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Environmental impact of woodchips deployed in the Norwegian Sea

A model- and literature-based assessment of biogeochemical changes

Report

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Abstract

The goal of this work is to assess the environmental impact of woodchip and calcium carbonate deployments in the Norwegian Sea as a marine carbon dioxide removal (mCDR) approach. For this we use the 2-Dimensional Benthic Pelagic Model (2DBP) coupled with biogeochemical Bottom RedOx Model (BROM). In this study we evaluate the maximum weight of woodchips that can be accumulated on the seafloor without dramatic changes in the oxygen regime, acidification and biogeochemistry that can negatively affect the local ecosystem.

Keywords: Carbon, Marine carbon dioxide removal, wood, modelling, review
Emneord: Karbon, marin karbondioksidfjerning, treverk, modellering, gjennomgang

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Preface

This report was written at the request of Running Tide Norway to review and model potential impacts of woodchip deployments in the Norwegian Sea for marine carbon dioxide removal.

Oslo, 26 March 2024

Summary

In this work we evaluated potential environmental impacts and risk factors related to the deployment of carbon containing mixtures of sustainably sourced hardwood and softwood forestry residues (organic carbon) and calcium carbonate to the seafloor of the Norwegian Sea (~3000-3300 m). For this we reviewed available literature sources and performed model-based assessments of potential biogeochemical changes. The model estimated the maximum amount of woodchips that can be accumulated on the seafloor without dramatic changes in the oxygen regime, acidification and biogeochemistry that can negatively affect the ecosystem. It was found that this threshold can be reached by a deployment of 2000 metric tonnes of woodchips in 24 hours in 1 km^2 surface area (Scenario S1 described in Section 2). Scenario S1 should lead to the accumulation of woodchips on the seafloor that should decompose for several years, leading to an increase of nutrient concentrations and dissolved inorganic carbon and a decrease of oxygen. Due to very low natural burying rates in the deep sea the deployed woodchips should mainly stay on the seafloor and any carbon remineralised from the woodchips will enter thermohaline circulation storage timescales of 100s to 1000s of years but will unlikely enter the longer geological timescales (million-year timescale). The oxygen levels in the bottom water in Scenario S1, while lower than natural conditions, are predicted to still be high enough and correspond to “good conditions” according to Norwegian water quality standards. However, the conditions associated with Scenario S1 are likely to be an extreme case because: 1) woodchips will likely float on the sea surface for several days where they will drift with surface currents on the scale of at least several kilometers before sinking and dispersing over a wider area, and 2) there is likely to be influences of mixing and upward vertical transport that will attenuate the sinking rate woodchips.

1 Introduction

1.1 Overview

The ocean plays a key role in the global carbon cycle and supports a range of biological and chemical mechanisms by which natural fast-to-slow carbon transfer occurs. This is an opportunity for developing carbon removal strategies that aim to shift anthropogenic atmospheric carbon from the fast carbon cycles (years to decades) to slower carbon cycles (thousands to millions of years). These carbon removal strategies must be designed to have a measurable net positive environmental and ecological impact, meaning that the benefits of the intervention must outweigh any potential negative impacts. The idea behind the present Running Tide initiative is to combine carbon containing mixtures of sustainably sourced hardwood and softwood forestry residues (organic carbon) and calcium carbonate and/or lime kiln dust (inorganic carbon), hereafter collectively referred to as *woodchips*. The woodchips will then be deployed in the Norwegian Sea (Figure 1.1), where they will sink to the seafloor (~3000-3300 m below the surface), thereby exporting carbon in woodchips from the fast carbon cycle to a slower carbon cycle. Rivers historically transported unquantified volumes of wood to the ocean, where it would subsequently sink to the seafloor. Human activities however, such as damming rivers and deforestation during the past few centuries, have reduced wood supply to the ocean by altering almost all components of tree production, recruitment, and transport. It is estimated that these anthropogenic changes have resulted in a decreased wood flux to the ocean of ~2 million m^3 $year^{-1}$ (Wohl & Iskin, 2021). This means that a proposed woodchip deployment of 50,000 m^3 $year^{-1}$, like what this project is investigating, amounts to only ~2.5% of the total annual missing global wood input to the ocean.

Decay of wood in the marine environment is a complex process (Fojutowski et al., 2014) which depends not only on environmental factors such as oxygen concentration, water temperature and salinity and biological factors, but also on the properties of individual wood types and species (Björdal & Nilsson, 2008). The mass decrease of wood in the marine environment is accelerated by wood-boring crustaceans and bivalves such as those from the family Xylophagaidae (Bienhold et al., 2013; Romano et al., 2020). These organisms can free energy from refractory compounds in wood at deep-sea wood falls, breaking them down into more labile forms of carbon, on which other animals are able to feed (Schander et al., 2010; Voight et al., 2020). In one Mediterranean study, these organisms have been observed to consume more than half of the total wood mass in six months (Charles et al., 2016). Wood decay rates are likely to be faster within near shore coastal habitats (Charles et al., 2022). However, in the absence of wood degrading crustaceans, as observed in coastal Antarctica for example, wood surface decay rates from soft rot fungi and bacteria were between 0.05 and 0.08 mm $year^{-1}$, about two orders of magnitude lower than normal (Björdal & Dayton, 2020). There is little known about the prevalence of wood-boring organisms in the Norwegian Sea and there is also little known about which bacteria colonize deep-sea wood falls or how the deposition of wood affects surrounding benthic communities (Fagervold et al., 2012; Palacios et al., 2009).

The goal of this study is to evaluate, in a Norwegian Sea context, several environmental risk factors identified by Running Tide. This evaluation is done in three parts: 1) a review of the available literature as it relates to specific risks (Sections 1.2, 1.3 and summarized in Table 7.2), 2) the development and application of a biogeochemical model (Sections 0 and 3), and 3) discussion of the model results (Section **Error! Reference source not found.**). The model is used to evaluate the maximum mass of w oodchips that can be accumulate on the seafloor without dramatic changes to biogeochemistry in the vicinity of woodchip addition that might negatively affect the local ecosystem. Driven, for example, by oxygen depletion or acidification. To investigate the spatial and temporal scales of the impact of woodchips on the water column and benthic biogeochemistry, we used a coupled model from the FABM family consisting of the C-N-P-Si-O-S-Mn-Fe biogeochemical model BROM (Yakushev et al., 2017) and the 2-dimensional benthic-pelagic transport model (2DBP), considering vertical and horizontal transport in the water and upper sediments along a transect centered on an impacted region (Yakushev et al., 2020). The model describes, in detail, the processes of organic matter mineralization in oxygen-depleted conditions that are vitally important for assessing biogeochemical impacts (i.e., denitrification, metal reduction, sulfate reduction). This model was previously used for the investigation of the fish farming waste impact on the seafloor biogeochemistry around a fish farm (Yakushev et al., 2020) and was used in several projects of the Research Council of Norway (Forskningsrådet 'Combined effects of multiple organic stressors from jellyfish blooms and aquaculture operations on seafloor ecosystems', JELLYFARM)[1], the Norwegian Environment Agency (Miljødirektoratet 'Modellering av Oslofjorden')[2] and the European Commission (Horizon 2020 'Tools for Assessment and Planning of Aquaculture Sustainability', TAPAS)[3].

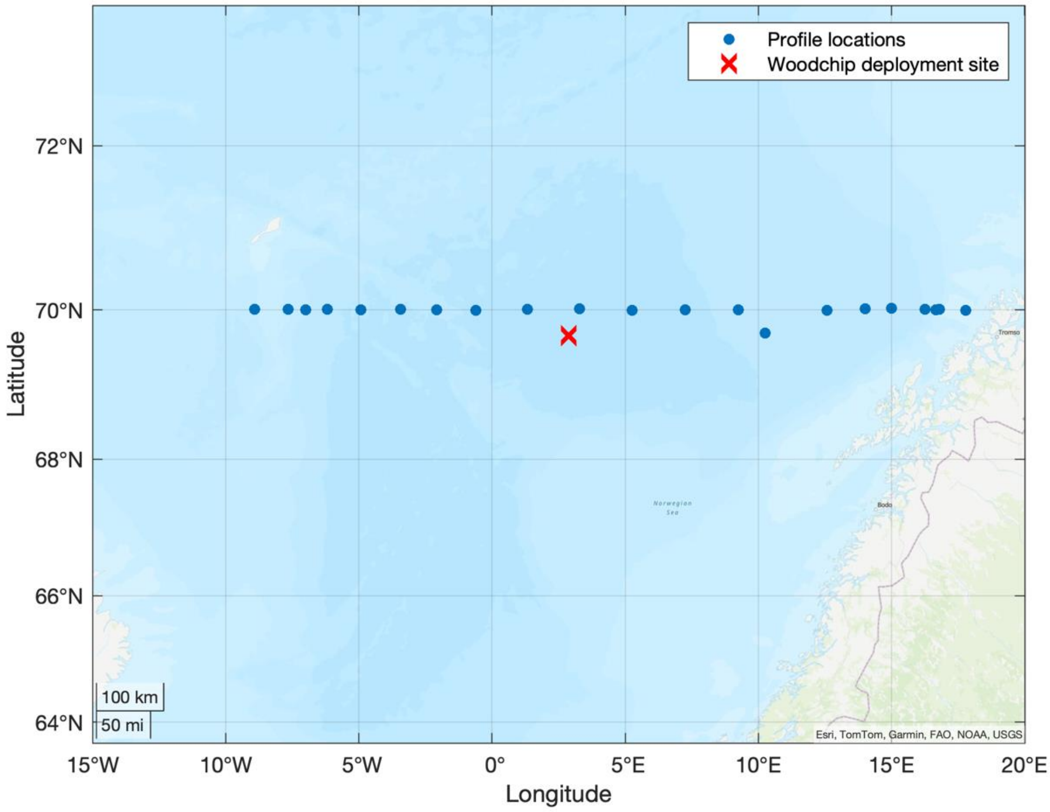

Figure 1.1. Location of the woodchip deployment site (red cross), with the location of carbonate chemistry profiles (blue dots) from the GLODAPv2.2023 database (Lauvset et al., 2024)

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[1] *https://prosjektbanken.forskningsradet.no/en/project/FORISS/244572*

[2] *https://www.miljodirektoratet.no/publikasjoner/2023/januar-2023/forprosjekt-for-modellering-av-oslofjorden-vurdering-av-aktuelle-modeller/*

[3] *https://cordis.europa.eu/project/id/678396*

1.2 Impact assessment for pelagic ecology

1.2.1. Shading of incident light

The deployment of woodchips will result in localised shading of the marine environment for as long as woodchips remain afloat (estimated float time by Running Tide is presently 2-4 weeks). This may impact phytoplankton photosynthesis by decreasing the light availability required for growth both in surface waters and in the deep chlorophyll maximum. Natural analogues for this type of episodic and short-term shading can be drawn from pumice rafts and algae growth such as Sargassum. However, most studies relating to these events have focused on coastal impacts related to coral and seagrass communities (Ohno et al., 2022; Ruiz & Romero, 2001; van Tussenbroek et al., 2017). Any adverse impacts caused by changes in the photic depth could be reduced by widely dispersing the woodchips and deploying them during autumn/winter months when light availability and photosynthetic activity/production is low in northern latitude systems like the Norwegian Sea.

1.2.2. Consequences to marine mammals in the area

Marine mammals have been known to ingest marine debris such as wood (da Silva Videla & Vieira de Araujo, 2021; Nascimento et al., 2023; Padula et al., 2023). Running Tide's *Catalog of Potential Environmental Exposures, Section 2.1.5 Physical Harm to Marine Mammals*, only addresses entanglement as a potential harm. According to ICES[4], out of the 23 species of marine mammals (7 pinnipeds, 1 polar bear, 6 baleen whales and 9 toothed whales) occurring regularly in the Norwegian Sea ecoregion, 9 are of particular importance: minke whale, fin whale (Balaenoptera physalus), humpback whale, and sperm whale dominate in biomass, but are mainly present in summer and autumn; hooded seal and bottlenose whale have a partial distribution in the Arctic; and harbour porpoise, grey seal, and harbour seal are resident on the continental shelf of Norway. Killer whales may occur all over the Norwegian Sea year-round but are mainly associated with the herring and mackerel migrations. Possible mitigation efforts could involve deploying woodchips in locations and times when vulnerable species are unlikely to be present.

1.2.3. Stimulation of epifauna and calcifiers: Woodchips

Wood is a very difficult substrate to degrade and only a few specialized organisms in nature have this capacity (Björdal & Dayton, 2020). Rafting organisms, on a variety of substrata, have been observed in all of the Nordic seas (e.g., Gudmundsson & Ingólfsson, 1967; Ingólfsson, 1995; Pethon, 1970; Svavarsson, 1982). They comprise of cyanobacteria, algae, protists, and invertebrates from most marine phyla. Marine hydrozoans, bryozoans, crustaceans and gastropods are the most common taxa that have been observed rafting (Thiel & Gutow, 2005). However, given the short floating time of the woodchips (2-4 weeks), and their remote deployment location, an increase in dispersal pathways for rafted organisms beyond their native distribution is unlikely. It is also unlikely that undesirable impacts to the carbon cycle from calcification (causing an increase in carbon dioxide) will result from rafted calcifying organisms. For example, the globally distributed rafting genus of barnacle, *Lepas*, can colonise floating objects rapidly and achieve sexual maturity within a few weeks after settlement (Tsikhon-Lukanina et al., 2001). Yet their distribution is typically restricted to tropical and temperate waters and have only rarely been observed in the colder waters of the Nordic Seas (Gudmundsson & Ingólfsson, 1967). Additionally, the blue mussel *Mytilus edulis*, is a common calcifier on shorelines of the northeast Atlantic and the high Arctic (Skibinski et al., 1983) and is an abundant fouling species on artificial offshore structures and installations (van der Stap et al., 2016). However, its calcification rate is slower in the cooler waters of the Nordic seas (Malone & Dodd, 1967) and its distribution offshore in the Norwegian Sea is likely limited by the absence of connecting artificial shallow hard substrates (Coolen et al., 2020).

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[4] *https://www.ices.dk/advice/ESD/Pages/Norwegian-Sea-Marine-mammals.aspx*

1.2.4. Stimulation of epifauna and calcifiers: Instruments

Same arguments as above, but with the potential for increased biofouling due to prolonged floating times of instruments used for monitoring woodchip deployment operations. To ameliorate any problems caused by biofouling, instruments can be equipped with anti-biofouling measures (wipers, copper plating, etc.) and/or could be retrieved or programmed to sink. However, due to their small numbers, any such impacts are likely to be small.

1.2.5. Organic carbon perturbation

From original Running Tide “Exposure Document”

The introduction of approximately 10,000 tons of terrestrial biomass/carbon buoys to the pelagic marine environment may result in additional labile dissolved organic carbon (DOC) or particulate organic carbon (POC) entering the water column. An introduction of an additional food source may perturb the abundance and diversity of endemic species. Similar to the effects of shading, the organic carbon perturbation will be transient and present for the length of time that carbon buoys are floating in the surface ocean. However, the exposure of introduced carbon to the surface ocean and effects on organisms may slightly lag the effects of carbon buoy presence depending on the abiotic- or biotic-mediated degradation of DOC and POC in the surface ocean.

As discussed, as it pertains to nutrient reallocation, a perturbation in the organic carbon quantity and composition in the surface water will affect a reallocation of calorie availability between the surface and midwaters. Most relevant to this consideration is any alteration in the quantity of labile DOC and POC produced by surface ecosystems, as measured via respiration of CO2 (surface ocean average: 1.2 g C m^{-2} day^{-1}. Particularly for the substrates that have smaller diameters where the ratio of surface area to volume is high, the rate of DOC leaching and OC dissolution may also be larger. Concentrations of OC in the surface ocean have a large range but average about 100 mg m^{-3} (Rasse et al., 2017).

Organic carbon in the form of dissolved organic carbon (DOC) can leach, or be released, from woodchips through abiotic processes such as dissolution in water. DOC leaching was observed in a denitrifying woodchip bioreactor. The release of DOC from woodchips during the reactor experiment was characterized by an initial high release over the first day, followed by a rapid decline (Abusallout & Hua, 2017). The initial effluent DOC of 71.8 mg L^{-1} in Day 1 decreased to 20.7 mg L^{-1} after 7 days of bioreactor operation. After 240 days, the average DOC concentration in the bioreactor effluent was 12.1 mg L^{-1}, with an average leaching rate of 6.11 g C m^{-3} day^{-1}. Assuming the initial woodchip concentration of ~0.35 m^3, an average density of 600 kg wood m^{-3}, and an average carbon content of 47.5% of wood by mass, the average leaching rate of 6.11 g C m^{-3} day^{-1} constitutes approximately 0.002% of total wood carbon per day. Svensson et al. (2014) observed different leaching patterns of organic compounds amongst different species of wood and wood chip size. Iseki et al. (1984) speculate that low density wood debris from wood mill dumping into the ocean may travel considerably further with the surface water where leaching of organic compounds may contribute to surface DOC before sinking into deeper water. Increases in DOC may result in increased bacterial production and subsequent decreases in available oxygen. This will cause fewer problems in the well-ventilated surface waters where oxygen is replenished rapidly from the atmosphere.

1.2.6. Alkalinity and dissolved inorganic carbon perturbation

From original Running Tide “Exposure Document”

Carbonate dissolution through carbon buoy placement in the surface ocean is an intentional exposure with the intended effect of increasing the alkalinity, dissolved inorganic carbon (DIC), and pH of the surface ocean. Alkalinity is an excess of base that acts to weaken or buffer ocean acidity caused by CO_2 emissions. Therefore, this alkalinity perturbation is intended to induce the novel flux of CO_2 from the atmosphere into the surface ocean. In the time between carbonate or cation dissolution and CO_2 influx, an increase in pH and inorganic carbon in the form of bicarbonate and carbonate may impact the ecology of the surface ocean, especially as it pertains to phytoplankton community composition. Changes in phytoplankton community composition in response to changing inorganic carbon concentrations have been observed on the order of a couple days to two weeks.

Similar to the exposure and effects of OC introduction, these chemical effects will be present during the time that carbon buoys are floating in the ocean surface and may persist longer than the floating carbon buoys due to differences in chemical transport times and rebalancing with atmospheric CO_2. Carbon buoy mineral dissolution occurs on the same temporal scale as changes to the phytoplankton community, possibly leading to impacts on the pelagic ecosystem from this exposure. At larger scales, the duration and spatial influence of this alkalinity perturbation is expected to have an enhanced impact on the global surface ocean chemistry.

Measurement of current dissolution rates of carbonate substrate coatings are ongoing and dependent on mineral structure. The total flux of IC into the ocean environment is estimated to be 1.5-3.0 $\times 10^6$ kg during a deployment season. Changes in phytoplankton community composition in response to changing chemical concentrations have been observed on the order of a couple days to two weeks. Substrate carbonate dissolution occurs on the same temporal scale as changes to the phytoplankton community, possibly leading to impacts on the pelagic ecosystem from this exposure.

At larger temporal and spatial scales, the influence of the dissolved alkaline materials added to the woodchips is expected to cause a large alkalinity perturbation to surface ocean chemistry (Bach et al., 2019). However, this short-lived pilot deployment will likely only result in a brief impact to surface waters in the deployment region. Moras et al. (2022) determined that quicklime (CaO) and hydrated lime ($Ca(OH)_2$), with a particle size <63 μm, dissolved in seawater within a few hours. Secondary precipitation of calcium carbonate was observed at aragonite saturation states (Ω_{ar}) >5. Reactions or processes that cause calcification should be avoided due to the CO_2 that is produced. Given the estimated floating time of woodchips, it is likely that most of the alkaline material added to the surface water will dissolve before sinking below the mixed layer. Care should be taken to avoid adding too much alkaline material that could increase $Ca(OH)_2$ concentrations as well as total alkalinity (TA) and result in supersaturated aragonite conditions. Also, the impact of woodchips deployed with $CaO/Ca(OH)_2$ added could be minimised if carried out in surface waters with lower total alkalinity, such as coastal Norwegian waters with significant riverine inputs and lower total alkalinity, e.g., Skagerrak, western Norway (Figure 1.2).

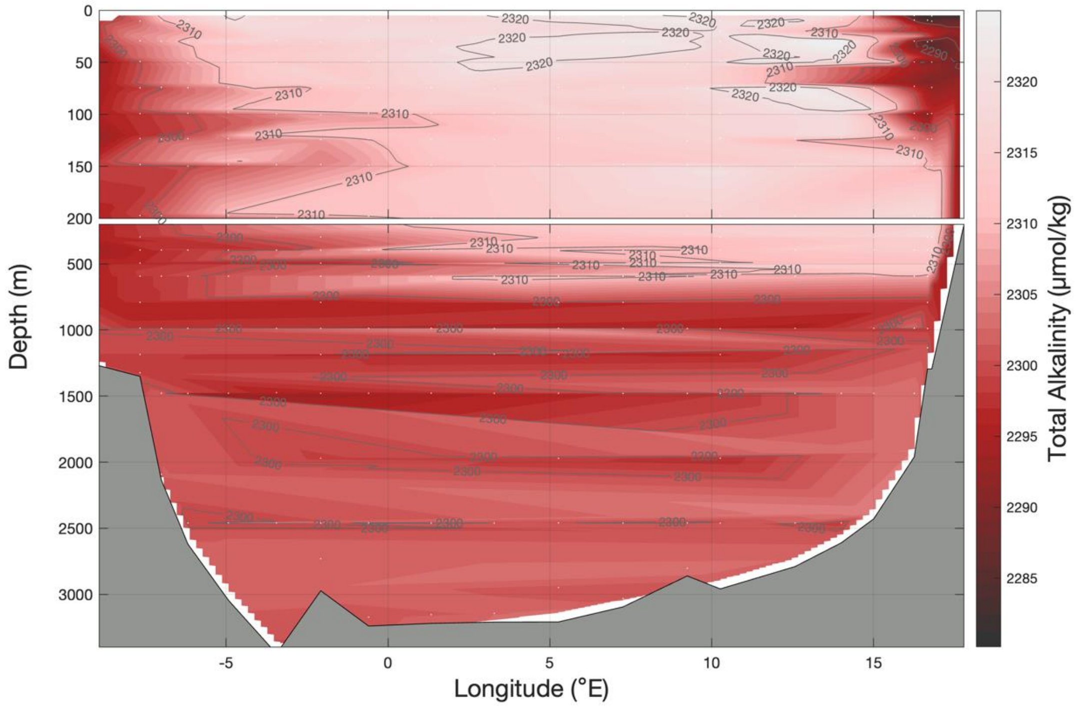

Figure 1.2. Concentration of total alkalinity (TA) across the Lofoten Basin (see Figure 1.1 for location). The white dots show the location of water samples. Note the change in depth scale at 200 m. Woodchip deployment location at ~2.88°E.

1.3 Impact assessment for benthic ecology

1.3.1. Altered benthic topography

Sunken wood on the seafloor can harbour a high diversity of macrofauna (Gareth Jones et al., 2001; Wolff, 1979) as well as the co-occurrence of free-living sulphate-reducing bacteria and methanogens and the presence of sulphide oxidizers (Fagervold et al., 2012). Model-predicted topographical impacts are presented at the end of Section 3.2 with Scenario S1 estimating a ~5 mm layer of woodchips.

1.3.2. Phytodetritus perturbation

Phytoplankton production in surface waters and subsequent sinking to the deep-sea benthos is an important process for carbon supply to deep sea ecosystems. Because only a small fraction (on average <1% of surface phytoplankton production) sinks to the deep-sea, it will be difficult to assess changes on a small amount. In the Greenland-Norwegian Sea region, maximum fluxes of phytodetritus – sinking phytoplankton and related particles – to depths up to 3000 m was observed to be in June, August, and September, which was following the pattern of vertical export of phytoplankton blooms from surface waters (Graf et al., 1995). One possible direct impact on the flux of phytodetritus could be any physical interactions between woodchips and phytodetritus such as accumulation or aggregation. This needs to be investigated further. Another impact would be if there is any impact on phytoplankton production such as affecting light availability and therefore phytoplankton growth. If deployments were carried out during less productive parts of the year (i.e., autumn, winter), these impacts could be minimised.

1.3.3. Pollution transport

Any pollutants initially associated with woodchips or adsorbed to woodchips prior to or during deployment will need to be assessed. A further assessment can be carried out when major pollutant type/class is identified. There is presently no further information related to pollution transport by woodchips to the deep sea.

1.3.4. Organic carbon perturbation

As dissolved organic carbon can leach from the woodchips deposited on the seafloor, the same assessment pertaining to organic carbon perturbation in the pelagic ecosystem (Section 1.2.5) mostly applies here too. Unlike surface waters though, oxygen consumed by bacterial production in the deep sea cannot be as easily replaced.

1.3.5. Increased oxygen consumption

The most important biogeochemical characteristic of water quality is the concentration of dissolved oxygen (DO) in the water and in the pore water of the sediments. Usually, in coastal regions, DO can penetrate just to several millimeters inside the sediments (the so-called Oxygen Penetration Depth). The presence of oxygen determines the state of so-called redox metals, iron (Fe) and manganese (Mn) and other nutrients, directly for nitrogen (N) and indirectly for phosphorus (P). The oxygen condition of natural waters is an important element of water quality legislation, e.g. in the Water Framework Directive[5] that Norway partakes in. There are several terms that are in use to describe the changes in oxygen condition, i.e. oxic, oxygen deficient, hypoxic, suboxic, anoxic. A frequently used boundary between oxic and hypoxic conditions is set at 2 mg L^{-1} (~63 µM (CENR, 2000)) or 2 ml L^{-1} (~89 µM (Diaz & Rosenberg, 2008)). The boundary between hypoxic and suboxic conditions is also arbitrary, this boundary should correspond to the biochemical threshold after which the dominant electron acceptors are oxidized ions of N (nitrate, nitrite) or oxidized species of metals (Mn(IV), Fe(III)), whereas DO becomes an auxiliary oxidant. A value of 10 µM is often used, which corresponds to the water layers with enhanced nitrification due to an upwards flux of ammonia. Once the oxidized species of nitrogen, manganese or iron and DO are completely depleted, organic matter microbial decomposition uses sulphate as the next electron acceptor for oxidation. This is the appropriate threshold for the term anoxic (Yakushev & Newton, 2012).

In Norway[6], the oxygen concentration in the bottom water of the coastal regions is classified as *very bad* = <1.5 ml L^{-1} (<67 µM), *bad* = 1.5-2.5 ml L^{-1} (67-112 µM), *moderate* = 2.5-3.5 ml L^{-1} (112-156 µM), *good* = 3.5-4.5 ml L^{-1} (156-201 µM), and *very good* = >4.5 ml L^{-1} (>201 µM). The selected deployment region is characterized by high bottom layer DO concentrations (Figure 1.3) of ~240 µM, which in the coastal water quality classification scheme is considered as *very good*. Model results from Scenario S1 in Section 3.2 predicts bottom water DO concentrations of ~180 µM which corresponds to *good* conditions.

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[5] *https://environment.ec.europa.eu/topics/water/water-framework-directive_en*

[6] *https://www.vannportalen.no/veiledere/klassifiseringsveileder/*

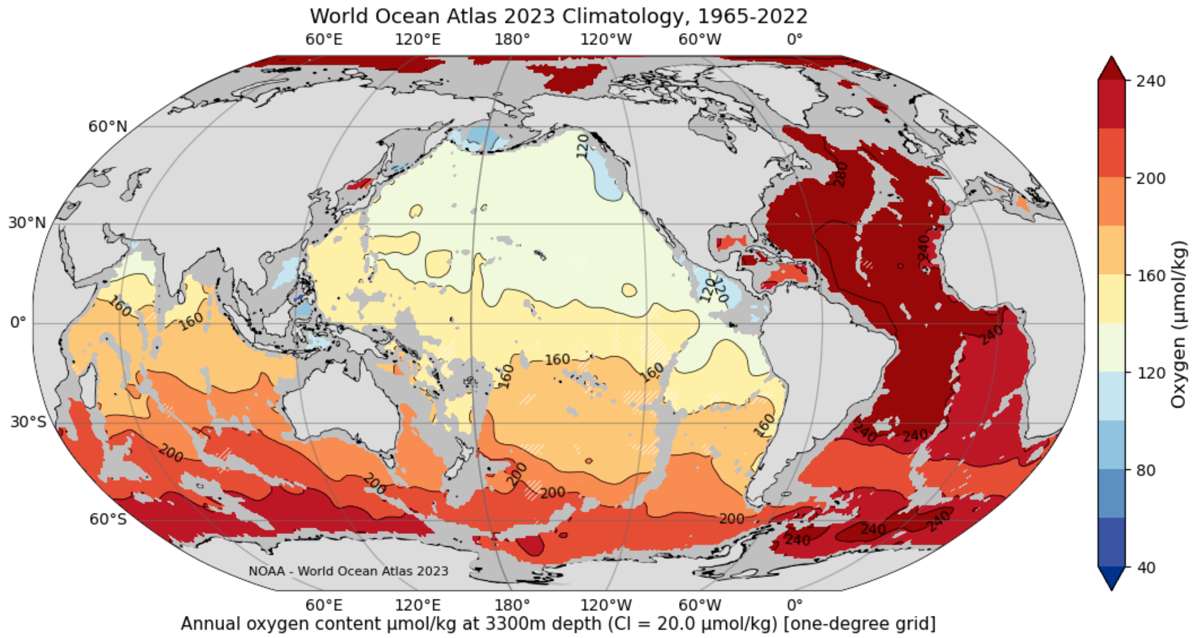

Figure 1.3. Climatology (1965-2022) of oxygen concentration at 3300 m depth. The proposed deployment location in the Norwegian Sea has naturally high oxygen concentrations due to its recent ventilation with the atmosphere (Reagan et al., 2023).

1.3.6. Dissolved inorganic carbon perturbation

From original Running Tide "Exposure Document"

By design, carbon buoy sinking will transfer organic carbon to the deep sea. Metabolic remineralization of this organic carbon will likely result in an increase in the DIC content of the benthic boundary layer via carbon dioxide, acidifying this region of water. This could adversely impact the lifecycle of marine organisms, especially benthic calcifiers. In addition, carbon buoys may contain alkaline minerals that did not entirely dissolve while floating in the surface ocean. This will also result in an increase in DIC via carbonate dissolution and will buffer acidity.

The original impact assessment is valid for Norwegian waters and does not require additional input. However, insights can be gained from model results related to sinking rates and where in the water column $CaO/Ca(OH)_2$ additions will dissolve and how much and how fast organic carbon from woodchips will be remineralized to CO_2. Because the residence time in surface waters of woodchips will likely be lower than carbon buoys, there is a possibility that $CaO/Ca(OH)_2$ might dissolve during the initial surface float period (2-4 weeks) while organic carbon and other acids may dissolve when the woodchips are at depth and/or resting on the benthos. The model-based sinking and distribution scenarios should be used to estimate the maximum limit of woodchip deposition per m^2 that will result in minimal dissolved inorganic carbon (DIC) perturbation.

1.3.7. Metabolic compound perturbation

From original Running Tide "Exposure Document"

Where regions of the ocean are or become sub-oxic, the degradation of organic carbon will proceed with alternative electron acceptors, producing methane, sulphide, or nitrous oxide, the presence of which will alter sediment biodiversity and species distributions, and may thus be harmful to sediment communities. The intensity and chemical character of organic material, as well as the depth of carbon placement, will affect the magnitude, space scale, and time scale of impact. For example, one experiment observed macroalgal degradation that occurred rapidly (less than a year) leading to a rapid but transient response in sulphur generation, while slower wood degradation rates resulted in local, reduced macrofaunal density and sulphur generation after multiple years.

Respiration of organic carbon will undergo diagenesis in a thermodynamically-favoured order which usually is oxic respiration until oxygen is depleted, followed by nitrate reduction, sulphate reduction, and methanogenesis. Efforts must be made to limit woodchip additions to a density at which bottom oxygen concentrations will not be affected. This is important from the metabolic compound perturbation perspective as well as other processes related to the benthos mentioned below (e.g., impact on demersal fish, ventilation of greenhouse gases). Model scenarios can be used similarly as for DIC perturbation – a safe maximum limit of woodchips per m^2 should be determined as to limit oxygen used in respiration of the additional organic carbon that is provided by woodchip deposition. If this level of woodchip addition is not exceeded, anoxic diagenetic processes and the production of hydrogen sulphide and methane can be avoided.

1.3.8. Alkalinity perturbation

From original Running Tide “Exposure Document”

Carbon buoy sinking may adjust the alkalinity of water in the benthic boundary layer through dissolution of carbonate minerals, thus increasing pH. While the carbonate in the buoys is designed to dissolve during flotation at the surface, some may remain attached to the buoys either due to rapid buoy sinking or incomplete dissolution. If these carbonate minerals are present during sinking below the lysocline, also known as the calcium carbonate compensation depth, rapid dissolution becomes increasingly likely.

The primary increase in alkalinity will likely be in surface waters where the added alkaline material, $CaO/Ca(OH)_2$, is expected to dissolve on <1 day timescales (Moras et al., 2022). If some alkaline material does sink with woodchips into the ocean interior, dissolution below the lysocline will occur at an even faster rate. Alkalinity perturbation could occur on the seafloor if woodchip carbon remineralization exhausts bottom oxygen and redox processes such as nitrate or sulphate reduction occurs.

1.3.9. Coral topography

From original Running Tide “Exposure Document”

The large deep-sea basins have flat areas with limited but varied deep-sea fauna. In some areas, the seabed has been examined in connection with planning and impact assessment of petroleum activity. Based on such information, the Institute of Marine Research has mapped selected coral reef areas.

Knowledge of other habitat types on the seabed in the Norwegian Sea beyond the reach of sunlight, and their role in ecosystems on a larger scale, is rather small. Both, for example, coral forests, sponge areas, deep-sea mountains, mud volcanoes and outflow areas for gas and carbonaceous liquid are generally little mapped and explored. The Mareano initiative is a comprehensive mapping of the seabed and is giving valuable information of the Benthic conditions in the Norwegian sea. New areas are contentious evaluated through the research project, to increase human knowledge of the benthic conditions. Little has been explored about the ecological significance of such natural types on the seabed.

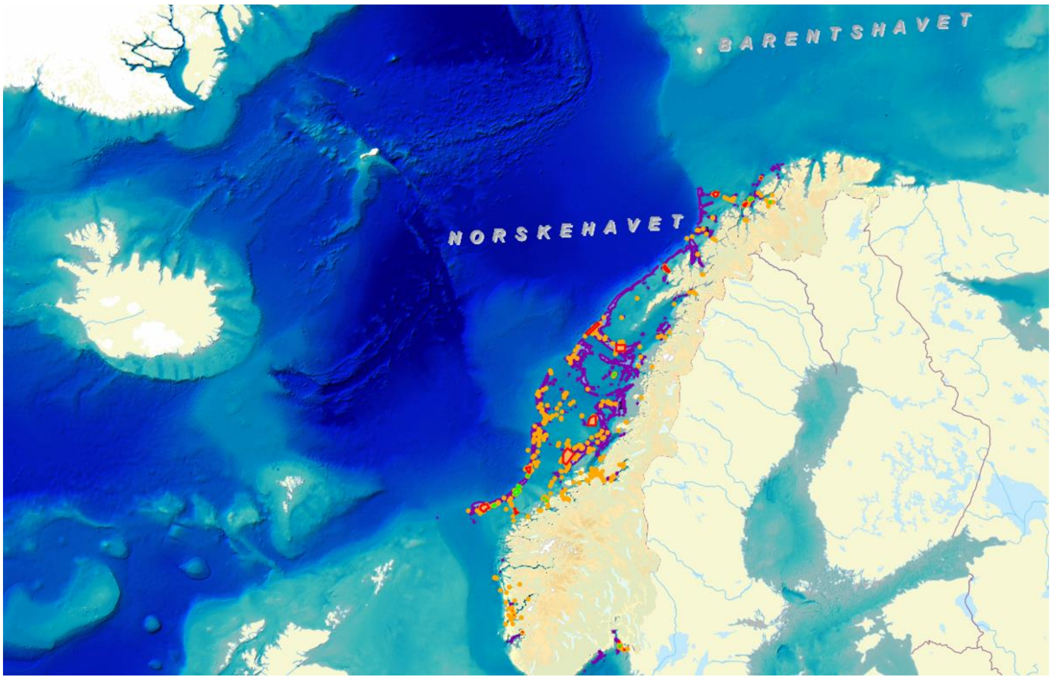

Figure 1.4. Location of coral marine protected areas (red polygons), observed coral reefs (orange dots), modelled coral reef areas (purple polygons) and identified coral reef areas (green polygons). Map from www.mareano.no[7].

Cold water corals (CWC) have been found in cold, dark, and deep parts of the world's oceans, including high latitude regions such as off the coast of Norway in northern Norway, western Norway, and in the outer Oslofjord. The largest known CWC reef to date is off the Lofoten peninsula on Røstbanken (35 x 4 km in size at ~300-400 m depth; Freiwald et al., 2004). CWC, however, have been found between ~50-4000 m depth around the world's oceans (Montseny et al., 2021). In Norwegian waters, CWC distribution has been found on the Norwegian shelf between ~200-400 m depth with the largest densities along the continental break (Figure 1.4; Falk-Andersson et al., 2017). CWC are often slow-growing and mainly sustained by feeding on particulate organic matter and zooplankton which they capture from seawater. The two primary anthropogenic threats for CWC are bottom fishing trawling or other oil/gas exploration bottom activity and ocean acidification. Woodchip deployment has not been previously assessed for CWC, but direct addition of large amounts over CWC could result in a smothering effect and inhibit natural feeding activities. Smaller amounts of woodchips could provide organic matter for nutritional requirements and the lime addition to woodchips could provide remediation for ocean acidification impacts on CWC calcium carbonate structures. In general, due to the potential impacts on slow-growing CWC and the difficulty that deep sea systems pose on restoration efforts (Freiwald et al., 2004), woodchip deployments should be focused on regions further offshore of CWC primary habitats. Although these deeper bottom habitats in the Lofoten Basin are below the aragonite saturation horizon ($\Omega_{ar} < 1$;

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[7] *https://kart.mareano.no/mareano/mareanoPolar_en.html?language=en&selectedLayers=532,533,531,690,590,545,545,293,293#maps/7572*

Figure 1.5), making their presence less likely, deployment areas should still be monitored for CWC colonies.

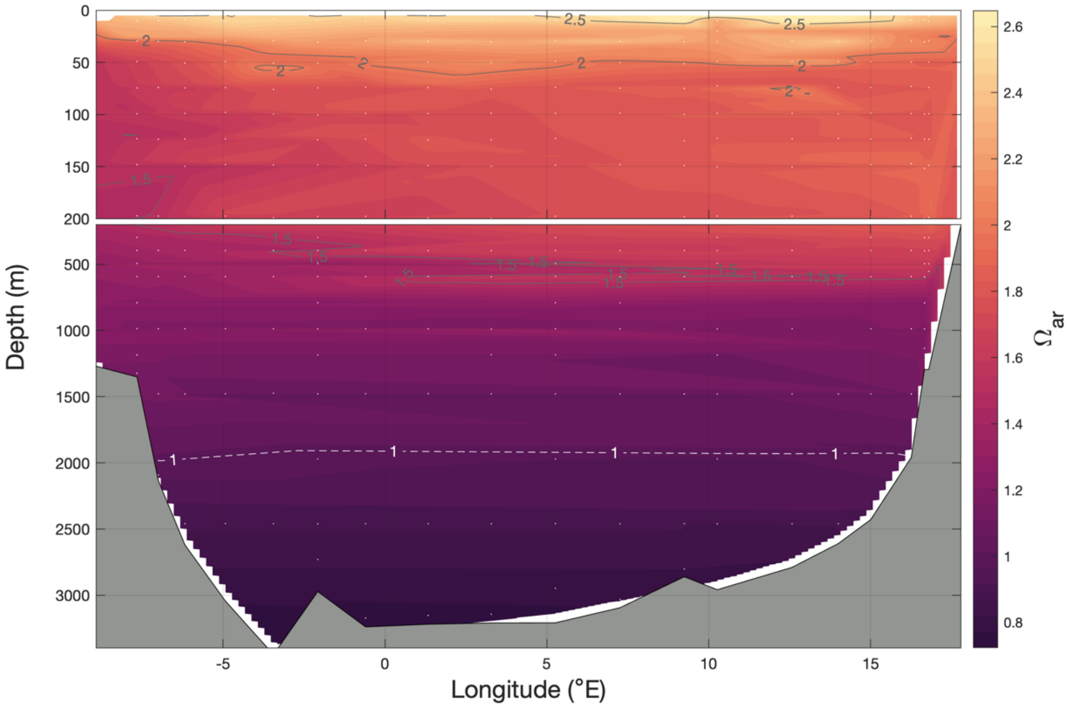

Figure 1.5. Saturation state of aragonite (Ω_{ar}) across the Lofoten Basin (see Figure 1.1 for location). The white dots show the location of water samples, the white dashed line shows the aragonite saturation horizon. Note the change in depth scale at 200 m. Woodchip deployment location at ~2.88°E.

1.3.10. Interference with commercial benthic fishing

From original Running Tide “Exposure Document”

While at the ocean floor, the deposited carbon buoys could be drawn into fishing trawls. Trawls net routinely dredge organic and manufactured materials from the sea floor. Based on topology and fishing activity in the area this is a highly unlikely incident and has been reviewed as not applicable.

Commercial trawling activities are typically carried out to a maximum of 1000 m depth. In Norway, bottom trawling has been primarily focused on the extensive continental shelf from western Norway and northwards to Barents Sea opening with target catch being cod and haddock as well as prawn. As with the cold-water coral case described above, the impact of woodchip deployment would be dependent on the scope of deployment and whether significant quantities of woodchips would be advected onto the continental shelf region. Since the deployment strategy is targeting deep waters (3300 m) in order to increase carbon sequestration potential, there is likely to be little overlap between woodchip deployments and benthic commercial fishing activities. Additionally, because fish are aerobic organisms, deployments must be limited enough to not impact bottom oxygen concentrations.

1.3.11. Interference with deep sea mining

From original Running Tide "Exposure Document"

Deposition of carbon buoy materials on the sea floor may interfere with future mining operations if the carbon buoys are deployed in areas over hard sediments. There is no substantially described mechanism through which this interaction would occur in the region of interest as of today. The benthic condition at the deployment site is mainly sediments and hence no interest for deep sea mining activity.

There might be an interest for deep sea mining at the Mohn ridge. However, the deployment site is not in the vicinity of this area and hence there is no conflict foreseen. In addition, the Carbon buoys are composed of non-exogenous materials to the seafloor and are small in form factor compared to existing variations in surface roughness. Carbon Buoys are not expected to measurably impact the topography of the seafloor in the project region and hence no impact a potential mining industry. Also, Deep Sea Mining equipment will have to be designed to level materials and not biomass, and hence limited consequences. To further address this, available data on deep sea mining operations may be included for consideration during site selection, if required.

Deep sea mining entails extraction of minerals (primarily rare earth elements, at present) from the sea floor at depths ranging from 200-6500 m. In early 2024, Norway started a process towards eventually issuing licenses for deep sea mining of nodules and crust enriched with rare earth elements in areas around Jan Mayen and Svalbard[8]. The woodchip deployment site is outside of the proposed deep sea mining area; however, some woodchips may float into this region. The few woodchips that do make it into this region would be widely dispersed are expected to not measurably impact the seafloor topography and hence no impact is expected on potential mining industry. Also, the organic nature of woodchips will likely not impact exploratory techniques such as side scan sonar or box core sampling.

1.4 Earth systems impacts

1.4.1. Methane release

Methanogenesis is a biogeochemical process in which microbes breakdown organic matter under anaerobic conditions. If woodchip deployment to the deep sea occurs at concentrations that are expected to result in organic carbon respiration and anoxic conditions, the possibility of methanogenesis and eventual ventilation is a possibility. Under oxic conditions (>2 mg L^{-1} or ~63 μM) the organic carbon respiration and CO_2 production biogeochemical pathway is favoured. If woodchip organic carbon is converted to methane (CH_4) instead of CO_2, this could have implications for the Earth's greenhouse effect since CH_4 is approximately 80 times more powerful than CO_2 as a greenhouse gas for 20 years after it is released (e.g., Mar et al. (2022)). To avoid a scenario in which methanogenesis would be favoured, all efforts must be made to avoid seafloor hypoxic or anoxic conditions from woodchip deployments.

1.4.2. Ventilation of metabolic greenhouse gasses

Greenhouse gases are gases that trap heat in the Earth's atmosphere. The main greenhouse gases are CO_2, CH_4, nitrous oxide (N_2O), and water vapour. With respect to organic carbon storage in the deep sea, such as woodchips, the primary greenhouse gas that will be produced is CO_2 through organic carbon respiration. Promotion of methanogensis, as described above, should be avoided. CO_2 that is produced via respiration will remain at the seafloor and isolated from the atmosphere on the ~1000-year timescale (Toggweiler & Key, 2001). The Norwegian Sea is situated in the North Atlantic where deep

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[8] *https://www.ft.com/content/44855d32-82c2-4f4c-b77c-1c21d3c1279f*

water formation occurs – the sinking of cold, dense water – and subsequent circulation towards the equator and eventual ventilation to the atmosphere, or upwelling, in other regions such as the Southern Ocean, Indian Ocean, or Pacific Ocean. Because thermohaline circulation is a natural circulation process (that can have some variations), the best strategy is to deploy carbon storage in an ocean basin where deep water formation occurs so that sequestration time is maximised. The Greenland-Norwegian Sea and the Weddell and Ross Seas (Southern Ocean) are the ocean regions where a large proportion of deep-water formation occurs (Rahmstorf, 2006).

2 Materials and methods

2.1 Model description

Here we use the biogeochemical modules Bottom RedOx Model (BROM) coupled with a vertical 2 Dimensional Benthic-Pelagic Model 2DBP (Figure 2.1), that considers processes occurring in the water column, benthic boundary layer (BBL), and sediments together. The BROM's module for carbon transformation describes processes in the carbonate system which can be used to calculate pH and carbonate saturation states, as well as formation and dissolution of carbonates (Figure 2.1). A detailed description of BROM is given in (Yakushev et al., 2017). These modules were integrated into an existing modular platform (Framework for Aquatic Biogeochemical Modelling, FABM; (Bruggeman & Bolding, 2014)), that coupled together transport driver 2DBP and BROM's biogeochemical blocks.

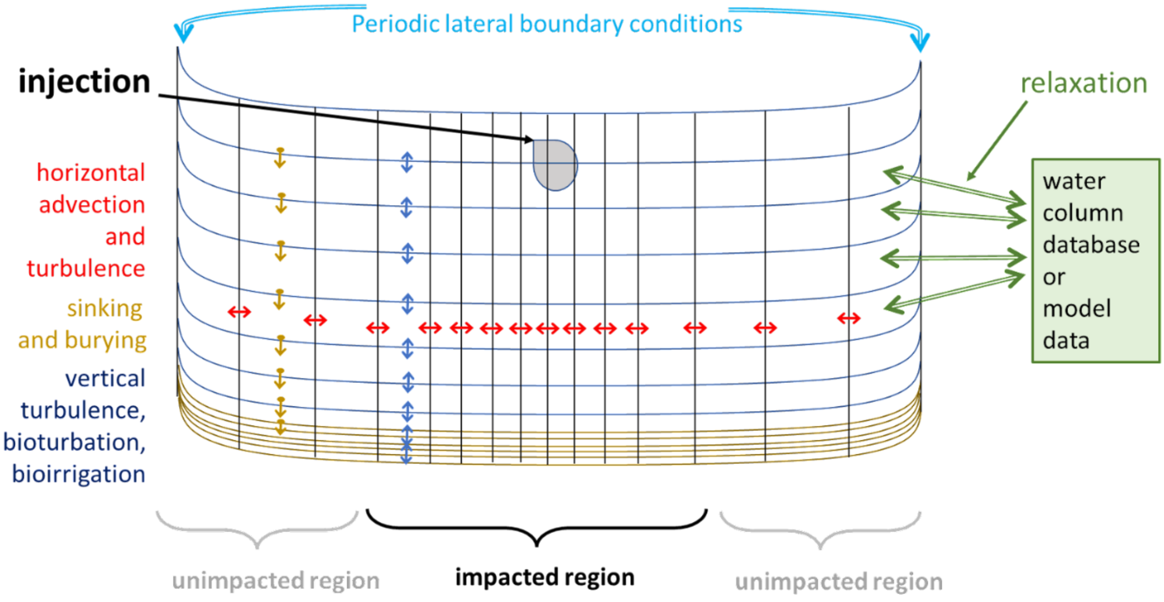

Figure 2.1. Scheme of 2-Dimensional Benthic -Pelagic Model 2DBP with the injection point in the center of the transect.

The constructed model allows for parameterization of injection of the studied woodchips, their transport due to advection and turbulence, dissolution, and oxidation. There were also considered processes of carbon containing compounds transformation connected with chemical processes (i.e. carbonate system equilibration) and biogeochemical processes (i.e. connected with organic matter synthesis and decay).

2.2 Hydrophysical forcing

The transport model 2DBP was forced by model outputs for the seasonal variability of temperature, salinity, ice cover changes, vertical turbulence, irradiance and current velocity from a ROMS-20 km model (Shchepetkin & McWilliams, 2005) applied for the Arctic Ocean (Ommundsen et al., 2008). Data from the closest ROMS-20 km grid point to the planned woodchip deployment site was used. The horizontal spatial resolution of 2DBP was 100 m in the center of the transect and increased toward the peripheral parts to 500 m. The vertical resolution of 2DBP was the same as ROMS (40 grid points for 50 m depth) in the water column and decreased in the limits of 100 cm BBL from 50 to 6 cm and then increased in the upper sediments from 0.05 cm to 2 cm.

2.3 Pelagic chemical forcing

The biogeochemical data for lateral relaxation were obtained from the TOPAZ-ECOSMO reanalysis system (Simon et al., 2015). It assimilates satellite chlorophyll observations and in situ nutrient profiles. The model uses the Hybrid Coordinate Ocean Model (HYCOM) coupled online to a sea ice model and the ECOSMO biogeochemical model. It uses the deterministic version of the Ensemble Kalman Smoother to assimilate remotely sensed color data and nutrient profiles. Data assimilation, including the 80-member ensemble production, is performed every 8-days. Atmospheric forcing fields from the ECMWF ERA-5 dataset are used. Monthly data were linearly interpolated to daily values. The received seasonal variabilities are shown in Figure 2.2.

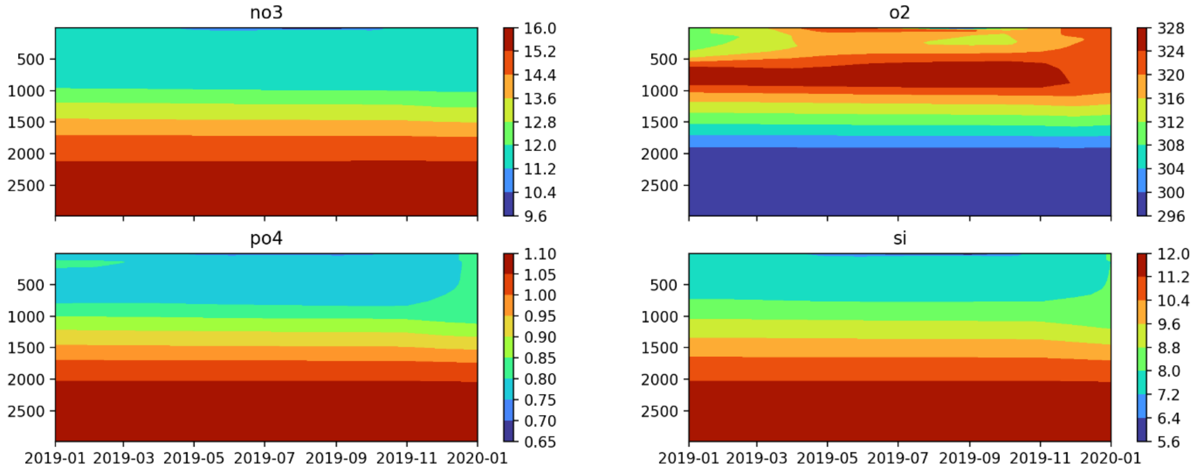

Figure 2.2. Seasonal variability of nitrate (NO_3^-, μM), phosphate (PO_4^{3-}, μM) and silicate (SiO_4^{4-}, μM), and oxygen (O_2, μM) in the selected region estimated with TOPAZ-ECOSMO reanalysis system.

2.4 Properties of the injecting woodchips

We assume that a mixture of woodchips (that is particulate organic matter, POM) and $CaCO_3$ and CaO is injected as one particle, that it sinks with the same velocity, and all these three substances can react with surrounding water on their way to the bottom and eventually deposit on the bottom. The weight ratio of the woodchip components was assumed to be POM:$CaCO_3$:CaO = 95:3:2% or 95:5:0% or 100:0:0%. At this stage we assume that the chemical composition of the POM follows the hypothetical organic matter composition with classical Redfield ratio i.e. $(CH_2O)106(NH_3)16H_3PO_4$.

Since the reaction between CaO and water is highly exothermic forming $Ca(OH)_2$ in a matter of seconds and $Ca(OH)_2$ will further dissolve into Ca^{2+} and $2OH^-$, it was assumed that the addition of 1 mol CaO leads to a 2 mol increase of total alkalinity; while not increasing the amount of dissolved inorganic carbon (Ilyina et al., 2013). Moras et al. (2022) determined that quicklime (CaO) and hydrated lime ($Ca(OH)_2$), with a particle size <63 μm, dissolved in seawater within a few hours.

Here we analyze results of numerical experiments with the following woodchip characteristics:

- Injection rate: ~2000 tonnes $24h^{-1}$ of woodchips for 1 deployment $year^{-1}$, in April.
- Area of deployment: (100 m X 100 m), (1 km^2)
- r_woodchip_decomp: 0.001 # Specific rate of POM decomposition into “natural” POM, (1 day^{-1})
- 0.039 day^{-1} (calculated from Charles et al. (2022) estimate of the 50% loss of weight in 1.1 year) lab. Also 25.6% 24 $weeks^{-1}$ (Henningsson, 1974).
- r_woodchip_diss: 0.0001 # Specific rate of leaching dissolution into DOM, (1/d) (0.000021 1/d (based on calculations using average hardwood/softwood density and carbon content, and data from Abusallout & Hua (2017))
- r_woodchip_miner: 0.001 # Specific rate of waste oxic mineralization into inorganic nutrients, (1/d) (Khanina et al., 2023)
- Sinking rate: 250 m day^{-1}, 500 m day^{-1}, 1000 m day^{-1}, 2000 m day^{-1} (about 2.4 cm s^{-1}). (Running Tide lab work 3-6 cm s^{-1})
- Decomposition of “natural” POM and DOM: is the same in BROM for fish farm modeling (Yakushev et al., 2020)

3 Results

The work on this project was performed in 2 stages: 1) calculation of the baseline distributions of the model variables that corresponds to the observed natural distributions and variability in the Norwegian Sea region selected for the planned project, and 2) numerical experiments on evaluation of the changes in the biogeochemical regime connected with the planned deployment of the woodchips.

3.1 Baseline distributions

At the first stage we calculated baseline distributions with seasonal variability forced by the TOPAZ-ECOSMO reanalysis system (Figure 2.2). After several hundred years spin-up period there were no changes between the consequent years (Figure 3.1), and repeated seasonal changes (Figure 3.2) and vertical distributions (Figure 3.3) comparable with the observations were received. In Table 7.1 we show the list of the BROM state variables, and their values observed in the abyssal regions of the Norwegian Sea and the World Ocean. The values from the performed literature analyses (from the Norwegian Sea and nearby regions) were used under the assumption that the biogeochemical features of the Norwegian Sea bottom are under similar conditions (i.e. temperature, salinity, pressure, low organic matter) (see maps in Hayes et al. (2021)). To validate the model, we used the available observations data and tuned model parameters and forced boundary conditions to receive distributions that satisfactorily correspond to the observed ones (Table 7.1 and Figure 3.2)

Natural seasonality of organic matter (OM) production and destruction was parameterized (Figure 3.2). The phytoplankton (Phy) bloom and increase of heterotrophic bacteria (Het) is followed by an increase in labile and refractory dissolved organic matter (DOML and DOMR, respectively) and labile and refractory particulate organic matter (POML and POMR, respectively), that eventually sink to the bottom. Most of the produced natural OM is re-mineralized in the upper hundred meters of the 3000 m deep water column, and only a small amount of OM reaches the bottom. This leads to a low burial rate of, 0.006 cm year^{-1}, that is comparable with the existing values for the deep Norwegian Sea and Fram Strait region, 0.05 and 0.08 mm year^{-1} (Björdal & Dayton, 2020). The POM buried in the sediments leads to oxygen consumption in the sediments and a small decrease of oxygen in the bottom water (from 300 µM in the surface layer to about 280 µM near the bottom) and upper sediment with a small seasonal variation (Figure 3.3). pH values (in total scale) decrease from 8.05 near the surface to 7.70 near the bottom. There is also seasonal variability in surface and bottom pH.

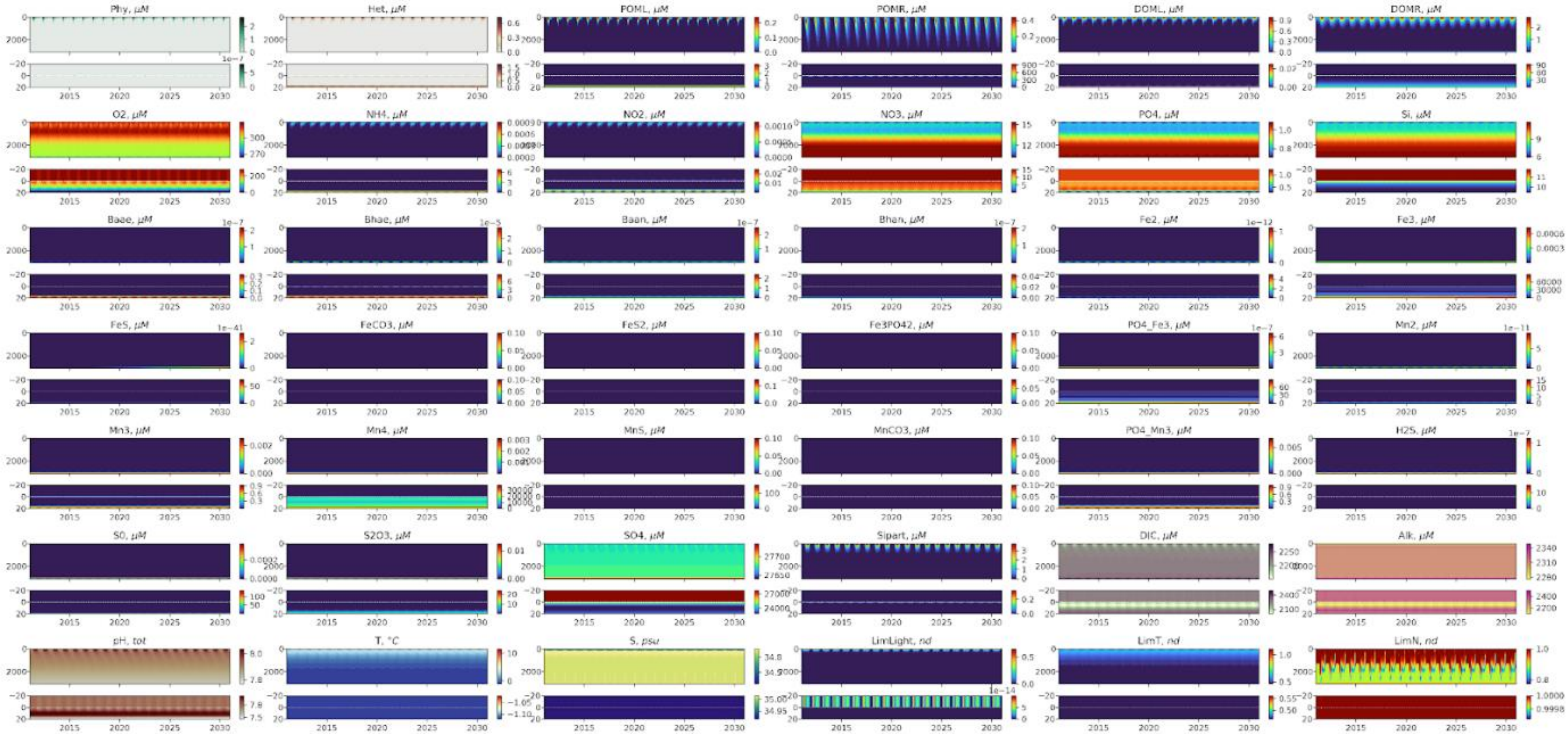

Figure 3.1. Calculation for the 10 years interannual variability after ~200-year spin-up period in the water column (upper panels, vertical axis in meters) and at the sediment-water interface (SWI). Bottom panels, vertical axis in centimeters from the sediment surface. See Table 7.1 for full variable names.

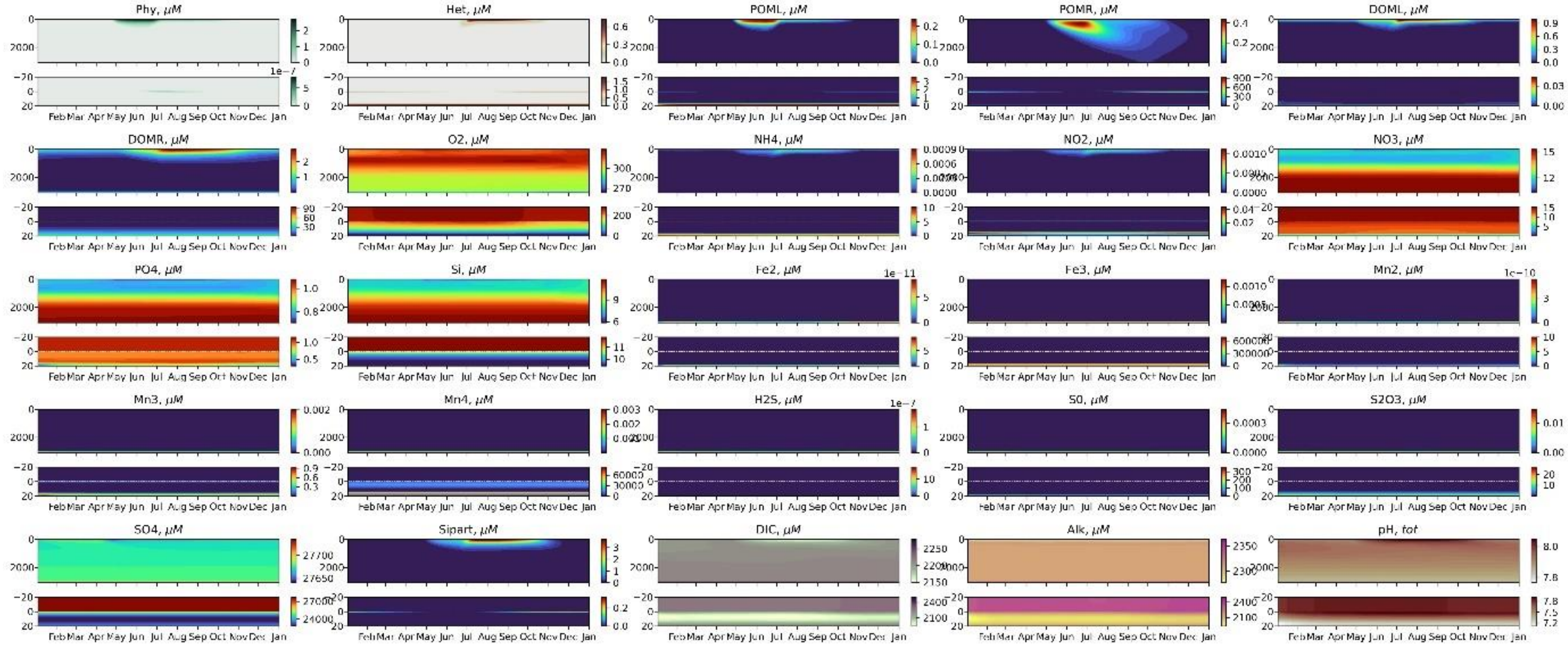

Figure 3.2. Seasonal variability for the last year of the spin-up period. See Table 7.1 for full variable names.

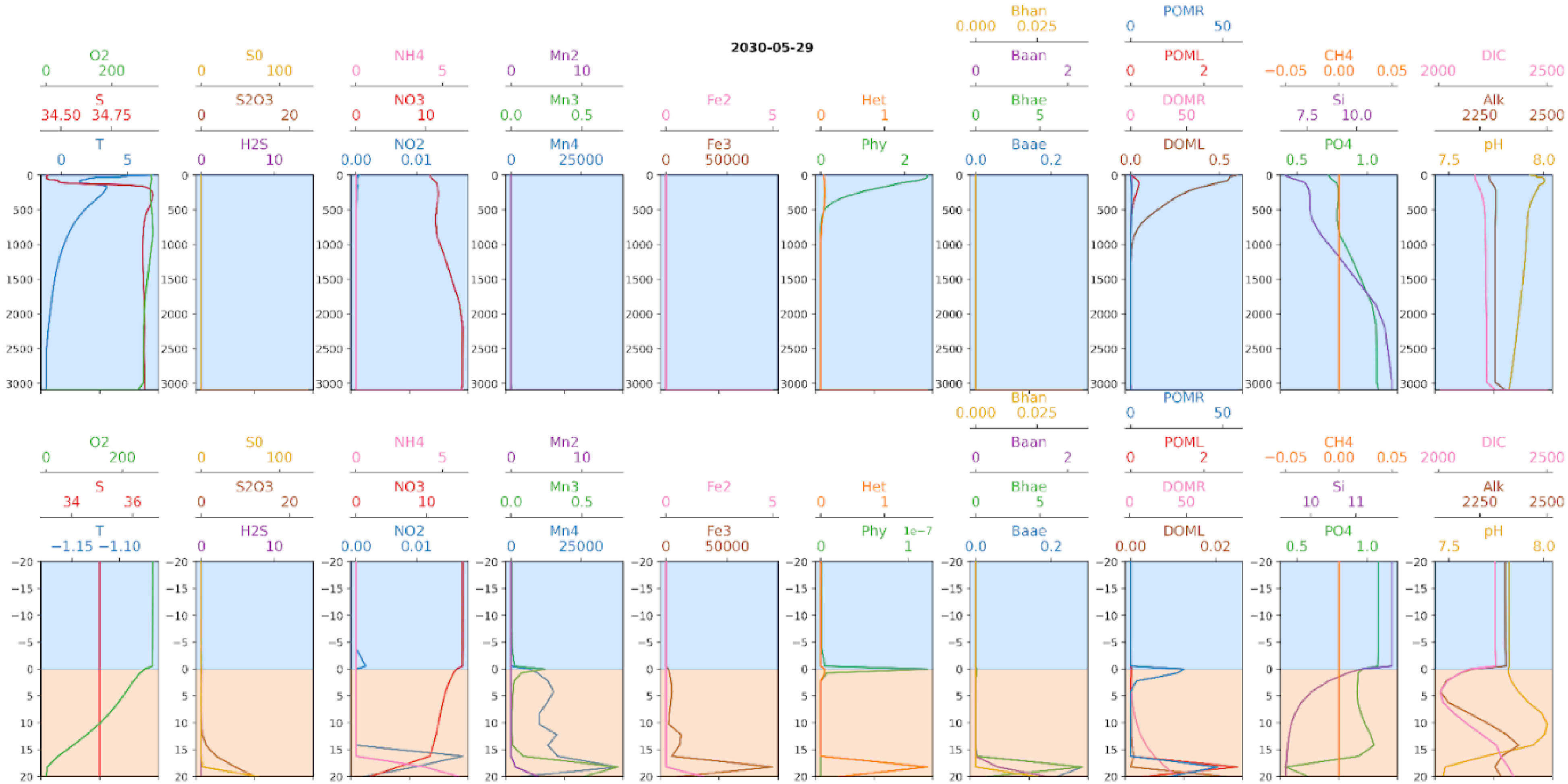

Figure 3.3. Baseline vertical distributions of model variables in the water column (upper panels, vertical axis in m) and at the SWI (bottom panels, vertical axis in centimeters from the sediment surface). See Table 7.1 for full variable names.

In the modeled 20 cm upper sediment layer (Figure 3.3), oxygen concentrations are high which is typical for the abyssal regions of the ocean (Table 7.1 and references therein). The modeled oxygen gradually decreases from 230 μM at the sediment-water interface to 0 μM at the 20 cm depth. That was assessed in the model by assigning the low boundary conditions with constant concentrations of oxygen consumers, NH_4, Fe(II), Mn(II), OM. The transformation of normoxic to anoxic conditions appears in the model at sediment depths of 15-20 cm, where the extremes of oxidized and intermediate forms of N, Fe, Mn and S are predicted. A comparable oxygen penetration depth (13 cm) was reported for the North Atlantic by (Papadimitriou et al., 2004). Alkalinity in the sediments depends on the chemical composition of the bedrock and can significantly vary in different abyssal regions. pH increases from 7.8 at the sediment-water interface to 8.0 at 10 cm depth and decreases again to 7.5 at 20 cm. These values are reasonable, but comparable in situ measurements in the selected region of the Norwegian Sea were not found.

3.2 Numerical Experiments

The simulated baseline distributions and variabilities were used as initial conditions for numerical experiments on the influence of the woodchip deployment on bottom biogeochemistry. The scenario S1 (Table 3.1) was selected as a “standard” deployment scenario in which the woodchips should be deployed over 24 hours in a small 1 km^2 ocean surface, and that will require the ship to return to the same position several times during 24 hours. It also assumed that the woodchips should start to sink immediately with the speed of 1.5 cm s^{-1}.

Table 3.1. Investigated scenarios during numerical experiments.

Scenario	**Deployed woodchips, tonnes (24 h)$^{-1}$**	**Surface water area of deployment**	**Sinking rate cm s^{-1}**	**Addition of $CaCO_3$, weight %**
S1	2000	1 km^2	1.5	5
S2	1000	1 km^2	1.5	5
S3	4000	1 km^2	1.5	5
S4	2000	1 km^2	0.75	5
S5	2000	1 km^2	0.375	5
S6	2000	1 km^2	1.5	0

Here we will describe the mechanism of reaction of the bottom biogeochemistry on disturbances forced by the deployment using the S1 scenario, and in the Discussion we will discuss changes connected with scenarios S2-S6 (Table 3.1; increases/decreases in woodchip deployment amount, decrease in sinking rate, and removal of $CaCO_3$) and we will summarize the formal connections between intensities of potential deployments and quantitative changes in biogeochemical parameters.

As it was stated above, the most important biogeochemical characteristic for the deep sea is the concentration of dissolved oxygen, that determines state of ecosystems and peculiarities of biogeochemical perturbations. In the low organic carbon deep sea abyssal regions, i.e. Norwegian Sea, the oxygen penetration depth can reach several centimeters or 10s of centimeters, which is primarily due to the lack of carbon availability and subsequent oxygen utilization. In this model the baseline condition of the oxygen penetration depth is 18 cm.

Figure 3.4 shows changes in woodchip and dissolved oxygen distributions in the water column and in the upper sediment for the timepoints before the deployment, 3 days after deployment and 6 months after the deployment.

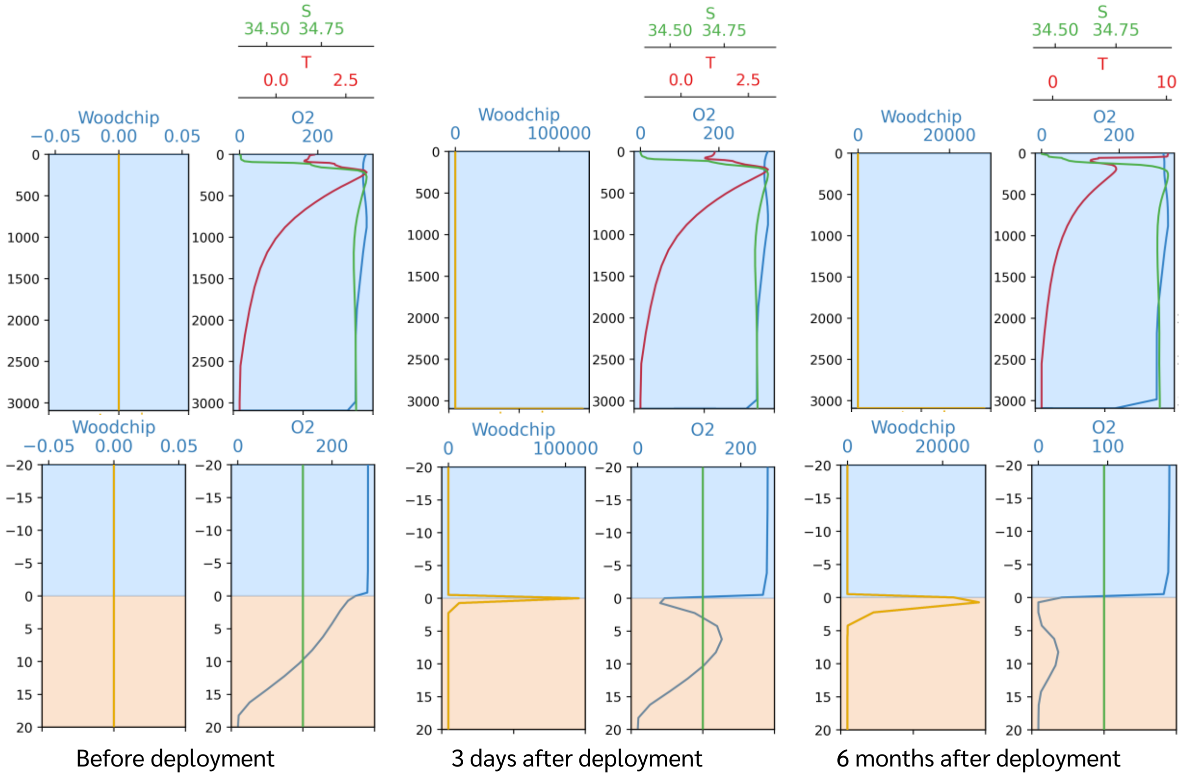

Figure 3.4. Vertical distributions of woodchips (yellow; μM N), dissolved oxygen (blue; μM), temperature (red; °C) and salinity (green; psu) at the deployment position before deployment (left), 3 days after the deployment (middle) and 6 months after the deployment (right) (Scenario S1). The top panels correspond to the water column (y-axis units: meters) and the bottom panels correspond to the sediment water interface (y-axis units: centimeters). See Table 7.1 for full variable names.

Starting from the 1st day the woodchips accumulate at the sediment-water interface, and in 6 months it leads to a formation of the oxygen minimum with hypoxic concentrations below the sediment-water interface (Figure 3.4). As shown in Figure 3.4, oxygen dramatically decreases to hypoxic levels in pore waters, but dissolved oxygen remains in high concentrations in the bottom water (~180 μM), corresponding to *good* conditions for Norwegian coastal waters[9].

Accumulation of woodchips on the seafloor in Scenario S1 is accompanied by an increase of particulate and dissolved organic matter, decrease of oxygen and pH that can be traced for several years after the deployment (Figure 3.5). These estimates correspond well to the results of an experimental addition of wood to the seafloor (Bienhold et al., 2013). Considering very slow modeled and observed rates of natural burying in the region (0.05-0.08 mm year^{-1}) (Björdal & Dayton, 2020), there should be no significant burial after the deployment and the woodchips should mainly stay at the bottom surface for many years. The model predicts an increase in nutrients and appearance of anaerobic heterotrophic bacteria that also correspond to the experimental studies (Bienhold et al., 2013).

Temporal changes at the seafloor surface are shown in Figure 3.6. It is predicted that under the Scenario S1 the biogeochemical disturbances will occur 3-4 km distance from the deployment point, and they can be traced for 4-5 years. As was mentioned above, the decrease of oxygen will not be large. In case of deployment of 5% weight $CaCO_3$, there should be no significant changes in pH and carbonate saturation.

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[9] *https://www.vannportalen.no/veiledere/klassifiseringsveileder/*

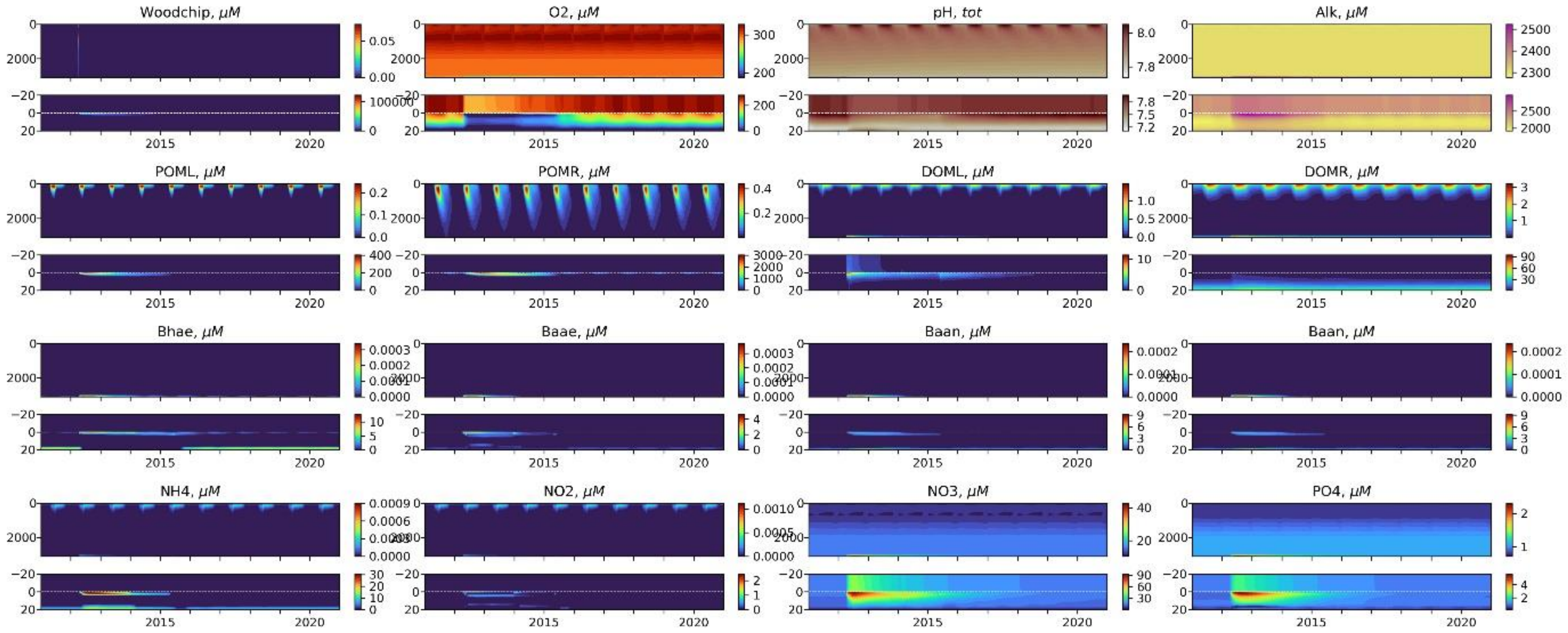


Figure 3.5. Interannual changes in the water column and sediments over a 10-year period; 1 year before woodchip deployment and 9 years after (95% woodchips + 5% $CaCO_3$; Scenario S1). See Table 7.1 for full names of modelled parameters.

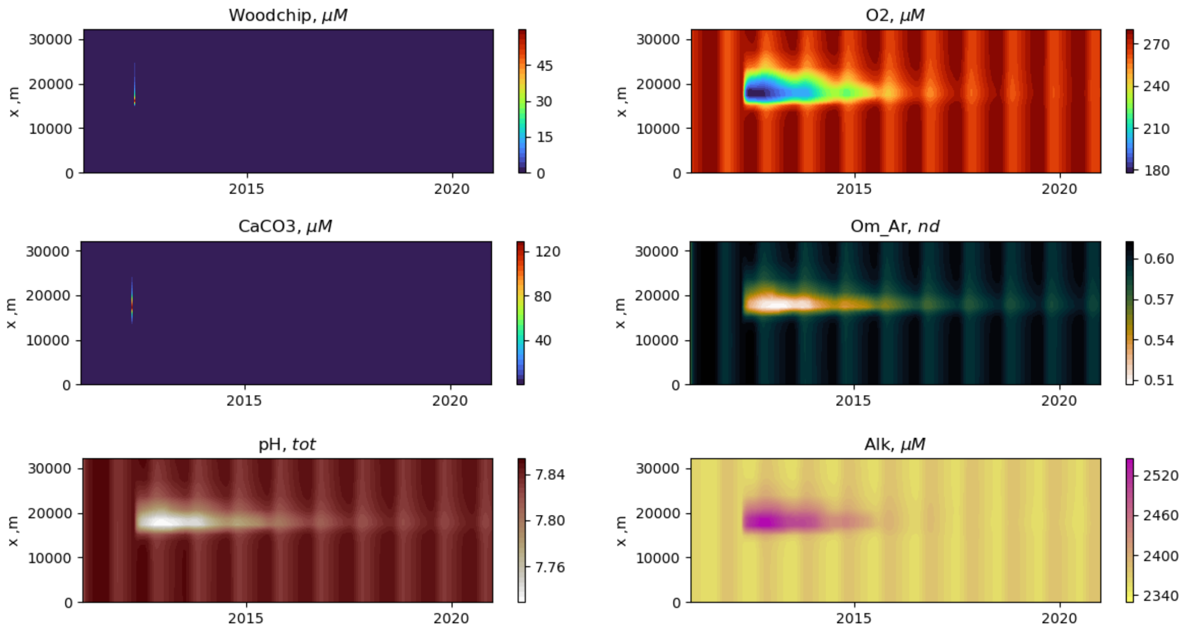


Figure 3.6. Interannual changes on the seafloor surface over a 10-year period; 1 year before woodchip deployment and 9 years after (95% woodchips + 5% $CaCO_3$; Scenario S1). Parameters include woodchips (μM N), oxygen (μM), $CaCO_3$ (μM), aragonite saturation, pH and alkalinity (μM). See Table 7.1 for full variable names.

The model predicts changes in the benthic fluxes after the deployment (Figure 3.7). First, there should be an increase in sediment oxygen consumption (SOC), the downward flux of oxygen into the sediments (from 0-1 mmol O_2 m^{-2} day^{-1} to 4-6 mmol O_2 m^{-2} day^{-1}). This flux should be accompanied by the upward fluxes from the sediments of inorganic and organic carbon (Figure 3.7), i.e. from 0-1 mmol C m^{-2} day^{-1} to 10-11 mmol C m^{-2} day^{-1} for DIC and from 0 mmol C m^{-2} day^{-1} to 0-2 mmol C m^{-2} day^{-1} for organic carbon. The difference of fluxes for oxygen and organic matter were demonstrated in the experimental wood deployment (Bienhold et al., 2013).

For Scenario S1, the model predicted maximum woodchip concentrations (46000 mmol N m^{-3} = 46 mol N m^{-3} = 300 mol C m^{-3} = 3600 g m^{-3}) will occur in a 5 mm layer (Figure 3.8). In reality, much higher horizontal mixing and slower sinking speed should result in a wider spread of woodchips and result in a much lower concentration and layer thickness on the bottom. The predicted woodchip layer in S1 is greater than 15 g C m^{-2} values estimated by Running Tide, which corresponds to ~0.06 mm layer of of woodchips. But, as we demonstrate here, even under S1 there should be depletion of oxygen and increase in nutrient concentrations in the pore waters, but still within acceptable water quality conditions in the bottom waters (Figure 3.5).

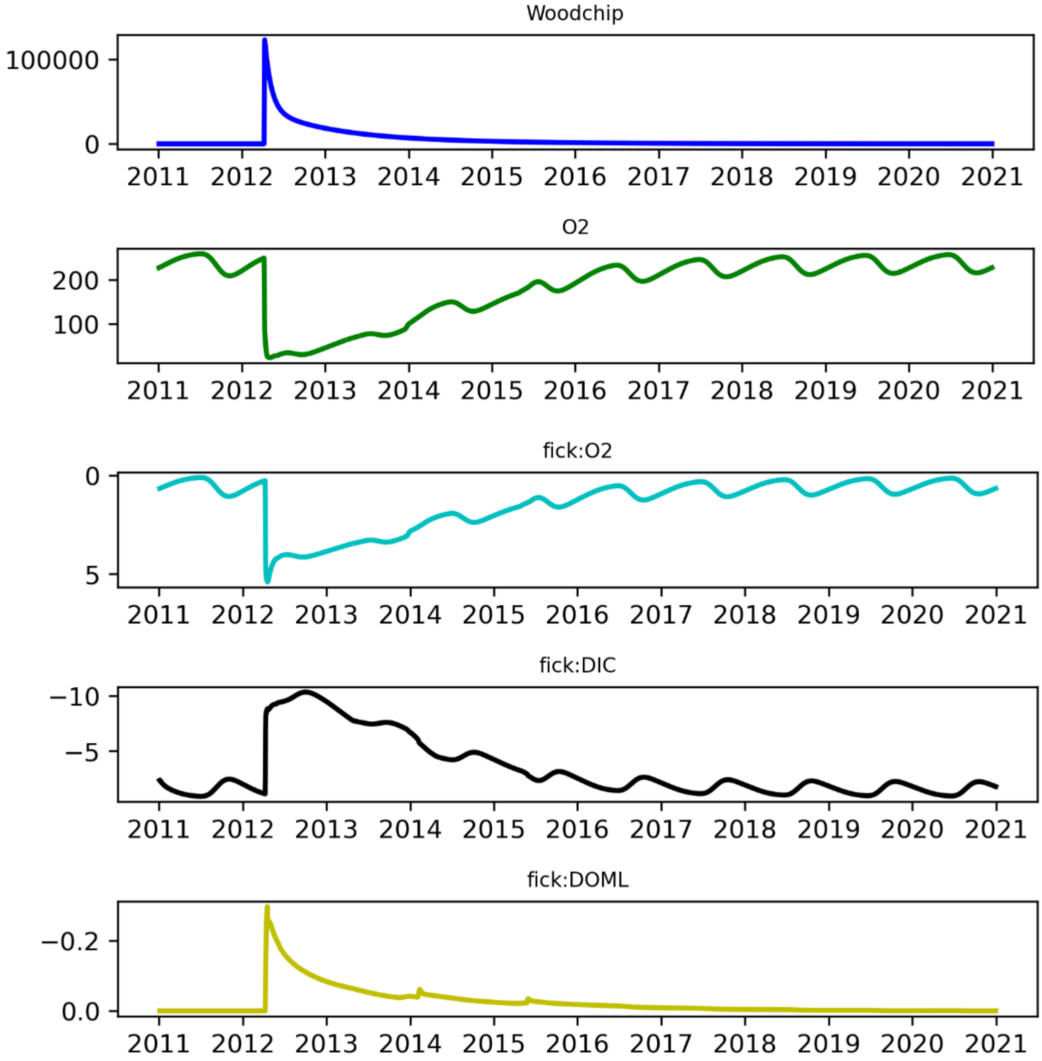


Figure 3.7. Interannual changes of bottom concentrataions of woodchip (μM N), oxygen (μM) and bottom fluxes (mmol m^{-2} day^{-1}) of oxygen (fick:o2), DIC (fick:DIC). and DOML (fick:DOML) (Scenario S1).

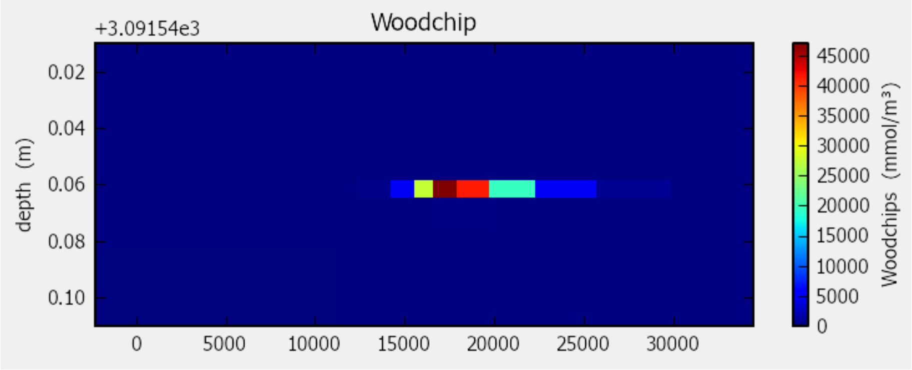


Figure 3.8. Distribution of woodchips in a transect through the deployment point 1 day after the deployment (Scenario S1). Units of mmol N/m^3 = μM N.

4 Discussion

The applied model has many assumptions and simplifications, and the coefficients used have many uncertainties. This includes coefficients presented in Section 2.4 related to the fate of the wood in seawater (rates of decomposition, leakage, mineralization, sinking rate, etc.), which can be improved in the future studies through laboratory and field experiments with wood particles. An assessment of sensitivity of various rates/coefficients was made using several additional scenarios (S2-S6; Table 3.1).

The intensity of the oxygen depletion depends on the amount of the settled woodchips which is primarily dependent on the amount of woodchips deployed and their sinking rate (Figure 4.1, Figure 4.2). The estimated area of seafloor affected is shown in Figure 3.6 for Scenario S1. The influence of sinking rates was tested in Scenarios S1 (1.5 cm s^{-1}), S4 (0.75 cm s^{-1}), and S5 (0.375 cm s^{-1}) and is shown in Figure 4.1. In the case of high sinking rate (Scenario S1; Figure 4.1, top) oxygen will decrease in the upper sediments for a period of several years within a 4 km distance from the depletion point. In the case of a lower sinking rate (Scenario S4; Figure 4.1 middle), the area of woodchips is larger (~8 km distance from the point of deployment) with smaller concentrations, and consequently the oxygen depletion is also lower. An even lower sinking rate (Scenario S5; Figure 4.1, bottom) will lead to lower woodchip concentration over a wide area on the bottom and virtually no effect on oxygen. A transect through the depletion point shows that after 15 days of the deployment (*Figure 4.2*), oxygen depletion in the porewater only occurs in case S1 (highest sinking rate). With the lowest sinking rate scenario (S5), a large proportion of woodchips is still in the water column, where decomposition begins to occur.

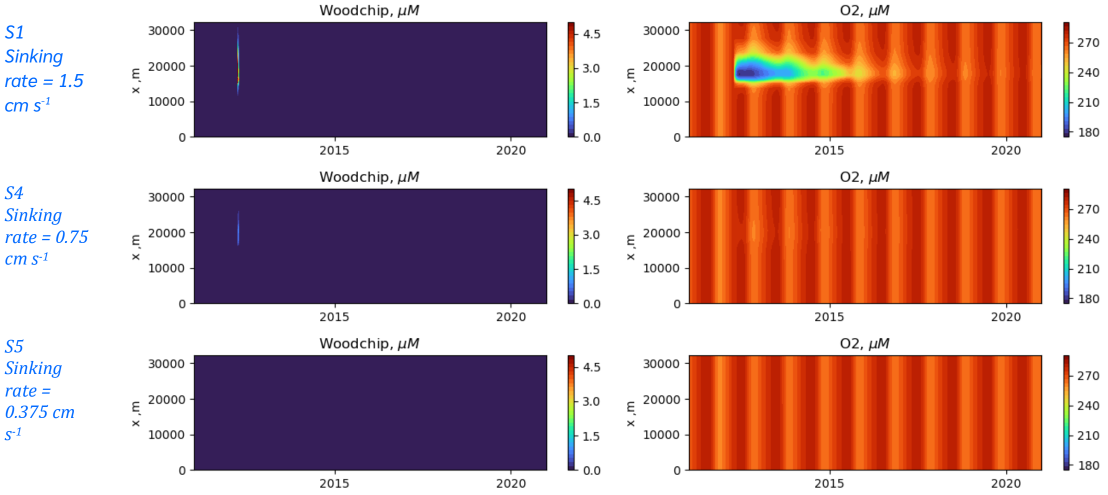


Figure 4.1. Interannual variability of woodchips (μM N) and DO (μM) at the sediment surface with woodchip sinking rate 1.5 cm s^{-1} (Scenario S1, top), 0.75 cm s^{-1} (Scenario S4, middle), 0.375 cm s^{-1} (Scenario S5, bottom).

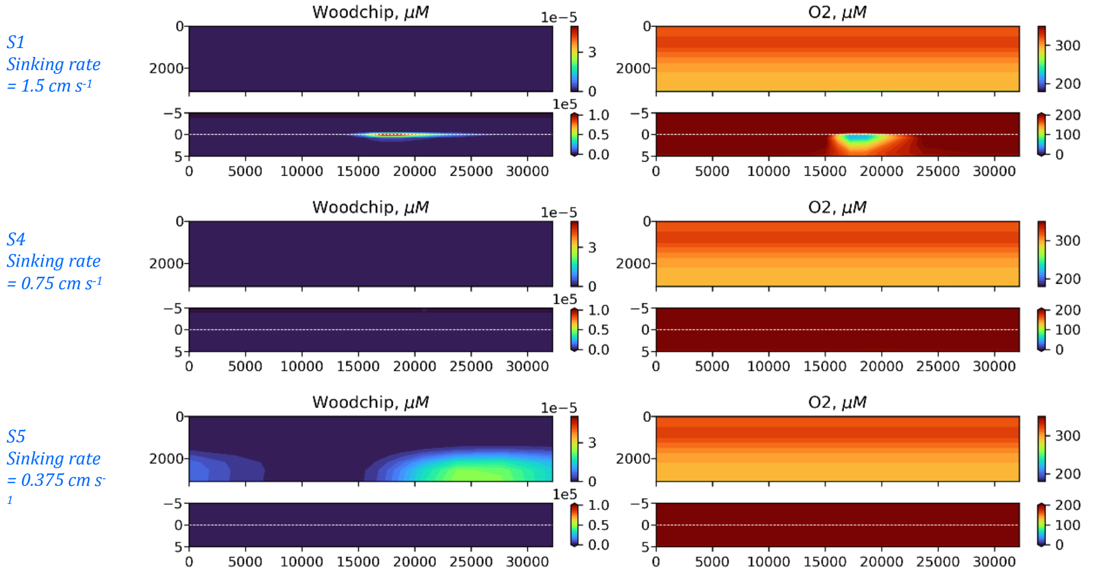


Figure 4.2. Influence of the sinking rate on the woodchips (µM N) and oxygen (µM) distribution in a 30,000 m (30 km) long transect through the deployment point after 15 days of deployment. Deployment location centered on 15,000 m.

Doubling the amount of deployed woodchips (Scenario S1 with 2000 tonnes v. Scenario S3 with 4000 tonnes) will lead to negative consequences for the bottom biogeochemistry in Scenario S3 (Figure 4.3) in comparison with (Figure 3.5). An excessive amount of organic matter will lead to oxygen depletion in the pore water and the bottom water to *very bad/bad* conditions. After depletion of oxygen there is predicted an intensive denitrification with disappearance of nitrate in the pore water and the bottom water. After depletion of nitrate there is predicted sulfate reduction and appearance of hydrogen sulphide, that will be toxic for the biota.

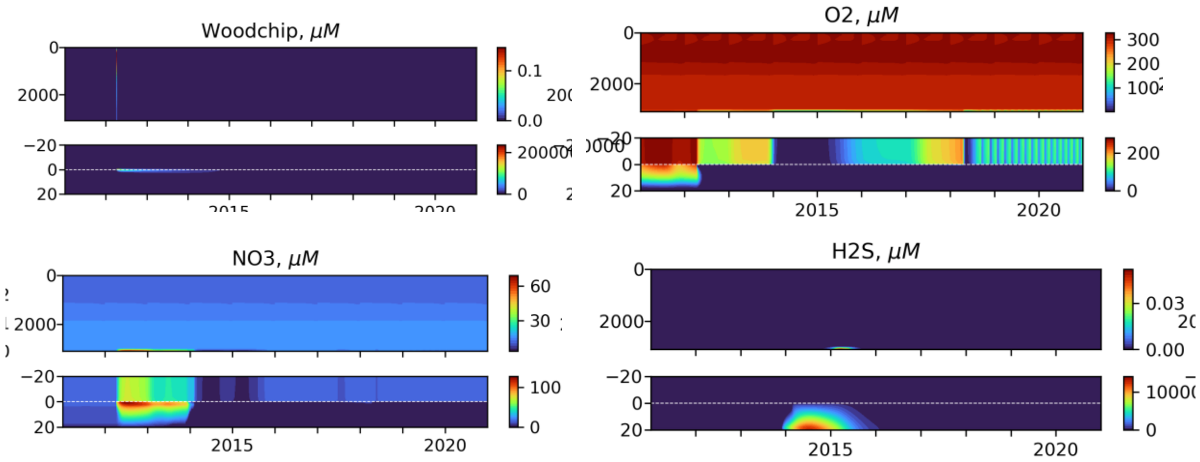
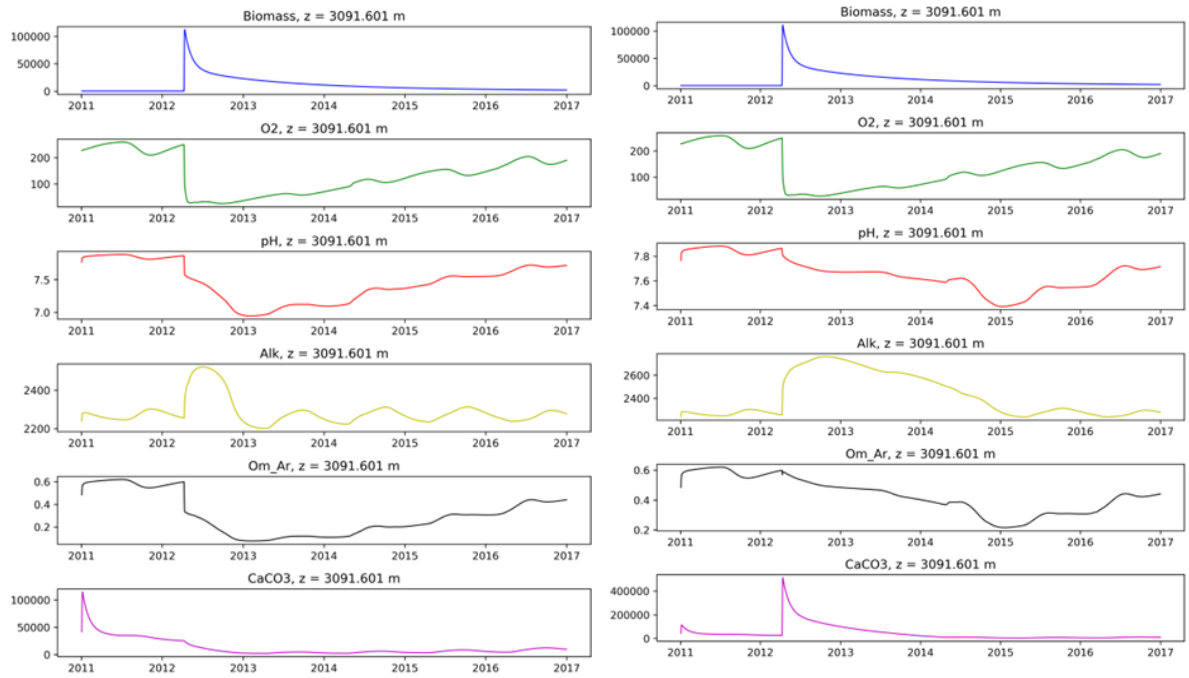


Figure 4.3. Interannual changes in the water column and sediments over a 10-year period; 1 year before woodchip deployment and 9 years after (95% woodchips +5% $CaCO_3$; Scenario S3). Parameters shown woodchips (µM N), oxygen (µM), nitrate (µM) and hydrogen sulphide (µM).

The modelled interannual changes at the sediment-water interface in the region with maximum accumulation of the woodchips are shown in Figure 4.4. Degradation of woodchips (through destruction, leaching and direct or indirect mineralization) leads to decreases of dissolved oxygen and pH. In the case of addition of the woodchips with added alkaline material (Scenario S6; Figure 4.4, left), a higher degree of acidification is predicted, i.e. decrease in pH from 7.8 to 7.0, decrease in aragonite saturation state and practically complete dissolution of the carbonate. An addition of a $CaCO_3$ (as 5% of the total woodchips mass; Scenario S1) (Figure 4.4, right) buffers the decrease in pH and buffers bottom alkalinity while it gradually dissolves during the first 4 years, that leads to a moderate decrease of pH to 7.4 only after 4 years after the deployment.



a) 100% woodchips

b) 95% woodchips + 5% $CaCO_3$

Figure 4.4. Interannual variability at the sediment surface of woodchips (μM N), oxygen (μM), pH, TA (μM), Ω_{ar}, $CaCO_3$ (μM), in case of deployment of 100% of woodchips (left) and 95% of woodchips and 5% of $CaCO_3$. The deployment occurred 01.04.2012 in model time.

In terms of shading of incident light in the upper water column, the worst-case scenario for woodchips persisting in surface waters (Scenario S4; 0.375 cm s^{-1} sinking rate), there were no indications that phytoplankton production during the April spring bloom period was limited due to potential shading of incident light. However, additional observations from woodchip deployments and water column light measurements should be carried out.

5 Conclusion

In this work we evaluated potential environmental impacts and risk factors related to the deployment of carbon containing mixtures of sustainably sourced hardwood and softwood forestry residues (organic carbon) and calcium carbonate to the seafloor of the Norwegian Sea (~3000-3300 m). For this we reviewed available literature sources and performed model-based assessment of potential biogeochemical changes.

Wood and wood-derived materials are not foreign to the marine environment. The pre-industrial flux of wood via catchments and rivers to the oceans is predicted to have been >6 million m^3 $year^{-1}$ and have decreased by ~30% over the past few centuries due to deforestation and land-use change (Wohl & Iskin, 2021). There is likely to be some degree of degradation (biotic and abiotic) of woodchips in surface waters and the seafloor, but the majority will likely be on longer timescales and on the seafloor. The impact on biological and ecological processes is not clear and therefore avoiding deployments in vulnerable locations or times is advisable (e.g., regions of known marine mammal populations, productive seasons for marine phytoplankton, areas where cold water corals are present, etc.). Additionally, proper scoping and follow-up observations should be carried out to ensure that impacts are minimal and, where possible, mitigative actions can be carried out.

The impact of woodchip deployments on ocean chemistry and therefore biology can potentially be severe, so the spatial and temporal scale of woodchip additions must be carefully planned to: 1) not increase saturation state of aragonite to >5, 2) not significantly increase dissolved organic carbon concentrations, and 3) not significantly affect dissolved oxygen concentrations in bottom waters which would cascade to several undesirable processes (anoxia, acidification, hydrogen sulphide production, methanogenesis, etc.).

For the modeling results, there is some uncertainty related to several coefficients related to how woodchips breakdown or are remineralised in the marine environment. These can be improved and constrained through targeted laboratory and field experiments. The various scenarios, however, provide a range of potential outcomes based on best available information. The model estimated that the maximum amount of woodchips that can be accumulated on the seafloor without dramatic changes in the oxygen regime, acidification and biogeochemistry that can negatively affect the ecosystem was Scenario S1 which was a deployment of 2000 metric tonnes of woodchips in 24 hours in 1 km^2 surface area (Scenario S1 described in Section 2). Scenario S1 should lead to the accumulation of the woodchips on the seafloor that should decompose for several years, leading to an increase of nutrient concentrations and dissolved inorganic carbon and a decrease of oxygen. Due to very low natural burying rate in the deep sea the deployed woodchips should mainly stay on the seafloor and any carbon reminerialised from the woodchips will enter thermohaline circulation storage timescales of 100s to 1000s of years, but unlikely to enter the longer geological timescales (million-year timescale). The oxygen levels in the bottom water in Scenario S1, while lower than natural conditions, are predicted to still be high enough and correspond to “good conditions” according to Norwegian Water Framework Directive standards for coastal waters.

The model predicted maximum thickness of the woodchip layer of 5 mm (in scenario S1) and should not significantly alter benthic topography and not significantly affect the bottom water biogeochemistry, although these alterations are likely to be measurable. An addition of $CaCO_3$ (as 5% of weight of the added woodchip mass) will lead to an increase of alkalinity that will buffer pH during the decomposition of the deployed woodchips.

Doubling of the deployment amount (4000 tonnes 24 h^{-1} 1 km^{-2}) is predicted to lead to negative consequences in the upper sediment and in bottom waters (Scenario S3) with depletion of oxygen to levels low enough to be characterized as “poor conditions”, which will then lead to processes of denitrification and sulphate reduction, appearance of hydrogen sulphide, enhancement of anaerobic bacteria communities, and other metabolic compounds perturbations that are likely to be harmful to sediment communities.

In summary, even though Scenario S1 of 2000 metric tonnes of deployed woodchips in 24 hours in a 1 km^2 surface area sinking at relatively high sinking rates results in relatively “good conditions”, according to Norwegian water quality standards, this scenario is likely to be an extreme case. This is because: 1) woodchips will likely not immediately begin to sink and instead float on the sea surface for several days where they will drift with currents on the scale of at least several kilometers before sinking and dispersing over a wider area, and 2) there is likely to be influences of mixing and upward vertical transport that will attenuate sinking woodchips.

Nevertheless, to avoid most of the potential risks, the deployment strategy should include the recommendation of constant ship movement during the deployment, that will increase the surface area over which woodchips will be deployed. Deployments in the winter season can be preferable due to better mixing in rough sea conditions and decreasing the potential interaction/impact on phytoplankton that bloom and are most productive during spring and summer. It should be recommended also to keep distance of >5 km between yearly repeated deployments. The addition of 5% $CaCO_3$ is necessary, because it buffers lowering of pH (acidification) that occurs during the decomposition of woodchips and organic matter on the seafloor.

6 References

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7 Appendix

Table 7.1. List of BROM variables and modeled concentration in the bottom sediment of the ocean abyssal regions

BROM variable	**Name**	**Notation (unit)**	**Modelled concentrations**	**Reference, comments**
Nitrogen				
NH4	Ammonia	NH_4 (μM N)	0-10	
NO2	Nitrite	NO_2 (μM N)	0-0.04	
NO3	Nitrate	NO_3 (μM N)	5-20	20-40 μM at 15 cm Angola (Rutgers van der Loeff, 1990)
PON	Particulate organic nitrogen	– (μM N)	0-400	
DON	Dissolved organic nitrogen	– (μM N)	0-100	
Phosphorus				
PO4	Phosphate	PO_4 (μM P)	0.2-1.5	
POP	Particulate organic phosphorus	– (μM P)		North Atlantic 0.05% Part.P (Demina et al., 2019)
DOP	Dissolved organic phosphorus	– (μM P)		
Silicon				
Si	Dissolved silicon	Si (μM Si)	9-12	
Sipart	Particulate silicon	– (μM Si)	0-0.3	Norwegian Sea 15% opal (Hayes et al., 2021). North Atlantic 28.8 % SiO_2 am (Demina et al., 2019)
Oxygen				
O2	Dissolved oxygen	O_2 (μM O_2)	0-280 (0-18 cm)	North Atlantic 20-40 μM at 15 cm (Rutgers van der Loeff, 1990). ~200 μM at 7 cm 69.998°N, 4.022°E, Lofoten Basin (Sauter et al., 2001). North Atlantic Oxygen Penetration 2-13 cm (Papadimitriou et al., 2004). 280 μM in the bottom water (Reagan et al., 2023)
Ecosystem parameters				
Phy	Phototrophic producers	– (μM N)	0-3	In the water column
Het	Pelagic and benthic heterotrophs	– (μM N)	0-1.6	
Bhae	Aerobic heterotrophic bacteria	– (μM N)	0-8	
Baae	Aerobic autotrophic bacteria	– (μM N)	0-0.4	
Bhan	Anaerobic heterotrophic bacteria	– (μM N)	0-0.09	
Baan	Anaerobic autotrophic bacteria	– (μM N)	0-0.4	
Carbonate system parameters				
Alk	Total alkalinity	– (μM)	2000-2500	North Atlantic 2900-3500 (Novichkova et al., 2019)
pH		NBS	7.66-7.88	North Atlantic 7.66-7.88 (Novichkova et al., 2019)
DIC	Dissolved inorganic carbon	– (μM C)	2000-2500	
CaCO3	Calcium carbonate	$CaCO_3$ (μM C)		Norwegian Sea 40-60% (Hayes et al., 2021). North Atlantic 40% (Novichkova et al., 2019). North Atlantic 40-80% (Demina et al., 2019)
Carbon				
CH4	Methane	CH_4 (μM C)	0	
POC	Particulate organic carbon	– (μM C)	40	North Atlantic 300-600 μmol kg^{-1} with an average sediment porosity 0.8 (Papadimitriou et al., 2004). North Atlantic 0.23-0.49% (Novichkova et al., 2019). Norwegian Sea 1-2% (Hayes et al., 2021). 0.2-1% (Sauter et al., 2001). North Atlantic 0.10-0.24% (Demina et al., 2019)

DOC	Dissolved organic carbon	– (μM C)	150	North Atlantic 100-500 μmol kg^{-1} (Papadimitriou et al., 2004). 100-1000 μM in the North Sea (Diesing et al., 2021)
Manganese				
Mn2	Dissolved bivalent manganese	Mn(II) (μM Mn)	0-15	10-50 μM at 15 cm different regions (Rutgers van der Loeff, 1990)
Mn3	Dissolved trivalent manganese	Mn(III) (μM Mn)	0-0.9	
Mn4	Particulate quadrivalent manganese	Mn(IV) (μM Mn)	0-750000	North Atlantic >450 μM (500 mg kg^{-1} tot part Mn) (Varnavas et al., 2001). North Atlantic 0.07% Mn (Demina et al., 2019)
MnS	Manganese sulphide	MnS (μM Mn)	0	
MnCO3	Manganese carbonate	$MnCO_3$ (μM Mn)	0	
Iron				
Fe2	Dissolved bivalent iron	Fe(II) (μM Fe)	0-15	
Fe3	Particulate trivalent iron	Fe(III) (μM Fe)	0-600000	0.8 g kg^{-1} tot part Fe (Varnavas et al., 2001). 3%? (Hayes et al., 2021). North Atlantic 4.3% Fe (Demina et al., 2019). Norwegian Sea 4-5% (Hayes et al., 2021)
FeS	Iron monosulphide	FeS (μM Fe)	0	
FeS2	Pyrite	FeS_2 (μM Fe)	0	
FeCO3	Ferrous carbonate	$FeCO_3$ (μM Fe)	0	
Sulphur				
S0	Total elemental sulphur	S (μM S)	0	
S2O3	Thiosulphate and sulphites	– (μM S)	0	
SO4	Sulphate	SO_4 (μM S)		North Atlantic 2.5-2.6 g L^{-1} (Novichkova et al., 2019)
H2S	Hydrogen sulphide	H_2S (μM S)	0	0 μM in majority of abyssal regions (Positive Eh in the North Atlantc (Novichkova et al., 2019))

Table 7.2. Summarised outcomes and possible mitigating actions from Sections 1.2, 1.3 and 1.4, along with model-based assessments associated with specific risks identified by Running Tide.

	Likely outcome	**Possible mitigating actions**
Impact assessment for pelagic ecology		
Shading of incident light	Brief localised shading while woodchips are floating. Worse-case modelling scenario for woodchips persisting in surface waters (S4) indicates no impact on phytoplankton production during the April spring bloom from shading.	Disperse woodchips widely during autumn/winter months when photosynthetic production is low.
Consequences to marine mammals in the area	Marine mammals have been known to ingest wood, but with unknown consequences.	Deploy woodchips in locations and times when vulnerable species are unlikely to be present.
Stimulation of epifauna and calcifiers: Woodchips	Due to remote location, brief floating time and cold temperatures, calcification and epifauna growth is unlikely.	None.
Stimulation of epifauna and calcifiers: Instruments	Due to the small number of instruments, impacts from biofouling are likely to be small.	Equip sensors with anti-fouling measures and/or retrieve instruments or program them to sink.
Organic carbon perturbation	Leaching of organic carbon from woodchips can be expected, especially during the first days. Bacterial production may decrease available oxygen but will be replenished rapidly from the atmosphere.	Disperse woodchips widely.
Alkalinity and dissolved inorganic carbon perturbation	Brief localised increase in surface water alkalinity is expected, which is a positive impact. DIC is not expected to change unless spontaneous calcification occurs.	Avoid changes in DIC (caused by calcification) by keeping aragonite saturation state below 5.
Impact assessment for benthic ecology		
Altered benthic topography	Worst-case scenario modelling (S1) predicts a ~5 mm layer of woodchips on the seafloor, but with higher horizontal mixing and slower sinking speeds, the layer of woodchips will be much thinner.	Disperse woodchips widely.
Phytodetritus perturbation	Physical disturbance by woodchips could influence accumulation/aggregation of phytodetritus. The subsequent impacts are unknown. Phytodetritus export could be further impacted if the woodchips cause changes to phytoplankton growth (i.e. through shading).	Deploy woodchips during less productive parts of the year.
Pollution transport	Presently no further information related to pollution transport by woodchips to the deep sea.	Further assessments to be done when major pollutant type/class is identified.
Organic carbon perturbation	Leaching of organic carbon from woodchips to be expected, although rate of leaching is likely to be much less by the time woodchips settle on seafloor. Bacterial production may further decrease oxygen on seafloor.	Disperse woodchips widely.
Increased oxygen consumption	The proposed deployment location has naturally high oxygen concentrations on the seafloor, which will provide a buffer against deteriorating water quality.	Disperse woodchips widely
Dissolved inorganic carbon perturbation	The slow decomposition of woodchips on the seafloor and the slow sedimentation rate in the region will lead to gradual increases in DIC. It is likely that most of this carbon will enter thermohaline circulation storage.	None.
Metabolic compound perturbation	The threshold modelling scenario for acceptable water quality (S1) predicts that anoxic diagenetic processes and the production of hydrogen sulphide and methane can be avoided.	None.
Alkalinity perturbation	Most alkalinity increases will be observed in the surface waters. Alkalinity perturbation could occur on the seafloor if woodchip carbon remineralization exhausts oxygen. See previous outcome.	None.
Coral topography	Corals are unlikely to be encountered in the deployment location.	They should be avoided if their presence is detected.

Interference with commercial benthic fishing	Due to the depth of the deployment location, there is likely to be little overlap between woodchip deployments and benthic commercial fishing activities.	Avoid impacts to aerobic organisms (fish) by managing bottom oxygen concentrations.
Interference with deep sea mining	The woodchip deployment site is currently outside of the proposed deep sea mining areas.	Avoid currents that may cause woodchips to drift into these locations.
Earth systems impacts		
Methane release	The threshold modelling scenario for acceptable water quality (S1) predicts that methanogenesis will not occur.	Efforts must be made to avoid seafloor hypoxic or anoxic conditions.
Ventilation of metabolic greenhouse gasses	It is likely that CO_2 produced via respiration in this region will remain at the seafloor and isolated from the atmosphere for 100-1000 years.	None.

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