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THE IMPACT OF PLOUGHING ON SEDIMENT MINERALIZATION RATES IN THE SALT MARSHES OF THE SOMME ESTUARY

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Abstract: Salt marshes are particularly popular with gatherers on foot, who harvest halophilic plants such as glasswort (*Salicornia* sp.) and annual sea-blite (*Suaeda maritima*). However, some other plants present in these rich and diverse ecosystems tend to replace the exploited species, such as the invasive English cord-grass (*Spartina anglica*). As a result, professionals are authorised to limit the spread of *S. anglica* through winter tillage within their concessions. Despite the recognition of these salt marshes as carbon sinks (blue carbon), no study to date has examined the impact of these activities on carbon budgets.

In this context, we investigated the intensity of carbon mineralisation by measuring CO₂ flux at the sediment-atmosphere interface using dark benthic chambers. We compared exchanges across similar plant covers in the salt marshes (bare sediment, *Salicornia* sp., *Suaeda maritima*, *Spartina anglica*) in three adjacent areas: 1) ploughed during winter 2022-23, 2) ploughed during winter 2023-24 and 3) unploughed/control.

The results revealed a clear alteration in the carbon exchange mechanisms within these systems following tilling operations, with a drastic reduction in mineralization intensity in the ploughed areas. Furthermore, the more recent the ploughing, the lower the intensity of carbon mineralization compared to the unploughed control. Post-ploughing resilience was also observed, although the sediments did not return to a biogeochemical functioning comparable to that of unploughed areas, even after 1.5 years without ploughing. These results highlight the considerable impact of ploughing on the functionality of these salt marshes in terms of carbon cycling. The next step will be to include primary production processes under light conditions in order to quantify the full influence of tillage on carbon budgets in salt marshes undergoing such management practices.

Keywords: Tillage, salt marshes, *Spartina anglica*, benthic chambers, carbon dioxide fluxes, carbon mineralization, blue carbon.

1 INTRODUCTION

Despite a huge tidal forcing, along the French coast of the Eastern English Channel, the estuaries undergo accretion processes of fine particles due to lower hydrodynamics and terrigenous inputs. Consequently, specific habitats such as mudflats and salt marshes are located on both sides of the main channel, the latter constituting vegetated estuarine intertidal zones. Of major ecological and geochemical importance, due to their role as a buffer between the fluvial and oceanic domains and the diversity of conditions found there, these salt marshes are particularly popular with gatherers on foot for harvesting halophilic plants such as glasswort (*Salicornia* sp.), sea aster (*Tripolium pannonicum*) and annual sea-blite (*Suaeda maritima*). Although these plants grow naturally, their exploitation by professionals in Somme estuary is limited to four concessions located near Le Crotoy (right bank) and La Pointe du Hourdel (left bank) (Figure 1), where these resources are collected by hand. However, other plants are present in these rich and diverse ecosystems, and tend to take over from the glasswort, such as the annual sea-blite (*Suaeda maritima*) or the invasive English cord-grass (*Spartina anglica*). In different parts of the world, several management practices aim to eradicate or to limit the invasion of the English cord-grass in salt marshes, among which mechanical control (hand removal, tilling, digging, disking, crushing), cutting or mowing, biological substitution or biological control by herbivory, smothering, heat treatments, herbicide use (Hedge et al., 2003, Roberts & Pullin, 2008). Even if the efficiency of these practices widely differs from one site to another, the temporality and regularity of the treatments, the combination of different practices, the adaptation to the size of the invasive patch(es) are of major importance (Li & Zhang, 2008; Gao et al., 2009). In the Somme estuary, each year, tillage is authorised and carried out in some areas of the concessions during the winter period (generally between 1st December of year *n* and 28th February of year *n*+1 - areas determined, controlled and followed by an environmental management structure) using a tractor equipped with a rotary harrow at the front and a rotavator at the rear (depth of tillage < 25cm).

While numerous studies have addressed the effectiveness of management practices, their impact on the diversity and functionality of salt marshes remains largely unexplored. However, it is urgent to quantify these

effects, especially considering that salt marshes are recognized as important carbon sinks (Endo & Otani, 2019, Macreadie et al., 2019). Plants in estuarine salt marshes fix atmospheric CO₂ as organic matter during photosynthesis, accumulating it in their tissues during growth and also burying it in the soil through their roots and the detritus produced by tissue loss (e.g., leaves). Consequently, salt marsh may capture more carbon than they release and store it in sediments for extended periods. These ecosystems are known as blue carbon ecosystems (Lovelock and Reef, 2020), emphasizing the positive contribution of these intertidal areas to carbon budgets (Artigas et al., 2015).

As a first step in quantifying carbon budgets, this study aims to characterize and quantify the role of tillage in carbon mineralization rates across different parts of salt marshes, by measuring carbon dioxide exchanges at the water-atmosphere interface.

2 MATERIALS AND METHODS

2.1 Sampling strategy

The research was conducted at Le Crotoy concession, where carbon dioxide exchanges at the sediment-air interface (during emersion period and in the dark) were compared across three adjacent areas (without mowing): an unploughed area (control), an area ploughed in winter 2022-23 (and not subsequently), and an area ploughed in winter 2023-24 (Fig. 1).

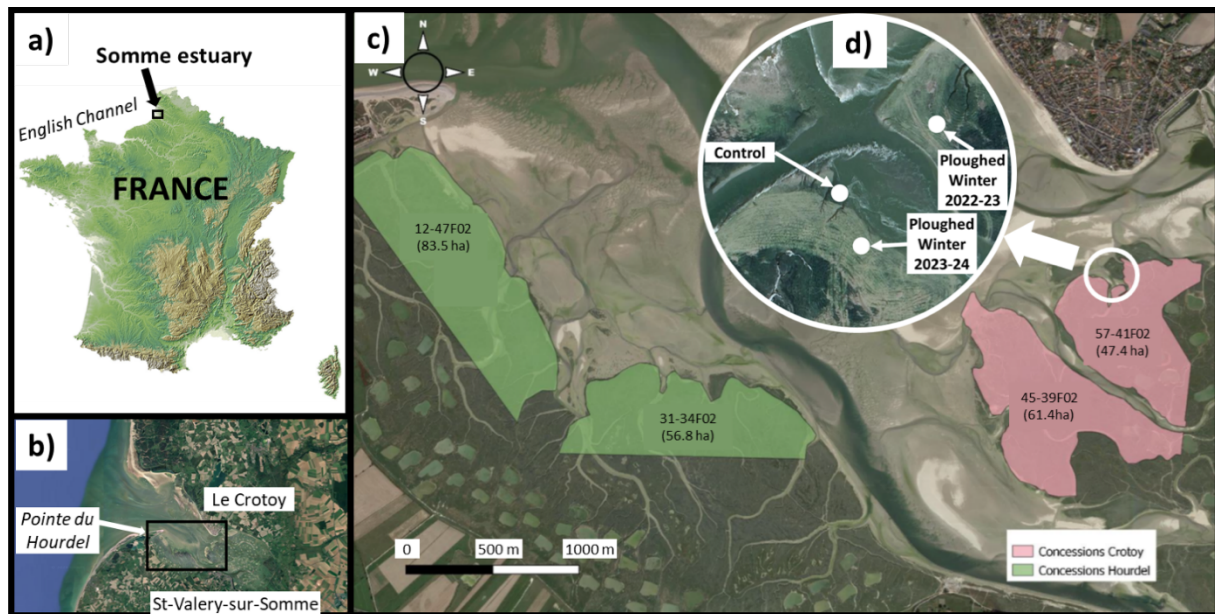


Figure 1. Area studied in the Somme estuary, along the eastern English Channel (a), between Le Crotoy and Saint-Valéry-sur-Somme (b), with concessions located along Le Crotoy (in pink) and Le Hourdel (in green)(c) the reference numbers of concessions and total surface in hectares (ha) are given for each zone - adapted from Becuwe et al., (2024). The 3 areas studied (control/unploughed, ploughed in winter 2022-23, and ploughed in winter 2023-24) are located less than 150 m distance from each other, in the easternmost concessions (d).

Four field campaigns were carried out in June and October 2024, during which carbon dioxide fluxes were measured in each area. For each area (control, ploughed in 2022-23, and ploughed in 2023-24), four sub-areas were pre-defined to represent the main plant species/ sediment types present in each location: i. Unvegetated bare sediments, ii. Sediments with *Salicornia* sp., iii. Sediments with *Suaeda maritima*, iv. Sediments with *Spartina anglica*.

In addition, triplicates measurements were made for each of the sub-areas (within 1m²), to account for small-scale spatial variability.

2.2 CO₂ fluxes at the sediment/atmosphere interface

We measured CO₂ exchanges at the sediment-atmosphere interface with the LI-COR 8100A device (LI-COR, Lincoln, USA), a semi-automatic dark benthic chamber equipped with an IRGA (Infra-Red Gas Analyser). The device consists of an opaque 'benthic chamber' (≈20cm i.d.), which is placed on a metallic base that is gently inserted 2 cm into the sediment. Once closed, the benthic chamber forms a hermetically sealed enclosure in which the temporal change of CO₂ concentrations, the water vapour content and air temperature, as well as the humidity and temperature of the substrate (measured with additional probes: GS1 Ruggedized Soil Moisture Sensor (Campbell Scientific, Edmonton, Canada) and Omega 6000-09TC soil temperature probe (Omega, Stamford, USA)) are automatically recorded. These measurements allow for

the calculation of dry CO₂ concentrations, enabling accurate quantification of CO₂ fluxes through a known sediment/air surface area (318 cm²).

After preliminary tests, a standard measurement protocol was consistently applied. This involved placing an opaque PVC cover over the base (already embedded in the sediment) for at least 10 minutes before starting the measurements, allowing photosynthetic organisms to complete the chemical phase of photosynthesis. Once this time elapsed, the cover was removed, the air is renewed by vigorous stirring, and the benthic chamber was placed on the base before starting the measurement process. The procedure consisted of 1 minute of homogenisation and purging of the pump and tubing systems (with the chamber open) followed by 3 minutes of measurements with the chamber hermetically closed. Back in the laboratory, fluxes were calculated from the slope of the CO₂ dry concentration versus time, obtained while the chamber was closed (considering an initial dead-band of 30 seconds) using the SoilFluxPro software (LI-COR, Lincoln, USA), which automatically accounts for all corrections (humidity, temperature, etc.). Given the temperature difference between sampling dates and times, we standardised CO₂ flux data to a temperature of 20°C using a Q₁₀ value of 2 (Boscolo-Galazzo et al., 2018). This calculation assumes that the intensity of a process doubles when the temperature rises by 10°C, as long as the temperatures remain within the physiological limits of the microorganisms implied.

2.3 Statistical analysis

Basic statistical analyses (T-tests, Pearson correlation), along with nested ANOVA, were carried out in R using the Stats package (version 4.2.1).

3 RESULTS AND DISCUSSION

3.1 General and temperature characteristics

The field experiments were carried out during low tide on 3 and 13 June, and 4 and 23 October, with the characteristics of the tidal cycle listed in Tab. 1.

Table 1. Dates, hours and environmental characteristics during the field campaigns.

Dates	Tide coefficient	Low-tide hour	Measurements		Sediment temperature Min / Max	Areas studied
			Start	End		
03/06/24	73	16h52	14h46	17h48	19.4 / 22.1°C	control, ploughed 2023-24
13/06/24	46	12h04	10h53	12h21	16.4 / 20.8°C	ploughed 2022-23
04/10/24	87	08h29	08h15	11h09	4.6 / 14.4°C	control, ploughed 2023-24
23/10/24	63	11h16	10h37	11h43	11.1/15.5°C	ploughed 2022-23

Significant differences were observed in the temperature of surface sediments within the benthic chamber on all dates. Overall, temperatures were significantly lower in October than in June (t-test, n=72, p<0.001***). However, the primary variation occurred throughout the day (depending on the amount of sunshine), with temperatures increasing by up to +9.8°C during the morning of 4 October. On 13 June, the average temperature ($\pm$ standard deviation) was $18.78 \pm 1.64^\circ\text{C}$, significantly lower than the $21.13 \pm 0.98^\circ\text{C}$ on 3 June (t-test, n=36, p<0.001***). The coldest temperatures (as low as 4.6°C) were recorded early in the morning on 4 October ($8.76 \pm 3.39^\circ\text{C}$), coinciding with exceptionally low temperatures for the first half of October (including four days with the second-lowest daily temperatures in Abbeville in the last 50 years, ranging from 6.0 to 7.1°C below the seasonal norms for 1981-2010, according to Météo-France). In contrast, measurements taken in the late morning of 23 October showed less variability ($13.02 \pm 1.39^\circ\text{C}$).

3.2 Raw and normalised CO₂ fluxes

As chemically-mediated processes, and consequently dissolved exchanges and mineralization rates, are sensitive to temperature, we normalized the measurements to an ambient temperature of 20°C. However, the general pattern observed is very similar to that of the raw (non-standardized) flux values (Fig. 2).

In June, normalized carbon dioxide exchanges ranged from very low values, around $0.68 \pm 0.40 \mu\text{mol.m}^{-2}.\text{s}^{-1}$ for bare sediments ploughed in 2023-24 to $49.55 \pm 14.31 \mu\text{mol.m}^{-2}.\text{s}^{-1}$ for sediments with *Suaeda maritima* ploughed in 2023-24. Furthermore, sediments with *Suaeda maritima* exhibited greater variability compared to other sediment types. The trend was similar across bare sediments and those with *Salicornia sp.*, *Spartina anglica* and *Suaeda maritima*. Except for the measurements taken from *Suaeda maritima* after ploughing in 2023-24, the control area consistently recorded the highest carbon dioxide exchanges, while sediments ploughed in 2023-24 showed the lowest values, with sediments ploughed in 2022-23 yielding intermediate values. This indicates a marked decrease in mineralization intensity from the unploughed/control sites, to those ploughed in 2022-23, and finally those ploughed in 2023-24.

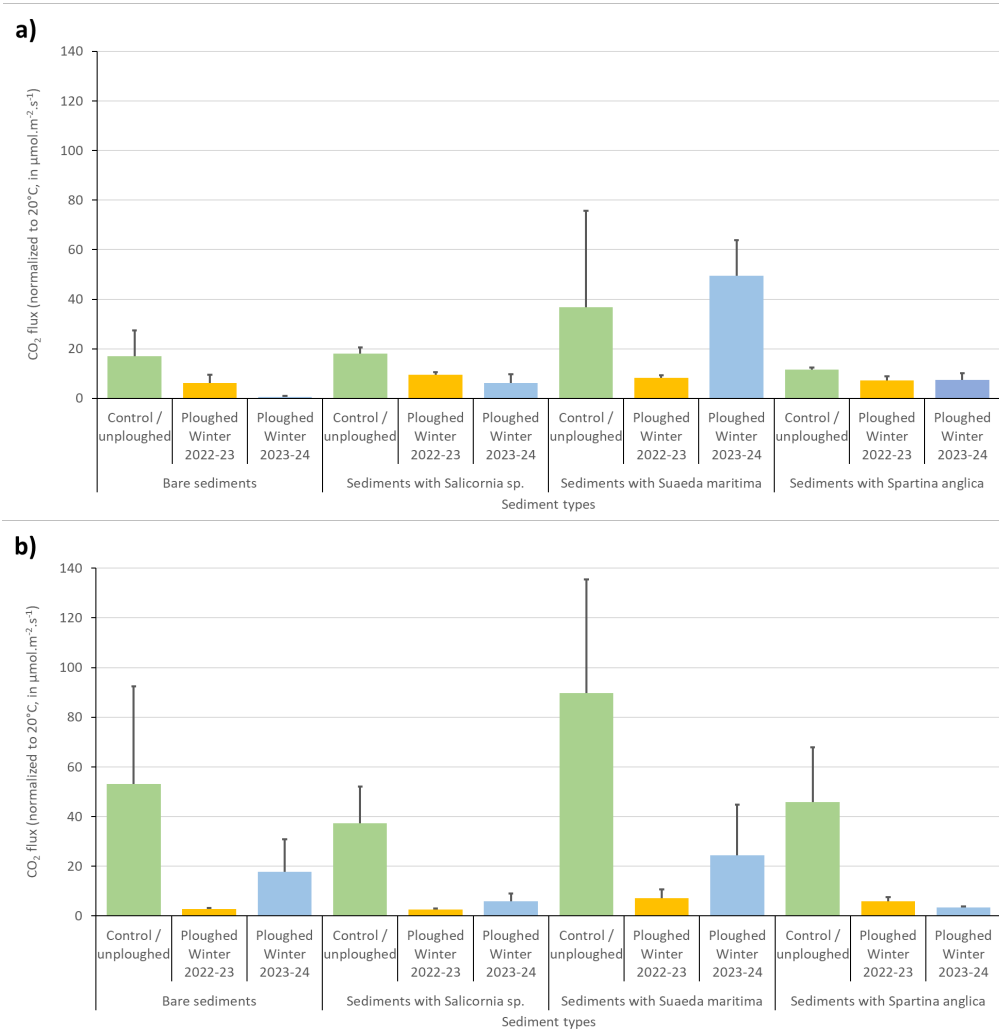


Figure 2: CO₂ fluxes measured at the sediment-air interface in the dark emersion chambers (normalised to the temperature of 20°C, see text) in the various areas and sub-areas studied, in June (a) and October (b).

In October, a similar pattern was observed, with the highest normalized values recorded in control/unploughed sediments, ranging from $37.41 \pm 14.75 \mu\text{mol.m}^{-2}.\text{s}^{-1}$ for sediments with *Salicornia* sp. to $89.70 \pm 45.71 \mu\text{mol.m}^{-2}.\text{s}^{-1}$ for sediments with *Suaeda maritima*. The lowest values were consistently recorded on sediment ploughed either in 2022-23 (bare sediments, sediments with *Salicornia* sp. and *Suaeda maritima*) or in 2023-24 (sediments with *Spartina anglica*). Overall fluxes were very low in the area ploughed in 2022-23, with average values falling within the range $2.65\text{--}7.12 \mu\text{mol.m}^{-2}.\text{s}^{-1}$ regardless of sediment type. In contrast, sediments ploughed in 2023-24 exhibited greater variability, with values ranging from 3.39 to $24.51 \mu\text{mol.m}^{-2}.\text{s}^{-1}$, depending on the sediment type.

A three-ways nested ANOVA, with 'seasons' as the first level, 'areas' as the second level and 'sub-areas' as the third level, was performed on all the normalized flux data ($N=72$). The analysis revealed significant differences between seasons ($p<0.05^*$), between areas ($p<0.001^{***}$), and between sub-areas ($p<0.05^*$). The most pronounced effect was observed at the area level, highlighting the greater influence of ploughing activity.

3.3 Discussion

Carbon dioxide fluxes at the sediment-atmosphere interface were measured using a semi-automatic opaque benthic chamber across different plant covers. As such, this approach does not account for primary production in carbon budgets, but it nonetheless provides an excellent estimate of the overall intensity of metabolism in surface sediments. It is important to note that the carbon dioxide exchange intensities recorded are higher than those observed in the sediments of intertidal mudflats, and are of the similar magnitude to those measured in other intertidal salt marshes along the eastern English Channel (Voltz, 2020). However, the measurements taken in the Canche estuary rarely exceed an intensity of $10 \mu\text{molCO}_2.\text{m}^{-2}.\text{s}^{-1}$ (Voltz, 2020), which suggests a very active metabolism in the salt marshes studied in the Somme estuary. This is likely linked to the fact that all these measurements were conducted in late spring

(June) and mid-autumn (October), when metabolic activity is close to its seasonal maximum, due to higher temperatures, sunshine intensity (day length and light intensity) and nutrient availability.

The results clearly show a reduction in the metabolic intensity associated with ploughing, regardless of the type of vegetation present. Metabolism is lower, as it is that for plants in the area ploughed in 2023-2024 (with the exception of *S. maritima*). Moreover, it is evident that more recent ploughing results in lower metabolism, which highlights two key points:

- i. the intensity of the disturbance associated with ploughing: the rate of carbon mineralisation is, on average, halved, except in the case of bare sediment, where post-ploughing metabolism is reduced by a factor of more than 10.
- ii. the resilience of this system: despite a significant disturbance, sediment metabolism gradually returns to its equilibrium state. It should be noted, however, that following a disturbance, the return to equilibrium is very slow, and the difference remains substantial even more than a year and a half after ploughing.

The fluxes measured in October on sediments ploughed in 2022-23 were generally much lower than those recorded on sediments ploughed in 2023-24, which is inconsistent with the results obtained in June, when a clear decrease was observed from the control area to the area ploughed in 2022-23, and then further to the area ploughed in 2023-24. This may be due to the exceptionally low air temperatures recorded in October 2024, particularly on 3-4 and 11-12 October, with minimum temperatures ranged from 3-5°C. These temperatures may have sharply and profoundly altered the 'summer' functioning of the biota in the salt marsh environment.

During the winter 2023-24 ploughing was delayed due to adverse weather conditions (regular and heavy rains causing flooding), and authorities were granted special authorization to carry out tillage until 8 March. In terrestrial systems, tillage is known to result in bursts of CO₂ emissions from the sediments within few hours after tillage, due to a rapid equilibration of soil CO₂ with atmospheric CO₂. Then, CO₂ emissions generally decrease until an equilibrium state observed after a few weeks (Zhang et al., 2008). However, the measurements acquired during this study, even in June (3 months after winter 2023-24 ploughing), very probably took place after the relaxation of the sediments, i.e. the period during which, after a disturbance, the sediments return to a stable biogeochemical functioning. In other words, this corresponds to the time required for the communities of macrofauna, meiofauna and above all bacteria, which are responsible for most of the mineralisation mechanisms, to be reconstituted and rearranged, and for the different mineralisation sequences (aerobic, anaerobic) to return to equilibrium. This was noted on site by the colouration of the sediments and the bedding patterns. However, furrows remained visible on the ploughed sites, with residual topography and the development of plant formations in parallel lines. Rather than returning to the original CO₂ flux, as is generally described in terrestrial areas (Zhang et al., 2008), we observed a clear decrease in CO₂ emission after tillage. Numerous studies in terrestrial environments highlight rainfall as key control factor for carbon dioxide emission from soils (Delsarte et al., 2021), but do not identify organic matter leaching as a significant factor influencing subsequent CO₂ exchanges. However, in intertidal areas, the current and waves during high tide may also lead to significant leaching of surficial sediment after tillage, which could substantially affect the amount and availability of organic matter, thereby reducing mineralisation rates over a period of 5 to 10 years, based on annual estimates of resilience rates.

In addition to the work conducted in this study, further research should include the characteristics (physiology, biomass...) of halophytic plants, as well as an analysis of organic matter (quantity and quality) in surficial sediments after tillage. Furthermore, the phenomenon of photosynthesis, measured using a transparent benthic chamber, should complement these analyses in order to quantify the carbon balance. The next step will be to quantify methane (CH₄) gas exchange at the sediment/air interface. Although methane fluxes are generally lower than those of carbon dioxide (Wei et al., 2020) methane is a greenhouse gas that is 28 times more potent than CO₂ over a century. This comprehensive approach will enable a definitive quantification of the impact of tillage on the dynamics of carbon storage in surface sediments.

4 CONCLUSION

Tillage significantly reduces the intensity of organic matter mineralisation in surface sediments, as measured by CO₂ fluxes at the sediment-atmosphere interface in the salt marshes of the Somme estuary. This effect is observed across all the main plant species encountered in this area, as well as on bare sediments, suggesting a broad impact of tillage on the availability of organic matter and/or on organisms (primarily microorganisms) in the surficial sediments, rather than a specific effect on the physiology or growth of halophytic plants.

While some resilience is observed in the system - with metabolism measured in the ploughed area in 2022-23 being intermediate between the unploughed state and the ploughed zone in 2023-24 - it is important to note that the return to the original state is very slow. Almost a year and a half after ploughing, the impact of

this disturbance remains highly significant. Although resilience appears consistent, we estimate that full recovery to the initial state may take between 5 to 10 years.

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