Bottom fishery impact generates tracer peaks easily confused with bioturbation traces

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Abstract. In the process of reworking sediments and thus shaping biogeochemical processes, marine bottom dwelling animals are thought to play a pivotal role in many benthic environments. This aspect of bioturbation (particle reworking) is often

10 partitioned into short distance local and non-local transport acting over relatively longer distances. Here we document that subsurface peaks, such as those typically attributed to biological particle transport in sediments, may equally be generated by otter boards in bottom trawling fishery. Boards can generate tracer peaks whereby they scoop sediment from the surface, flip it over and deposit it onto the adjacent sea floor. These peaks are indistinguishable from those (presumably) generated by benthic fauna in a process whereby. We demonstrate this for the particle tracer chlorophyll a in silty sand from the Western

15 Baltic Sea with fauna that generally does not burrow deep in a global comparison. Our inability to distinguish the driving processes generating the peaks indicates limits to our understanding of magnitude and spatial extend of bioturbation traces in this environment. It also poses a problem to the assessment of fishery resource use and benthic ecosystem services. However, we can clearly identify macrofauna and not otter boards as the cause for peaks at the sites investigated here.

1 Introduction

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Bottom trawling introduces anthropogenic disturbance to the seafloor. Research addressing different aspects of this activity is accumulating for it causes partial destruction of benthic habitats and its biota (Sparks-McConkey and Watling, 2001; Watling and Norse, 1998), alters sediment structure both physically and in their granulometry (Oberle et al., 2016a; Bradshaw et al., 2012, 2021), suspends finer grain sizes from the bulk sediment and may affect contaminant deposits (Oberle et al., 2016b).

25 Trawling also interacts with other pressures on the benthic ecosystem such as contaminant deposits or hypoxia (Oberle et al., 2016b; Bunke et al., 2019; van Denderen et al., 2021).

While investigations aim to detect and quantify the effects of fishing gear at the seafloor there are at least two (major) difficulties. First, patterns showing the potential impact on sediments may in some cases also stem from disturbances, natural or anthropogenic, other than trawling (Bunke et al., 2019). Deep reaching storms, particle reworking by bioturbating fauna,

30   construction and dredging activity leave traces of disturbance at the seafloor as well. Secondly, localisation of the impact on the sea floor and sampling usually take place with limited spatial precision, which is why a majority of studies relies on statistically capturing average effects in areas of certain trawling intensities. The latter also have a "fuzzy" delineation characterized by fishing intensity measures such as bottom trawls per year (bt yr^{-1} or swept area ratio (SAR). The scenarios presented by Oberle and co-workers (2016b) nicely demonstrate this latter difficulty. Their scenario 2 of a trawling board

35   cutting into the ground can be detected only when sampling takes place precisely at the impacted site (showing oil derivatives buried by the board in Oberle et al., 2016b). The other three scenarios rely on combining several measures and deduction of the overall motions of particles during mixing of the sediment usually by repeated trawling impacts.

Particle reworking by bioturbating organisms is an important aspect of transport for substances at and just below the sediment-water interface (SWI). While specific motions associated to their way of life (burrow construction, feeding, defecation …)

40   move particles in all spatial directions, at vastly different time intervals and over very different distances at any one time, the macroscopic pattern of the sum of these individual reworking events is mostly dealt with in simplified ways. A common differentiation describes numerous and small ("local") transport steps as an erratic, non-directional mixing process (analogous to diffusion) and observes "non-local" transports when directional transport over longer distances takes place and creates concentration peaks in vertical concentration profiles.

45   The interpretation of peaks in experimental (glass beads, luminophores) or natural tracer distributions (radioisotopes, chlorophyll) as signs of non-local transport is widespread (Blair et al., 1996; Meysman et al., 2003; Morys et al., 2016, 2017; Oberle et al., 2016b; Wheatcroft et al., 1994). Peaks are observed regardless of persistence in the stable tracers used or tracer "age" (decay time, degradation). Natural decay of the tracer allows to "look back in time", depending on the decay constant, by about 70 days (two half-lives at 0.02 d^{-1}) with the peak concentration declining to 25 % of its original value. Decay thus

50   determines whether a peak will remain visible or if the event merges into the overall mixing which is usually dealt with as diffusion analogue. Compiling data on the frequency of use and geographic coverage of studies employing different tracers, Solan et al. (2019) showed that next to radioisotopes the naturally occurring chlorophyll a molecule (Chl-a) is commonly used. Transport of particles in sediments potentially always implies changes in availability, concentration or distribution of food (organic particles), contaminants and oxidising agents such as iron oxides. It additionally affects dissolved electron acceptor

55   distribution; as concomitant fluid movement is inevitable. This fosters the interest in bioturbation as an important regulator for bacterial activity and diagenesis (Aller, 2014) The Western Baltic Sea also harbours seafloors among the most intensively trawled areas of the world (Amoroso et al., 2018).

In the framework of research on impacts of trawling in the Fehmarn Belt area, western Baltic Sea (https://www.io-warnemuende.de/dam-mgf-baltic-sea-home.html) we measured the depth distribution of chl-a in order to study bioturbation.

60   Trawling can be massive in this area and tracks demonstrating the impact have been thoroughly analyzed (Schönke et al., 2022). Peaks detected in area of investigation are usually attributed to *Arctica islandica*, the dominant reworking bivalve, or other biota of the community. However, intense trawling raises the question of an alternative origin of the peaks.

The Iceland clam *Arctica islandica* is the longest-lived non-colonial animal known to science (Wanamaker et al., 2008). It commonly inhabits depths between 10 and 280 m in fine-grained muddy sand (Ridgway and Richardson, 2011). As a suspension feeder, it feeds on phytoplankton and lives just below the sediment surface, from where it maintains contact with seawater via its short siphon (Winter, 1969). *A. islandica* is classified as a surface biodiffusor (also: surficial modifier/biodiffusor; Queirós et al. 2013) based on its surface dwelling activity. Its activity causes constant and random local transport of particles over short distances in the uppermost centimetres of the sediment (Kristensen et al., 2012; Queirós et al., 2013). However, the species also shows a behaviour known as "survival by metabolic suppression" induced by hypoxia, when it burrows to deeper horizons. Therefore, the Iceland clam is also considered a "downward conveyor" that translocates particles to depth by non-local transport (Kristensen et al., 2012; Morys et al., 2017). In a 1999 benthic study, a wide distribution of the organism was found at depths ranging from 15.6 m to 29.6 m. Mean abundance was 91 ind./m² with a AFDM biomass of 15 g/m². In Mecklenburg Bay, *A. islandica* accounts for 99% of the biomass representing the most important species below the halocline (Morys et al., 2017; Zettler et al., 2001).

We conducted an *ex situ* experiment to mimic otter board effects at the sediment- water interface and compared it to field data. We subsequently performed an *in situ* experiment with trawling and immediate targeted sampling by scuba divers. Our aims were to i) mimic the genesis of chl-a peaks experimentally, ii) compare these with peaks originating from trawling effects and finally iii) to discuss the likelihood of confusion of these peaks with those generated by bioturbation.

2 Material and Methods

We performed experiments *ex situ* in a mesocosm and *in situ* by setting trawl marks to provide proof of principle of mechanisms operating. We investigated the changes of particle distribution brought about by the mechanic impact of otter trawling.

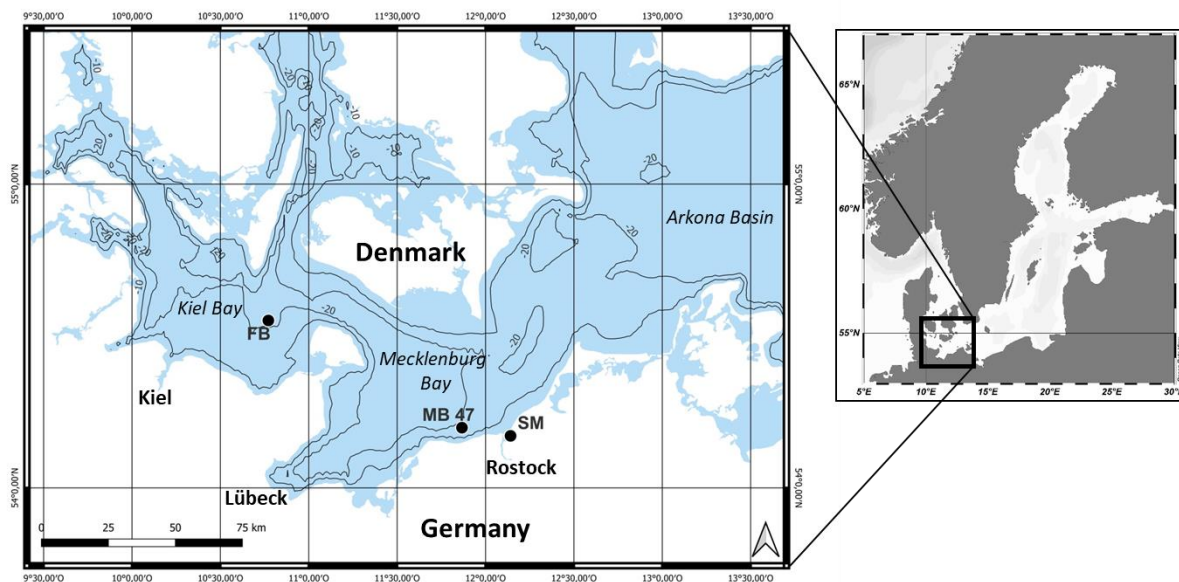



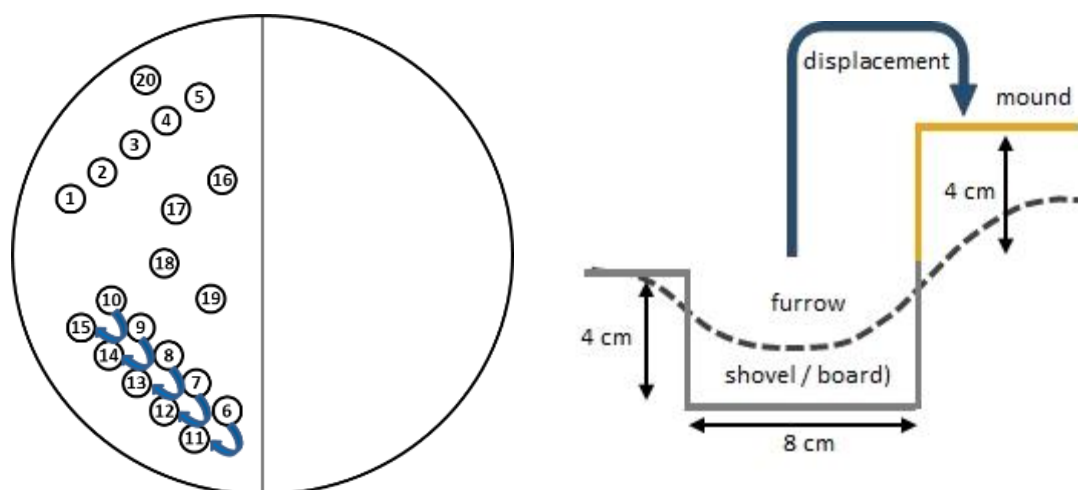
Figure 1: Locations in the Western Baltic Sea where (1) random sampling revealed sub-surface tracer peaks in the field (FB), (2) an
in situ trawling experiment was performed (MB 47) and (3) sediment was retrieved for an _ex situ_ mesocosm experiment (SM).

Ex situ

In April 2021 we simulated the mechanical trawling impact at a small scale in a mesocosm using a shovel and a rake. The
mesocosm consisted of a circular aquarium (0.8 m diameter, 1 m height) which had been filled 3 month before with sandy
sediment to reconstruct a natural, horizontally homogeneous vertical chl-a distribution. The lowest sediment layer consisted
of 15 cm sieved sand (0.5 mm) that had been stored in the dark for > 3 months. This was overlain by 8 cm freshly sieved
sediment from a field site close by? (see figure 1, Schnatermann (SM)) that had been removed from 2 – 10 cm depth, excluding
the upper 2 cm surface layer sediment with much microphytobenthos at this shallow location (SM, 0.5 m water depth). Finally,
the uppermost layer in the mesocosm contained 2 cm of sieved surface material from that field site harboring a rich
microphytobenthos community. The upper 10 cm of sediment consisted of silty fine sand (m.d. 190 µm) with C_{org} similar to
the sediment at the _in situ_ experimental site (unpublished data). The mesocosm stood outside the university buildings at ambient
light and temperature (temperature range 2 to 16 °C) and was covered by 15 cm of water (10 psu).

On April 8 2021, we manipulated the surface sediment with a shovel (~8 cm wide) and a rake according to the scheme in figure
2. We excavated sediment scoop by scoop to about 4 cm depth from the surface (track leading along sediment core position
6 – 10) and deposited it to the left onto the adjacent sediment surface (from position 11 – 15). The resulting "furrow" and
"mound" of about 40 cm length showed a surface topography with wave-like cross section as shown in figure 2 (dashed line).

We also pulled a rake through the sediment along the core positions 1 – 5 mixing the sediment to ~ 2 cm depth while slowly moving up and down. This is to mimic the impact of the trawl net with its ground rope ("net"). Immediately after the

105 manipulation five 36 mm inner diameter acrylic cores were sampled in rows along each of the structures created (cores 1 – 15), while controls were randomly placed across the area (positions 16 – 20).

110 **Figure 2: A: Sampling scheme on the left side of the mesocosm; a corresponding experiment on the right side including bioturbating organisms is not addressed here. Cores 1 – 5 net, 6 – 10 furrow, 11 – 15 mound, and cores 16 – 20 controls. B: Schematic of sediment excavation. Dashed line indicates final surface topography.**

In situ

115 On the 19th of June 2021 a small otter trawl typical for the area was performed at 20 m water depth at approximately 54°12'N and 11°52'E (MB 47) by RV "Solea", while RV "Limanda" and further research vessels conducted a series of associated measurements and sampling (Fig. 1). The site at 20.3 m depth is inhabited by *Arctica islandica* (46 Ind. m^{-2}) in much the same way as the investigation area Fehmarn Belt (s. below). Sediments consisted of silty fine sand (m.d. 180 µm; C_{org} 0.9 % dw). Scuba divers sampled the net area (effect of footrope) in one trawl track. Control cores were taken in the untrawled vicinity

120 that same day. Five 36 mm inner diameter cores were taken randomly in an area of 1 m² each. On a second trawl track sampling by scuba diving occurred from furrow and mound areas. Here cores were inserted along the axis of the shallow furrow carved by the otter board (Fig 3). Material excavated by the board lay in irregular piles on the outer rim of the furrow. Cores were inserted along the highest ridge of these piles parallel to the direction of the furrow.

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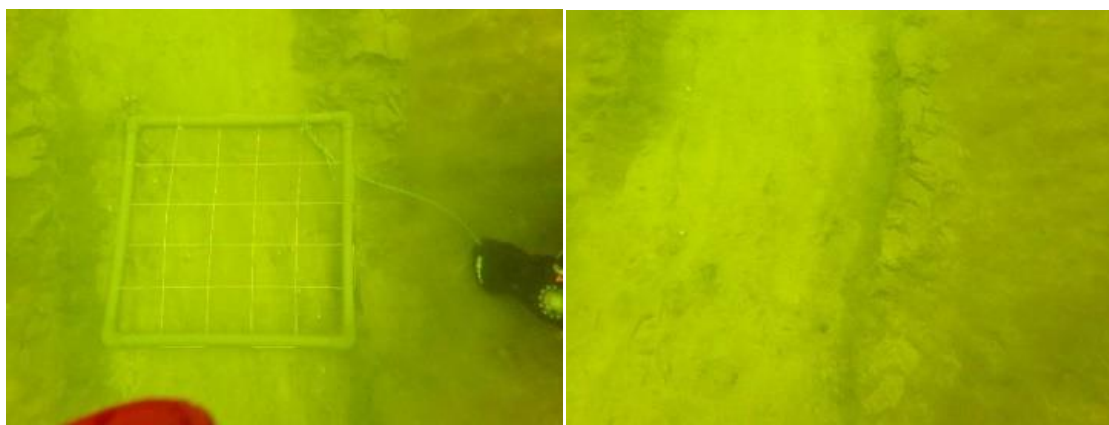
Figure 3: UW photographs of otter board track visible as light sediment (counting square: 50 cm width). The material displaced from the furrow is visible as mound with transversal cracks on the right hand side of the lighter furrow (right photo). Photographs curtesy of H. Pielenz.

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Field data

In the Fehmarn Belt area random sampling by multiple corer (MUC) was performed in 2020 and subsequent years for chl-a depth distribution to describe the bioturbation activity. Cores were sliced at the same intervals as below; the 10 cm diameter slices were mixed and treated as reported below.

135   The site is characterized by muddy fine sand (median diameter 50 µm; C_{org} 5.5 % dw) (Gogina and Schönke, 2020) and is dominated by *A. islandica* (43 Ind. m⁻²). Sampling of the benthic macrofauna was performed using a van Veen grab (75 kg, sieve lid) with a sampling area of 0.1 m² and sieving (0.5 mm) on 30 grab hauls. Samples were preserved with 4% formaldehyde seawater solution in sea water mixture.

140   **Processing**

Processing took place within three hours after core retrieval. Sediment was carefully extruded from the tube and cut in intervals of 0.5 cm to 2 cm depth, followed by 1 cm slices to 8 cm and 2 cm slices to a final depth of 12 cm. Layers were homogenized with spatula in Petri dishes. One cm³ of sediment was subsampled using a cut syringe and placed in a centrifuge tube for storage at -18 °C. For pigment extraction samples were thawed, mixed with 8 ml > 96% ethanol and vortexed for 5 s. They

145   were then extracted in the dark at ~7 °C for 22 - 24 hours with one additional mixing step several hours into the extraction. Prior to the measurement samples were centrifuged at 2000 rpm for 4 minutes. Chlorophyll fluorescence was measured (Trilogy, module CHLA, Turner Designs), with additional acidification prior to the determination of phaeopigments (50 µL 1

N HCl). Chl-a concentrations (mg cm^{-3}) were calculated from raw fluorescence values following JGOFS Report 19 (1994). We calibrated the fluorimeter using a spectrophotometrically determined standard curve.

150   Rates of chl-a decay required for modelling particle reworking (Sun et al., 1991) were obtained by incubating (7 °C) surface sediment in the dark in re-sealable containers. During 35 days, three parallel samples were removed at different time intervals and treated as described above. From the temporal decline of chl-a concentration a pseudo-first order constant, k_d, was calculated.

155   **Modelling data**

The distribution of chlorophyll concentrations with depth was used to infer rates of transport. Soetaert et al. (1996) derived a hierarchical model family consisting of six models of increasingly complex biological transport. The simplest model describes the tracer distribution without mixing by organisms and only depending on decay and sediment accumulation. In model 2 diffusive mixing is included (D_b [cm² y^{-1}]). Starting from model 3, all subsequent models include 'non-local' transport of tracer

160   from the sediment surface to depth with increasingly complexity. Here we will group the non-local terms, injection (J) and ingestion (r), from models 3, 4 and 4a and not interpret them further. A level of p &> 0.05 was used for statistical significance in modelling (see Soetaert et al., 1996 for details).

165   **3 Results**

The two experiments provided similar displacement of surface sediment onto the adjacent seafloor. The effect of removal was visible as surface topography, however only with a small vertical displacement of the sediment-water interface. In the *ex situ* experiment freshly piled up sediment from the mound slid back into the adjacent furrow leaving a vertical difference of about 2 cm between furrow and mound. In the field the furrow was somewhat deeper (~4 cm). The displaced sediment generates a

170   peak in the vertical profile of particulate chlorophyll in both experiments. The profile shape indicates that the peaks result from the fact that the sediment material is flipped over. Maximum surface concentrations of two interfaces meet at depth of about 1.25 cm (Fig 4). This generates a pronounced signal of sediment movement. A much higher concentration close to the sediment surface in the *ex situ* experiment than at the *in situ* site results from the sediments rich in microphytobenthos sampled in preparation of our experiment from a shallow local site.

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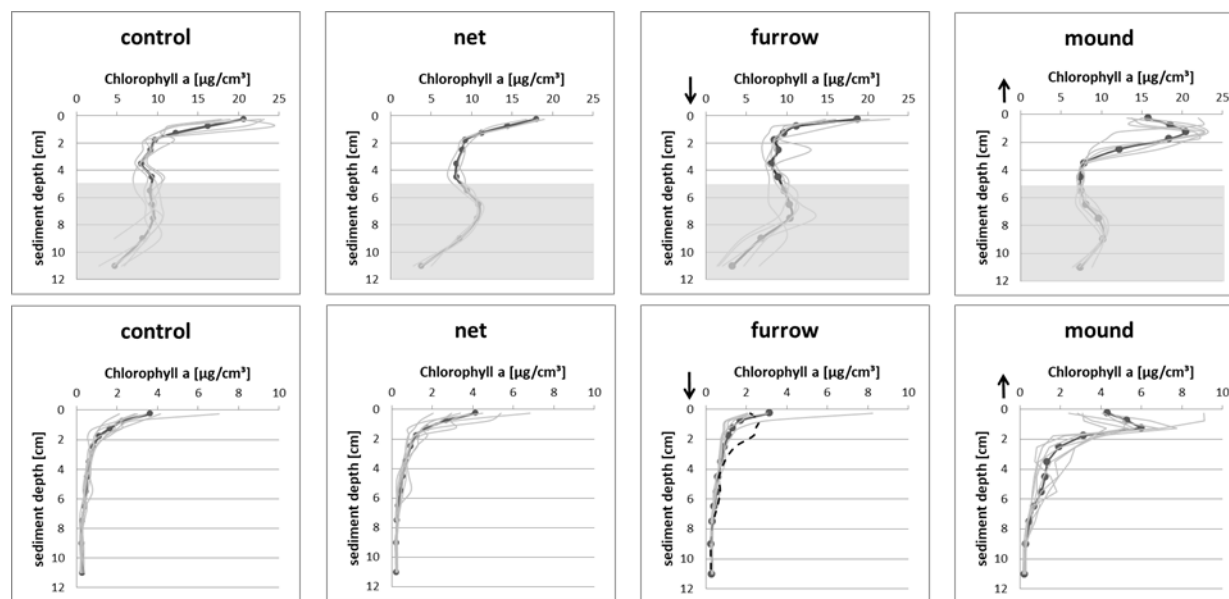
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Fig 4: Averaged (bold) and individual chl-a tracer profiles (grey) for both *ex situ* (upper row) and *in situ* experiments (lower row). Dashed line in lower furrow panel represents one core sampled with an individual of *Arctica islandica* found at 2 cm depth. Arrows indicate that the topography of the sediment water interface was shifted relative to control or net areas by approximately 1 - 1.5 cm: down in the furrow and up in the mound area. Shaded area in upper panels indicates elevated pigment levels not relevant to the
185 **present discussion but generated by mishandling during preparation of the experiment.**

In Fehmarn Belt 7 out of 11 profiles randomly sampled showed peaks of different maximum concentration and depth. Figure 5 depicts three examples and one profile without peak. Most peaks are positioned within the top 2 cm of the sediment with the exception of one single peak at 3 – 5 cm shown in Fig. 5. These peaks are commonly interpreted as signs of non-local transport resulting from faunal activity.

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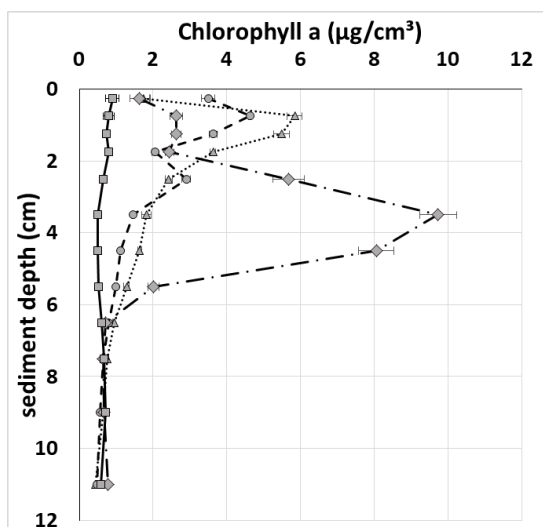
Figure 5: Examples of peaks detected in Fehmarn Belt during random sampling by multiple corer.

We compiled qualitative information on non-local and local reworking in Table 1. The overview includes three field sites with muddy sediment or silty fine sands. Peaks are a frequent feature in sediments from Mecklenburg Bay and Fehmarn Belt when

195 sampled randomly from ships. Without explicitly targeting specific features produced by demersal fishery gear - net, mounds or furrows, - 32 to 64% of samples depict peaks. In the two experiments where trawl features were specifically sampled peaks were most abundant in mound areas (70 – 80%). Samples from furrows display comparatively many profiles without any mixing, however they also show local and non-local mixing at roughly equal numbers. Net areas and control areas are similar in that they are dominated by local mixing in the trawl experiment. In the *ex situ* experiment, depth below 6 cm show artefacts

200 in tracer distribution generated during preparation of the experiment. This may have consequences for the modelling results, therefore respective values in table 1 should be considered with caution.

Tab.1: Compilation of results from targeted sampling in the two experiments, highlighting local versus non-local transport as interpreted using the software mixing.exe (Soetaert et al., 1996). Numbers of depth-profiles modelled and percentage of non-local
205 **modelling results are shown in brackets. For comparison randomly obtained results in the Fehmarn Belt area in 2020 and Mecklenburg Bay (Morys et al., 2016) are reported.**

	local (Db)	non-local (J; r)	no mixing
Field Trawl Experiment (7 of 14)			
control (n=7)	6	1 (14)	0
net (n=7)	6	1 (14)	0
furrow (n=7)	3	2 (28)	2
mound (n=7)	2	5 (71)	0
Ex situ Experiment			
control (n=5)	2	3 (60)	0
net (n=3)	0	3 (100)	0
furrow (n=5)	1	1 (20)	3
mound (n=5)	1	4 (80)	0
Fehmarn Belt 2020 (n = 11)	3	7 (64)	1
Mecklenburg Bay (n = 22)	10	7 (32)	5

4 Discussion

Two experimental approaches to sediment reworking by otter board trawling show largely identical results. Both simulated *ex situ* sediment reworking and targeted sampling of *in situ* otter board marks revealed the same pattern. This leads us to conclude, at least qualitatively, that the mechanism acting is the same. Deposition of part of the excavated surface sediment onto the adjacent sediment-water interface generates concentration peaks of the particle tracer chl-a. These peaks resemble those of biogenetic origin in non-local bioturbation. This similarity poses a problem in areas like Fehmarn Belt where chl-a peaks in the vertical sediment profile may stem from bioturbating infauna or fishery gear on the seafloor. The uncertain origin of the observed peaks may affect the assessment of for instance the intensity of bioturbation. Similarly, addressing quantitative aspects of otter board disruption of the seafloor may be difficult. Peaks found in our *ex situ* experiment were made by shovelling sediment and consciously depositing it upside down onto the adjacent sediment. This created peaks which on average display a peak concentrating of 20 µg chl-a cm^{-3} at 1.25 cm depth. After shovelling, the sediment visibly slid to both sides of the newly formed mound, but particularly into the furrow. The relatively narrow furrow compared to the excavation depth (4 cm) might have promoted this sliding effect compared to the field experiment with a wider furrow. The chl-a profiles imply that a net deposition of 1 cm remained. The concentration (Fig. 4) declines upwards and downwards at similar rates and approaches the background of about 8 µg cm^{-3} at 3.5 cm depth. This is 2.25 cm below the original sediment water interface and corresponds

225 well to concentrations in control and net areas below 2 cm. Concentrations in the upper one cm of the furrow are surprisingly high on average. This may be a result of sediment sliding back from the mounds.

The pattern in the *in situ* experiment is the same as *ex situ* despite very different levels of concentrations. In the field experiment, we cannot rule out bioturbation traces or older trawling tracks that were no longer visible at the site when diving. The impact by the ground net remains undetectable. Surface mean concentrations of 4 µg cm^{-3} decline quickly with depth.

230 Furrow surface concentrations are somewhat lower than controls and correspond to a net decapping effect of ≤ 1.5 cm in the field. The peak at 1.25 cm depth in the mound resembles that in the *ex situ* experiment. With 6 µg cm^{-3} its average concentration is higher than z=0 concentrations in the controls and may indicate some sorting mechanism active. Morys et al. (2021) described surface sediment removal by dredging with very similar patterns in the furrow zone. Overall, the generating mechanism and the effect of this type of trawling board on the particle tracer profile appear clear.

235 There are more or less pronounced additional peaks visible in many of the profiles and panels (*in situ*: net, furrow, mound; *ex situ*: net, furrow, mound). In the profile highlighted in the *in situ* furrow (Fig. 4), however, we found an *A. islandica* individual of 2 cm length at the peak depth; in view of the core diameter (36 mm) we attribute this peak directly to the activity of this animal. Patchiness in concentrations in horizontal and vertical direction is obvious in both field and *ex situ* data. Inappropriate mixing in the *ex situ* experiment and older traces of organisms or trawling in the *in situ* data may be responsible. This is a

240 reminder that there may always be peaks left without known origin, and that averaging is advisable.

We regularly encountered chl-a peaks in Fehmarn Belt. MUC-sampling here was random, that is the position of any tube on the MUC can only be as precise as 1 m (using Ultra-Short Base Line (USBL) acoustic positioning). Also we cannot intentionally core any structure generated by fishing gear or animal siphons of *A. islandica*. In Fehmarn Belt, 7 of 11 randomly cored locations displayed peaks at depths comparable to our experimentally generated peaks (Tab. 1; Figs. 4, 5). One peak

245 differed in concentration and depth. These peaks cannot be assigned to either fishing or bioturbation with any certainty. Below we will pursue the questions 1) if this problem is unique to our area of investigation in Fehmarn Belt, 2) which consequences it may have in the ecosystem and 3) if there are ways to resolve it?

Uniqueness

250 We suspect that the origin of peaks in a given area can only be inferred if the bioturbating organisms, the gear used and intensity of fishing are known. In the areas investigated here, *A. islandica* is the benthic organism dominant in biomass (Zettler et al. 2001) and is thought responsible for reworking of sediments (Morys et al., 2016, 2017). The area is also among the most heavily trawled in the North Sea and Baltic Sea region (Amoroso et al., 2018).

In general, both transport phenomena, biological non-local reworking and physical trawling impact, will move sediment

255 particles the same way, at least on a relatively course scale of centimeters as employed here. The underlying processes - particularly of bioturbation - may involve smaller steps of individual particle displacement that blend into seemingly diffusive transport (Meysman et al., 2003), but this is irrelevant to the observations made here.

As long as the depth to which the transports affect the sediment are comparable and both mechanisms co-occur, they may generate undistinguishable peaks in the depth distribution. Morys et al. (2017) used a pairwise comparison of the fauna present
260 and the occurrence of a peak within the same sediment core to convincingly argue for the animals causing that peak. The authors found positive correlations in 40-70% of the 22 investigated profiles. This is compelling evidence for biogenic origin of peaks. While there is little direct proof of a cause-effect relation of biological peak generation in the literature, there is no doubt that some benthos does generate peaks by non-local transport mechanism (e.g. Blair et al., 1996).

The pattern of particle tracers generated by ground trawling, however, have not been established. Nets are reported to mix
265 surface sediments (Tiano et al.; Oberle et al. 2016b). In our study the simulated and real net impact make profiles indistinguishable from controls. This implies that sediment mixing appears to be quasi random and similar in both cases. We thus conclude that these net impacts are not detectable in chl-a depth distributions. Boards and rolls keeping the net gear open. Specifically, and applicable to the data presented here, Morys et al. (2021) and Bradshaw et al. (2021) reported a removal of the top sediment layer decapping vertical distributions of sedimentary material. Our data indicate the mechanism of excavation
270 and reversed deposition of chl-a containing particulate material. This mechanism is generating a peak similar to the biogenic peaks found by Morys et al. (2016, 2017) in close proximity to both our field sites (Mecklenburg Bay).

Consequences

As one consequence, resuspension associated with bottom trawling impacts the ecosystem (Bradshaw, 2012). Effects within
275 the sediment, as another consequence, may be visible when heavy gear is used. Oberle et al. (2016b) deciphered trawling effects on sediments off the Iberian west coast by combining lithological information, traces from recent oil pollution and highly resolved spatial information on bottom trawling. Without information as closely targeted as out sampling by scuba divers, the authors suggested five scenarios of impact. Scenario 2 is the one mirroring our turnover of surface sediment. The former sediment surface is buried and tracer appears at 18 cm rather than 6 cm, the usual mixing depth by animals and currents
280 at the site. Here, the large difference in depth makes a differentiation between biogenic (shallow) and fishing boards (deep) possible. Oberle et al. (2016b) attribute mixing of sediments by trawl boards on the Iberian shelf to 35 cm sediment.

In the Fehmarn Belt area fishing gear is comparatively light. While peaks and tracer profiles look very much alike, their genesis implies different consequences. Removing and overthrowing sediment can burry animals, a process which does not usually happen during bioturbation. Particularly smaller surface-dwelling benthos (cumacea, ophiurids) may not be able to escape
285 from a slap of sediment deposited above them. Larger burrowers like *A. islandica* have the ability to escape, depending on the height of deposits above the original sediment surface (Bromley 1996, Powilleit and Kleine 2009). Some fauna may be excavated from the sediment or damaged during board passage and become available for predators and scavengers. Reports on the shift of functional groups/ towards smaller size and possibly opportunistic fauna caused by bottom trawling support this (Sparks-McConkey and Watling, 2001; Hiddink et al. 2019).

290 Reversal of the top sediment may affect sediment biogeochemistry, since it changes chemical gradients completely close to the sediment-water interface at the mounds. In the troughs decapping exposes anoxic sediments to oxygenated overlying water. In either case these events disrupt steady-state biogeochemical distributions and initiate transient states of solute fluxes and redox reactions in the sediment (Bradshaw et al. 2021; Morys et al. 2021; Tiano et al., 2019). On the other hand, bioturbation may also lead to non-steady-state situations (Aller 2014).

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Ways to resolve

Tracer peaks generated by non-local transport of particles appear differently depending on tracer half-life. The slower a decay the longer peaks will persist. Thus, repeated events of transport produce peaks at different depth merging as new peaks emerge while the oldest still remain (^{210}Pb). We determined the half-life of the chlorophyll as 50 d, effectively making peaks visible

300 for about 150 days. During this time peak concretions would drop to 25 % and start to fade into background noise.

Strictly speaking, local and non-local are end-members of a continuum of transport steps from smaller to larger step-sizes (Meysman et al., 2003; Schiffers et al., 2011). Following current understanding smaller and more frequent steps as described by the Einstein-Smoluchowski-relation are the essential steps in diffusive mixing. These cannot be resolved with the course vertical resolution we apply, though methods exist to do so (Schiffers et al., 2011). Our comparatively large steps on the order

305 of centimeters, with presumably longer resting times, should not be as frequent and, therefore, should be longer visible. This is where half-life and step size together point to a certain persistence of peaks, particularly in shorter lived tracers.

Can knowledge of the environment and probability help to resolve the issue, since differences in peak generation are unlikely to show up in tracer half-life or tracer type? In our Fehmarn Belt data set, we cannot assign a single peak with any certainty to biological or physical reworking. We may arrive at a conclusion by employing some generalized information on faunal

310 abundance and behavior as well as trawling intensity as outlined below. Fehmarn Belt is amongst the areas with very high fishing intensity globally (Amoroso et al. 2018). ICES assesses trawling effort as $SAR_{subsurface}$, swept area ratio below 2 cm sediment depth (v. Dorrien, pers. communication/2023 project report; ICES database: https://doi.org/10.17895/ices.data.20310255.v3; Eigaard et al., 2016) with 0.1 per quarter. This number relates strictly to mobile bottom-contacting gear and includes specific information regarding gear and vessel size, but lacks high spatial

315 resolution. Here we averaged 4 areas (size: 5.6 x 3.2 km area, i.e. 17.9 km²) from April - June 2020 overlapping with the research area in which we sampled and detected peaks in June 2020. Although it is difficult to relate this information to the very nature of physical scouring effects and their spatial distribution on the seafloor, it is the best information available. With $SAR_{subsurface}$ we can imagine that otter boards affect below surface sediment in 10 % of the area within this quarter (April - June 2020). We can equally imagine that the probability of an otter board generating a peak is 0.1 for every m^{-2} in three months

320 or 0.4 m^{-2} yr^{-1} if homogeneously spaced.

On the other hand, *A. islandica* are likely to move daily. Their abundance in Fehmarn Belt amounts to around 40 individuals m^{-2}. The animals move during hypoxia induced burial, but otherwise stay close to the sediment surface because of their short

siphon. They move the shells when gaping and closing in response to threat by demersal predators and food supply for filter-feeding. Ballesta-Artero et al. (2017) demonstrated that gaping activity in these bivalves changes seasonally with food supply,

325 but shows a minimum of 1-2 gaping events per month during lowest activity in winter. The authors could not determine the frequency of gaping during high activity phases, but it is certainly higher. We assume that shell movement during gaping is a mechanism allowing surface material including chl-a pigments to slide along the shell into deeper sediment layers (anywhere to 4 cm depth, the size of Arctica-individuals). Forty individuals could produce at least 40 transport events per month or 480 m^{-2} yr^{-1}.

330 The spatial aspects of the particle transport events discussed above are particularly difficult to assess, since patchy occurrence of *A. islandica* and clustering of trawl tracks are frequently observed. The numbers calculated suggest 3 orders of magnitude higher frequencies for biogenic non-local transport (480 m^{-2} yr^{-1} versus 0.4 m^{-2} yr^{-1}). We consider it conservatively safe to assume that the majority of peaks detected in Fehmarn Belt stem from *A. islandica* active on a daily scale. Future exclusion of fishery in the area will provide a test field in which the persistence of peaks may be tested and their origin confirmed.

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Data availability

Data are presently not available from a data repository, because it seems unnecessary for the review process or for the readers to access depth profiles of chlorophyll. Figures 4 and 5 include the data necessary to validate the conclusions made in this

340 manuscript. Data are available from the corresponding author. If necessary, however, we will supply the data in a repository with doi in due time.

Author contributions

All authors provided data and contributed to writing this manuscript. CR, JL and LP sampled and measured in the experiments, MP and SF in the field data. SF and MP provided the concept and ost of the figures, SF wrote the manuscript.

345 **Competing interests**

The contact author has declared that none of the authors has any competing interests

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