

Response to Reviewer 1: Sebastiaan Van de Velde

We would like to thank Dr. Van de Velde for the time taken to read and review our manuscript, and for raising relevant aspects that need clarification in the text. Please find below our detailed responses to his comments.

- 5 1. I feel that the title does not really reflect the contents. Most of the paper deals with the impact of bottom trawling fishing on the sedimentary organic matter dynamics, of which the arrival of fresh organic matter is part. Perhaps something like ‘the impact of trawling on organic matter dynamics in sediments of the Gulf of Castellammare (SW Mediterranean)’ would be more appropriate.

RESPONSE: We believe that the title emphasizes the novelty of our manuscript, since previous papers have already addressed the impacts of bottom trawling in sediment erosion and depletion of sedimentary organic matter, but not on the recent deposition of fresh sediment. Nevertheless, we have modified the title to “Organic matter contents and degradation in a highly trawled area during fresh particle inputs (Gulf of Castellammare, SW Mediterranean)” to englobe the different aspects studied in our manuscript.

- 15 2. I like that the paper is written very concisely and to the point. I do however feel that the abstract is a bit out of balance with the rest of the paper. If possible, I would try to shorten it somewhat.

RESPONSE: The abstract has been condensed in the revised manuscript.

- 20 3. Introduction: It might be relevant to mention the common depth range of the sediment that is resuspended after trawling, as it might be important when considering the impact of changing the frequency of trawling. For example, if your site has a sedimentation rate of 0.15 yr⁻¹, and you decrease trawling frequency to once every 10 years, and the trawl resuspends the upper 15 cm of sediment, the impact is still considerable.

RESPONSE: Indeed, knowing the depth-range of sediment that is resuspended by bottom trawlers would be crucial to understand the vulnerability of our study site to bottom trawling activities and establish efficient management strategies. There have been studies that model the amount of sediment resuspended by bottom trawlers, which indicate that type of trawling gear, sediment grain size, and hydrodynamic drag exerted by the trawling gear influence the mobilization of sediment (see O’Neill and Ivanovic, 2016, *ICES Journal of Marine Systems*; O’Neill and Summerbell, 2016, *Journal of Marine Systems*). These studies highlight that penetration depth of trawling gear on the seafloor and sediment resuspension do not always present an evident positive correlation, since some of this sediment is simply overturned and/or displaced laterally. Hence, providing a penetration depth of bottom trawling gear would not be indicative of the depth-range of sediment being resuspended, either. With our data, we cannot provide information on the amount of sediment being eroded per trawler. However, we have sufficient evidence, based on our results, that the overall erosion rate of trawlers is greater than the sedimentation rate in the Gulf of Castellammare. This is inferred due to the coincident penetration depths of both excess ²³⁴Th and excess ²¹⁰Pb, which have considerably different half-lives, indicating that the upper 2 cm of sediment was recently deposited, whereas sediment below these sections had been

deposited more than a century prior to sampling (see P10 L13-18 in the revised manuscript). This highlights the vulnerability of bottom trawling in deep environments, where the sedimentation rate is lower than shallower continental shelves. Please see the response to your comment 6, which also deals on management strategies to mitigate this impact.

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4. P10L14: Would you expect coarser sediment to be washed away following trawling induced resuspension? I would assume the inverse happens, that the finer-grained, OM rich material gets washed away, and the coarser material remains behind. Also, the grain size of the trawled site has near-identical values for its grain size. Unless you mean that the finest material does not settle as fast as the intermediate grain sizes (but that should then be explained a bit clearer).

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RESPONSE: Indeed, we should observe the advection of fine sediment, and not coarse sediment, with a preferential deposition based on particle size. The untrawled core was collected approximately 1 km downcurrent from trawling grounds, where silty sediment will be preferentially deposited in comparison to finer sediment such as clay particles. Clay sediment, however, can remain in suspension and travel greater distances, eventually redepositing farther away. For instance, a study on the distribution of trawling-induced resuspension of sediment in the Koster Sea on the west coast of Sweden observed that silt particles can travel up to 7 km from trawling grounds, whereas finer clay particles can travel beyond 28 km (Linders et al., 2018, *ICES Journal of Marine Systems*). We acknowledge that this message may not have been clear due to poor word choice, referring to “silt” particles as “coarse” sediment. The amended manuscript now reads (see P10 L28 – P11 L01 in the revised manuscript):

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“Provided the high capacity of bottom trawling gear to resuspend sediments (Martin et al., 2014a, 2014c; Oberle et al., 2018; Puig et al., 2012), the siltation of superficial sediments on the untrawled site could be explained by the preferential deposition of siltier particles resuspended from an adjacent trawling ground located ~1 km up-current from this sampled site (Fig.1). Finer clay particles resuspended by bottom trawlers can be advected at farther distances along the margin (Linders et al., 2018).”

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5. P10L22-26: Another explanation could be that the resuspension and mixing stimulate the breakdown of organic matter that is already present, thus leading to lower concentrations. This is also what you allude to in P11L15-23, an increase in mineralization rates due to the mixing of refractory and fresh compounds. If it is noticeable after the deposition of fresh material, I assume it will play a role over the longer term too. Most likely the truth exists somewhere in the middle, and the impact of bottom trawling induced resuspension events is likely very dependent on the exact grain size. For example, we found recently that this mixing stimulates organic matter breakdown in a fine grained (63% clay) sediment in the North Sea (van de Velde et al., 2018, Scientific Reports), whereas Tiano et al. (2019, *ICES Journal of Marine Science*) found that sediment metabolism actually went down after trawling. The North Sea site of Tiano et al. (which is a reference you should include) was much however much sandier (30% silt, 40% fine sand). Maybe it would be worth expanding the discussion a bit, and considering both end-member scenarios.

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RESPONSE: Diverse results have been found on the fate of OM in trawling grounds, some of them summarized in Martin et al., 2014, *Anthropocene*. As the reviewer mentions, one of the reasons of these contradictory results could be the type of sediment in each environment: whether trawling occurs on non-cohesive sandy seafloors or on cohesive muddy seafloors. We

limited our study to comparing the effects of bottom trawling to other cohesive environments (including the results portrayed in van de Velde et al., 2018, *Scientific Reports*), and merely distinguishing between biogeochemical impacts in shallower and deeper trawling grounds. We agree with the reviewer that it would be worth exploring the influence of grain size, but it is not the scope of this paper. We believe that a proper review of the impacts of bottom trawling on the biogeochemistry of OM should be done to assess the influence of grain size, water depth, and other factors. Nevertheless, we have included the following sentences in the Introduction of the amended manuscript (see P02 L11-16 in the revised manuscript), which highlight the broad range of effects that bottom trawling can generate in different environments:

“The effects that these perturbations generate on sedimentary OM can vary in cohesive (i.e. muddy sediment with high clay content) and non-cohesive (i.e. sandy seafloor) sediment. For instance, trawling on cohesive sediments can increase superficial concentrations of sedimentary OM (Palanques et al., 2014; Pusceddu et al., 2005a; Sciberras et al., 2016; Polymenakou et al., 2005), whereas trawling on coarse non-cohesive sediments can exert null or minimal effects on OM contents and benthic community metabolism (Hale et al., 2017; Tiano et al., 2019; Trimmer et al., 2005).”

6. P11L29: this is a nice section to end the discussion, maybe it would be worth expanding this a bit, maybe by being a bit more concrete in the potential mitigation effects? This could be related to my comment about the depth of the bottom trawling, how long would temporary need to be to really mitigate the effect?

RESPONSE: Our study suggests that the ephemeral deposition of fresh and nutritious sediment could be sustaining the otherwise starved benthic communities. Establishing temporal trawling closures would allow a longer-lived deposition of fresh sediment, temporarily restoring sedimentary OM in trawling grounds which could be beneficial to the benthic communities inhabiting this area. However, with the punctual information we have of the impacts of bottom trawling and the effect of the deposition of fresh sediment, we can not provide additional details of how a temporal trawling closure should be implemented (i.e. length or season of the trawling closure). Hence, we believe that further studies assessing the viability of these mitigation practices should be carried out.

From the sedimentological perspective, a temporal trawling closure would not solve the issue of erosion in trawling grounds. For instance, assuming a regional sedimentation rate of $0.09 \text{ g}\cdot\text{cm}^{-2}\cdot\text{yr}^{-1}$, or $0.15 \text{ cm}\cdot\text{yr}^{-1}$, a trawling closure of a decade would allow the accumulation of $0.9 \text{ g}\cdot\text{cm}^{-2}$, or 1.5 cm of “new” sediment. Such a long trawling closure isn’t feasible from a socioeconomic perspective, nor efficient. To solve this problem, other management strategies that reduce the rate of erosion would need to be studied, such as reducing the trawling frequency or changing their trawling gear to minimize sediment remobilization. This additional issue has been addressed in the revised manuscript by modifying the discussion’s closing paragraph from the original manuscript to the following (see P12 L16-22 in the revised manuscript):

“These results confirm that actions aimed at mitigating the impacts of bottom trawling include the implementation of temporary fishing closures, allowing for a longer-lived deposition of fresh OM on the seafloor. However, such temporary trawling closures would most probably not allow the full restoration of fresh sediment from trawl-induced erosion, given the low sedimentation rates found on these deep environments. Further management strategies would need to be implemented to mitigate the impacts of

bottom trawling erosion (Depestele et al., 2019), which would magnify the effect of temporary closures on the restoration of sedimentary OM in nutrient-deprived trawling grounds.”

Minor editorial suggestions:

5 As a more general remark, you say you sliced cores in triplicate, but I only see one profile per figure and per site (and the captions says that the error bars represent the analytical error). What happened to the other 2 cores that were sliced?

10 RESPONSE: Triplicate cores were taken only for organic matter analyses (protein, carbohydrate, lipid, phytopigment, turnover rates), whereas the remaining analyses (dry bulk density, grain size, radiochemical analyses, and elemental analyses) were carried out in one sediment core from each site. We specified that error bars in Fig. 4, for instance, represent analytical errors, and we should have also specified that Figs. 5 and 7 represent mean and standard errors of triplicate samples. This has been clarified in the revised manuscript (see P04 L19-20 of the revised manuscript) and in the figure captions.

15 P2L13-15: ‘concentrations of sedimentary organic matter in superficial sediments tend to increase’ and later ‘stimulate mineralization of buried and refractory organic matter’ This seems contradictory to me, as stimulating mineralization would decrease organic matter.

20 RESPONSE: Indeed, this would seem contradictory and should be clarified. High OM concentrations initially lead to high remineralization, which eventually lower sedimentary OM concentrations. It is basically an issue of the time-scale of these processes. In Polymenakou et al., 2005, *Continental Shelf Research* and in Pusceddu et al., 2005, *Continental Shelf Research*, the onset of trawling activities initially led to higher sedimentary organic matter concentrations, possibly due to mixing, which was accompanied with higher OM degradation. However, re-sampling of these trawled sites a few months later indicated a decrease of sedimentary organic matter concentrations, attributed to the high degradation rates observed earlier. Nevertheless, this apparent
25 contradictory sentence was removed to avoid confusions. See the response to your comment 5 for how this issue was clarified.

P3L17: move ‘are’ between ‘sedimentary organic matter’ and ‘by’

30 RESPONSE: This grammatical correction has been included in the revised manuscript (see P03 L21 of the revised manuscript).

P4L13: you mention that you slice cores on deck, up to 9cm depth, but later you show figures with date up to 20 cm depth? (e.g. Fig.2)

RESPONSE: We sliced triplicate cores intended for organic matter analyses up to 9 cm, whereas the remaining cores, used to analyse the remaining parameters (dry bulk density, grain size fraction, radiochemical analyses), were completely sliced in 1 cm intervals (see P04 L19-20 of the revised manuscript).

5 P5L11: why did you limit measurements to the upper 5 cm? I assume that is because activities dropped below the detection limit, but it might be nice to mention that here.

RESPONSE: Only the upper 5 cm were analysed for excess Th-234 since samples need to be measured within two half-lives (approximately 6 weeks), after which 75 % of excess Th-234 would have decayed, rendering its quantification unreliable and with a high uncertainty. Since we didn't find detectable concentrations of Cs-137 in the trawled site in these upper 5 cm, we considered unnecessary to analyse deeper samples of this core, whereas gamma measurements for Cs-137 in the untrawled core were conducted for deeper layers until concentrations were below detection limit. This has been clarified in the revised manuscript (see P05 L21 in the revised manuscript).

15 P8L8: Maybe it is not relevant for this paper, but why would the CaCO₃ contents differ?

RESPONSE: Trawled sites presented higher (~27 %) CaCO₃ concentrations than the untrawled site (~17 %) in the upper 10 cm, although the difference becomes smaller at deeper sections in the cores. This could be related to differences of (or proximity to) riverine sediment sources, or to a higher presence of broken shells or foraminifera. With the available information, we cannot explain the exact reasons for this phenomenon and we prefer not to speculate about this aspect in the paper.

P11L18: Aller (1994) is not an appropriate reference, this paper deals with bioturbation and redox oscillations, not self-priming.

25 RESPONSE: This reference was accordingly removed in the revised manuscript (see P12 L4 in the revised manuscript).

Figs 2 and 3 could be combined into 1

RESPONSE: We would rather keep these two figures separate, since combining them would make the figure too dense.

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Response to Reviewer 2: Xavier Durrieu de Madron

We would like to thank Dr. Durrieu de Madron for the time taken to read and review our manuscript. Our detailed responses to his remarks and how they were addressed in the revised manuscript are provided below:

5 Page 2, Lines 18-19. The comparison of the impact of storms versus trawling is not discussed in the article by Durrieu de Madron et al, 2005, but by Ferré et al, 2008. (Ferré B., X. Durrieu de Madron, C. Estournel, C. Ulses, G. Le Corre (2008). Impact of natural and anthropogenic (trawl) resuspension on the export of particulate matter to the open ocean. Application to the Gulf of Lion (NW Mediterranean). Continental Shelf Research, 28, 2071–2091).

10 RESPONSE: The reference has been corrected in the amended manuscript (see P02 L19 in the revised manuscript).

Page 3, Lines 6-8 Since when has bottom trawling been practiced on the continental slope? Is it since the 1990 ban or was this area trawled before? This information would be useful to give an effective duration of trawling activity in the study area.

15 RESPONSE: Intense bottom trawling activities in the Castellammare region has been practiced for decades prior to the banning. The following sentence has been included in the revised manuscript (see P03 L7-10 in the revised manuscript):

20 *First data of bottom trawlers in the area go back to the 1960s, but this fishery became more active since the 1980s (European Commission Fisheries & Maritime Affairs, 2014), as a result of the modernization of the Sicilian trawling fleet (L.R. 1/1980, L.R. 26/1987).*

Page 2, Line 26. It is a cyclonic circulation (anti-clockwise) and not an anticyclonic circulation. On the other hand, I imagine that currents on the continental shelf are variable and strongly impacted by wind, while the circulation along the continental slope is probably more permanent. I suggest simply writing "A cyclonic along-slope current dominates the Gulf's circulation".

25 RESPONSE: This mistake has been corrected in the amended manuscript (see P03 L31 in the revised manuscript).

Page 3, Lines 12-13. The sampling strategy includes three multi-tube corer deployments at the same station from which 3 cores are collected. Did you analyze each slice of sediment of the 9 cores thus collected and then estimate the mean and standard deviations, or did you mix all the sedimentary material of the different cores before analyzing it and the error bars shown correspond then to the instrumental error.

30 RESPONSE: Three sediment cores from triplicate multicorer deployments were retrieved at each station for organic matter analyses (proteins, carbohydrates, lipids, phytopigment, and turnover rate analyses). These

analyses were conducted for each slice of the 9 sediment cores. The mean and standard errors of each sampled section was calculated for each depth at both sites (trawled and untrawled) and these results are presented in Figs. 5 and 7. On the other hand, a single sediment core from one of the three deployments was used to analyse the remaining parameters (sediment dry bulk density, grain size, radiochemical analyses). For these analyses, the error bars of Figs. 2-4 correspond to their analytical error. This has been clarified in the Figure captions of the revised manuscript.

Page 3, Line 21-24. Can you indicate the size limits between clays and silts, and silts and sands?

RESPONSE: The size limits between clays ($< 4 \mu\text{m}$), silts ($4\text{-}63 \mu\text{m}$), and sands ($> 63 \mu\text{m}$) were given in Table 1. However, they have also been included in-text under Sect. 2.3 (see P04 L28 in the revised manuscript).

Page 4, Line 2. Indicate the maximum depth of the cores on which these analyses were performed.

RESPONSE: Pb-210 analyses were conducted downcore until 37 cm and 49 cm for the trawled and untrawled site, respectively. This information has been included in the revised manuscript (see P05 L9-10 in the revised manuscript).

Page 7, Line 8-13. It would be useful here and for the discussion to know more about the fishing gears. Can you specify the main types and characteristics of bottom trawls used by fishermen in this region? Are they beam or otter trawls? Are they equipped with rollers or chains?

RESPONSE: Bottom trawling in the Gulf of Castellammare is mainly conducted by bottom otter trawls. The following sentence has been included in the revised manuscript (see P03 L6-7 in the revised manuscript):

Bottom trawlers in this gulf operate using otter trawl gear, a trawling technique which consist of dragging a wide net that is held open and in contact to the seafloor by two otter doors (Martín et al., 2014a).

Page 10, Lines 14-16. Do you have any information on the intensity of the bottom current to estimate their capacity to transport or even remobilize fine sediment?

RESPONSE: Bottom current in the upper shelf of the Gulf of Castellammare has an average speed of $0.1\text{-}0.2 \text{ m}\cdot\text{s}^{-1}$, but can sometimes reach $0.4 \text{ m}\cdot\text{s}^{-1}$ (Sarà et al., 2006). Unfortunately, there is no data of bottom currents on the slope close to our sampling sites, but assuming similar bottom current intensities as those observed on the shelf, it wouldn't cause enough shear stress to remobilize the fine-grained cohesive sediment of our study site. This information has been included both in 2.1 Study area and in the aforementioned section (see P03 L30-32 in the revised manuscript).

Page 10, Lines 29-34. Do you think that the benthic and epi-benthic communities are the same between the two sites (trawled and untrawled) given the differences in the substrate? Could different species induce significant differences in the organic matter turnover rate? Meiofauna biodiversity is not addressed in this article, but I think it would be interesting to consider this possibility in the discussion (if it makes sense)?

RESPONSE: Turnover rates were calculated from extracellular enzymatic activities produced by bacteria, hence, the turnover rates presented in our manuscript don't reflect metazoan consumption of organic matter. Nevertheless, trawling will undoubtedly cause differences not only in sedimentary organic matter, but also in epi-benthic communities, as observed in deep bottom trawling grounds off the NW Mediterranean (Pusceddu et al., 2014, PNAS). A separate paper dealing with epi-benthic community in sediment cores collected during the ISLAND cruise is under development. This under-construction paper will partly deal with the effects of bottom trawling, using our current manuscript as reference of the physical impacts of bottom trawling and its effect in organic matter content and degradation in the Gulf of Castellammare.

Captions of Figures 2, 3, 4, 5 and 7. Explain the vertical blue and red scales, as well as acronyms (SML: Surface Mixed Layer, constant SR : constant Sedimentation Rate)

RESPONSE: The vertical annotations have been explained in the figure caption of the revised manuscript.

List of important changes

1. Changed the title based on comments from reviewer 1.
2. Condensed abstract, as suggested from reviewer 1.
3. Added variable impacts by bottom trawling on seafloors with different grain sizes (P02 L11-16), as suggested by
5 reviewer 1.
4. Additional information of bottom trawling in the Gulf (P03 L6-10), as suggested by reviewer 2.
5. Corrected hydrodynamic description of the Gulf and included additional data (P03 L30-32), as suggested by reviewer
10 2.
6. Clarification of sampling strategy and sediment core subsampling and analyses (P04 L9-10, L19-20, P05 L21, and
figure captions), as suggested by both reviewer 1 and 2.
7. Restated the advection of resuspended sediment by bottom trawlers (P10 L28 – P11 L01), as suggested by reviewer
1.
8. Included the potential capacity of recovery of fishing grounds from a sedimentological perspective (P12 L16-22), as
suggested by reviewer 1.

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Organic matter contents and degradation in a highly trawled area during fresh particle inputs (Gulf of Castellammare, SW Mediterranean)

Effects of the arrival of fresh organic matter on eroded and nutrient-depleted trawling grounds (Gulf of Castellammare, SW Mediterranean)

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Abstract. Bottom trawling in the deep sea is one of the main drivers of sediment resuspension, eroding the deep-seafloor and altering the content and composition of sedimentary organic matter (OM). The physical and biogeochemical impacts of bottom trawling on the seafloor were studied on the continental slope of the Gulf of Castellammare, Sicily (Southwestern Mediterranean) through the analysis of two triplicate sediment cores collected in trawled and untrawled sites (~550 m water depth) during the summer of 2016. Geochemical and sedimentological parameters (excess ²¹⁰Pb, excess ²³⁴Th, ¹³⁷Cs, dry bulk density, and grain size), elemental (organic carbon and nitrogen) and biochemical composition of sedimentary OM (proteins, carbohydrates, lipids), as well as its freshness (phytopigments) and degradation rates were determined in both coring locations. The untrawled site had a sedimentation rate of 0.15 cm₂-yr⁻¹ and presented a 6-cm thick surface mixed layer that contained coarser-siltier sediment with low excess ²¹⁰Pb concentrations, possibly resulting from the resuspension, posterior advection, and eventual deposition of siltier-coarser and older sediment from adjacent trawling grounds. In contrast, the trawled site was characterized by was highly eroded and presented compacted century-old sediment highly, as shown by the lack of excess ²¹⁰Pb and high dry bulk densities. The continuous erosion in the trawled site has led to the depletion-depleted in of-OM components, which were between 20% and 60% lower than those in the untrawled site, as well as to statistically significant differences in the biochemical composition of OM. Nevertheless/However, the upper 2 cm of the trawled site consisted of

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recently accumulated sediments; enriched in excess ^{234}Th , excess ^{210}Pb , and phytopigments, ~~which while OM contents had similar OM contents were similar to those surface sediments~~ from the untrawled core. ~~This fresh sediment presented protein turnover rates of 0.025 d^{-1} , which doubled those quantified in surface sediments of the untrawled site. The enhancement of remineralization rates in surface sediment of the trawled site was associated to~~ the arrival of fresh ~~sediment-particles in-on~~ a chronically-trawled deep-sea ~~site-region~~ that is generally deprived of OM ~~was associated with an enhancement of remineralization rates, reflected by protein turnover rates of 0.025 d^{-1} , which doubled the rates quantified in surface sediments of the untrawled site.~~ We conclude that the detrimental effects of bottom trawling can be temporarily and partially abated by the arrival of fresh and nutritionally-rich OM, which stimulate the response of benthic communities. However, these ephemeral deposits are likely to be swiftly eroded due to the high trawling frequency over fishing grounds, highlighting the importance of establishing science-based management strategies to mitigate the impacts of bottom trawling.

1 Introduction

Bottom trawling is among the most extensive forms of anthropogenic activities affecting marine ecosystems (Amoroso et al., 2018; Eigaard et al., 2017) and it is one of the most harmful in terms of fish stock overexploitation (Pauly et al., 2002), destruction of habitats (Kaiser et al., 2002; Simpson and Watling, 2006), and physical impact it exerts on the sediments (Martín et al., 2014a; Oberle et al., 2018; Puig et al., 2012). Since bottom trawling targets benthic and demersal fisheries, its gear is designed to be in continuous contact with the seafloor, scraping the bottom, resuspending large volumes of sediment (O'Neill and Ivanović, 2016; Palanques et al., 2014), and causing significant erosion (Martin et al., 2014b; Oberle et al., 2016). The resuspension of sediment releases nutrients and organic matter (OM) to the overlying water column, and degradation of ~~sedimentary organic matter~~OM can be accelerated through enhanced microbial activity (Durrieu de Madron et al., 2005; Pusceddu et al., 2005b, 2015). ~~The effects that these perturbations generate on sedimentary OM can vary depending on the environment in since cohesive (i.e. muddy sediment with high clay content) and non-cohesive (i.e. sandy seafloor) sediment have different specific surface areas and biogeochemical properties that alter OM content and preservation on the seafloor.~~ For instance, ~~trawling on cohesive sediments can tend to increase superficial concentrations of sedimentary OM (Palanques et al., 2014; Pusceddu et al., 2005a; Sciberras et al., 2016;) , possibly as the result of sediment mixing by the trawling gear, which uproots OM from deeper layers and stimulates mineralisation of buried and refractory OM through oxygenation, ultimately decreasing initial OM (Polymenakou et al., 2005), whereas, in contrast, trawling on coarse ,non-cohesive seafloor sediments does can exert null or minimal effects not n't present significant changes in on sedimentary OM concentrations, nor in its contents and benthic community metabolism (Hale et al., 2017; Tiano et al., 2019; Trimmer et al., 2005).~~

Additionally, concentrations of sedimentary organic matter in superficial sediments tend to increase (Palanques et al., 2014; Pusceddu et al., 2005a), possibly as the result of mixing and oxygenation of the deeper layers by the trawling gear, which ultimately stimulate mineralisation of buried and refractory organic matter (Polymenakou et al., 2005; van de Velde et al.,

2018). Most of these impacts have been documented in shallow environments, where sediment and organic matter-OM fluxes are generally high and sediment resuspension and organic matter-OM remineralization induced by bottom trawling can be comparable to those induced by natural high-energy events such as storms (Buscaill et al., 1990; Dellapenna et al., 2006; Durrieu de Madron et al., 2005; Ferré et al., 2008; Pusceddu et al., 2005b). Since these natural physical disturbances are
5 persistent, shallow benthic communities generally present higher resilience to the impacts of bottom trawling than communities that live in less disturbed areas, such as the deep sea (Kaiser, 1998).

However, bottom trawling has been progressively expanding to deeper environments (>200 m depth) ~~over the last 60~~ since the 1950s years (Morato et al., 2006; Roberts, 2002), driven by technological advances in parallel with an on-going depletion of shallow-water fisheries (Koslow et al., 2000; Martín et al., 2014a). At such depths, natural sediment fluxes to the seafloor and
10 resuspension processes tend to be low. Hence, bottom trawling has become a major mechanism of sediment resuspension on continental slopes, leading to eroded environments in trawling-fishing grounds (Martín et al., 2014b, 2014c; Puig et al., 2012). Resuspended particles can then be exported by ambient currents across- and along-margin as enhanced nepheloid layers (Arjona-Camas et al., 2019; Wilson et al., 2015), or as sediment gravity flows (Martín et al., 2014c; Puig et al., 2012) ultimately generating anthropogenic sedimentary depocenters (Puig et al., 2015; Paradis et al., 2017, 2018).

15 Contrary to the observed increases in total organic carbon on muddy continental shelf trawling grounds (Palanques et al., 2014; Polymenakou et al., 2005; Pusceddu et al., 2005a), the continuous removal of sediment by trawlers on continental slopes ~~of this region~~ have significantly impoverished bulk organic carbon as well as its labile and fresh pools (Martín et al., 2014b; Pusceddu et al., 2014; Sañé et al., 2013). The loss of organic matter has also reduced organic carbon turnover rates on slope trawling grounds, severely impacting the meiofauna and, at the same time, promoting the abundance of taxa with opportunistic
20 life strategies (Pusceddu et al., 2014). However, the combined effect of bottom trawling erosion along with the alteration of sedimentary organic matter, which usually represents the fundamental energy source for commercial deep-sea benthic species, is not fully understood.

The Gulf of Castellammare holds one of the most important bottom trawling grounds in the Northern Sicilian shore (~~Southwestern-southwestern~~ Mediterranean Sea). Bottom trawlers in this Gulf operate using otter trawl gear, a trawling technique which consists of dragging a wide net that is held open and in contact with the seafloor by two otter doors (Martín et al., 2014a). First data of bottom trawlers in the area go back to the 1960s, but this fishery became more active since the 1980s (European Commission Fisheries & Maritime Affairs, 2014), as a result of the modernization of the Sicilian trawling fleet (L.R. 1/1980, L.R. 26/1987). Fishing stocks within this gulf were declining alarmingly until the Sicilian Government established in 1990 a trawling ban area in the inner shelf (L.R. 25/1990), delimited by the junction between Capo Rama and
25 Torre dell'Uzzo (Fig. 1). Since the establishment of this closure, both demersal biomass and catch per unit effort (CPUE) of artisanal fisheries (non-towed bottom gear and pelagic gear) have increased in that area (Pipitone et al., 2000; Whitmarsh et al., 2002). However, bottom trawlers have been concentrating their efforts beyond the restricted area in the mid-continental slope (> 500 m depth), leading to a decrease in CPUE since the trawl ban as a result of the continuous overexploitation of fishing stocks (Arculeo et al., 2014; Whitmarsh, 2002). A more recent management strategy aimed to prevent the collapse of

Sicilian fisheries established a 30-day bottom trawling closure per year, that can occur from the 1st of August to the 31st of October (Decreto 1339/2001).

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Despite the numerous studies that address the effects of the trawl ban in the Gulf of Castellammare (Fanelli et al., 2008; Romano et al., 2016; Pipitone et al., 2000; Whitmarsh et al., 2002), no studies have yet assessed the impacts of bottom trawling on the Gulf's-gulf's sedimentary environment. This study aims to reveal whether erosion prevails in bottom trawling grounds and what are the consequent alterations on sedimentary organic matter are, by comparing sediment cores collected in a trawled and untrawled site in the Gulf of Castellammare. The degree of erosion will be estimated based on sedimentological parameters and radioactive tracers with different half-lives (^{210}Pb , $t_{1/2} = 22.3$ years; ^{234}Th , $t_{1/2} = 24.1$ days), whereas the alterations on sedimentary organic matter will be determined based on its quantity, composition, and nutritional quality. The coupled analyses of radioactive tracers and biomarkers will also provide insights on the effects of the arrival of fresh sediment on impacted trawling grounds.

2 Methods

2.1 Study area

The Gulf of Castellammare is one of the widest bays of the northern coast of Sicily, with over 70 km of coastline, enclosed by the-Cape Rama to the East and Cape San Vito to the West (Fig. 1). A cyclonic along-slope current dominates the Gulf's circulation at an average speed of $0.1\text{-}0.2\text{ m}\cdot\text{s}^{-1}$ on the upper continental shelf, which can sometimes reach maximum speeds of $0.4\text{ m}\cdot\text{s}^{-1}$. An easterly anticyclonic current dominates the Gulf's regional circulation (Istituto Idrografico della Marina, 1982; Sarà et al., 2006). The seafloor morphology consists of a sub-horizontal gently-sloping continental shelf that extends approximately 5 km offshore. The continental slope is around 11° steep down to 500 m water depth, and then gradually decreases to around 1.5° at 1300 m water depth (Lo Iacono et al., 2014). Several small, narrow submarine canyons cut the slope, breaching the shelf break at 120 to 140 m depth (Lo Iacono et al., 2014). Small seasonal torrents discharge into the Gulf, namely the Nocella, Jato and San Bartolomeo rivers, with annual average discharges between $0.24\text{ m}^3\cdot\text{s}^{-1}$ and $0.32\text{ m}^3\cdot\text{s}^{-1}$ (Regione Siciliana, 2007). Storm-induced flash floods can cause short flushing events of up to $1.2\text{ m}^3\cdot\text{s}^{-1}$ that transport significant amounts of nutrients into the sea (Calvo and Genchi, 1989).

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2.2 Sediment core sampling

In the framework of the FP7 EU-Eurofleets 2 ISLAND (ExplorIng SiciLian CAnyoN Dynamics) cruise on board the R/V *Angeles Alvariño*, sediment cores were collected in August 2016 from trawled and untrawled sites in the Gulf of Castellammare. Sampling locations were selected based on the distribution of operating trawlers using data from Vessel Monitoring System (VMS) (see Sect. 2.8). Sampling took place prior to the temporal fishing closure in the Gulf of Castellammare, which took place that year between the 17th of September to the 16th of October. This ensured that sediment cores reflect the alterations caused by bottom trawling persisting in this deep environment.

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A total of five multicore deployments were conducted using a K/C Denmark A/X six-tube multicorer (inner diameter 9.4 cm) in trawled and untrawled sites along the 550 m contour lines. However, only one trawled and one untrawled sites could be sampled (Fig. 1), possibly due to high sediment compaction at the trawled sites, as experienced by Martin et al. (2014b), and/or due to the swell during the coring operation that could hamper a successful triggering of the multicorer.

- 5 Triplicate sediment cores were retrieved at each site from three independent multicore deployments to account for spatial variability of organic matter analyses. The sediment cores were sliced on deck (0-1, 1-3, 3-5, 5-7, and 7-9 cm) and stored in calcinated aluminium foil at -20°C until analysis of organic matter content. At each site, a single sediment core from one of the three deployments was reserved for sedimentary, radiochemical, and elemental analyses. This sediment core was sliced on-deck at 1 cm intervals and kept in sealed plastic bags at -20°C until freeze-dried in the laboratory for analyses.
- 10 Prior to sediment recovery, the remotely operated vehicle (ROV) Seaeye Falcon, from the University of Plymouth (UK), collected visual evidence of trawling impact at the trawled sampling site and of no impact at the control site to corroborate the sampling strategy (Fig. S1).

2.3 Sedimentary characteristics

- Dry bulk densities of sediment cores were calculated by dividing the net dry weight corrected for salt content by the sample volume. Grain size fractions of sand (> 63 µm), silt (4-63 µm), and clay (< 4 µm) were obtained using a Horiba Partica LA-950V2 particle-size analyser, with an accuracy of 0.6% and a precision of 0.1%. Prior to analysis, 1-4 g of sample was oxidized using 20% H₂O₂ and sediment particles were disaggregated with P₂O₇.
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2.4 Radiochemical analyses

- Concentrations of ²¹⁰Pb were determined through the analysis of its decay product ²¹⁰Po by alpha spectrometry following the method described by Sanchez-Cabeza et al. (1998), assuming secular equilibrium of both radionuclides at the time of analysis. Between 150 and 300 mg of homogenized ground samples were spiked with ²⁰⁹Po as a chemical yield and microwave-digested using concentrated HNO₃, HF, and H₂BO₃. The resulting solutions were evaporated and reconditioned with 1 M HCl. Polonium isotopes were spontaneously deposited onto silver discs while stirring at 70°C for at least 8 hours. Alpha emissions of ²⁰⁹Po (4883 keV) and ²¹⁰Po (5304 keV) were quantified using Passivated Implanted Planar Silicon (PIPS) detectors (CANBERRA, Mod. PD-450.18 A.M.) and the Genie™ data acquisition software. Supported concentrations of ²¹⁰Pb in the sediment cores were obtained by averaging constant concentrations of total ²¹⁰Pb from the bottom of the core, from 2 to 37 cm for the trawled core and from 27 to 49 cm for the untrawled core, assuming complete decay of excess ²¹⁰Pb at these depths. Supported ²¹⁰Pb concentrations were corroborated by measuring ²²⁶Ra concentrations through its decay product ²¹⁴Pb (295 and 352 keV) in several samples along each core by gamma-spectroscopy, using calibrated geometries in a well-type high-purity germanium detector (CANBERRA, Mod. GCW3523).
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Concentrations of ²³⁴Th were also measured by gamma-spectroscopy through the 63 keV emission line. Given its short half-life (24.1 days), samples were measured within two half-lives (~6 weeks) since sampling, which only allowed the measurement

of the upper 5 cm of the trawled and untrawled cores. Samples were re-measured at least 6 months later, after excess ^{234}Th had decayed, to obtain supported ^{234}Th concentrations, equivalent to ^{238}U concentrations. Excess ^{234}Th was calculated by subtracting total ^{234}Th from supported ^{234}Th , accounting for ^{234}Th decay and in-growth from ^{238}U since sampling.

Concentrations of ^{137}Cs were also quantified by gamma-spectroscopy through the emission line at 662 keV. Gamma measurements of the untrawled sediment core were extended in depth to 20 cm, whereas in the trawled core measurements were limited to the upper 5 cm since no ^{137}Cs was detected in that core.

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2.5 Elemental analyses

Analyses of total carbon, organic carbon (OC) and total nitrogen (TN) were carried out with an elemental analyser (Costech ECS Analyzer 4010), according to the procedure described in Nieuwenhuize et al. (1994). Samples for OC analysis were first decarbonated by acid-fuming the samples in the presence of 12 N HCl during 24 h and repeatedly adding 100 μL of 2 N HCl to the sample until effervescence ceased. Inorganic carbon (IC), quantified as the difference between total carbon and organic carbon, was converted to calcium carbonate (CaCO_3) concentrations using the molecular mass ratio of CaCO_3 :IC (100/12), assuming all inorganic carbon present is in the form of CaCO_3 . To account for analytical error, replicate analyses were performed for samples every 5 cm throughout the cores. An average percentage error of 1.2 % was obtained for carbon whereas nitrogen presented a slightly higher average percentage error of 1.9 %.

2.6 Biochemical composition of sedimentary organic matter

Total proteins, carbohydrates, and lipids were quantified spectrophotometrically (Varian Cary® 50 UV-Vis) according to the methods described in Hartree (1972) and modified by Rice (1982), Gerchakov and Hatcher (1972), Bligh & Dryer (1959), and Marsh and Weinstein (1966). The analyses of proteins and lipids were carried out on 0.1-0.6 g of frozen sediment, whereas carbohydrate analyses were done on previously-dried sediment. Protein, carbohydrate and lipid contents were transformed into carbon equivalents using 0.49, 0.4 and 0.75 $\text{mg C}\cdot\text{mg}^{-1}$ as conversion factors, respectively, and their sum reported as biopolymeric C (Fabiano et al., 1995). Chlorophyll-a and phaeopigments, after extraction with 90% acetone, were quantified fluorometrically (Shimadzu RF-6000) according to Lorenzen and Jeffrey (1980), and modified by Danovaro (2010) for sediments. Total phytocarbon concentrations were defined as the sum of chlorophyll-a and phaeopigment concentrations and converted into carbon equivalents using a conversion factor of 40 (Pusceddu et al., 2010).

2.7 Sedimentary OM freshness and degradation rates

The contribution of phytocarbon to biopolymeric C was used as a proxy to estimate OM freshness: since in the deep sea there is no *in situ* primary production, higher values of this ratio are associated with recently-deposited material of algal origin (Pusceddu et al. 2010).

Since N is the most limiting factor for heterotrophic nutrition and proteins are N-rich products, sedimentary OM degradation was estimated using the degradation rate of proteins, obtained from the analysis of extracellular aminopeptidase activities.

Aminopeptidase activity was estimated fluorometrically after incubation of approximately 0.1 g of sediment with 100 μ M L-leucine-4-methylcumarinyl-7-amide for 1 h in the dark. This substrate, when exposed to extracellular aminopeptidase, produces fluorescence with an intensity proportional to the enzyme activity. Fluorometric analyses were carried out before and after incubation, and the difference was used to calculate protease activities (Danovaro, 2010). The results were converted to carbon equivalents using the conversion factor of 72 ng C \cdot nmol protease⁻¹ (Fabiano and Danovaro, 1998). Turnover rates were then calculated by dividing protein-C degradation rates by protein-C sedimentary contents.

2.8 Trawling effort from VMS data

Fishing intensity of the Italian bottom trawling fleet was obtained using data provided by Vessel Monitoring System (VMS), the main tracking device used for monitoring fishing activities. According to the Common Fisheries Policy of the European Union (European Commission, 2003), fishing vessels with length-over-all equal to or larger than 15 m must be equipped with a VMS transmittant, called "Blue-Box". It estimates the position of the vessel by Global Positioning System, and sends this information, along with the speed and heading of the vessel, to the network of the Coastal Guard by Inmarsat-C to the Fishing Monitoring Centre in less than 10 min at 2-hour time intervals. Fishing intensity was calculated using yearly VMS data from 2007 to 2015, whereas for 2016, only VMS data from January 1st to August 10th were taken into account, prior to sampling. Trawling frequency was represented as number of times trawled per grid cell (200 x 200 m) during each year. The native VMS data were processed using the R package VMSbase (Russo et al., 2014). The size of the grid was defined considering the error associated to the reconstruction of the trawling hauls as described by Russo et al. (2011).

2.9 Statistical analyses

Statistical analyses were used to test whether OM quantity and biochemical composition (protein, carbohydrate, lipid, and phytopigment concentrations), freshness (the phytopigment to biopolymeric C ratio), and degradation rates (sedimentary protein turnover rates) were statistically different between trawled and untrawled sites in the upper 9 cm of sediment cores. The analysis consisted of two orthogonal factors: site (trawled vs. untrawled) and depth in the sediment (5 levels: 0-1 cm, 1-3 cm, 3-5 cm, 5-7 cm, 7-9 cm). Permutational analyses of variance (PERMANOVA), either in the univariate (variable by variable) or multivariate contexts, were based on Euclidean distances of previously normalized data using 999 permutations of residuals with unrestricted permutation of raw data (univariate tests) or under a reduced model (multivariate tests) (Anderson 2001). Since for almost all tests the interaction between factors was significant, we conducted post-hoc permutational pairwise comparison tests between trawled and untrawled sites for each sediment layer and among sediment layers for trawled and untrawled sites, separately. Given the restricted number of unique permutations, p-values were obtained from Monte Carlo simulations (Anderson and Robinson, 2003). Bi-plots produced after Canonical Analysis of Principal components (CAP) were used to visualize the differences between trawled and untrawled samples in terms of organic matter biochemical composition (Anderson and Willis, 2003). All statistical analyses were performed using the routines included in the PRIMER 6+ software.

3 Results

Bottom trawling in the Gulf of Castellammare is limited to the mid-slope (> 500 m), beyond the trawling-ban area. In the main bottom trawling ground, where the trawled core was retrieved, hauls generally follow the contour lines on a W-E direction (Fig. 1). Fishing effort generally increased since 2007, with a predominating trawling frequency of 1 to 40 hauls per grid cell during that year, which then increased to around 60 to 100 hauls per grid cell since 2013 (Fig. S2). A smaller trawling ground opened since 2012 towards the eastern side of the Gulf, close to Cape Rama, opened since 2012 (Fig. 1, S2). Although trawling frequency for 2016 was only computed from January to August, this year presented highest fishing effort in comparison to the previous years. In 2016, the temporal trawling closure occurred between the 17th of September to the 16th of October in the Gulf of Castellammare, after sampling the sediment cores. Hence, sediment cores retrieved during the cruise will have registered the effects of bottom trawling in these deep environments.

3.1 Physical characteristics

The untrawled sediment core presented an excess ²¹⁰Pb concentration profile that extended to 25 cm in depth, with a total inventory of 17900 ± 900 Bq·m⁻² (Fig. 2a; Table 1). In the upper 6 cm, excess ²¹⁰Pb concentrations slightly decreased towards the surface from 372 ± 22 Bq·kg⁻¹ to 272 ± 15 Bq·kg⁻¹ (Fig. 2a). Below, excess ²¹⁰Pb concentrations presented a continuous decrease between 6 and 25 cm, from which an average sediment accumulation rate of 0.090 ± 0.003 g·cm⁻²·yr⁻¹, equivalent to 0.151 ± 0.005 cm·yr⁻¹ (R² = 0.995) (Table 1) was calculated applying the Constant Flux : Constant Sedimentation model (CF:CS, Krishnaswamy et al., 1971). This sedimentation rate was independently validated by ¹³⁷Cs. Detectable concentrations of ¹³⁷Cs appeared at 17 cm depth, which was ascribed to the first detonations of thermonuclear weapons in the early 1950s. Above, ¹³⁷Cs concentrations depicted a broad concentration maximum at 8-13 cm, centred at 10-11 cm. This maximum was attributed to the combined accumulation of the maximum fallout prior to the cessation of nuclear atmospheric testing in 1963 as well as the deposition of ¹³⁷Cs emitted from the Chernobyl accident in 1986 (Fig. 2a). The deposition of ¹³⁷Cs from each of these events could not be distinguished due to the low sedimentation rate and the sampling resolution of this core. Concentrations of excess ²³⁴Th ranged between 71 and 97 Bq·kg⁻¹ between 2 and 5 cm, decreased to 37 ± 7 Bq·kg⁻¹ at 1-2 cm and was not detected on surface sediments (0-1 cm) of the core (Fig. 2b). The penetration depth of excess ²³⁴Th could be greater than the upper 5 cm analysed, leading to an inventory of at least 1080 Bq·m⁻² (Table 1). Dry bulk density of the untrawled site remained constant in the upper 7 cm at ~0.5 g·cm⁻³, gradually increased to ~0.7 g·cm⁻³ at 15 cm, and then remained relatively constant with depth (Fig. 2c). The upper 6 cm presented coarser grain size consisting of higher silt (77 %) and lower clay (22 %) fractions, in comparison to the rest of the core, which had lower silt (44 %) and higher clay (54 %) fractions (Fig. 2c, Table 1). CaCO₃ concentrations were constant in the upper 10 cm, with an average concentration of 18.4 ± 0.4 %, decreased to ~15 % at 15-20 cm, and then slightly increased with depth until ~20 % at 30 cm (Fig. 4d).

In the sediment core collected from the trawled site, both excess ²¹⁰Pb and excess ²³⁴Th were only present in the upper 2 cm, with inventories of 340 ± 30 Bq·m⁻² and 1000 ± 50 Bq·m⁻², respectively (Table 1, Fig. 3a,b). ¹³⁷Cs was not detected in the

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upper 5 cm analysed. Dry bulk density rapidly increased from $0.4 \text{ g}\cdot\text{cm}^{-3}$ to $0.7 \text{ g}\cdot\text{cm}^{-3}$ in the upper 3 cm and kept increasing to $\sim 0.8 \text{ g}\cdot\text{cm}^{-3}$ at 13 cm, from where it remained relatively constant with depth (Fig. 3c). Despite the slight coarsening of grain size in the upper 2 cm, this core presented constant grain size along the upper 37 cm, consisting of higher clay (57 %) and lower silt (41 %) fractions, (Fig. 3c, Table 1), similar to grain sizes below 6 cm of the untrawled site. Concentrations of CaCO_3 averaged at $26.9 \pm 0.7 \%$ in the upper 10 cm, whereas the deeper layers had lower concentrations of $\sim 24 \%$ (Fig. 3d).

3.2 Sedimentary organic matter

Trawled and untrawled sediment cores presented different OC and TN concentration profiles (Fig. 4). The untrawled core had OC concentrations of $\sim 0.9 \%$ in the upper 20 cm which then decreased to $\sim 0.8 \%$ at 35 cm. In contrast, the trawled core presented OC concentrations that fluctuated between $\sim 0.8 \%$ and $\sim 0.7 \%$ with depth. Similarly, concentrations of TN in the untrawled core were $\sim 0.13 \%$ in the upper 20 cm, which then decreased to $\sim 0.10 \%$ at 35 cm, whereas the trawled core presented TN concentrations varying between $\sim 0.11 \%$ and $\sim 0.09 \%$ with depth. For both OC and TN, concentrations in the upper 20 cm were $\sim 20 \%$ lower in the trawled site in comparison to the untrawled site, reaching similar concentrations at 30 cm in depth (Fig. 4). Profiles of OC/TN ratio presented similar values in both sites, varying between 6.5 and 7.5 throughout the core (Fig. 4c).

In general, organic matter quantity was higher in the untrawled site than in the trawled site, with the exception of surface layers, which presented similar concentrations in both sites (Fig. 5). Protein concentrations in the untrawled site were $1.5 \text{ mg C}\cdot\text{g}^{-1}$ in the upper 3 cm, increased to maximum concentrations of $\sim 3 \text{ mg C}\cdot\text{g}^{-1}$ at 3-7 cm, and decreased to $2.4 \text{ mg C}\cdot\text{g}^{-1}$ at 7-9 cm. The trawled site had similar $\sim 1.5 \text{ mg C}\cdot\text{g}^{-1}$ protein concentrations in surface sediment that increased to almost $2.5 \text{ mg C}\cdot\text{g}^{-1}$ in the deepest layer analysed (Fig. 5a). Carbohydrate concentrations in the untrawled site presented decreasing concentrations from between 0.7 and $0.9 \text{ mg C}\cdot\text{g}^{-1}$ in the upper 3 cm to $0.44 \text{ mg C}\cdot\text{g}^{-1}$ in the deepest layer, whereas the trawled site had constant concentrations of $0.42 \text{ mg C}\cdot\text{g}^{-1}$ in the upper 9 cm of the trawled site (Fig. 5b). Untrawled and trawled sites had similar lipid concentrations of $\sim 0.6 \text{ mg C}\cdot\text{g}^{-1}$ in the topmost sediment layer, decreasing to $0.34 \pm 0.03 \text{ mg C}\cdot\text{g}^{-1}$ and $0.17 \pm 0.01 \text{ mg C}\cdot\text{g}^{-1}$ at 7-9 cm of the untrawled and trawled cores, respectively (Fig. 5c). Biopolymeric C concentrations were constant ($2.5 \pm 0.1 \text{ mg C}\cdot\text{g}^{-1}$) along the upper 9 cm of the trawled core, whereas concentrations increased in the untrawled core from $2.9 \pm 0.2 \text{ mg C}\cdot\text{g}^{-1}$ in the topmost layer to $\sim 4 \text{ mg C}\cdot\text{g}^{-1}$ in the 3-7 cm layer, before returning to similar values observed in the surface layer (Fig. 5d). In both sites, phytopigment profiles showed decreasing trends, with a sharper decrease in the trawled site from $126 \pm 7 \mu\text{gC}\cdot\text{g}^{-1}$ in the top layer to relatively constant values of $39 \pm 5 \mu\text{gC}\cdot\text{g}^{-1}$ below 3 cm, whereas the untrawled site showed a gradual decrease from $161 \pm 18 \mu\text{gC}\cdot\text{g}^{-1}$ in the topmost layer to $77 \pm 12 \mu\text{gC}\cdot\text{g}^{-1}$ in the deepest one (Fig. 5e).

Statistical analyses of the data indicated that both sampling site and core depth had significant effects on the quantity of sedimentary OM (Table S1). The post-hoc comparison tests (Table S2) demonstrated that OM contents between trawled and untrawled sites were generally statistically different only below the topmost sediment layer (0-1 cm), with the exception of carbohydrates.

3.3 Organic matter biochemical composition, freshness, and turnover rates

Variations in the biochemical composition of sedimentary OM in terms of protein, carbohydrate, lipid, and phytopigment contents were assessed through PERMANOVA test (Table S3). The results revealed that the biochemical composition of sedimentary OM not only differed between trawled and untrawled sites, but that these differences varied depending on the depth in the core. The consequent post-hoc pairwise tests between the trawled and untrawled sites at all sediment layers indicated that the biochemical composition of sedimentary OM, similarly to the OM content, varied significantly between trawled and untrawled sites at all depths, excluding surface sediments (Table S4). The bi-plot produced after the canonical analysis of principal components (Fig. 6) revealed that the vertical variations in the biochemical composition of sedimentary OM in the untrawled sediment core are greater than those observed at the trawled site, ~~as observed from the greater spatial distribution of the trawled samples in the bi-plot in comparison to the untrawled samples. On the other hand, the proximity of superficial samples of trawled cores to most of the untrawled samples in the bi-plot illustrates a resemblance in ; and that their biochemical composition of superficial sediments from the trawled site resemble that of superficial sediments from the untrawled site.~~

The contributions of phytopigment to biopolymeric C and the protein turnover rates in trawled and untrawled sites are given in Table S5 and illustrated in Fig. 7. The relative contribution of phytopigments to biopolymeric C were similar in superficial sediments of trawled and untrawled sites, with relatively high values (~5 %) that decreased with depth in both sites, although more pronouncedly in the trawled site, ~~reaching ~1.4 % at 5-7 cm,~~ than in the untrawled site, ~~reaching 2.5 % at 7-9 cm~~ (Fig. 7a). Turnover rates were significantly higher in the upper 3 cm of ~~the~~ trawled site (0.017-0.025 d⁻¹) in comparison to the ~0.015 d⁻¹ of ~~the~~ superficial sediment of the untrawled site (Table S5b, Fig. 7b). Below, turnover rates decreased to ~0.005 d⁻¹ for both sites.

4 Discussion

4.1 Long-term impacts of intense bottom trawling

Evidence of the long-term impacts of intense bottom trawling are clear in a trawled site of the Gulf of Castellammare. ROV images from the trawled area present a barren seafloor, with several deep linear furrows hundreds of meters long and up to 70 cm deep, presumably caused by ~~heavy the~~ trawling gear's ~~heavy otter doors~~ (Fig. S1a). The shallow penetration depth of excess ²¹⁰Pb in the trawled core suggests that only the upper 2 cm of sediment had been recently deposited on top of highly compacted sediments (0.7-0.8 g·cm⁻³) that had accumulated more than 100 years ago, considering the absence of excess ²¹⁰Pb (Fig. 3a,c). These sedimentological patterns are characteristic of a seafloor eroded by trawling activities, as observed in other trawled regions with shallow horizons of excess ²¹⁰Pb and exposed over-consolidated, century-old sediments (Martín et al., 2014b; Oberle et al., 2016; Paradis et al., 2017, 2018). The uprooting of old sediment in this trawled site, with only a thin accumulation of recent sediment in superficial layers, reveals that the rate of sediment erosion induced by the high trawling

frequency is greater than sediment accumulation rates in the Gulf of Castellammare. Furthermore, the coincident penetration depth of both excess ^{210}Pb and ~~excess~~ ^{234}Th in the trawled site (Fig. 3a,b) indicates that the accumulation of fresh sediment would have occurred after the passage of the last trawler over the sampling area, and thus reveals that trawling frequency controls the residence time of fresh sediment in these trawling grounds.

5 In contrast, excess ^{210}Pb inventories were two orders of magnitude higher in the untrawled core. This core had a sedimentation rate of $0.151 \pm 0.005 \text{ cm}\cdot\text{yr}^{-1}$, comparable to those quantified at similar depths in the Mediterranean Sea (DeGeest et al., 2008; Miralles et al., 2005; Sanchez-Cabeza et al., 1999). The upper 6 cm of this core had excess ^{210}Pb concentrations that slightly decreased towards the surface, a deep penetration depth of excess ^{234}Th , and low dry bulk densities (Fig. 2a,b), altogether signs of biological mixing (Arias-Ortiz, et al. 2018; Pope et al., 1996; van Weering et al., 1998). The influence of bioturbation in this site is corroborated by the presence of several burrows directly observed during ROV dives prior to sampling (Fig. S1b). Sediment mixing caused by bioturbation could explain the broad ^{137}Cs concentration maximum observed at 8-13 cm, attributed to the combined accumulation of ^{137}Cs from the 1986 Chernobyl accident and from the 1963 global fallout, as well as diluting the 1954 signal with depth (Fig. 2a). However, bioturbation alone cannot account for the coarsening of sediment observed in the upper 6 cm (Fig. 2c; Table 1). Provided the high capacity of bottom trawling gear to resuspend fine sediments (Martin et al., 2014a, 2014c; Oberle et al., 2018; Puig et al., 2012), the siltation of superficial sediments on the untrawled site coarsening could probably be explained by the preferential deposition arrival of siltier (i.e., coarser) sediment particles resuspended from originating from trawling-induced resuspension at an adjacent trawling ground located ~1 km up-current from this sampled site (Fig. 1?) whereas finer clay particles resuspended by bottom trawlers can be advected at farther distances along the margin (Linders et al., 2018). This siltier sediment which would have been posteriorly redistributed along the margin and preserved within the surface mixed layer of the untrawled site (Fig. 1).

20 Excluding the fresh superficial layers of the trawled site, the chronic erosion induced by bottom trawling resuspension considerably depleted the trawled site of both OC and TN by ~20 % in comparison to the untrawled site (Fig. 4; Table 1). Concentrations of OC and TN were similar in the deeper layers of both sites, where sediments would have accumulated more than a century ago, revealing that bottom trawling re-exposes old sediment impoverished in OM (Fig. 4; Table 1). Similarly, 25 the trawled site had lower proteins (-5 to -38 %), carbohydrates (-13 to -58 %), lipids (-36 to -52 %), biopolymeric carbon (-12 to -37%), and phytopigments (-53 to -67 %) than the untrawled site, with the exception of superficial layers (Fig. 5). These results are in accordance with previous studies that showed comparable losses of organic matter in slope trawling grounds, reinforcing the concept that chronic and intensive bottom trawling depletes these deep-sea sedimentary habitats trawling grounds of sedimentary organic matter, promoting their degradation over time of deep-sea sedimentary habitats (Martin et al., 2014b; Pusceddu et al., 2014; Sañé et al., 2013), whereas the opposite occurs in shallow shelf trawling grounds (Palanques et al., 2014; Pusceddu et al., 2005a).

4.2 Effects of the arrival of fresh sediment

During the ISLAND Cruise, ROV dives showed high settling fluxes of large particulate matter aggregates to the seafloor (Fig. S1). In both sampled sites, evidence of recent accumulation of surface sediments was provided by the presence of excess ^{234}Th and high concentrations of phytopigments (Fig. 5e), a compound that usually represents the most important food source for deep-sea heterotrophic consumption (Pusceddu et al., 2010; Stephens et al., 1997). This indicates that the Gulf of Castellammare was receiving highly nutritious organic matter inputs during the sampling period. Indeed, both the composition of sedimentary organic matter and the relative contribution of phytopigment to biopolymeric C were similar in the fresh superficial sediments in both trawled and untrawled sites. However, the subsurface, century-old sediments of the trawled site have distinctively different organic matter composition and significantly lower nutritional quality in comparison to its untrawled counterpart (Fig. 6, 7a). This suggests that, aside from the ephemeral deposition of fresh OM that will be swiftly eroded by bottom trawlers' gear, deep-sea trawling grounds are generally characterized of nutritionally-poor organic matter contents (Pusceddu et al., 2014; Sañé et al., 2013), which increases the dependence on the supply of fresh OM in order to sustain benthic communities. This hypothesis is corroborated by the higher OM turnover rates in surface sediment of the trawled site in comparison to the untrawled site (Fig. 7b), which reveal a promptly-enhanced stimulation of microbial activities resulting from the recent accumulation of fresh and nutritionally-enriched OM on the trawled site. In fact, benthic communities in areas that have severe nutrient limitations, such as in eroded sediment of this trawled site or in oligotrophic deep-sea regions, react instantaneously to food pulses (Bett et al., 2001; Fabiano et al., 2001; Witte et al., 2003). In contrast, the untrawled site, characterized of relatively higher total organic matter contents as well as fresh and bioavailable compounds throughout the core, presented slowly decreasing concentrations of phytopigment to biopolymeric C with depth as well as lower protein turnover rates, revealing a lower consumption of labile OM and a relatively reduced dependence on the arrival of fresh OM (Fig. 7a).

The higher OM turnover rates observed in the freshly-deposited surface layers of the trawled site also indicate a greater efficiency of OM consumption and remineralization in the trawling ground in comparison to the untrawled site. This enhanced mineralization through self-priming can occur when fresh and degradable organic matter, such as fresh phytoplankton, arrives to areas with more refractory compounds (Aller, 1994; Canfield, 1994; van Nugteren et al., 2009), as was observed in a shallow trawling-disturbed area in the southern North Sea, off the Belgian coast (van de Velde et al., 2018). Similarly, bottom trawling in the shallow Thermaikos Gulf (Aegean Sea) intensified microbial activities, which enhanced nutrient cycling and organic carbon mineralisation (Polymenakou et al., 2005; Pusceddu et al., 2005a). This could have been attributed to the combined effect of trawling-induced mixing of superficial labile OM with more degraded subsurface OM, along with the continuous arrival of fresh OM to these shallow continental shelves (Buscail et al., 1990; Tselepides et al., 2000).

In contrast, surface sediments collected in a deeper and intensely-trawled flank of La Fonera Canyon, in the NW Mediterranean margin, presented significantly lower turnover rates than the nearby untrawled grounds (Pusceddu et al., 2014). However, those sediment cores did not present signs of recently-accumulated sediment as observed in our sampling sites,

further proving the dependence on the arrival of fresh and nutritionally-rich sediment in intensely trawled grounds to support benthic organisms living in these impacted deep-sea environments.

The high nutritional quality and OM turnover rates in recently-accumulated sediments from the trawled site suggest that high OM fluxes ~~in the Gulf of Castellammare~~ could help deep bottom trawling grounds recover the nutritional characteristics of sedimentary OM. These results ~~highlight confirm~~ that actions aimed at mitigating the impacts of bottom trawling ~~should consider include the establishing implementation of~~ temporary fishing closures, ~~which would allow allowing for~~ a longer-lived deposition of fresh OM on the seafloor, ~~temporarily restoring sedimentary OM in trawling grounds. However, such temporary trawling closures would most probably not allow the deposition of sufficient the full restoration of fresh sediment to recover from the trawl-induced erosion induced by bottom trawlers, given the low sedimentation rates found on these deep~~ environments. Further management strategies would need to be ~~studied~~ implemented to ~~reduce the rate~~ mitigate the impacts of bottom trawling erosion to mitigate these impacts (Depestele et al., 2019), which would ~~as well as that~~ magnify the ~~influence effect of temporary trawling closures in on the restoration of sedimentary OM in these nutrient-deprived trawling grounds. Further studies should be aimed in this direction to properly assess the effectiveness of establishing seasonal trawling closures as a management strategy to restore bottom trawling grounds.~~

15 5 Conclusion

Chronic and intense deep bottom trawling in the Gulf of Castellammare erodes large volumes of sediment, exposing over a century-old, compacted sediment that is depleted in OM. This continuous erosion limits the accumulation of fresh sediment, since any recently-deposited particulate matter is promptly removed due to the high trawling frequency. Nevertheless, we present evidence that the short-lived deposition of recent and nutritionally-rich organic matter leads to high turnover rates of labile OM. Our results emphasize that nutrient-deprived and eroded deep bottom trawling grounds are highly dependent on the arrival of fresh and nourishing particulate organic matter to sustain benthic communities, which can temporarily and partially abate the detrimental effects of bottom trawling in superficial sediment.

Author contribution

SP, AP, PP, and CL designed the scientific study. SP and CL retrieved the samples. SP and DM performed the analyses and TR processed the fishing effort data. SP wrote the manuscript. All authors contributed to the interpretation and discussion of the results, as well as the revision of the manuscript.

Competing interests

The authors declare that they have no conflict of interest.

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Figures and Tables

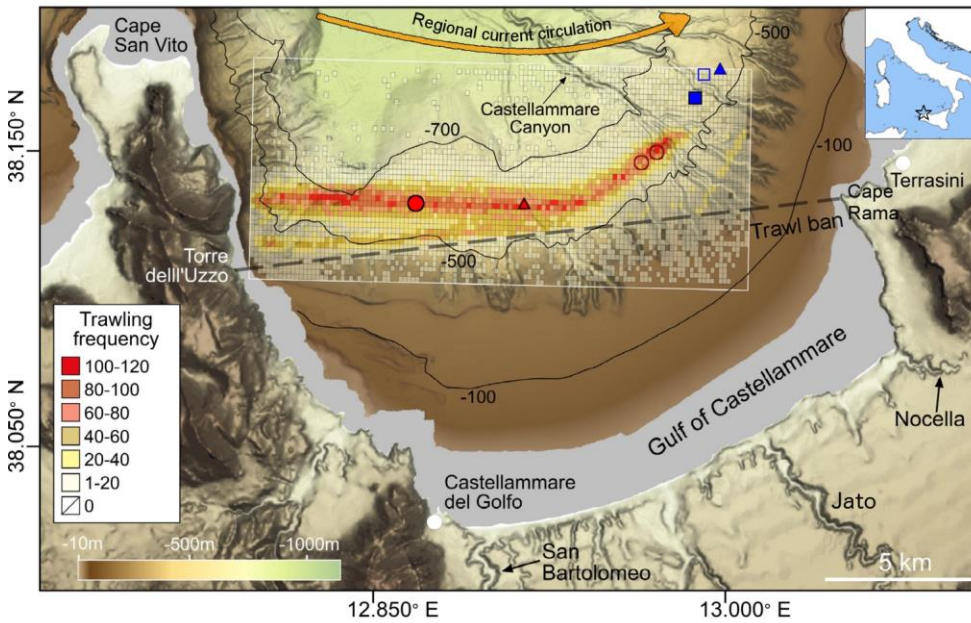


Figure 1: Bathymetric map of the Gulf of Castellammare. Location of the sediment cores sampled on the trawled (red circles) and untrawled (blue squares) sites. Unfilled sampling points indicate unsuccessful sediment core deployments. Seafloor images obtained from ROV dives are shown with triangles (see Fig. S1). The distribution of trawling grounds as trawling frequency (number of total hauls per grid area) in 2016 (January 1st to August 10th) was calculated for a 200 x 200 m grid. The limit of the trawl banned area between Torre dell'Uzzo and Cape Rama is indicated by a dashed line. Main trawling harbours (Castellammare del Golfo and Terrasini) and the most relevant ephemeral rivers (San Bartolomeo, Nocella, and Jato) are also annotated. The yellow arrow illustrates the direction of the regional surface current.

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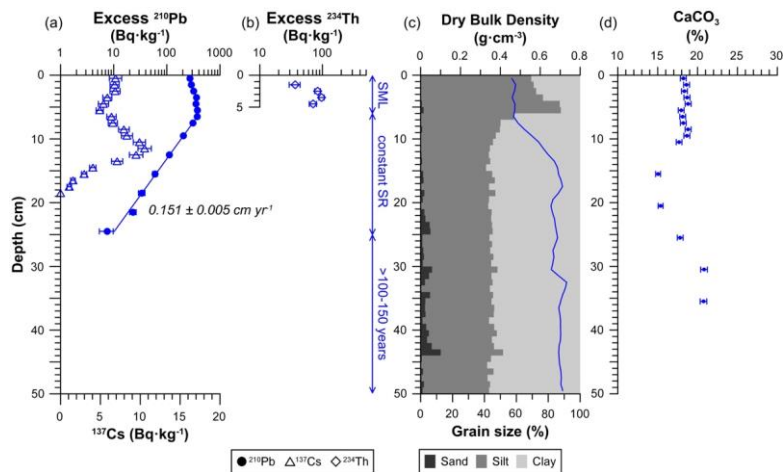


Figure 2: Sedimentological and geochemical characteristics of the untrawled sediment core. (a) Concentration profiles of excess ^{210}Pb (circles), indicating the average sedimentation rate below the upper 6 cm, and ^{137}Cs (triangles). (b) Concentration profile of excess ^{234}Th in the upper 5 cm. (c) Dry bulk density and grain size. (d) CaCO_3 concentration profile. The analytical error is given in horizontal error bars. Vertical scales indicate the process that has occurred in the depth range given. SML: Surface Mixed Layer; SR: Sedimentation Rate.

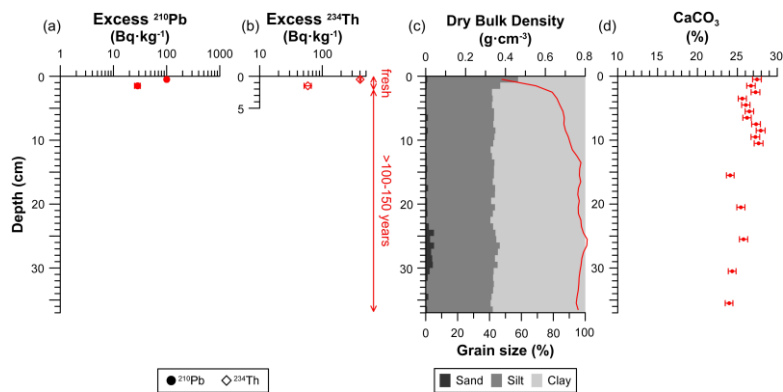


Figure 3: Sedimentological and geochemical characteristics of the trawled sediment core. (a) Concentration profiles of excess ^{210}Pb . (b) Concentration profile of excess ^{234}Th in the upper 5 cm. (c) Dry bulk density and grain size profile. (d) CaCO_3 concentration profile. The analytical error is given in horizontal error bars. Vertical scales indicate the process that has occurred in the depth range given. SML: Surface Mixed Layer; SR: Sedimentation Rate.

Table 1: Summary of main parameters of the trawled and untrawled cores. Data for grain size, CaCO₃, OC, TN, and OC/TN correspond to average values ± 1 standard deviation of that layer. MAR: mass accumulation rate, SAR: sediment accumulation rate.

Core	Layer (cm)	Excess ²³⁴ Th inventory (Bq·m ⁻²)	Excess ²¹⁰ Pb inventory (Bq·m ⁻²)	Sedimentation rates		Grain size (%)			CaCO ₃ (%)	OC (%)	TN (%)	OC / TN
				MAR (g·cm ⁻² ·yr ⁻¹)	SAR (cm·yr ⁻¹)	Sand (> 63 μm)	Silt (4-63 μm)	Clay (< 4 μm)				
Untrawled	0 – 6	> 1080 ± 70	7310 ± 160	Surface mixed layer		< 1	77 ± 8	22 ± 8	18.4 ± 0.3	0.96 ± 0.02	0.133 ± 0.002	7.2 ± 0.2
	6 – 25	-	10480 ± 490	0.090 ± 0.003	0.151 ± 0.005	1.5 ± 0.4	44 ± 5	54 ± 4	17 ± 2	0.93 ± 0.03	0.132 ± 0.004	7.1 ± 0.2
	25 – 50	-	-	*		3 ± 2	42 ± 2	55 ± 2	20 ± 2	0.79 ± 0.06	0.110 ± 0.010	7.2 ± 0.4
Trawled	0 – 2	1000 ± 50	340 ± 30	Fresh sediment		< 1	52 ± 8	48 ± 8	27.1 ± 0.5	0.79 ± 0.02	0.101 ± 0.002	7.8 ± 0.4
	2 – 37	-	-	*		1.4 ± 1.5	41.4 ± 1.1	57.3 ± 1.3	26.1 ± 1.3	0.73 ± 0.03	0.103 ± 0.007	7.1 ± 0.4

* Section depleted of excess ²¹⁰Pb, corresponding to sediment deposited before ~1900.

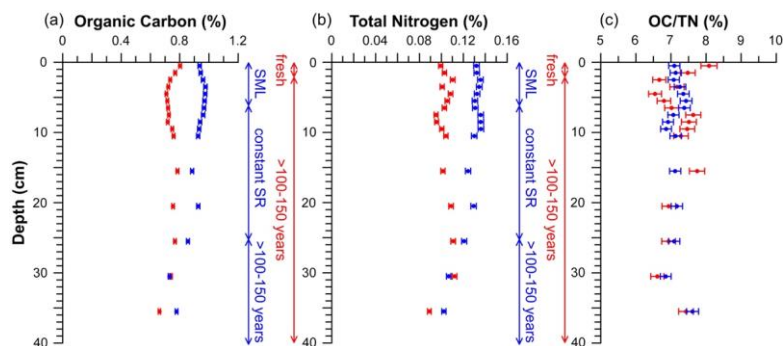


Figure 4: Profiles from elemental analyses of untrawled (blue) and trawled (red) cores. Organic carbon (a), total nitrogen (b), and the OC/TN ratio (c). The analytical error is represented by error bars. Vertical scales indicate the process that has occurred in the depth range given for both untrawled (blue) and trawled (red) sediment cores. SML: Surface Mixed Layer; SR: Sedimentation Rate.

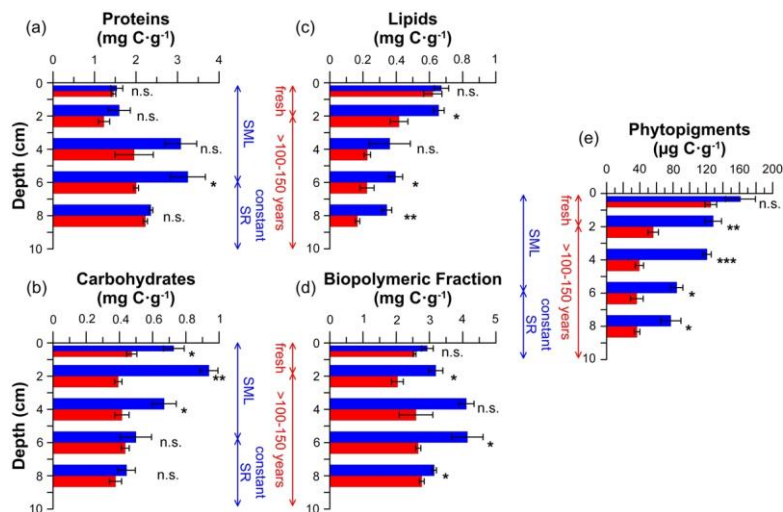


Figure 5: Organic matter quantity of untrawled (blue) and trawled (red) sites. Proteins (a), carbohydrates (b), lipids (c), biopolymeric carbon (d), and phytopigments (e). Bar graphs and error bars illustrate the mean values and standard errors at each site and depth of the triplicate sediment cores collected. Asterisks next to bars denote significant difference of post-hoc permutational pairwise tests between trawled and untrawled sites: * = $p < 0.05$; ** = $p < 0.01$; *** = $p < 0.001$; n.s. = not significant. Vertical scales indicate the process that has occurred in the depth range given for both untrawled (blue) and trawled (red) sediment cores. SML: Surface Mixed Layer; SR: Sedimentation Rate.

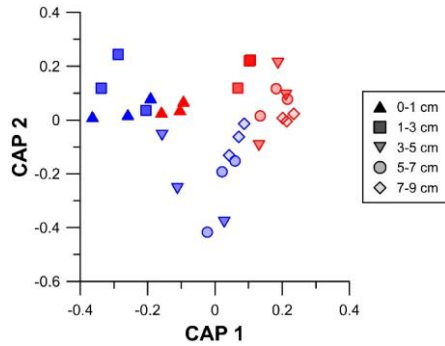


Figure 6: Variations in the biochemical composition of the sedimentary organic matter. Bi-plot after canonical analysis of the principal coordinates. Note that symbols represent the same core depth for both trawled (red) and untrawled (blue) sites, and that increasing depth is also illustrated by a fading filling.

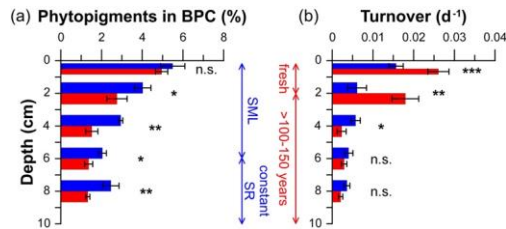


Figure 7: Organic matter freshness and degradation rates of trawled (red) and untrawled (blue) cores. Relative contribution of phytopygments to biopolymeric C (a) and protein turnover rates (b). Bar graphs and error bars illustrate the mean values and standard errors at each site and depth of the triplicate sediment cores collected. Asterisks next to bars denote significance of post-hoc permutational pairwise tests between trawled and untrawled sites: * = $p < 0.05$; ** = $p < 0.01$; *** = $p < 0.001$; n.s.= not significant. Vertical scales indicate the process that has occurred in the depth range given for both untrawled (blue) and trawled (red) sediment cores. SML: Surface Mixed Layer; SR: Sedimentation Rate.