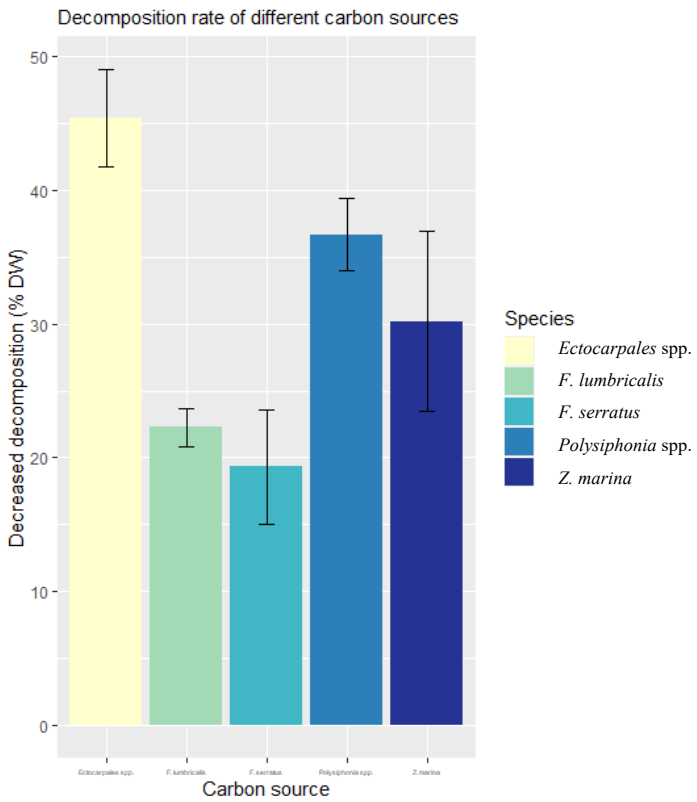

Figure 8 *Decomposition rate (%) of different carbon sources (Ectocarpales spp., F. lumbricalis, F serratus, Polysiphonia spp. and Z. marina), measured in percental decrease after the five-week study period.*

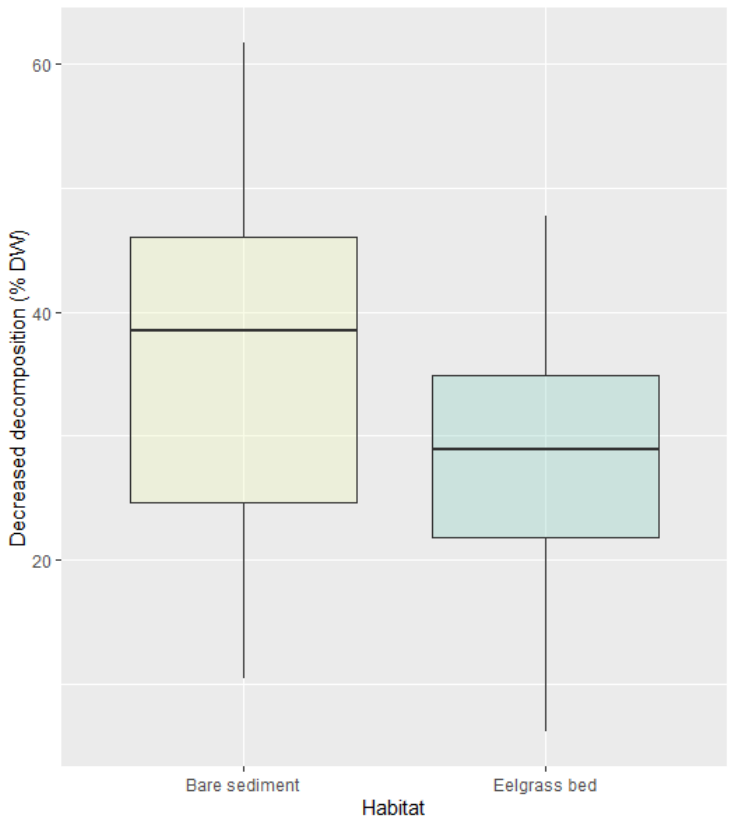

Figure 9 *Decomposition rate (%) in the studied bare sediment and eelgrass bed, measured in percentage dry weight decrease after a five-week period.*

3.4 Environmental factors

Environmental characteristics and biometrics for the eelgrass bed are displayed in Tables 4 and 5, respectively.

Table 4 *Environmental factors, including temperature (°C), salinity (‰), dissolved oxygen (mg/L), pH and depth (cm) displayed as averages (including standard deviations) over the five-week sampling period.*

	Temperature (°C)	**Salinity (‰)**	**Dissolved oxygen (mg/L)**	**pH**	**Depth seagrass meadow (cm)**	**Depth bare sediment (cm)**
Average	8.81	20.50	13.46	8.67	142.98	74.01
Standard deviation	1.85	1.62	2.47	0.49	24.28	25.76

Table 5 *Biometrics of the studied eelgrass bed, including shoot density (shoots/m^2), shoot height (cm) and biomass (g dry weight/m^2) displayed as averages (including standard deviations).*

	***Z. marina* shoot density (shoots/m^2)**	***Z. marina* shoot height (cm)**	**Algal biomass (g dry weight/ m^2)**	**Above ground *Z. marina* biomass (g dry weight/ m^2)**	**Below ground *Z. marina* biomass (g dry weight/ m^2)**
Average	173.13	19.49	67.96	8.95	168.05
Standard deviation	80.51	8.24	109.34	9.18	85.87

4. Discussion

In general, the methane production was relatively low (0.39 ± 0,67 CH_4 µg m^{-2} h^{-1}) when compared to average production in Nordic seagrass meadows (Asplund et al., 2022). This could be due to that the current study was conducted at water temperatures of around 9°C in comparison to Asplund et al. (2022) where water temperatures were above 20°C. The carbon content in the sediment was 0.70 ± 0.20%, a value that is quite high when compared to other European seagrass meadows (Dahl et al., 2016). These low methane emissions and relatively high carbon content indicates that the area is an efficient blue carbon sink, potentially acting as a blue carbon hotspot.

4.1 Methane

As the results showed, no significant correlations were found between methane production and carbon source nor between methane production and habitat. Some trends can be seen in figure 5a and 5b. However, there are too few replicates to be sure if any of the trends are due to actual differences between the carbon sources and not just a coincidence.

The methane production was low (0.39 ± 0.67 CH_4 µg m^{-2} h^{-1}, spring values), both in comparison to values from a previous study in the same bay (2.1 µg m^{-2} h^{-1}, winter values) (Dickinson, 2022) and compared to average production in Nordic *Z. marina* meadows (0.3-3.0 µg m^{-2} h^{-1}, summer values) (Asplund et al., 2022). These low levels could probably partly be explained by the cold temperature in the water during which the experiment was performed. However, as Dickinson (2022) showed, there have been higher levels of

background methane production in even colder temperatures than what was observed in this study, indicating that there are other factors that also influencing the methane production. This could be due to other natural factors such as low or varied activity of the microbial communities (Liss & Johnson, 2014), varied amount and composition of particulate organic matter deposition (Grasset et al., 2021), how much of the produced methane is being directly oxidized by methanotrophs (Saunois et al., 2020) or anthropogenic effects (Rosentreter et al., 2021). However, methane emission did increase over the sample period. This could probably be explained by an increase in temperature as well as decomposition.

No significant difference in methane production was observed between bare sediments and eelgrass meadows. This is in line with previous research done by Asplund et al. (2022). A possible explanation for this could be that most of the methane produced in the sediment is oxidized by methane-oxidizing archaea or by the fact that methane production is generally low due to a domination of sulfate-reducing bacteria in the sediments (Orphan et al, 2001). As much as 90% of the methane produced in the sediment is oxidized before reaching the sediment-water interface (Reeburgh et al., 1993).

The fact that no difference was found between carbon sources could mean several things. It could simply mean that there are no differences in methane production between the treatments during the degradation of the different carbon sources. However, that is unlikely due to their difference in decomposition rate and previous studies have found differences in methane production during decomposition of other aquatic plants in other temperatures (Grasset et al., 2021). One possible explanation is the repeated stirring of the sediment around the teabags, this could have oxidized the sediment so that aerobic decomposition occurred and caused any methane produced to be oxidized. Another explanation could be that the experiment should have been extended to better capture a larger timeframe of the decomposition. It could also have been caused by the chambers not being in field for long enough to accumulate enough methane to give differentiated readings. Because the levels of methane were so low and close to atmospheric values it could also be caused by minor mishandlings of the samples during sampling, storage and analysis. However, it should be noted that because of the cold temperatures methane emissions are expected to be low and differences therefore more difficult to distinguish.

As seen in the graphs, there is a large spread in the data. This means that there is a lot of natural variation in the methane fluxes at the sediment-water interface. This is known from before, see for example Asplund et al. (2022). Knowing this could be of importance for future studies in order to better pinpoint which factors influence the methane fluxes and isolate the ones subject for the study.

4.2 Sedimentary carbon content

The Gullmar Fjord have previously been pinpointed as a potential sedimentary carbon content hotspot with 2.79% ± 0.50% organic carbon in the sediment (Dahl et al., 2016). Even though this bay showed a much lower level (0.70%±0.20%) it is still higher than other studied European areas (Dahl et al., 2016). This indicates that the area sequesters a lot of carbon thus acting as a blue carbon sink.

The carbon content of the sediment is very low in comparison to the amount of carbon within the teabag. This indicates that the teabags were filled with a sufficient amount of carbon to not be outweighed by natural carbon levels in the sediment and therefore any differences found in methane production can be attributed to the content of the teabags.

Seagrass meadows had a significantly greater carbon content than bare sediments. Asplund et al. (2022) found a significant correlation between sedimentary carbon content and methane production in Nordic Seagrass meadows and these results should therefore indicate that seagrass meadows are more likely to emit more methane than bare sediment. A possible explanation to this is that the sediment in seagrass meadows produce more methane but the seagrass also oxidizes the sediment more, resulting in less methane reaching the water. This is consistent with previous research that states that seagrass is known to influence the sediment micro community (Cúcio et al., 2016) and that methane production is known to decrease with seagrasses oxygen production (George et al., 2020).

4.3 Decomposition rate

The filamentous algae had the fastest decomposition rate whereas the non-filamentous algae had the slowest. This indicates that filamentous algae are a more labile carbon source and could mean that they do not result in as much refractory carbon in the sediment. If this is true, that would mean that seagrass meadows overgrown with filamentous algae could be less

effective as carbon sinks than other meadows, in relation to the amount of carbon within the area.

All carbon sources showed only partial decomposition. This means that the sample period was not long enough to fully capture the decomposition and part of the methane production phase was therefore not measured. However, all carbon sources decomposed to some extent. This indicates that the teabag worked as a semi permeable wall, allowing microorganisms to enter but not the carbon source to escape.

Bare sediment showed a faster decomposition rate than in the seagrass meadow. This could possibly be explained by the lower carbon content in the bare sediment. It might also be affected by the difference in depth between the two sites, possibly affecting the decomposition. It could also be caused by a difference in sediment composition, resulting in more heterotrophic decomposition in the bare sediment. However, these are things that needs to be studied to confirm.

4.4 Sources of error and future improvements

In order to fulfill the aims of this study a new method was developed, combining the use of static gas chambers (Asplund et al., 2022; Al-Haj et al., 2022) with the use of the teabag method (Keuskamp et al., 2013). In general, the method seems to work although it had some flaws that should be discussed.

One of the major flaws was that even though the teabag was marked with poles there was no way of knowing exactly where in the sediment it was buried, this resulted in the chamber not always being placed over the teabag. Another problem was that some of the teabags broke form the chamber pressing down on them. There are several ways these two problems could be fixed. One would be to simply use larger chambers, increasing the odds placing it over the teabag but not puncturing it. Another would be to tie the teabag to a smaller pole that would fit within the chamber, that way you would know exactly where the teabag is and put the chamber above it.

Another problem was that the chambers sometimes leaked. Not that many samples were lost due to this but in future studies a much more consistent method would be to weld the pipe to the lid as well as the lid to the chamber instead of using glue and marine sealant.

The teabags were all filled with 5 g of wet weight. This resulted in them being rather different in size and made comparisons less accurate. For future studies, it is therefore recommended that the teabags are filled with the same amount of carbon equivalents instead of the same weight. This could be done if carbon content analysis was performed on the plant species in advance.

For future studies it would be recommended to sample over a longer time period in order to capture all decomposition. It would also be recommended to do it during the summer when methane emissions are thought to be highest (Dickinsson, 2022). Future studies are also recommended to include CO_2 and N_2O emissions to better understand all the greenhouse gas fluxes during decomposition. Finally, it would also be recommended to compare any future findings to more controlled laboratory experiments as it is yet not fully understood which environmental factors influence the methane fluxes in marine sediments.

5. Summary and conclusion

Methane emissions were relatively low in the study area. No significant correlation was found between carbon source and methane production nor between habitat type and methane production.

No significant correlation between carbon source and sedimentary carbon content was found. However, there was a significant difference between bare sediments and eelgrass meadows. The high level of carbon in the sediment of the seagrass meadow indicates how effective the area is as a blue carbon sink.

The carbon sources only partly decomposed, indicating that a longer time period would have better captured the full decomposition. Filamentous algae decomposed faster than non-filamentous algae, this indicates that they are a more labile carbon source and might leave less refractory carbon in the sediment, thus not being as efficient for carbon sequestration.

The method of using static gas chambers combined with the teabag method seems to work and with some improvements could be of use in similar studies in the future.

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