Ocean Afforestation's effects on deep-sea biogeochemistry

By Merel Lanjouw
Supervisor Olivier Sulpis
Second supervisor Jack Middelburg

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Summary

If climate change is left unchecked it will lead to unprecedented deterioration of human health, economy and ecology. According to the IPCC, in order to avoid severe consequences, global warming will need to be limited to 1.5°C. However, the 1.5°C warming will be exceeded if current trends continue, which is why the need for Carbon Dioxide Removal (CDR) has become increasingly apparent. Ocean afforestation is currently one of the most promising CDR approaches, with the least competition for space, high carbon sequestration potential and high technical feasibility. Ocean afforestation approaches attempt to sequester carbon by sinking seaweed to deep-sea areas. This research looks at the consequences of the seaweed input to deep-seafloor. An early diagenetic model called RADI is used to predict the fate of the carbon and the effect on biogeochemistry. The model was adapted to include new sources of sedimentary organic matter, such as seaweed (*Sargassum, Saccharina, Macrocystis*) and Sugarcane bagasse, which are currently considered potential candidates for ocean afforestation purposes.
Sargassum, an invasive free-floating species, has a large sequestration potential and is readily available. Sinking *Sargassum* in pulse, large amounts over short times, leads to high carbon retention in the sediment (up to 25% after two years) but leads to hypoxic conditions in the sediment for at least two years after addition. Continuous *Sargassum* sinking also leads to carbon sequestration but with a much less invasive impact on the seafloor. The carbon from continuous sinking does not remain in the sediment but is remineralized and flows out to the bottom water as inorganic carbon. *Saccharina*, an edible coastal species, could be used to grow on free floating organic buoy. Having the additional sequestration benefit from the carbon fixed in the organics. Carbon retention is highest for the pulse addition of this seaweed (33% after two years), compared to a continuous approach (30%) in which the seaweed is added over longer timescales in small amounts. Since this pulse input also leads to hypoxic conditions in the sediment, the continuous approach is more favourable for this approach. *Macrocystis*, the giant kelp known for forming ecosystems, is a fast-growing coastal species. This species requires harvesting and baling for use in carbon sequestration. Carbon retention is much higher for pulse addition (30%). Sugar cane bagasse is an agricultural residue with high carbon content. Sinking this residue to anoxic basins, has been proven to retain more carbon than in oxygenated bottom waters. This can be confirmed with the results which showed a carbon retention of up to 50% after two years. The effect on the benthic biome is also less intense since the low oxygen conditions already necessitate a specialized microbiome. Sugarcane bagasse is furthermore the only addition capable of increasing bottom water pH. Whereas all seaweed approaches had higher dissolved inorganic carbon than alkalinity flow to the bottom water, resulting in net acidification. This research provides a first look into the effects of ocean afforestation on deep sea biogeochemistry, and illustrates the importance of the composition, quantity and input duration of the seaweed used.

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Table of Contents

Summary 1
Introduction 4
Climate change and carbon dioxide removal 4
Ocean afforestation 6
Politics, social perceptions and economics 7
Biogeochemistry deep sea 8
From production to sequestration 8
Carbonate system 10
Low oxygen conditions 10
The role of seafloor biota 11
Sequestration potential 11
Macroalgae, phytoplankton or seagrasses 12
Sargassum (Fluitans and natans) 13
Saccharina latissima (sugar kelp) 13
Macrocystis pyrifera (Giant kelp) 13
Terrestrial biomass 14
Research question and aim 14
Method 15
Documenting ocean afforestation initiatives 15
Model implementation 16
Time 17
Bioturbation and irrigation 17
Decay/degradation 17
Particulate organic carbon flux 18
Sensitivity analysis 21
Results 1
Oxygen 1
Alkalinity 3
Fate organic carbon 28
Sensitivity analysis 30
Discussion 28
Ocean afforestation approaches 28
Effects on biogeochemistry and fate of organic carbon 29
Risks 30
Limitations 31
Conclusion 32

References 33
Appendices 39
Appendix 1: adjusted variables RADI 39
Appendix 2: species parameters 41
Appendix 3: location parameters 42

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Introduction

Climate change and carbon dioxide removal

Reduced food and water security, increased extreme weather events, irreversible losses to terrestrial and marine ecosystems are some of the consequences of climate change that can be observed today (IPCC, 2022). If emissions are left unabated, the amount of people affected climate change will increase, with increased risks to food and water security but also new risks to mental health and ecosystem services (energy, coastal protection, cultural). These factors will increase inequality, lead to more climate migrants and have severe economic consequences. Limiting global warming to 1.5 degrees will be essential to prevent human, economic and ecological losses. However, reaching this goal will require countries to reduce their emissions to near zero by 2050, something that will not be obtained if current trends continue (United Nations Environment Programme, 2022). To limit warming to 1.5°C the IPCC acknowledges the need for carbon dioxide removal technologies (IPPC, 2022). Removing Carbon Dioxide from the atmosphere for sequestration purposes is called Carbon Dioxide Removal (CDR). CDR is defined by the IPCC (2022) as any form of carbon dioxide storage induced by humans. The most common CDR approaches are direct CO_2 capture from the air, direct storage in terrestrial or marine reservoirs or usage of natural carbon sequestration systems. In order to remove CO_2 from the atmosphere for long enough to avoid severe consequences, the carbon needs to move from the fast to the slow carbon cycle (Riebeek 2011). The fast carbon cycle consist mainly of carbon fixated and released by organisms through respiration or degradation. The excess CO_2 in the atmosphere, however, comes mainly from fossil fuels. Carbon stored in this form can naturally move from its reservoir to the atmosphere and back, but normally takes 100-200 million years (Riebeek, 2011). Fossil fuels are therefore part of the slow carbon cycle, which describes the slow transfer of carbon between the oceans, atmosphere and lithosphere over thousands to millions of years. By burning the fossil fuels, the carbon moves from the slow to the fast carbon cycle since it cannot return to its previous reservoir in the same time it takes to burn. Still, CO_2 can be taken up by the oceans over very short timescales, making earth's oceans an important carbon sink, absorbing approximately a third of the total anthropogenic emissions (3.0 of 10.2 Gt C/yr) (Friedlingstein et al., 2022). However, the ocean has a larger potential as a carbon sink. Anthropogenic carbon absorbed in the ocean primarily resides in the photic zone, either as part of organisms (e.g., phytoplankton) or as dissolved inorganic carbon with fast turnover times. Which can be demonstrated by looking at one major carbon fixating system: phytoplankton communities. Of the phytoplankton net primary productivity, producing 50 Pg C annually, only 10 pG C is exported to the ocean interior, of which 2 Pg C is deposited on the sediment and only 0.2 Pg C is buried (Middelburg, 2019), leading most carbon fixated by phytoplankton to re-enter the atmosphere over short timescales (within decades), whereas carbon in the ocean interior and bottom waters/sediment will remain there for hundreds to thousands of years. The slow carbon cycle acts in the ocean in the form of sinking photosynthetically fixed carbon in organic matter or carbon rich skeletons to the deep sea, where the carbon can be incorporated into sediments and eventually subducted into the Earth interior, on timescales of millions of years, or stay in dissolved form in deep sea bottom waters, which won't resurface for hundreds to thousands of years (Riebeek, 2011). CDR approaches are utilizing different processes from the slow carbon cycle to fix carbon over 1000 years, which is often considered 'permanent' in CDR approaches (https://frontierclimate.com/) (Table 1).

Table 1: summary of common CDR approaches

CDR name	Description
Land based	
Afforestation/reforestation	Planting or restoring (usually) forests to increase carbon storage in the soil and organisms
Biochar	Made by burning organic matter under low oxygen conditions, biochar can be used to fix additional carbon in soils
Direct air capture	Pumping CO_2 directly from the atmosphere into storage
Bioenergy with carbon capture and storage	Crops are used for biofuel production and the CO_2 produced is stored, usually in depleted gas reservoirs
Ocean based	
Ocean fertilisation	Iron fertilisation: adding iron sulphate directly to areas where phytoplankton growth is limited by iron concentration, the additional phytoplankton growth should as a result fix more CO_2 and eventually increase carbon sequestration Artificial upwelling: pumping nutrient rich deep waters to the surface to increase algal growth and therefore carbon sequestration
Enhanced weathering	Weathering minerals in coastal areas which take up CO_2 when dissolving. Additionally increasing alkalinity, therefore countering ocean acidification
CO_2 injection	Injection CO_2 into deep sea formations. Direct CO_2 injection into deep waters has been rejected and currently replaced with injection into basalt formations (Kelemen et al., 2019)
Ocean alkalinisation	Increasing pH to counter ocean acidification and increase CO_2 uptake (see Biogeochemistry deep sea)
Ocean afforestation	Growing seaweed and consequently sinking the organic matter in the deep sea, effectively sequestering the CO_2 fixated by the seaweed

Though it is likely a combination of CDR techniques is needed to maximize chances of success and reach CO_2 reduction goals, ocean-based CDR has many benefits compared to other techniques. Mainly because land-based CDR techniques require area which could otherwise be used for agriculture or nature restoration. Direct air capture, though it does not require much land, is very expensive and the energy needed for the process would save more emissions if it was used in industrial processes (Jacobson, 2019). However, the different ocean-based CDRs mentioned in Table 1 also have benefits and downsides.

- Ocean fertilisation has been a controversial technique with low social acceptance, changes to upper ocean ecosystems with possible harmful blooms and unknown risks, oxygen depletion in the ocean interior and highly uncertain efficacy (Williamson et al., 2012).
- Enhanced rock/mineral weathering is quite permanent and not resource limited, however it does require a lot of energy for mining, transport and processing and the process can be slow and have unknown environmental consequences (Raza et al., 2022).
    - Ocean alkalinisation, which overlaps with enhanced weathering, has similar benefit and downsides (Ilyina et al., 2013).
- Geological CDRs such as CO_2 injection are economically and technically feasible and have higher public acceptance but require a lot of monitoring, has a shortage of suitable locations and has a risk of leakage (Raza et al., 2022).
- One of the most promising CDR techniques is ocean afforestation, which is a cheap, fast and repeatable process with possibly the least process emissions.

In the following paragraph this CDR technique will be explained, by looking at the technical aspects as well as the social and economic impacts.

Ocean afforestation

Ocean afforestation refers to growing (usually) macroalgae with the purpose of carbon sequestration. The macroalgae are grown in locations which normally do not contain large quantities of seaweed, either on the open sea or on seaweed farms. This new growth can be implemented in many different forms, commonly as seeded ropes or artificial reefs, where seeded ropes are most commonly used in seaweed cultivation for the global market. Seaweed farms, even when not used for carbon sequestration, have a very high CDR potential. Naturally formed detritus allows for carbon sequestration and harvested seaweeds can be used for food, biofuel and cosmetics, replacing land-based products and therefore reducing the amount of land or fossil fuel used (Kraan, 2013). When seaweed is used for CDR, the biomass is either immediately sunk by pumping to greater depths or transported/processed before being sunk. Processing is applied to either extract nutrients and other valuable ingredients or to bundle the seaweed to facilitate sinking. Transport allows the seaweed to be sunk at a chosen location, to reduce ecosystem impacts or to reach full sequestration potential.

Though technically not afforestation, some initiatives intend to use naturally (though increasingly invasive) occurring *Sargassum (Fluitans* and *natans)* to pump to >1000 m depth. Other initiatives intend to sink terrestrial biomass, which, though it also does not fall within the definition of ocean afforestation, shares the same goal.

Ocean afforestation can be compared to reforestation as both intend to grow seaweed, however the goal of ocean afforestation is to sink the seaweed whereas reforestation is mainly used for ecosystem restoration. In marine reforestation degraded seagrass meadows or kelp forests are restored by seeding algae or technical measures such as artificial reefs. Restoring ecosystems has many benefits, since it allows carbon to be fixed in the plants and sequestered in the sediment. Secondly, bare seafloors are subject to wave and tidal actions which releases carbon and nutrients, which significantly reduces when ecosystems are present. Though reforestation has its additional benefits in coastal protection, biofiltration and harvesting, the actual sequestration potential of restored coastal ecosystems is uncertain. Sequestration potential of coastal seaweed ecosystems is estimated by calculating the portion of seaweed (% of NPP) which leaves the system as particulate organic matter and is stored out of contact with the atmosphere. Up to 11% of the total carbon fixed in seaweed ecosystems can be sequestered this way, though these are still rough estimates (Krause-Jensen & Duarte, 2016). On the contrary, nearly all carbon fixed in afforestation can be used in carbon sequestration. Ricart et al. (2022) also argued that ocean afforestation is a much more efficient option compared to traditional coastal blue carbon restoration or conservation efforts. Mainly because the coastal areas, where seaweed naturally occurs, covers less than 0.2% of the total ocean, whereas seaweed cultivation can be expanded to open ocean areas, reducing pressure on coastal systems while still contributing to climate mitigation. Lastly, a potential 48 million square kilometres of ocean are suitable for seaweed cultivation and if this area was solely used for carbon sequestration it could remove 2 million tonnes of CO_2 per year (Froehlich et al., 2019).

Many aspects of ocean afforestation need to be considered before implementation, concerning economic, ecological, political and societal risks and benefits. Lastly, the effects of such an increased amount of organic matter on the deep seabed will have an unknown impact on deep sea biogeochemistry which is the focus of this research.

Politics, social perceptions and economics

"*Producing large volumes of seaweeds for human food, animal feed and biofuels could represent a transformational change in the global food security equation and in the way we view and use the oceans.*" ("Seaweed Aquaculture for Food Security, Income Generation and ...") (World Bank, 2016, p. 1)

In practice ocean afforestation as a CDR technique is heavily limited by policy, as well as a lack of scientific understanding of its effects on ecosystems and biogeochemistry, especially over longer time scales. Research by Bertram & Merk (2020) explored public perceptions on CDR methods and how they influence future deployment. They found that CDR methods that seemed more natural were often favoured by the public, irrespective of the methods effectiveness. Afforestation on land is often looked upon as natural and therefore favourable, suggesting that ocean afforestation is likely to be perceived positively as well. Apart from the sequestration potential, seaweed cultivation has been mentioned many times as essential to Sustainable development Goals from the United Nations (2015). Seaweed aquaculture could generate income in developing countries, improve food security, provide clean(er) energy, improve responsible consumption and production, contribute to climate action and benefit life in water and on land (through replacing land use for food and fuel). This makes ocean afforestation one of the best CDR approaches to date.

Though social perceptions are important to CDR implementation, financial and technical feasibility will eventually determine whether ocean afforestation as a CDR approach will be used and how it will be applied. Different approaches include different species, locations and processing. For location the main options are coastal or offshore cultivation, both which have benefits and downsides. Cultivation in coastal areas is technically feasible and cheap due to the existence of seaweed farms, however, the transport of the seaweed to the open sea as well as either pumping or bundling the seaweed to sink, is time intensive and increases emissions. Generally offshore aquaculture is more expensive than coastal aquaculture, due to the increased transport and labour costs (Ross, Tarbuck & Macreadie, 2022). Offshore cultivation comes in two forms, either on fixed platforms or on (free) floating devices. The fixed platforms can be wind farms or oil platforms, which reduces transport and personnel costs due to the existing maintenance personnel and allows for multi trophic aquaculture. Though this approach is technically feasible it is still much more expensive than traditional seaweed cultivation, research from 2016 showed that current seaweed prices would need to increase 300% for cultivation on wind farms to become economically viable (van den Burg et al., 2016). Two main options are available for the (free) floating approach. The first being autonomous vehicles which can navigate the waters and measure environmental conditions to optimise growth, resulting in effective cultivation but high development and maintenance costs. The second option is a buoy made from biodegradable matter, which follows the currents and sinks when their density exceeds that of water, taking all cultivated seaweed with them. The biodegradable buoy has much lower costs, requiring no maintenance and are cheap to produce. However, since no tracking is possible it is much harder to quantify how much carbon is sequestered or to monitor the effects on local ecosystems.

One last approach to ocean afforestation is aimed at indirectly reducing emissions, by using seaweed to replace land-based products with higher process emissions. Since seaweed grown on farms still has some sequestration potential, this approach is currently more economically favourable. The market for seaweed has grown from 4.2 million tonnes/yr of algae in 1990 to 35.1 million tonnes/yr in 2020 (Fao, 2022). Algae can be used for a variety of products and uses depending on their composition, which determine the value they possess in the global market. High lipids contained in algae are used in oil-based products and industries. Algae with high carbohydrate concentrations are suitable for biofuel. Algae can also be harvested for unique compounds such as pigment, vitamins, minerals and amino acids. Some algae produce extracellular polymeric substances such as Polyhydroxyalkanoates which are used in bioplastic production (Singh & Dhar, 2019). Lastly, specific algae such as *Asparagopsis* has shown remarkable potential in bio feed application. Research by Kinley et al. (2020) demonstrated that supplying a high grain diet with only 0.20% *Asparagopsis,* the methane emissions in steers was reduced by 98% alongside weight gain improvements.

Though seaweed has increased in value and application, an incentive may be needed for seaweed farmers to use the seaweed for CDR (Duarte et al., 2017). Carbon offsets might be the solution here, allowing companies to put a price on climate mitigation and incentivising good practices. The voluntary carbon market is already selling carbon offsets for CDR practices (CarbonCredits.com, 2022).

Biogeochemistry deep sea

Perceptions of the deep-sea are often of oligotrophic and even anoxic environments, with low biological abundance and activity. Though this is true for certain parts of the ocean, the ocean floor is diverse in many aspects. Varying in temperature, salinity, oxygen and nutrient concentration, depth and more. All these variables influence benthic organisms, i.e., organisms living on or in the seafloor. Food supply for benthic life is mostly in the form of allochthonous organic matter (OM), and only a small portion through chemoautotrophy and locally recycled OM (Danovaro, Snelgrove & Tyler, 2014). The allochthonous OM is mainly produced by phytoplankton in the photic zone and reaches the seafloor either vertically (sinking) or laterally (advection). The horizontal influx of OM is referred to as lateral flux and is due to advection from the continental margins, where biological activity is high. Deep-sea canyons can collect large amounts of OM over time and can sometimes even be considered eutrophic. Vertically transported material can occur continuously or as pulse events. Pulse events are fast, high concentration OM drops and are often referred to as food falls which come in the form of whale, fish, macroalgae or even phytoplankton falls (Danovaro, Snelgrove & Tyler, 2014). If seaweed is sunk for CDR purposes, it is most likely to resemble food falls.

From production to sequestration

When an organism dies or detritus is produced, the OM is immediately subject to microbial degradation. Degradation is important for carbon sequestration since it influences the amount of carbon reaching the seafloor as well the fate of the carbon on the seafloor. Degradation is generally high in the photic zone and as the material sinks into the aphotic zone, degradation decreases. This implies that in order to increase sequestration, the OM should leave the photic zone as fast as possible. The OM reaches the seafloor as particulate organic matter (POM) which settles on the top of the sediment and migrates to deeper layers through bioturbation or by being buried under new layers of settling material such as new POM, calcium carbonate and clay. On the sediment surface the higher concentration of fauna and bacteria results in higher degradation rates, which decrease when the POM moves deeper into the sediment where consumer abundance decreases. The rate at which organic matter degrades depends on a variety of conditions and processes. Sinking speed and size are the most important in the water column, determining how much degradation can take place before it reaches the seafloor. The chemical makeup of the POM determines whether it is labile or refractory and conditions such as temperature and pH affect microbial communities and activity (Mayer, 1995). Furthermore, degradation requires electron acceptors, which can transform organic carbon into inorganic carbon (Middelburg, 2019). Oxygen is always the preferred electron acceptor because of the high free energy release associated with oxygen-associated OM degradation, but deeper in sediments, when oxygen concentrations lower, other degradation pathways take over, in order based on the reactions free energy :

Table 2. The decrease of reactivity with depth is related to its accessibility, the availability of electron acceptors and the fact that the most labile material has already degraded in the top layer, leaving more refractory matter to be buried. Particulate organic matter is often referred to as Particulate Organic Carbon (POC), to facilitate sequestration calculations. The amount of POC is based on the carbon content of the specific organic matter and is often given in grams of carbon per (k)g of dry weight seaweed.

Table 2: degradation pathways with the reaction occurring with Redfield organic matter and free energy available.

Degradation pathway	Reaction (Cai et al., 2010)	Gibbs free energy (Middelburg, 2019)
Aerobic respiration	$(CH_2O)_{106}(NH_3)_{16}(H_3PO_4) + 138\ O_2 \rightarrow 106\ CO_2 + 16\ HNO_3 + H_3PO_4$	-475
Denitrification	$(CH_2O)_{106}(NH_3)_{16}(H_3PO_4) + 0.8 * 106NO_3^- + 0.8 * 106H^+ \rightarrow 106\ CO_2 + 0.4 * 106\ N_2 + 16NH_3 + H_3PO_4$	-448
Manganese oxide reduction	$(CH_2O)_{106}(NH_3)_{16}(H_3PO_4) + 2 * 106MnO_2 + 4 * 106H^+ \rightarrow 106\ CO_2 + 2 * 106Mn^{2+} + 16NH_3 + H_3PO_4$	-349
Iron(hydr)oxide reduction	$(CH_2O)_{106}(NH_3)_{16}(H_3PO_4) + 4 * 106FeOOH + 4 * 106H^+ \rightarrow 106\ CO_2 + 4 * 106Fe^{2+} + 16NH_3 + H_3PO_4$	-114
Sulphate reduction	$(CH_2O)_{106}(NH_3)_{16}(H_3PO_4) + 106/2SO_4^{2-} + 106H^+ \rightarrow 106\ CO_2 + 106/2H_2S + 16NH_3 + H_3PO_4$	-77
Methanogenesis	$(CH_2O)_{106}(NH_3)_{16}(H_3PO_4) > 106/2\ CO_2 + 106/2CH_4 + 16NH_3 + H_3PO_4$	-58

Modelling is a useful tool to research the fate of the organic matter, however it does require knowledge on a lot of parameters surrounding the environment and the organic matter. In practice it is challenging to provide a good estimate of reactivity and burial, due to the large number of processes involved depending on the location and environmental factors. In 1D modelling degradation is usually determined by the depth and reactivity of the OM (Stolpovsky, Dale & Wallmann, 2018). In many current earth system models the degradation of POC is described as a function of burial rate and POC rain with linear decay kinetics (Stolpovsky, Dale & Wallmann, 2018). The POC rain can consequently be based on in situ measurements but cannot be extrapolated to a global scale model (Arndt et al., 2013). In most models the refractory fraction of POC is regarded as undegradable over large timescales (~10^3 years), resulting in the refractory fraction being approximately equal to the carbon burial (Stolpovsky, Dale & Wallmann, 2018).

Though carbon is the most abundant nutrient in OM, nitrogen and phosphorus are essential for all organisms. Nitrogen in organic matter is degraded or taken up by other organisms. Degradation produces NH_3 (ammonia), which can be oxidized into nitrate NO_3 or nitrite NO_2 which can consequently be used again for nitrification. Proteins contain most nitrogen and are easily degradable, which is why C:N ratio increases with degradation in particulate matter, effectively increasing the carbon content (Yoshimi et al., 2003). Phosphorus is degraded into phosphate, an essential nutrient, but in much lower concentrations. Both ammonia and phosphate have buffering capacities, meaning that can slow down acidification. However, reactions within the carbonate system are the dominating controls over seawater pH changes.

Carbonate system

Particulate inorganic carbon reaches the seafloor mostly as carbonate minerals. Calcite and aragonite (calcium carbonate) are produced by calcifying organisms and after the organisms dies the mineral either falls as rain on the seafloor or dissolves (Middelburg., 2019). Dissolution occurs when the water is undersaturated, when Ca^{2+} and CO_3^{2-} concentration fall below a certain level. This concentration is determined by something called the saturation state. The saturation state of calcite changes when the surrounding pH and temperature change, which is why ocean acidification can lead to calcite dissolution. When CO_2 dissolves in water, bicarbonate and carbonate are produced:

$$CO_2 + H_2O \leftrightarrow H_2CO_3 \leftrightarrow H^+ + HCO_3^- \leftrightarrow 2H^+ + CO_3^{2-}$$

The added protons result in a lowering of the pH: acidification. The increase in protons leads to a shift in the carbonate balance from carbonate to bicarbonate and CO_2 see Figure 1, the decreased dissolved carbonate lowers the saturation state and facilitates additional calcite dissolution (Sulpis et al., 2017).

Ocean afforestation could therefore affect the carbonate system by the following sequence of effects: POC reaches the seafloor and degrades, producing CO_2, the dissolved CO_2 lowers the pH and the calcite saturation state, which eventually leads to calcite dissolution. In returns, calcite dissolution releases dissolved Ca^{2+} and HCO_3^{2-}.

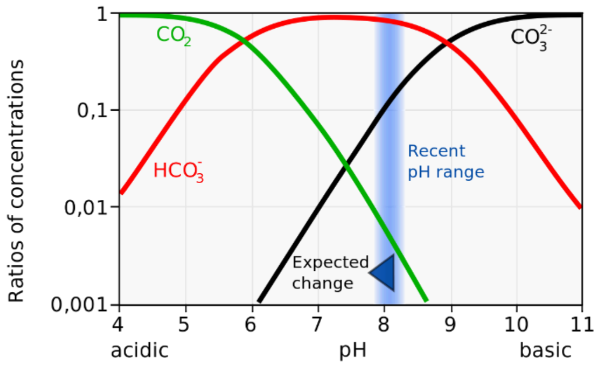

Figure 1: Bjerrum plot: carbonate balance based on pH, the lower the pH becomes the more dissolved carbonate shifts to bicarbonate and CO_2 (Middelburg, 2019)

$$CaCO_3 \leftrightarrow Ca^{2+} + CO_3^{2-}$$
$$CO_3^{2-} + H^+ \leftrightarrow HCO_3^-$$

Since carbonate and bicarbonate can absorb protons, this reaction actually increases alkalinity, where alkalinity is a measure of the capacity of seawater to resist acidification. The other degradation pathways, except methanogenesis, also add to the total alkalinity but the oxidation of the reduced metabolites produce (strong) acids. Mainly nitrification and iron, manganese and sulphur oxidation have an acidifying effect (Sulpis et al., 2022). The deeper in the sediment this occurs, the lower the acidifying effect is, since reoxidation with oxygen is prevented and for instance FeS is produced from the reoxidation of iron with sulphide which does not consume alkalinity.

Low oxygen conditions

Organic matter reaching the seafloor is almost fully remineralized, leaving only 0.4% buried in the sediment (Middelburg, 2019). Sinking biomass to anoxic basins, however, has been proven to preserve 50% more OM (Jessen et al., 2017). Anoxic, and even hypoxic, conditions decrease macrofaunal and microbial activity, which in turn decreases degradation and bioturbation. Hypoxic conditions can originate when the organic matter degradation uses more oxygen than can be supplied from the bottom waters and the use of other forms of chemical energy for degradation. Thus, the OM is degraded at a much slower rate (Jessen et al., 2017). Although it can be beneficial to preserve more OM for sequestration purposes, low oxygen conditions are detrimental to benthic life in more than one way. The absence of oxygen will shift the microbial community to anaerobic respiration which utilises the other oxidants, the products of anaerobic respiration can range from toxic hydrogen sulphide to greenhouse gas methane. This could lead to sediments becoming methane emitters (Grasset et al., 2018). Overall, low oxygen conditions are beneficial for carbon sequestration but disadvantageous for aerobic benthic life, creating anoxic conditions is therefore harmful to ecosystems but using existing anoxic basins for sequestration might be very efficient.

The role of seafloor biota

Bioturbation and irrigation are the two most important factors for heterogeneity on the seafloor (Snelgrove et al., 2018). Burrowing organisms mix the sediment alongside the OM deposited on top, and irrigation provides solutes, most importantly electron acceptors, to greater depth. This redistribution influences microbial communities and therefore indirectly, degradation and burial. In ocean afforestation, a pulse input of POM can result in an immediate increase in benthic macrofaunal activity and the consequential drop in oxygen concentration. However, research by Witte et al. (2003) showed that the response of microorganisms to allochthonous POM can be delayed by weeks. On the other hand, small but continuous input of OM might be more beneficial to the microfauna as opposed to macrofauna. Modelling bioturbation therefore requires some simplification of the process, which usually includes averaging among benthic communities, and calculating location specific bioturbation rates based on POM rain and oxygen availability. The response of the microbial community is limited to a response to changing POM influx and electron acceptors availability. This approach shows the general patterns in bioturbation but misses some specific details. For example, preferential degradation occurs when there are different types of organic matter available. The freshest, most labile, organic matter will be degraded first. Leading to higher retention times and less mixing for the more refractory POM.

Though ocean and sediment biogeochemistry have been researched extensively, the effect of ocean afforestation on the biogeochemistry of the seafloor has only been hinted at. Almost all articles on ocean afforestation focus on the effect on climate mitigation and the water column, only referencing the unknown impacts on the seafloor. For instance, Boyd et al. (2022) mentioned the consequent ecological effect on benthic communities by the change in food supply, without further investigation. To gain an understanding of the effect of ocean afforestation on deep sea biogeochemistry, different ocean afforestation scenarios will have to be tested, a task that can be accomplished through modelling. In the following paragraphs the information needed to model different scenarios are outlined.

Sequestration potential

The sequestration potential of ocean afforestation is highly dependent on the species and environmental conditions. Macro algae are generally more refractory than phytoplankton, as shown by Ortega et al. (2019) macroalgal DNA had an attenuation rate of only 37.7% /km compared to the 86% /km for phytoplankton. Furthermore, they discovered that the largest portion of algal DNA on the seafloor (63%) belonged to red algae, whereas brown algae consisted of 26% and green algae was 11%. Red and brown algae contain refractory polysaccharides (carrageenan and fucoidans respectively) in the cell wall to prevent degradation, which are absent in green algae. The more refractory nature of red and brown algae might make them more suitable for ocean afforestation practices. The actual carbon sequestration of these algae depends on the carbon content and growth rate. Seaweed growth can be limited by nutrients, temperature, light, diseases, grazing, currents, salinity and nutrient/light competition with phytoplankton (Ross, Tarbuck & Macreadie, 2022).

Other factors which influence sequestration potential are:

- Particle size: a higher surface to content ratio results in faster degradation due to microbial colonisation

- Gas vesicles: gas vesicles allow detached algae and algal matter to be transported to parts of the ocean with greater depths. During the drift the labile compounds of the OM are degraded, and the matter is more refractory material when it sinks. The gas vesicles need to collapse before the matter is able to sink, the collapse is either triggered by transport to deep water (during storms) or by the growth of the higher density calcifiers.
- Degradability and sinking speed: depend on species, depth and environmental conditions (biogeochemical) and determine the amount of carbon reaching the seafloor and the time it takes to be remineralized.
  - C:N:P: Algal biomass loses nitrogen faster than carbon, increasing C:N ratio over time. (Conover, Green & Thornber, 2016).
- Location: carbon is stored away longer in the deep sea of the North Pacific >1400 years, compared to the North Atlantic 700-900 years (DeVries & Holzer, 2019)
  - Coastal areas: coastal areas receive organic matter from terrestrial sources as well as marine sources, terrestrial OM will have been somewhat degraded and more refractory material will enter the water column.
  - Open sea:
    - Depth: the deeper the seafloor, the longer it will take the carbon to re-enter the atmosphere
    - Anoxic basins: oxygen is required for efficient degradation, hypoxic and anoxic conditions increase sequestration by preserving 50% more OM (Pedersen et al., 2021; Jessen et al., 2017).
    - Local conditions: such as pH, oxygen, salinity, benthic activity, calcite rain and other conditions which influence degradation and burial

Predicting carbon sequestration with models requires a lot of information on the POC input and local conditions. However, the fate of the carbon at the seafloor is not necessarily relevant for sequestration calculations. Since the seawater at greater depths (>1000 m) will likely not resurface in coming decades to centuries, all carbon reaching this depth can be considered sequestered. However, when the bottom waters eventually resurface due to ocean currents and the thermohaline circulation, very alkaline water will result in additional CO_2 uptake by the surface water, on the other hand seawater with lowered pH will result in an CO_2 flux back to the atmosphere.

Macroalgae, phytoplankton or seagrasses

Many macroalgal species are suitable for ocean afforestation, which species is used depends on a lot of factors. Namely, which species are native to the area, have high productivity and carbon content. What other (economic/ecological) uses does the species have? What are the risks and benefits associated with cultivation? What are the degradation and sinking rates? Lastly, which species are already being used in experimentation?

In literature, sequestration potential for many genera has been researched. Mainly species with high sequestration rates or CO_2 assimilation rates, such as *Palmaria, Porphyra, Ulva, Enteromorpha, Sargassum, Ascophyllum* and *Fucus,* have gained attention in research (Chung et al., 2011). However, when comparing carbon sequestration companies/initiatives a clear preference can be noted for *Sargassum*, followed by *Saccharina* and *Macrocystis*, with some mentions of *Ulva, Ecklonia, Kappaphycus* and *Euchema* (Table 3). In the following paragraphs these first three species will be discussed.

Sargassum (Fluitans and natans)

Sargassum species are one of the most well-known free floating macro algae. The genus is becoming more widespread due to changes in wind patterns and increased nutrient concentration (Wang et al., 2019). Traditionally found in the sargasso sea, this genus has now spread over the Atlantic and Caribbean and is mostly known for washing up on coasts, leaving a harmful degrading matter. The main growth occurs over the summer, which leads to a major *Sargassum* wash up on beaches in July and August. The degrading biomass releases H_2S and ammonium which causes respiratory and other health problems, alongside methane which is a potent greenhouse gas. Removing *Sargassum* both from coasts and the ocean, is a time-intensive and expensive task. However, due to its high carbon content (30% DW) *Sargassum* has a strong carbon sequestration potential which might be beneficial to solving the problem. Not only its carbon content makes *Sargassum* a favoured species for CDR, also its ability to grow in the open sea, and its natural occurrence in large quantities. Companies such as Pull to Refresh (https://pulltorefresh.earth/), Fearless Fund (https://www.fearlessfund.org/) and Seafields (https://www.seafields.eco/) intend to use *Sargassum* for sequestration purposes. Another initiative, SOS carbon (https://soscarbon.com/), is a Caribbean based initiative whose main focus is to minimise the economic, human health and environmental impact of *Sargassum*. Their approach is to remove the *Sargassum* before it reaches the beaches. SOS carbon has already experimented with collecting and sinking *Sargassum* and is looking toward scaling up (Gray et al., 2021).

Sargassum can naturally sequester carbon when particulate *Sargassum* reaches the deep sea. However due to the gas vesicles, most of the Seaweed remains in the surface layer and even after the seaweed has died the gas vesicles keep the OM afloat. Still, *Sargassum* residue has been found at depths of 5000 m, where the species is carried down due to wind induced circulation which causes it to become negatively buoyant and sink to the bottom (Johnson & Richardson, 1977). This effect of pressure on the sinking of *Sargassum* is embraced by many sequestration initiatives. Where the *Sargassum* is collected and sunk to depths over 200 m where it is expected to be non-buoyant and past the mixed layer, reducing the grazing rate and likely to reach the seafloor within 40 hours (Johnson & Richarson, 1977; Gray et al., 2021).

Saccharina latissima (sugar kelp)

Sugar kelp is an edible species occurring on temperate and polar northern Atlantic and Pacific coasts and grows in the winter season. Due to the high growth rate, high carbon content and growth in winter, this species is very suitable for CDR without competing with other algae. Initiatives such as Green Ocean Farming (https://www.greenoceanfarming.com/), Running Tide (https://www.runningtide.com/) and Phykos (https://www.phykos.co/) intend to use this species for sequestration. Sugar kelp has many other applications in food, feed, alginate, fertiliser, medical, pharmaceutical, cosmetics and biofuel industries. Furthermore, it is suitable for integrated multi trophic aquaculture, can be cultivated in sheltered and exposed sites and is native to the Atlantic (Peteiro, Sánchez & Martínez, 2016). C:N ratio is highest in September, making this the optimal time for sinking due to the high carbon content and least loss of essential nutrients (Gevaert et al, 2001).

Macrocystis pyrifera (Giant kelp)

Macrocystis is the algae known for the formation of Kelp forests, an essential ecosystem habitat for many species. The algae are mainly harvested for food and alginates, but at least one initiative called the Southern Ocean Carbon Company (https://southernoceancarbon.com/) intends to use this seaweed for CDR. It is one of the fastest growing and largest algae, growing up to 60 m long with a maximum daily growth of 60 cm. Most growth occurs after august when the nutrient concentrations are highest. Natural sequestration occurs through particulate *Macrocystis* released from the forest. Particulate matter from *Macrocystis* leaves the ecosystem in two ways, either they are consumed by organisms who leave or whose excretion leaves the ecosystem or parts break off from tidal and wave energy. The fast growth makes *Macrocystis* suitable for CDR, additionally though *Macrocystis* has a preference for colder waters the species has a wide tolerance for temperature making the approach more climate change resistant.

Terrestrial biomass

Though the term afforestation can arguably not be used on this technique. Sinking terrestrial biomass can sequester carbon as well, and therefore falls under the CDR category. Though even more is unknown about the interactions between this type of biomass and the benthic environment. The concept uses terrestrial biomass by-products, which would otherwise largely be released as CO_2 back into the atmosphere. The initiative Carboniferous (https://www.carboniferous.co/) intends to sequester carbon by using Sugarcane bagasse and Running Tide (https://www.runningtide.com/) aims to use woody biomass alongside sugar kelp.

Terrestrial woody biomass degradation has been the most studied terrestrial matter in the oceans due to the existence of well-preserved shipwrecks scattered all over the oceans. Showing that woody biomass which is already slowly degradable in terrestrial environments by fungi and bacteria, is very refractory in marine environments. Largely due to the availability of oxygen, which the fast-decaying terrestrial organisms require free access to (Björdal, 2012). In water wood-degrading fungi take over at a much slower rate.

Research question and aim

The aim of this research is to explore which processes respond to the influx of seaweed on the seafloor, what happens to the biogeochemistry within the sediment/bottom waters, and in which form the carbon is sequestered. This research incorporates methods used by known ocean afforestation initiatives into a biogeochemical model to generate a set of realistic and applicable simulations and predictions. Ocean afforestation effects on deep-sea environments has, to our knowledge, not been studied so far. A comparative study of the carbon sequestration efficiency of various organic matter types considered for ocean afforestation is also absent from the literature. The results of this research can be used in both developing more efficient ocean afforestation methods and in future policy decisions concerning CDR techniques on political and corporate level.

This research attempts to answer the following research question by using an early diagenesis model:

How does Ocean Afforestation affect the biochemical make-up on the deep-seafloor and what is the fate of the added carbon?

Method

Documenting ocean afforestation initiatives

A broad search was done for initiatives which intend to use ocean afforestation for carbon sequestration, mainly using the google search engine directly but also by looking at science and news articles (Table 3). The POC input magnitude and composition used for the present study were based on existing proposals from the above-mentioned initiatives. For each initiative, the specific technique and seaweed species were reported and described (Table 3). For each seaweed species, the C:N:P ratios (its elemental composition), degradation rate and net primary productivity (NPP) were looked up in literature or estimated by using data on seaweed with comparable composition. Multiple initiatives were contacted in order to obtain estimates for the seaweed carbon fluxes that would accumulate on the seafloor. The terms used to find initiatives in google were: ocean afforestation, initiatives, sinking seaweed, macroalgae, ocean carbon sequestration and blue carbon initiatives.

The following scientific search terms were used in google scholar: seaweed, macroalgae, *Ulva, Sargassum, Laminaria, Saccharina* and *Macrocystis*, in combination with carbon sequestration, blue carbon, sinking, net primary production and POC. The terms used to find the decay rates were: decay rate, decomposition, respiration, degradation. All variables were documented and mutually compared.

Table 3: carbon dioxide removal and blue carbon initiatives alongside the description of the process and selected (seaweed) species

Initiative name	Concept	Species	Website
Pull To Refresh (2022)	Solar powered vessel sinks algae to at least 1000 meters depth	*Sargassum*	https://pulltorefresh.earth/
Running tide (2023)	Buoys made from forest residue and limestone, seeded with kelp. Sinks after specific time, de-acidifying the ocean and sequestering carbon.	Sugar kelp *(Saccharina latissima)*	https://www.runningtide.com
Fearless Fund (2022)	Monitoring *Sargassum* belt for cost-effective biomass harvest. And possibly artificially seeding areas	*Sargassum* (naturally occurring)	https://www.fearlessfund.org/
Seaforester (2023)	Restoring natural seaweed habitats. Seeding small rock with algae	Dependent on location	https://seaforester.org/#story
Southern Ocean carbon company	Growing native kelp on hemp ropes Harvest for either biochar (fertilizer) or transport it to the deep ocean for sequestration	Giant Kelp *(Macrocystis pyrifera)*	https://southernoceancarbon.com/
Coastal CO_2 Removal Belt	Construct artificial reefs to grow seaweed alongside the Korean coast to act as a carbon sink.	*Ecklonia cava Ecklonia stolonifera*	Chung et al., 2013
SOS carbon (2022)	Caribbean initiative to clean up *Sargassum* and consequently sink it for carbon sequestration to about 150-200 m depth. After which the pressure will cause the *Sargassum* to sink.	*Sargassum*	https://soscarbon.com/
Seafields (2022)	Mid ocean aquafarm irrigated with warmed, nutrient-rich deep water in the centres of the inward-	*Sargassum (fluitans & natans)*	https://www.seafields.eco/

	rotating, subtropical gyre. Partial nutrient recovery on site, bale, compress and sink carbon rich leftovers. Aims to capture a gigatonne of CO_2 per year of a 55000 km2 farm		
Carboniferous (2023)	Using agricultural by-products to bale, ballast and sink to anoxic basins	Rice straw and sugar cane bagasse	https://www.carboniferous.co/
First gigaton carbon removal	Seaweed grown locally by native farmers in Philippines. Transported, weighed, baled and sunk to below 1000 m	*Kappaphycus (striatum & alvarezii) Euchema spinosum*	https://firstgigaton.com/
Seaweed generation	Invasive seaweed is intercepted by an aquatic robot, captured, compacted and dropped to >1000 m	*Sargassum*	https://www.seaweedgeneration.com/
Kelp blue (2023)	Planting large scale giant kelp forests, 2,3% of NPP is exported as POC	*Macrocystis*	https://kelp.blue/CO2-removal/
Phykos (2022)	Robotic seaweed growth platform. migrates to optimise growth. Harvested and sunk to 1500 m	Kelp	https://www.phykos.co/#tech

Model implementation

The RADI model (Sulpis et al., 2022) was selected as the tool to answer the research question. The RADI model is an early diagenesis model, designed for use in deep-sea environments, which includes POC and $CaCO_3$ accumulation at the sediment-water interface, and simulates POC degradation as well as $CaCO_3$ dissolution and precipitation kinetics. RADI also includes organic matter degradation through six different oxidation pathways, as well as transport processes such as bioturbation, (bio)irrigation, advection, and diffusion, notably through a diffusive boundary located above the sediment-water interface.
While the original version of RADI included phytoplanktonic-like organic matter, the present study focuses of seaweed degradation delivered to the seafloor through intense pulses, thus several model developments were made. The paper by Sulpis et al. (2022) contains extensive model description and evaluation, whereas this paper focuses on developments specific to seaweed degradation and associated consequences. RADI is publicly available on GitHub [RADI-model] and was adapted for this research in its MATLAB (R2020a) version. The original model was modified to include an additional organic carbon flux, for which parameters such as composition and decay should be adjustable. New variables were created for the C:N:P ratio, decay rates and the POC flux (Foc). In the RADI model all calculations which used these variables were adjusted or duplicated to create a realistic response. When new variables were created within the RADI model these were added to the equation later on as well, so that for example when both natural and Foc react with oxygen, the oxygen used in both reactions was subtracted from the O_2 concentration.

Time

The RADI model uses a continuous input of organic carbon from sinking detritus and phytoplankton. However, ocean afforestation mechanisms often rely on sudden sinking or pumping of seaweed to the deeper levels, known as pulse inputs. In the context of the simulations this means that large amounts of POC will accumulate on the seafloor for a specific amount of time. This required some alterations to the models. Adjustable time input elements were introduced to specify when the POC input starts and when it ends.

Bioturbation and irrigation

Bioturbation and irrigation rates are computed as a function of the flux of organic carbon that reaches the sediment-water interface (Foc), and they both decrease with depth in the sediment. This complicated the model adjustment because there are two options to implement the bioturbation of the new input.

- Different bioturbation rates for the natural POC and forced POC flux, where both bioturbation rates are summed for the remaining solids (and irrigation rates are summed for the solutes)
- Combined bioturbation rate, where the rate is computed from the sum of the two POC fluxes (natural and forced) and is the same for all solids (and the same irrigation rate for all solutes)

Using different bioturbation rates allows modelling of preferential degradation. Which occurs when a portion of fresher POM is degraded faster/sooner than the remaining fraction. When fresh seaweed is pumped to abyssal depth, the POM is less degraded than naturally sunk algae because of the reduced time spend in the water column. Which might result in the seaweed being degraded and mixed through the sediment at a different rate than the background POM. However, because bioturbation rates are computed as a function of the POM reaching the sediment, once the seaweed addition ends the flux becomes zero and therefore the irrigation and bioturbation rate as well. Even though a portion of the seaweed is still present in the sediment and is being degraded. Therefore, it is unrealistic to use different bioturbation rates for the natural and seaweed POM flux.
This why the combined bioturbation was chosen for the model. Which sums both fluxes to compute the bioturbation and irrigation rates. Before and after addition the model uses the background rates again, computed with only the natural POM flux. However, when using the combined bioturbation, preferential degradation cannot be modelled and the response after the added POC input has stopped might not be realistic. Still, due to the lack of data on this subject, using a combined bioturbation is the most reliable method.
This combined bioturbation scheme was implemented into the model by calculating bioturbation and irrigation twice, once with the background Foc and once for the natural plus the added Foc. An if statement was added to the RADI model function which distinguishes between the two Foc, and consequently specifies which bioturbation and irrigation variables are used.

Decay/degradation

The decay rate is one of the most important parameters to obtain relevant and reliable results. Decay rates for algae can vary by up to a factor 1000, determining whether the carbon remains in organic form for hundreds of years or is remineralized within a day (Arndt et al., 2013). However, decay rates are not specific to a certain species of seaweed, they are rather based on the composition of the OM and the interaction with the environment (Mayer, 1995). For instance, OM with high nitrogen concentrations often has high decay rates (Conover, Green & Thornber, 2016). Degradation therefore depends on the algae composition, microbial communities and environmental conditions. In the RADI model three degradation rates are used for three reactive fractions of the organic matter: fast degrading, slow degrading and refractory (not degrading on relevant time scales for the model) and are calculated as a function of Foc, following Archer et al. (2002). This results in a very coarse estimate of degradation and leaves a crude understanding of the changes in biogeochemistry and actual carbon sequestration. Whenever possible, decay rates from literature were used (Table 4).

Particulate organic carbon flux

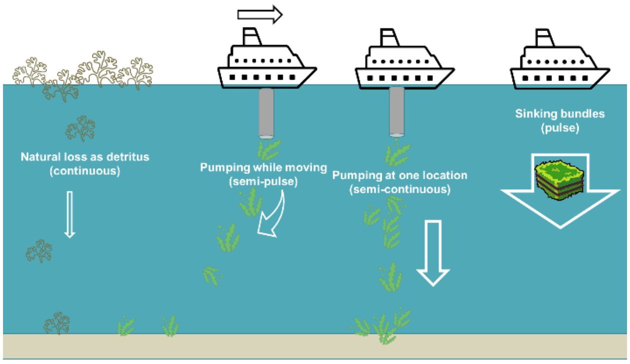

Figure 2: different types of seaweed sinking. Semi-pulse shows smaller amounts reaching the seafloor over a short time (within a day). Semi-continuous show a high amount reaching the seafloor over longer times (weeks to months). The ship is used for illustrative purposes, any fixed or floating platform could be used for the semi-continuous and pulse additions.

Four approaches to ocean afforestation were selected and supplemented with data from literature and personal contact with ocean afforestation initiatives. In Table 4 all relevant data is presented. Both the continuous, semi-continuous and pulse (Figure 2) sequestration were modelled, because most initiatives were not able to give the Foc in mol/m2/a, these values are based on a range of data from literature. The pulse input resembles ocean afforestation most, since it mimics sudden (induced) sinking of seaweed. The continuous sinking resembles the natural sequestration of species, where some detritus or dead seaweed naturally reaches the seafloor. For *Sargassum* and *Saccharina* a natural sequestration of 11% of the total growth was used according to Krause-Jensen & Duarte (2016) Whereas for *Macrocystis* a value of 2.3% was reported by Bayley, Marengo & Pelembe (2017).

Table 4: the different runs based on real life approaches and data from literature (see appendix 2 for calculations for the flux). Northern Atlantic (N. Atl.), Equatorial pacific (Eq. Pac.), Southern Ocean (Southern O.) See appendix 3 for more information.

Run	Sarg_puls	Sarg_con	Sac_puls	Sac_con	Sac/wood	MC_puls	MC_con	SCB
Species	Sargassum	Sargassum	Saccharina	Saccharina	Saccharina	Macrocystis	Macrocystis	Sugar cane bagasse
Amount (mol C/m2)	27.50	3.03	45.80	10.84	Variable	41.37	0.95	3.37
Saccharina/wood (total of 500 g)	-	-	-	-	9:1 7:3 5:5 3:7 1:9	-	-	-
C:N:P	797:47:1	797:47:1	630:70:1 (Lubsch, Lansbergen & Poelman, 2020)	630:70:1	216:16:1 (A. Tune, Personal communication, 15 November 2022)	222:11:1 (Atkinson & Smith, 1983)	222:11:1	405:20:3 (Frazão et al., 2020)
Fast decay (/yr)	170	170	Variable*	Variable*	Variable*	Variable*	Variable*	5.84
Slow decay (/yr)	0.5	0.5	Variable*	Variable*	Variable*	Variable*	Variable*	Variable*
Fast/slow/refractory	0.70/0.27/0.03	0.70/0.27/0.03	0.70/0.27/0.03	0.70/0.27/0.03	Variable°	0.70/0.27/0.03	0.70/0.27/0.03	0.26/0.27/0.03 (Pedersen et al., 2021)
Duration	3 days	1 year	3 days	1 year	3 days	3 days	9 months	3 days
Location	N. Atl.	All	N. Atl.	All	N. Atl.	Eq. Pac.	All	All

*The variable decay rates are calculated as follows:
Fast decay = 1.5e-1 * (Foc*1e2)^0.85
Slow decay = 1.3e-4 * (Foc*1e2)^0.85
° The variable fast/slow/refractory fraction is based on 0.7/0.27/0.03 for *Saccharina* and full refractory (0.0/0.0/1) for wood

For *Sargassum*, the approach is focussed on carbon sequestration and solving the invasive *Sargassum* problem. Pull to Refresh indicated they want to remove all invasive *Sargassum* (L. Tincher, personal communication, 2 October 2022). In order to include this in the model, a high *Sargassum* density and carbon content was used to calculate the carbon flux. This was based on the assumption that the *Sargassum* grown in one square metre would be sunk to a patch of a square metre at the bottom. In reality the *Sargassum* may be collected in nets over larger areas and sunk as one batch over a much smaller surface area (resulting in much higher organic carbon fluxes) (SOS carbon). A value of 8.25 kg/m2/a for high density *Sargassum* mats was reported by Gouvêa et al., (2020 & 2021), which corresponds to 27.50 mol C/m2/a, the highest expected *Sargassum* density which will be sunk at once. Possible degradation [occurring in the water column] was not included in the calculation because the pumping to greater depth will result in faster sinking and presumably less biological activity (thus degradation). However, the organic matter will not reach the seafloor at once, due to differing sinking rates across types of particles. Furthermore, once on the seafloor, these 8 kg of *Sargassum* biomass spread over one square metre will take longer to mix with the sediment than it would for smaller amounts. Still, the response of the seafloor biota is very fast as macrofauna and microorganisms immediately start consuming newly delivered organic matter (Witte et al., 2003). The delayed response led to an estimated 3 days in which the POC reaches the sediment, for the semi-continuous approach the same amount was added over two months time. The 3 days are somewhat arbitrary, but still classifies as a pulse input and was generally the shortest time span which ran without errors for the specified resolution. The N. Atl. location was chosen for this approach since it is closest to the habitat of *Sargassum* (Figure 3). However, all approaches were modelled for multiple locations (Figure 3, Figure 4 and Figure 5).

Figure 3: N. Atl. Location (Google, n.d.) (Hales et al., 1994)

Figure 4: Eq. Pac. location (Google, n.d.) (Hammond et al., 1996)

For *Saccharina lattisima* a high yield for cultivation was taken because the species does not naturally occur in the open sea. Research by Peteiro, Sánchez & Martínez (2016) found a yield of 16.1 kg fresh sugar kelp m^{-1} rope in 5 months. The initiative Running tide intends to cultivate *S. Lattissima* on kelp buoys made from woody biomass. This affects the ratio of degradable/refractory biomass reaching the seafloor. However, since no exact ratio could be supplied for the ratio *Saccharina* to woody biomass the pulse runs were done without the woody biomass. Additional runs were performed combining different ratio of *Saccharina* and woody biomass (Table 4). For sugar kelp the N. Atl. location was chosen as the location since it is closest to the experimental sites of Running tide.

For *Macrocystis*, the seaweed has to be cultivated near the coast or on ropes due to its physiology. The initiative Southern Ocean Carbon Company suggested cultivation on hemp ropes which will be harvested and sunk for carbon sequestration (Brancher et al., 2020). To include this in the model, a high yield for rope cultivation was found in research by Gutierrez et al. (2006) of 14.4 kg/m rope when seeded in April and harvested in December. The 14.4 kg/m rope corresponds to approximately 41.37 mol/m2 assuming the growth on one meter of rope will be sunk to one square meter of ocean floor, for calculations see Appendix 2: species parameters. However, because this species will have to be transported to open sea, it is much more likely that the seaweed will be bundled and sunk in higher density. Due to the lack of information, the extent of this baling is unknown and therefore not modelled. A value of 2.3% of the NPP is naturally exported and used as natural sequestration for *macrocystis* (Bayley, Marengo & Pelembe, 2017) and since *Macrocystis* is seeded in April and harvested in December, the natural sequestration is distributed over these 9 months. However, it is difficult to predict when the POC is lost in this time period, though it is likely to increase over time, with high amounts during storms and little afterwards. In order to avoid complicating the model by incorporating this fluctuating POC, the actual flux is distributed over the 9 months equally, which resulted in a Foc of 9.92 mol C/m2/a. The Southern O. location (Figure 5) is closest to Tasmania, where the Southern Ocean Carbon Company is located.

Figure 5: Location Southern O. (Google, n.d.) (Sayles et al., 2001)

The sugar cane bagasse was the only terrestrial species used here that was solely used for sequestration and sunk to an anoxic basin. From a personal communication with D. Felker (6 October 2022), 100 g/m2/a was used as a realistic production rate. Because the material was sunk in an anoxic basin the bottom water oxygen concentration had to be changed and new steady state variables had to be created. Since oxygen concentration could not be set to zero, which caused NaNs to form in the results, it was set to 5e-6 mol/m3. All three location present in RADI were used to model the response to sugar cane bagasse, however the N. Atl. location is the closest location to the intended location by the initiative Carboniferous: the Orca basin (Figure 6).

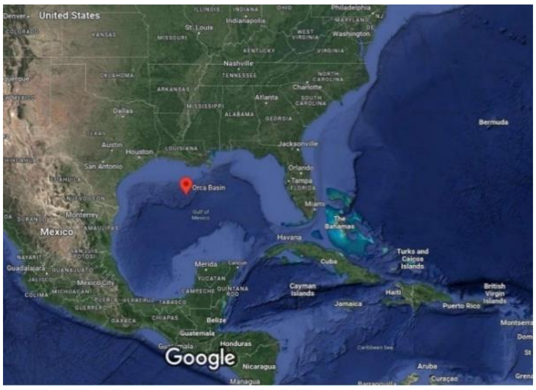

Figure 6: Orca basin (Google, n.d.)

Once the relevant processes in the model were adjusted, a new live script was created to make a user-friendly code to choose the species, location and input duration. In this code the values reported in Table 4 are implemented. The model was first run for each location without any changes to the parameters in order to gain control results. Consequently, for each species the model was run for all three locations. Time and depth resolution were changed accordingly to avoid numerical errors. Outputs were generated in the form of depth/time profiles and graphs at specific moments in time. Carbon retention and TA, DIC diffusive flux differences/ratio were calculated, in order to gain insight in the bottom water changes as well as carbon sequestration.

$$Carbon\ retention\ (\%) = \frac{[\sum Foc_{seaweed}] - ([\sum F_{DICseaweed}] - [\sum F_{DICnatural}])}{[\sum Foc_{seaweed}]} \times 100$$

$$\frac{TA}{DIC} = \frac{[\sum F_{TAseaweed}]}{[\sum F_{DICseaweed}]}$$

$$TA - DIC = [\sum F_{TAseaweed}] - [\sum F_{DICseaweed}]$$

$[\sum Foc_{seaweed}] = sum\ of\ the\ allochtonous\ POC\ reaching\ the\ sediment$
$[\sum F_{DICseaweed}] = sum\ of\ the\ diffusive\ DIC\ flux\ through\ the\ sediment - water\ interface$
$[\sum F_{DICnatural}] = sum\ of\ the\ diffusive\ DIC\ flux\ without\ allochtonous\ POC$
$[\sum F_{TAseaweed}] = sum\ of\ the\ diffusive\ TA\ flux$

For a full list of variables see the RADI paper (Sulpis et al., 2022), in Appendix 1 the variables which are adjusted or created are listed.

Sensitivity analysis

A sensitivity analysis was performed to test the robustness of the model and to further increase understanding of the relation between the different variables in the model. The approach chosen for this sensitivity analysis is based on the uncertainty of certain variables, such as decay rates and percentage of refractory compounds in the POC. The goal of this analysis is to test to which extent each model parameter influences carbon sequestration. The variables used for the sensitivity analysis based on uncertainty are decay rates, ratio fast/slow/refractory OM and bioturbation schemes. The variables chosen to simulate their effect on sequestration are bottom water oxygen concentration, POC influx, input duration and C:N:P ratio. When choosing what seaweed species to use for the sensitivity analysis the location, natural occurrence and abundance were considered. *Sargassum* is a free growing species in the open ocean and found in great quantities, furthermore, it was one of the few species for which set decay rates were available, making it the perfect candidate for the sensitivity analysis. The values chosen for each parameter were based on expected variation in the species or environment. It is not meant to be a complete analysis of the uncertainty in the model, but rather an indication of the effects these parameters have on the fate of the carbon in the sediment. The Northern Atlantic location, see Figure 3 (Hales et al., 1994), was chosen because it is closest to the growing area of *Sargassum*. In Table 5 the parameters which were tested are listed for each run.

Table 5: sensitivity analysis runs and parameters

Run	ref	Kf40	Kf17	Db0.	Db3	991	442	dO_2	dO_2	dO_2	dOw	T0.5	T1	T2	T3	T4	T5	T6	T15	T18
Fast decay rate [/yr]	70	40	170	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Slow decay rate [/yr] kslow	0.5	0.08	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
POC flux [mol/m3/yr]	3.03	-	-	-	-	-	-	-	-	-	-	10	10	10	10	10	10	10	10	10
Bioturbation background	2.69e-05	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Bioturbation seaweed	3.13e-04	-	-	0.06	3,00 E-05	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Irrigation		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Ratio fast/slow/refractory	0.7/0.27/0.03	-	-	-	0.90/0.09/0.01	0.4/0.4/0.2	-	-	-	-	-	-	-	-	-	-	-	-	-	-
dO_2w (bottom water concentration) [mol/m3]	0.2803	-	-	-	-	-	-	0.4	0.2	0.1	2,00 E-03	-	-	-	-	-	-	-	-	-
Input duration (months)	12	-	-	-	-	-	-	-	-	-	-	0.5	1	2	3	4	5	6	15	18

Results

The results presented here are not meant to be accurate predictions of consequences of each specific approach but rather a showcase of a range of consequences dependent on different types of input. Furthermore, any unknown compositional variation within and between species might give different responses, therefore these results should be considered as guidelines rather than predictions.

The following terms will be abbreviated in the results:

- DIC, dissolved inorganic carbon includes CO_2, HCO_3, CO_3 and CH_4
- TA, total alkalinity is a measure for the capacity of seawater to neutralize acids
- (P)OM (particulate) organic matter
- (P)OC (particulate) organic carbon

Oxygen

A steady state sediment oxygen profile shows the highest concentration near the sediment-water interface, and a consistent drop to greater depths. The addition of POC results in an immediate drop in oxygen at the interface. After which oxygen concentrations decrease over deeper layers due to mixing, upwards diffusion and reactions with reduced metabolites. The profile for oxygen is very similar for all types of pulse addition to oxygenated bottom waters: as soon as the POC is added, most oxygen disappears in a very short time across all depth layers. However, the time between the POC addition and the depletion of oxygen in the sediment depends on the quantity, the mixing and the decay rates of the POC (Figure 7).

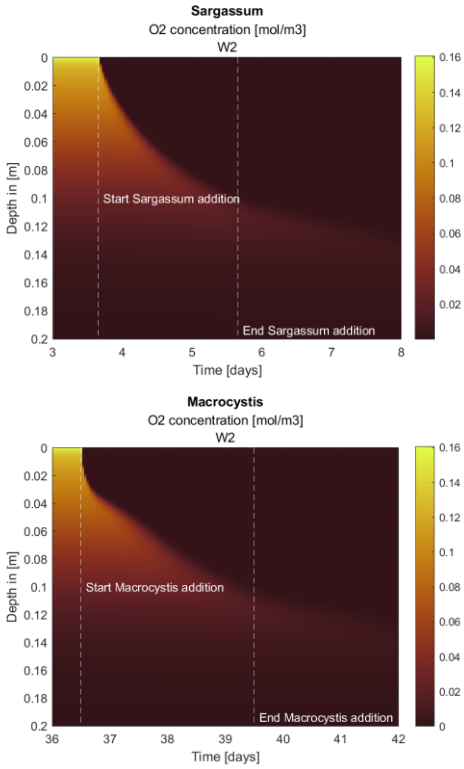

Figure 7: profile for pulse addition of Sargassum and Macrocystis to the Eq. Pac. location

Irrigation is important for oxygen supply to deeper levels in the sediment, because it acts substantially faster than diffusion. Increased irrigation therefore decreases the time needed to return to steady state conditions and allows for the faster aerobic degradation at deeper levels. Since irrigation is closely linked to **bioturbation**, both rely on benthic (macro)fauna and degradability. Pulse inputs of POC show increased bioturbation and irrigation but also faster depletion, which can be seen in Figure 7 as the oxygen depletion occurs faster for the higher POC input by Macrocystis. Contrastingly, irrigation supplies oxygen to deeper levels, whereas bioturbation supplies POC to deeper levels which is degraded using oxygen, meaning that as long as the POC is supplied there is both a higher flux of oxygen **to**, as well as higher consumption **of** oxygen at deeper levels in the sediment.

The time it takes to form a new steady state, after addition ends, depends on the amount of organic matter left in the sediment (ratio slow and fast degrading) and its degradation rates, as well as the bottom-water and porewater composition. Oxygen and POC profiles for the N. Atl. Location can be seen in Figure 8 and Figure 9 for *Saccharina* and *Sargassum* and the difference can be observed between the continuous and pulse additions. Two addition types are shown for comparison, adding the same amount of POC over three days (pulse) and 2 months (semi-continuous). The continuous addition clearly recovers fastest for both species. However, when comparing the pulse and semi-continuous runs a clear difference can be seen for *Saccharina*, showing a faster recovery for POC added over three days. The same cannot be observed in the *Sargassum* plot. The most notable difference between these two species is the fact that *Sargassum* has a set decay rate, whereas *Saccharina* has a decay rate dependent on the POC input. Because the POC input had to be higher for the 3 days addition to add up to the same total as two months, the decay rate is also much higher. Higher decay rates deplete the organic matter faster as can be seen in Figure 8, allowing oxygen to return to steady state faster.

Lastly, mainly the slow degrading fraction of POC determines the oxygen concentration profile after addition ends. The fast degradation fraction disappears within hours to days, after which the oxygen is mainly used to degrade the slow degrading fraction. Bioturbation mixes the POC downward and irrigation provides oxygen, spreading out oxygen usage over time.

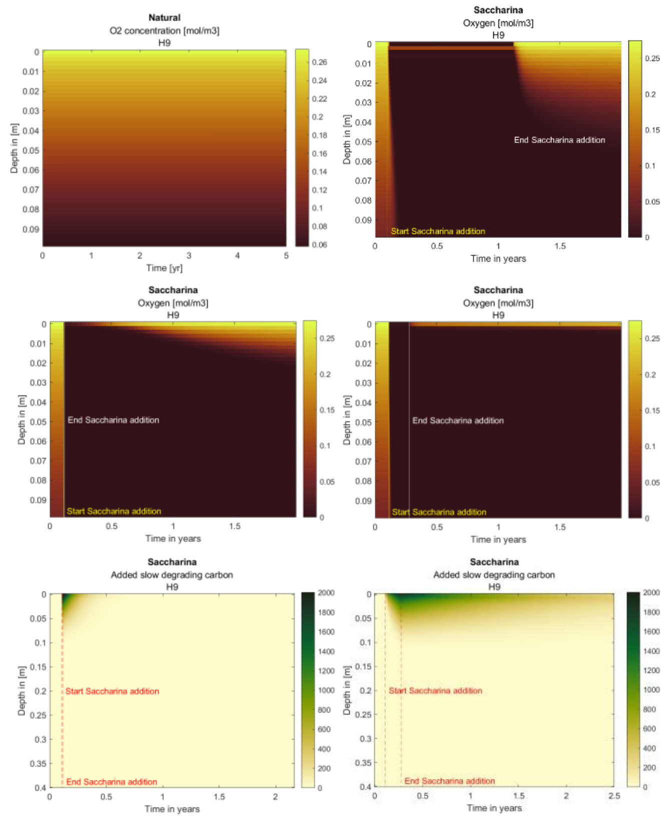

Figure 8: Saccharina, top left: natural oxygen profile. Top right: continuous addition. Middle left: pulse addition three days. Middle right: semi-continuous addition two months. Bottom left: slow degrading fraction pulse 3 days. Bottom right: slow degrading fraction semi-continuous 2 months. Oxygen and POC are in mol/m3

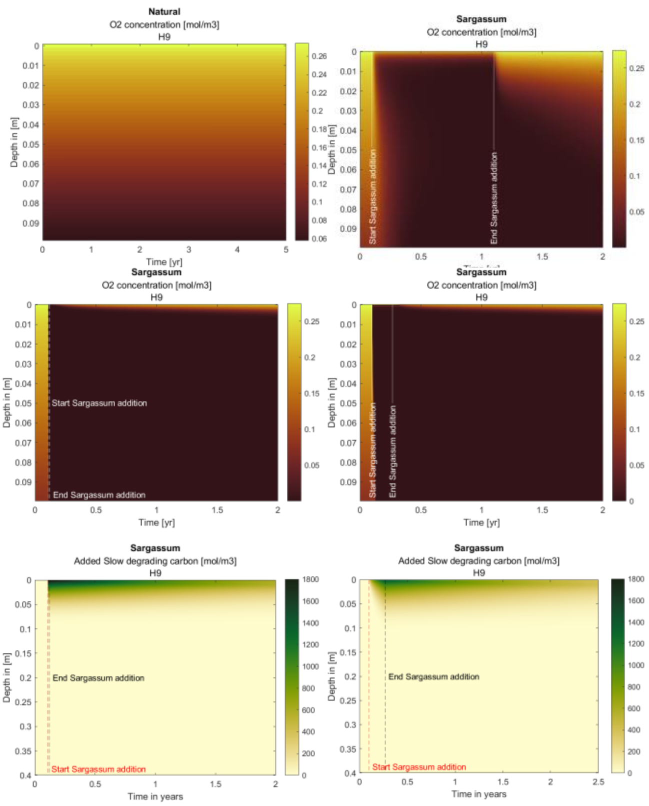

Figure 9: Sargassum, top left: natural oxygen profile. Top right: continuous addition. Middle left: pulse addition three days. Middle right: semi-continuous addition two months. Bottom left: slow degrading fraction pulse 3 days. Bottom right: slow degrading fraction semi-continuous 2 months. Oxygen and POC are in mol/m3

In a steady state system, there is an oxygen flow from the bottom water to the sediment, driven by aerobic OM degradation. Oxygen flow to the sediment is higher for pulse additions, where more oxygen is used for degradation over a shorter time. Interestingly, the oxygen flux is higher for the continuous addition of *Sargassum* compared to *Saccharina* even though the POC input is lower (Table 6). For the pulse addition of *Macrocystis* and *Saccharina* the oxygen influx is much higher for *Macrocystis,* even though the POC inputs are comparable. Lastly, the runs combining different ratios of *Saccharina* and woody biomass, does not show the highest oxygen flux for the high seaweed concentration, but rather for equal amounts of seaweed and woody biomass (5/5 ratio, Table).

Alkalinity

In steady state Ca^{2+} and CO_2 increase with depth and calcite decreases with depth. When organic matter is added on the surface and mixes downward through bioturbation, CO_2 is produced in these layers and diffuses in all directions. Due to the carbonate balance and calcite saturation state, the increased CO_2 leads to a drop in pH and dissolution of calcite. This can be seen in the profiles in Figure 11, calcite concentration drops near the surface due to dissolution and Ca^{2+} and CO_2 are produced and diffuse down, generating alkalinity.

Figure 10, t=0 shows that in the steady state alkalinity increases (steadily) with depth, which is a result of the balance between the alkalinity production and consumption, where diffusion and calcite dissolution/precipitation processes dominate. From the moment that the additional organic material is added (t=0.1) the degradation begins, and total alkalinity increases. For as long as the POC is added the alkalinity mainly increases near the sediment water interface and either flows out to the bottom water or diffuses down in the porewaters. The highest alkalinity can be found near the surface just after adding the OM, but the peak can be found migrating deeper in the sediment over time (Figure 10).

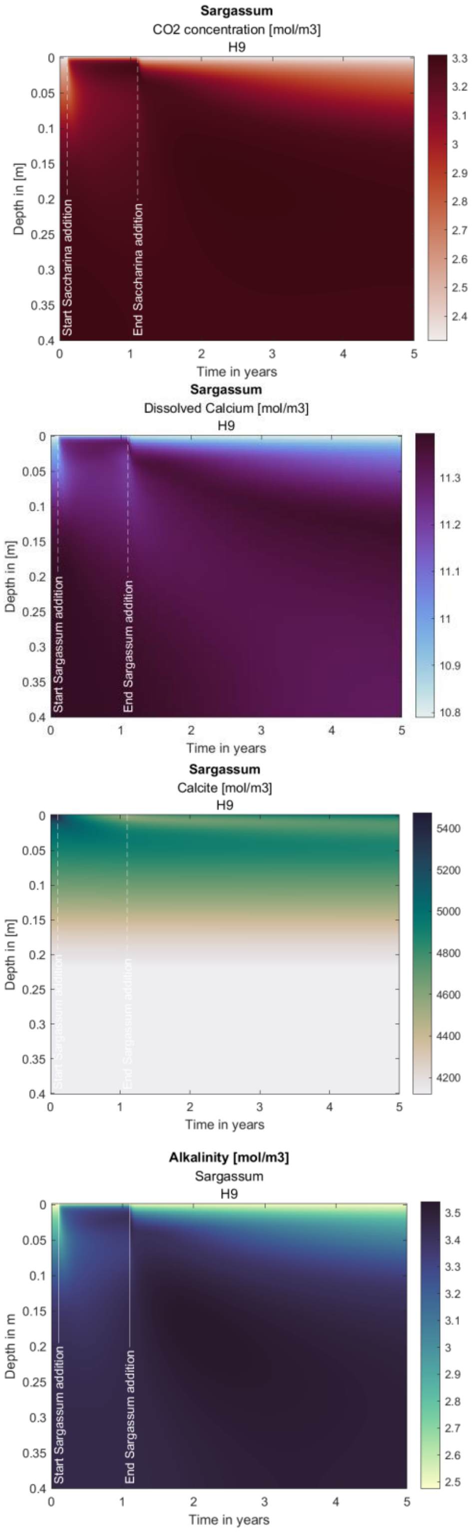

Figure 11: Ca2+, CO2, calcite and alkalinity profile for Continuous Sargassum addition

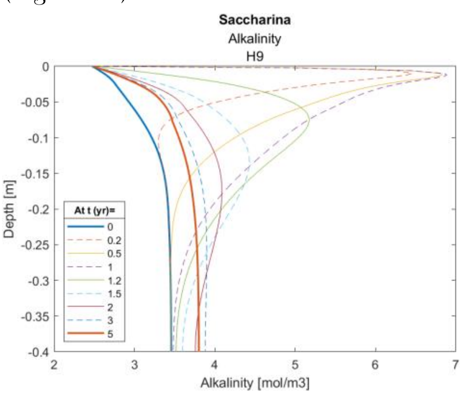

Figure 10: alkalinity profile for continuous Saccharina addition at the N. Atl. location. The different colours represent the depth profile at different moments in time. The addition starts at t = 0.1, after which a clear increase of alkalinity near the surface can be seen. The over time the peak decreases and migrates downward until the profile is similar to the profile at t=0

Since alkalinity is produced by calcite dissolution and anaerobic OM degradation, the alkalinity profile will depend on the type and amount of degradation, therefore indirectly on the quantity POC and the composition. The composition influences alkalinity through the decay rates, faster degradation leads to faster production of CO_2 and carbonate. When the POC is added as a pulse flux, bioturbation and irrigation increase, and high amounts of alkalinity are produced which mix quickly into deeper layers of the sediment. For continuous additions, the alkalinity increases less and is mixed through the sediment more slowly. Because of the intense increase in bioturbation during a pulse influx, the POC is mixed quickly over the first decimetre of the sediment, after which it degrades in these layers. The increased alkalinity production in deeper layers can be seen in Figure 13. The continuous input results in much shallower mixing (Figure 12), which makes the POC more easily accessible for degradation, over longer time periods leading to a higher DIC and alkalinity flux across the interface.

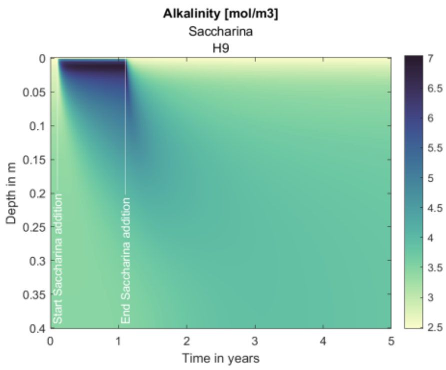

Figure 12: Alkalinity graph for continuous addition of Saccharina

This flux along the sediment water interface gives a good indication of changes to bottom water chemistry. Any product in the sediment which exceed bottom water concentration will diffuse out, but much faster if it is produced near the sediment interface. Since there is alkalinity and DIC production, both will flow out of the sediment, whereas oxygen is depleted and flows in. As expected, higher concentrations of POC rain will result in higher O_2 influx and higher DIC and alkalinity flux across the sediment-water interface.

The **alkalinity** profile in the sediment and the alkalinity flux across the sediment-water interface differ for each location and are closely linked to the incoming organic carbon and bottom water oxygen concentration. Aerobic degradation and methanogenesis have the lowest TA production whereas the other degradation pathways produce more alkalinity.

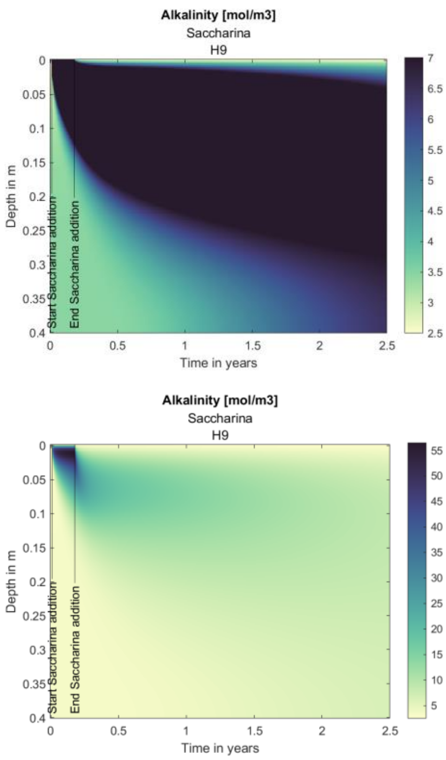

Figure 13: Alkalinity graph for pulse addition of Saccharina. The top graph is set to the concentration range of the previous figure, whereas the bottom graph shows the actual concentrations.

Alkalinity production and flux to the bottom water are highest for pulse additions *Saccharina* (Figure 14) and Macrocystis and lowest for sugarcane bagasse. *Saccharina* and Macrocystis have the highest POC input (45.8 and 41.4 mol/3 days respectively) and consequently higher degradation rates. The continuous input is comparable for all additions, but lowest for Macrocystis (Figure 15) which has a low continuous POC input (0.95 mol/9 months), showing little alkalinity and DIC production and fast recovery.

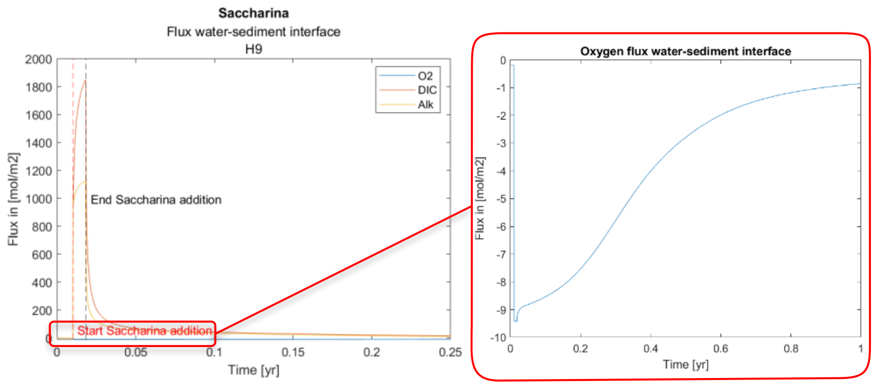

Figure 14: Saccharina pulse input, in and out flow over the sediment-water interface

The sugarcane bagasse in the anoxic basin degrades much slower due to the lack of oxygen and consequential lack of mixing, which prevents the OM from coming in contact with degraders at greater depths. This can be seen clearly in the sediment-water interface fluxes (Figure 16), where after the organic matter influx stops it takes almost a year for the excess DIC and alkalinity to leave the sediment whereas in oxygenated environments the DIC and alkalinity stabilises in a few days to weeks.

TA/DIC ratio is highest for sugarcane bagasse, which can be clearly linked to the low oxygen conditions. Which can be seen in Table 6 and is further explored in the Sensitivity analysis. However, there does appear to be a clear relation between higher TA/DIC ratio and addition types. For *Sargassum* the TA/DIC is highest for pulse addition, whereas for *Saccharina* and *Macrocystis* TA/DIC is highest for (semi) continuous addition. For the *Saccharina*/woody biomass run the TA/DIC was highest for the highest seaweed concentration (9/1 seaweed/woody biomass).

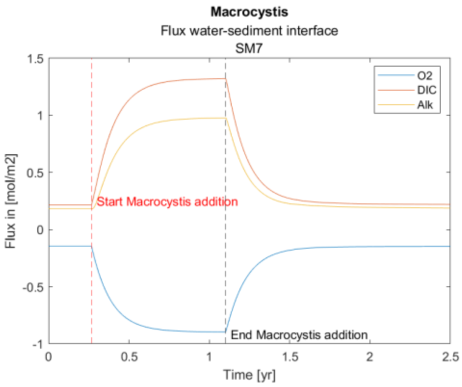

Figure 15: Macrocystis continuous addition, in and out flow over the sediment-water interface

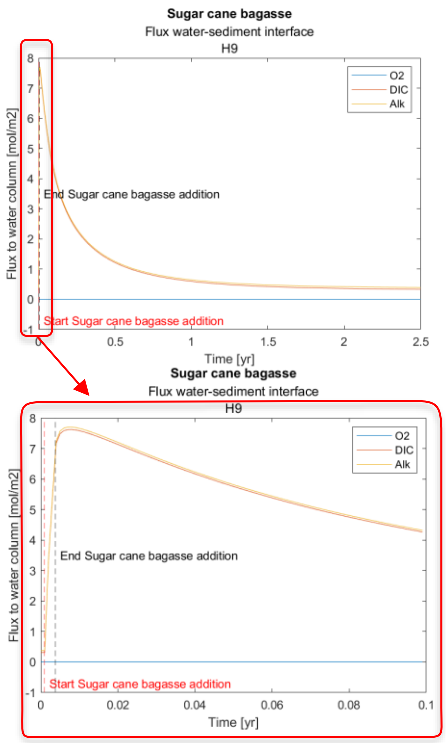

Figure 16: Diffusive fluxes across the sediment-water interface for sugar cane bagasse in an anoxic basin

Table 6: sediment-water interface fluxes, carbon retention and TA/DIC ratio

Species	Sargassum					Saccharina					Sugarcane	
Location	N. Atl.			Eq. Pac.		N. Atl.			Eq. Pac.	Southern O.	N. Atl.	Southern O.
Input duration	1 year	3 days	2 months	1 year	1 year	1 year	3 days	2 months	1 year	1 year	3 days	3 days
Sinking	Continuous	Pulse	Semi-continuous	Continuous	Pulse	Continuous	Pulse	Semi-continuous	Continuous	Continuous	Pulse	Pulse
bottom water O_2 [mol/m3]	0.28	0.28	0.28	0.17	0.17	0.28	0.28	0.28	0.17	0.23	0.00*	0.00*
POC input to top layer sediment (mol/m3)	3.03	27.50	27.50	3.03	27.50	10.84	45.80	45.80	10.84	10.84	3.37	3.37
Carbon sediment retention (%)	-15,03	29,56	15,63	-4,96	32,56	31.86	33.91	17.59	35.55	25.53	50.13	52.24
TA/DIC diffusive fluxes	0.73	0.77	0.69	0.73	0.79	0.79	0.69	0.92	0.69	0.66	0.99	0.96
TA-DIC diffusive fluxes	-0.93	-4.41	-8.37	-0.85	-3.88	-1.54	-9.28	-3.41	-2.14	-2.72	-0.02	-0.06
Species	Macrocystis							Saccharina + wood				
Location	Eq. Pac.		Southern O.	N. Atl.				N. Atl.				
Input duration	9 months	3 days	9 months	9 months	3 days			3 days				
						Seaweed/wood ratio		9 to 1	7 to 3	5 to 5	3 to 7	1 to 9
Sinking	Continuous	Pulse	Continuous	Continuous	Pulse			Pulse				
bottom water O_2	0.17	0.17	0.23	0.28	0.28			0.28	0.28	0.28	0.28	0.28
POC (mol/m3)	0.95	41.37	0.95	0.95	41.37			3.11	7.05	10.98	14.57	18.85
Carbon sediment retention (%)	0.64	32.69	2.45	2.67	31.73			9.67	29.25	49.89	69.52	90.38
TA/DIC diffusive fluxes	0.81	0.64	0.70	0.69	0.61			0.90	0.88	0.87	0.89	0.88
TA-DIC diffusive fluxes	-0.18	-10.11	-0.28	-0.29	-11.13			-0.29	-0.58	-0.62	-0.42	-0.18

*Bottom water concentrations were set to near zero in order to imitate anoxic bottom water conditions

Fate organic carbon

The carbon from the POC either remains in the sediment as (dissolved) inorganic carbon or (refractory) organic carbon or leaves the sediment as CO_2 or CH4, carbon retention in the sediment is higher for intense pulse addition and low bottom water oxygen.

Organic carbon decreases with depth in a steady state system, due to the equilibrium between incoming POC and degradation & bioturbation. When allochthonous POC reaches the sediment, the system needs time to reach a new steady state. Though it does not become clear from the graphs whether the organic matter is mixed deeper, it is mixed much faster for the pulse input. Because of the relatively short POC pulse addition, the system does not have enough time to form a steady state, resulting in a steep incline of mixing depth during addition. As soon as bioturbation returns to normal the POC in deeper layers are mixed and irrigated less, the slower replenishing of electron acceptors means that the OM degrades slower. This shows why pulse addition leads to higher carbon retention in the sediment compared to the continuous influx.

For the background POC (phytoplankton), the carbon present in the sediment is also mixed faster during the addition process, leading to a relative decrease of POC at the surface and an increase at depth. After the addition stops the background organic carbon slowly returns back to a steady state profile. The three fractions of POC each have a very distinct sediment profiles (Figure 17). The first, fast degrading, fraction of added POC is contained to the top millimetres of the sediment, degrading faster than bioturbation can mix. The slow degrading fraction is confined to the top few centimetres and stays in the sediment up to a few years after the influx stops. The refractory fraction hardly degrades and is distributed in the sediment over time due to bioturbation.

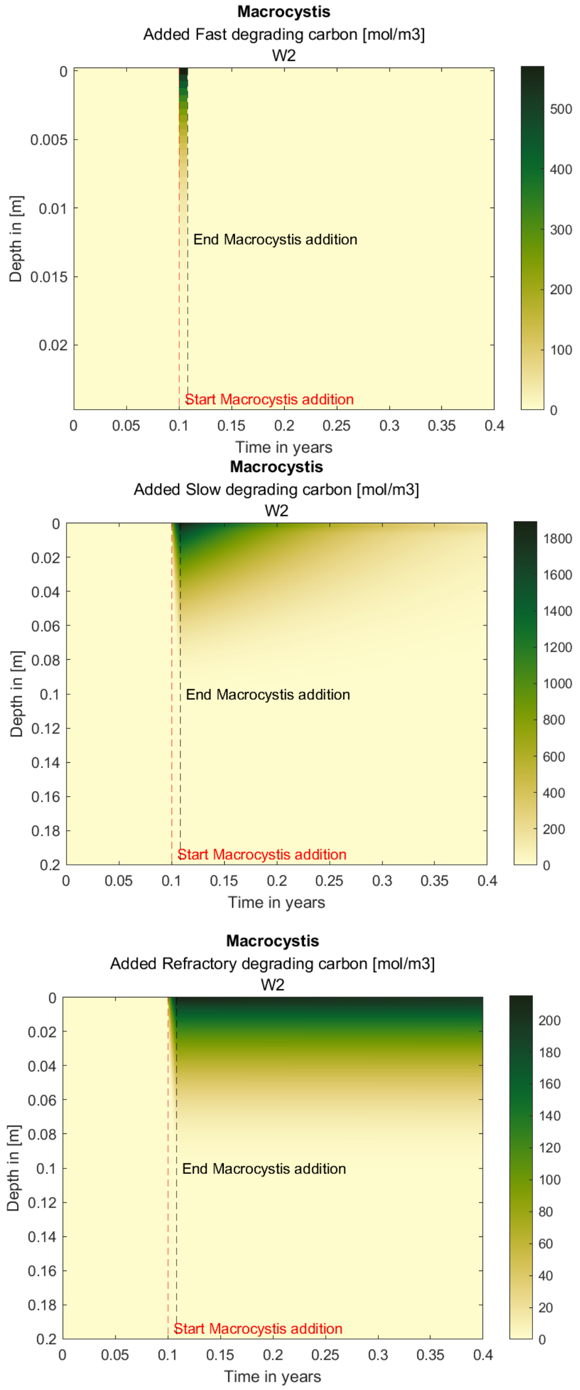

Figure 17: fast, slow and refractory degrading fractions of Macrocystis. Noted that the fast-degrading fraction is plotted on a shallower depth range

The sugarcane bagasse in the anoxic basin remains very shallow in the sediment due to the lack of mixing. The anoxic conditions prevented aerobic degradation, leading to longer retention times. However, the presence of other electron acceptors leads to the slow anaerobic degradation of the fast and slow degrading fractions. Whilst the refractory fraction forms a layer on top or within the first few millimetres of the sediment (Figure 18). In Figure 19 the H_2S production can be seen, showing increased concentrations near the surface just after addition.

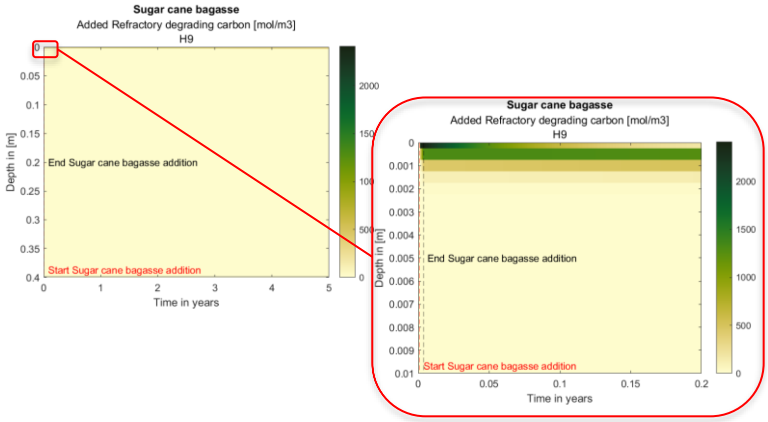

Figure 18: Sugarcane bagasse to anoxic sediment, left is full profile, right is zoomed in.

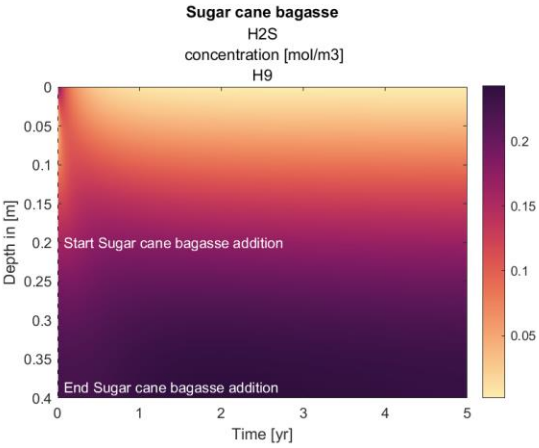

Figure 19: H_2S profile for Sugarcane bagasse

A more extensive look at carbon retention in the sediment has been performed on *Saccharina* and *Sargassum*, for which a continuous input was modelled for a small amount, and a two runs for the same amount spread over 3 days and 2 months (Table 6).
For *Sargassum* the highest carbon retention after two years can be seen for the 3-day input duration, as well as the highest TA/DIC. For *Saccharina*, the highest carbon retention can also be found for 3-day addition but the highest TA/DIC ratio for the 2 months. Furthermore, the continuous addition of both species had very different effects on carbon retention. Where the 30% of the carbon from *Saccharina* remained in the sediment after two years, *Sargassum* showed a negative retention of -15%. Negative retention means that all added POC was remineralized plus some carbon which was already in the sediment. This discovery is further examined in the sensitivity analysis.

Saccharina/woody biomass had highest carbon retention at highest woody biomass concentration, which is set as a fully refractory fraction.

Nitrification is the first anaerobic degradation pathway following oxygen depletion. NO_3 is clearly used for degradation in both the pulse and continuous additions. The other degradation pathways, namely manganese oxide, iron oxide and sulphate reduction are mainly used in pulse addition and only to a small extent in continuous additions. H_2S is therefore mainly produced by pulse additions and sugarcane bagasse but most is reoxidized before reaching the bottom water.

Sensitivity analysis

The size of the fast, slow and refractory degrading fractions regulates sediment and bottom water chemistry as well as carbon retention. A large fraction of fast degrading POC leads to a high carbon flux to the bottom water due to the high decay rates. The lower decay rate of the slow degrading fraction leaves time for the POC to mix to deeper layers where it is less likely to diffuse out over short time scales. Resulting in higher carbon retention for large slow and refractory degrading fractions. Bioturbation is independent of the changing fractions, though this is due to the model formulation which calculates bioturbation based on total POC influx. Even though the ratio between fast, slow and refractory degrading fractions would surely affect bioturbation and irrigation.

Negative carbon retention like for the continuous *Sargassum* addition can also be seen in the sensitivity analysis for long addition times (>6 months), high oxygen concentrations (> 0.2 mol/m3), high fast degrading fraction (≥0.7), high fast and/or slow decay rates (≥ 40 & 0.08), low bioturbation (≈3e-5).

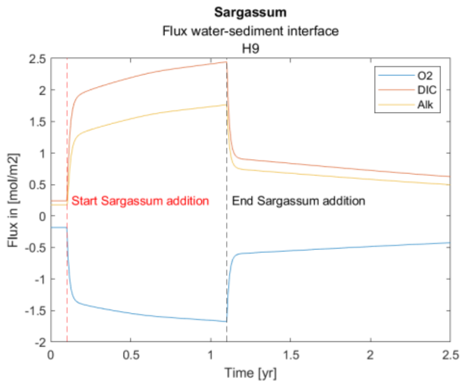

Figure 20: 0.4/0.4/0.2 fast/slow/refractory ratio

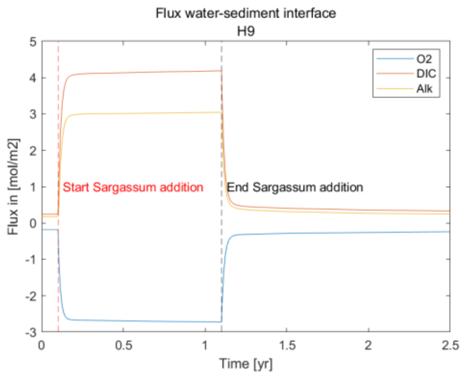

Figure 21: 0.9/0.09/0.01 fast/slow/refractory ratio

The sediment-water interface flux of DIC and TA is higher and more immediate for the 0.9/0.09/0.01 (fast/slow/refractory) than for the 0.4/0.4/0.2. In Figure 20 it can be seen that for 0.4/0.4/0.2 it takes considerably more time to reach the maximum outflux than for 0.9/0.9/0.01 (Figure 21), something that can also be observed for the higher bioturbation (Figure 22 & Figure 23). The delayed and reduced flux to the bottom water has different reasons for the different parameters. The change in ratio means that a larger fraction has the slow degradation rate, delaying the response. The higher bioturbation spreads the POC over greater depths, which consequently takes longer to degrade and longer for the products to reach the sediment-water interface. For both the 0.4/0.4/0.2 and the bioturbation of 0.06 the carbon retention in the sediment is also higher (Table 7). Furthermore, more oxygen is depleted at high bioturbation which then takes longer to return to the original oxygen profile. Not only added material but also the background phytoplankton POC is mixed deeper, adding to sequestration. Another parameter contributing to sequestration are the **decay rates**. Where high decay rates decrease carbon retention in the sediment and low decay rates increase it. Higher decay rates also lead to more DIC produced relative to TA, and therefore has an acidifying effect on the water column.

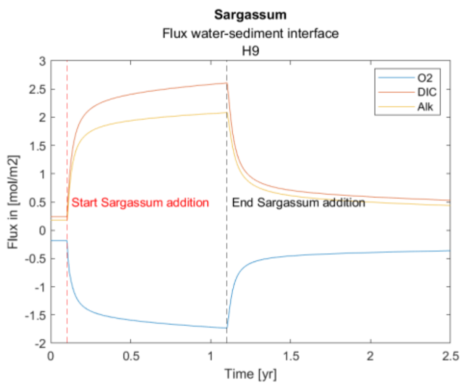

Figure 22: bioturbation 6e-2

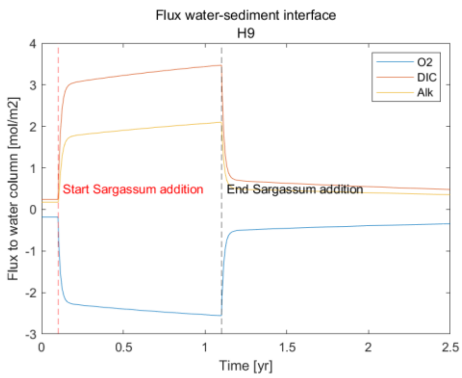

Figure 23: bioturbation 3e-5

Bottom water oxygen concentration regulates the oxygen supply to the sediment, which in turn regulates the degradation pathways. Directly, by oxidation of POC and indirectly by

oxidation of metabolites. Therefore, low concentrations will result in a decrease of aerobic degradation and an increase in anaerobic degradation products. Because the benthic fauna responsible for bioturbation also utilise oxygen, the mixing will also decrease at low oxygen concentrations. This is very apparent in the results as well, where low oxygen produces less alkalinity and DIC and the mixing is shallower (Table 7).
When comparing input duration, it appears that the input duration for optimal carbon retention in the sediment lies somewhere between half a month and two months (Figure 24).

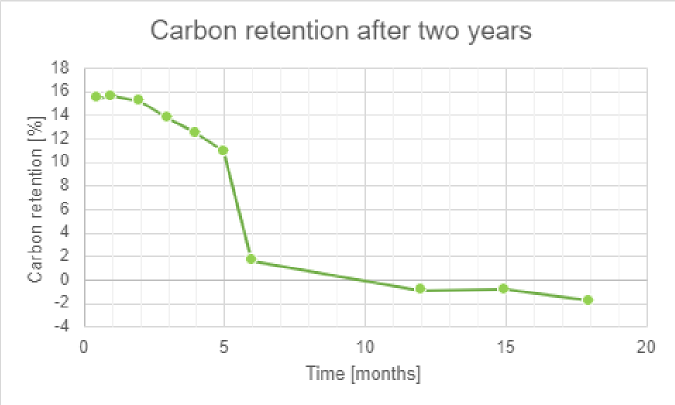

Figure 24: carbon retention as a result of input duration

Table 7: out- and inflow over the sediment water interface and carbon retention for all sensitivity runs

Run	ref	442	992	kf170	kf40 ks0.08	Db0.06	Dbs3e-5	C:N:P1106:38:1	$dO_2w0.28$	$dO_2w0.2$	$dO_2w0.1$
dO_2	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.20	0.10
Foc	3.03	3.03	3.03	3.03	3.03	3.03	3.03	3.03	10.00	10.00	10.00
Input duration	1 year	1 year	1 year	1 year	1 year	1 year	1 year	1 year	1 year	1 year	1 year
C%	-0.46	19.30	-31.90	-13.73	-0.69	15.38	-9.30	-15.68	-0.94	6.43	17.16
TA/DIC	0.76	0.72	0.73	0.69	0.74	0.83	0.59	0.73	0.75	0.75	0.77
TA-DIC	-0.98	-0.67	-1.09	-1.07	-0.80	-0.43	-1.36	-0.95	-2.51	-2.31	-1.89
Run	$dO_2w0.4$	T0.5	T1	T2	T3	T4	T5	T6	T15	T18	
dO_2	0.40	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28	
Foc	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	
Input duration	1 year	1/2 month	1 month	2 months	3 months	4 months	5 months	6 months	15 months	18 months	
C%	-9.72	15.43	15.56	15.16	13.73	12.44	10.89	1.61	-0.89	-1.81	
TA/DIC	0.76	0.84	0.84	0.83	0.81	0.80	0.79	0.79	0.74	0.73	
TA-DIC	-2.61	-1.39	-1.33	-1.43	-1.60	-1.74	-1.87	-2.08	-2.62	-2.71	

Discussion

This study explored the effect of ocean afforestation on deep seafloor biogeochemistry by modelling different types of particulate organic matter input to the sediment in three locations. The early diagenesis model RADI was used and adapted to add POC fluxes of different composition, quantities and over different time scales in order to visualise the impact on carbonate species, alkalinity and oxygen among others. Understanding the biogeochemical response to allochthonous input is essential to estimating the short- and long-term changes to the benthic environment. As well as understanding the fate of the sequestered carbon and predict at which timescales the carbon will potentially resurface.

Sinking allochthonous organic matter to deep sea sediments is an effective way to remove carbon dioxide from the atmosphere. However, the effects on deep sea biogeochemistry cannot be neglected, since ocean afforestation can have significant short- and long-term consequences. Added POC to the seafloor always results in a reduction of oxygen and other electron acceptors. Sinking high quantities of seaweed at once, pulse inputs, often results in hypoxic conditions in the sediment which can take years to replenish. The reason for this slow return is because the fastest way to supply oxygen to deeper layers is through irrigation, which relies on benthic activity which is suppressed under hypoxic conditions. Generally, smaller amounts of POC added over longer times helps avoid hypoxic conditions but this assumption conflicts with another finding. When modelling the response to *Saccharina*, the input duration for the same influx (2 kg/m^2 = 45.8 mol C) was set to 3 days and 2 months. Notably, in this case the oxygen concentrations flow back to the sediment faster for the three-day addition compared to the two months. This is likely due to the increased decay rates, which is calculated based on POC input per time unit, which is higher over the three days in order to arrive at the same total POC input. The higher decay rates remove more POC during addition, which consequently uses less oxygen after addition. When the input duration for *Sargassum* was changed, which has a set decay rate, the recovery for the three day and two-month addition were very similar for both 3 days and 2 months, confirming the assumption that decay rates influence this response. The way that decay rates are set in modelling is somewhat arbitrary, where rates are often parameters adjusted in order to fit the model results to real life data. A better understanding of decay rates is nevertheless necessary to more accurately predict the responses to POM. One of the main questions that will have to answered is whether decay rates are actually dependent on the amount and type of POM or rather on the benthic community and local conditions (pH, temp, oxygen). The answer will be essential when considering carbon sequestration potential and effect to biogeochemistry.

Ocean afforestation approaches

The Running tide approach is based on growing *Saccharina* on buoys made from terrestrial matter. Adding the seaweed in pulse additions appeared to give the highest carbon retention (up to 25%) and TA/DIC ratio, but the oxygen depletion connected to this addition could be detrimental to benthic life. The continuous addition of *Saccharina* still had one of the highest carbon retention with 31.9% after two years. The combined runs of *Saccharina* and woody biomass showed that the 1/9 ratio (seaweed/wood) had the highest carbon retention (90.4%), but the 9/1 ratio had the highest TA/DIC ratio (0.90). Whereas the 5/5 ratio showed the highest oxygen depletion. Overall, spread out or low quantity sinking of *Saccharina* with woody biomass seems to be the best approach.

The pull to refresh approach is based on sinking naturally occurring *Sargassum.* Highest carbon retention (25% after two years) for this species is also for pulse addition, whereas the continuous addition actually showed negative carbon retention (-15% after two years), meaning that not only all the added POC is remineralized but also carbon stored in sediment flows to the bottom water as inorganic carbon. This difference to other approaches might be attributed to the fixed decay rate for *Sargassum.* The decay rate is much lower for pulse addition leading to slower degradation compared to pulse additions of the other approaches but faster degradation for continuous additions. This fast degradation produces a lot of CO_2, which triggers calcite dissolution and produces alkalinity that eventually enters the bottom water. The slower decay rates for the pulse addition led to excessive oxygen usage over longer times, leaving the sediment in hypoxic conditions for longer. A compromise between high carbon retention and low impact will have to found to optimize this approach.

The Southern Ocean Carbon company approach is based on sinking cultivated *Macrocystis.* Carbon retention is higher for pulse addition, ≈32% for pulse additions after two years, whereas only 0.6-2.7% for continuous addition. *Macrocystis* has a less depletory effect on oxygen compared to the other seaweed, therefore bundling seaweed for sinking might be the most effective approach.

The carboniferous approach is based on sinking residual terrestrial matter to anoxic basins. OM which would normally release all the containing carbon back in the atmosphere in a few years. This approach had the highest sediment carbon retention (50% after two years) and had the least acidifying effect on the bottom water. The added sugarcane bagasse forms a layer on top of the sediment, because there is no bioturbation in anoxic water, no mixing or irrigation occurs. Furthermore, due to the low degradation rate, the carbon can remain in its organic form for multiple years. Since most degradation occurs via anaerobic pathways relatively more alkalinity is produced, being approximately equal to the DIC production. The alkalizing effect on the bottom waters in accordance with research by Fakharee, Planavsky & Reinhard (2022) which state that reduced oxygen penetration depth leads to increased alkalinity production and consequent flux to the bottom water. Though H_2S was produced by this approach, the concentration was relatively low due to the low degradation and the conditions in the orca basin are already very saline and sulfidic. The current approach of sinking 100 g/m2 is effective and has limited effects on biogeochemistry.

Effects on biogeochemistry and fate of organic carbon

The difference between TA and DIC concentrations in seawater shows a strong relation with pH (Xue & Cai, 2020). In Figure 25 from Xue & Dai (2020) the relation is visualised. This can be related to the outflow of TA and DIC into the bottom waters. Since the pH is based on an absolute difference, when the outflow of TA and DIC are not equal, the pH will change. When the DIC flux is higher than TA, the pH will decrease, if TA is higher the pH will increase.

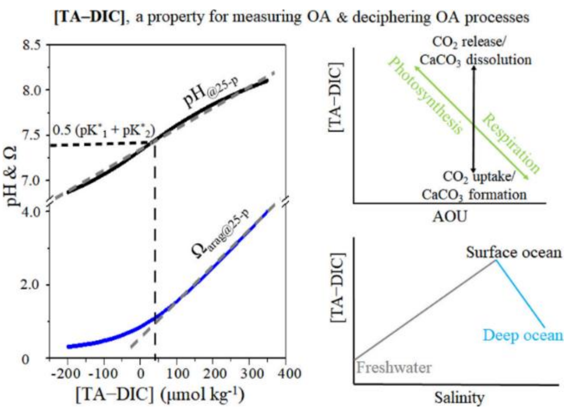

Figure 25: Graph by Xue & Dai (2020) showing the relation of the absolute difference between TA and DIC to pH. OA in this figure stands for Ocean Acidification

Adding seaweed to oxygenated sediments will result in more DIC production compared to total alkalinity, resulting in a lowering of the bottom water pH. However, when organic matter is added to hypoxic or anoxic sediments, relatively more alkalinity is produced. In some cases even increasing the pH of the bottom water. The pH and alkalinity of the bottom water are relevant for the benthic ecosystem and eventually for the atmospheric carbon when the water resurfaces. Where more alkaline water allows CO_2 uptake and high DIC concentration decreases CO_2 uptake. The location of CO_2 production is important for the alkalinity profile and the outflow of DIC and TA. The deeper the POC is mixed the slower degradation occurs and the deeper in the sediment CO_2 is produced. CO_2 production at depth leads to alkalinity production at depth, which is retained longer in the sediment. CO_2 production near the interface, leads to high TA and DIC outflow. Oxygen concentrations are also relevant for carbon retention in the sediment. Since bioturbators need sufficient oxygen levels to function, and high POC input leads to high biological activity and oxygen depletion which slows down degradation. Because oxygen is used in the fast degradation pathways, oxygen correlates both with bottom water acidification and fast POC mineralisation, resulting in reduced carbon retention in the sediment.

Integral to optimizing ocean afforestation practices, is finding the ideal approach to sinking seaweed. The question is whether to sink the seaweed at once/one location or spread it out over time and space. From this research it appears that more carbon is retained in the sediment at high inputs, meaning that sinking all the seaweed at once is ideal for carbon sequestration. There does appear to be an optimum, where for *Sargassum* the optimal carbon retention lies somewhere between 0.5- and 2-months input duration, though this is likely to differ per species and location. Furthermore, very refractory POC is more likely to be retained within the sediment. However, most ocean afforestation initiatives showed no intention to process the seaweed, instead mostly fresh biomass is sunk. Organic material which has had time to drift and sink has degraded most of its labile OM and will be more refractory in nature, which has less effect on sediment biogeochemistry and is less likely to enter bottom waters as DIC. This seemingly contradictory practice of sinking fresh OM should be considered carefully. Apart from the effect on ecosystem and reduction of sediment carbon retention, fresh material also contains more essential nutrients which consequently also disappear from the nutrient cycle over large time spans. Disturbing both the surface and deep-sea ecosystem balance. From a carbon accounting standpoint current approaches can be considered effective. However, considering carbon sediment retention increases the time the carbon is stored away and the stability of benthic ecosystem, it would be advisable to process (nutrient extraction) the seaweed before sinking. Which allows an additional economic benefit, reduces ecosystem impact and increases the carbon retention (by increasing the refractory nature. Lastly, harvesting certain compounds will replace land-based product, adding to the Sustainable development Goals and ensure additional societal benefit.

Risks

The main risks of ocean afforestation are light and nutrient competition at the surface of the ocean and oxygen depletion and toxic by-products at benthic levels. There are many known and unknown risks with dumping organic material in the ocean. Organic matter has a strong and close link to biological activity and water chemistry. At the surface, if the macroalgae is cultivated offshore, macroalgae and phytoplankton compete for light and nutrients (Boyd et al., 2022). Competition for nitrogen and phosphorus leads to either a decrease in phytoplankton growth, reducing natural carbon sequestration from phytoplankton POC, or lower macroalgal productivity. Since phytoplankton have been shown to decrease nutrient concentrations at the surface waters to nearly zero (Bach et al., 2021), the competition seems inevitable. However, the extent of the sequestration offset depends on the overlap between the macroalgal growth area and phytoplankton blooms. A solution to this problem is either fertilisation/artificial upwelling of nutrient-rich deep-sea water or strategic seaweed production. Another risk to growing seaweed offshore, is the uncertainty of the effect the pH, temperature, nutrient and light changes have on growth and the quality of the POM (Boyd et al., 2022).
One more risk of large scale open sea cultivation of seaweed is demonstrated by Bach et al. (2021) who showed that the CO_2 removed from the surface water by *Sargassum* in the great Atlantic *Sargassum* belt required 2.5-15 months to be replenished by air-sea CO_2 diffusion, whereas the residence time of the

surface layers in these location are only 0.3-1.5 months, not fulfilling the CDR potential. Though this CO_2 depleted water may fulfil its potential over longer timescales, it is not suitable for short time CDR calculations. Lastly, when naturally occurring seaweed such as *Sargassum* are used for sequestration, the population is likely to decline over the years. If initiatives intend to continue using naturally occurring species, an effort will have to be made to ensure the population is maintained.

On the seafloor there are two main risks. Oxygen depletion which happens when more oxygen is used up in degradation than can be replenished, is detrimental to benthic life. Furthermore, when oxygen is depleted other degradation pathways will take over. Normally, the metabolites of the reaction are oxidised to their original form by the remaining electron acceptors. At very high OM fluxes, however, the degradation pathways are faster than the reoxidation and the metabolites can get released into the bottom waters. Especially methane and hydrogen sulphide provide a risk since the first one is a greenhouse gas and the second is toxic to most aquatic life. Lastly, oxidation of the metabolites produces protons leading to the acidification of the bottom water. Still, there also benefits associated with ocean afforestation, such as reducing eutrophication caused by human activities, providing habitat for other organisms such as fishes, and locally reducing ocean acidification (Ross, Tarbuck & Macreadie, 2022).

Limitations

The goal of this study is not to make exact predictions of the biochemical response to ocean afforestation. Rather it is aimed at providing a guide to the effect different ocean afforestation approaches can have on the biogeochemistry of the seafloor. Information on the duration of the system returning to steady state after addition is purposefully omitted. Not only are steady states a theoretical condition, due to the physical, chemical and biological variability in each moment in time. It also gives a false sense of 'safety', that after a certain period of time the consequences of an action are negated, regardless of the consequences the action has had on the composition of the benthic community or on water chemistry. Furthermore, the model gives an indication of a response to a forcing rather than exact value for sequestration, duration and changes. The research and model can be used in future research to make more accurate predictions if all parameters are known. Following are some limitations to this study which can be improved upon.

Large amount of POC deposition on the sediment limit oxygen supply and increase the sediment height. Resulting in an altered influx of oxygen to the sediment as well as a lower POC mixing due to time it takes benthic biota to transport and process the OM. This could not be implemented into the model because it required altering the sediment height and estimating the decrease in oxygen inflow.

Furthermore, because bioturbation is calculated with the total POC input, this means there is no differentiation between the fast, slow and refractory degrading OM. Invalidating any relation between these variables, whereas in reality labile and refractory matter have significantly different effects on bioturbation. Lastly, the bioturbation implemented in this model changes instantly from the background bioturbation to the new value based on the additional POC. Though this might not be realistic, the actual time it will take for bioturbation and irrigation to adjust to new organic matter inputs is unknown and should be further researched.

Apart from being anoxic, the orca basin used in the Carboniferous approach is also extremely saline and sulfidic. How this influences the sequestration should be explored in further research. One thing that could happen is that the density of the organic matter is not high enough to sink through the saline layer, ending up spread over the halocline where degradation rates and oxygen concentration are different from the seafloor.

Most of the values used in the model, such as decay rates and ratios, are estimations or averages. The greatest progress could be made in this field with experimental data taken in various deep-sea locations.

It would supply the model with more parameters as well as the option to tweak the other parameters in the model to match real life data. Lastly, the model could be expanded to include more locations, coupled to a global climate model or allow differentiation between benthic species on a functional level.

Conclusion

Ocean afforestation affects deep seafloor biogeochemistry by producing CO_2 and depleting oxygen through degradation. Calcite concentration decreases due to decreased saturation state and produce dissolved calcium and carbonate. The carbonate alongside the anaerobic degradation products increase alkalinity which leads to an outflow to the bottom water of both alkaline products and dissolved inorganic carbon. For pulse additions, large amount of POC added over short times, methane and H_2S are produced. Hypoxic conditions in the sediment occur in almost all ocean afforestation approaches and can only be avoided by either using continuous addition, more refractory matter or using larger areas to sink the seaweed.

In order to optimise carbon sequestration, initiatives should look at carbon retention, TA and DIC production as well as oxygen depletion and production of reduced metabolites. This research provides a method to estimate the optimal conditions to maximise carbon retention in the sediment, which affects parameters such as input time and location choice. Carbon retention is highest (up to 50% after two years) for low oxygen basins and pulse addition added over 0.5-2 month time. Combining the seaweed with refractory terrestrial biomass is also an effective way to increase carbon retention. Other factors which increase carbon retention are low decay rates and high bioturbation. When adding to oxygenated bottom waters, however, spreading the POC input out over time and space is essential to avoid hypoxic conditions in the sediment, which can be detrimental to benthic life. Furthermore, pulse input can have an acidifying effect on the sediment and bottom waters.

The run which added sugarcane bagasse to anoxic bottom water, was the only one having a net alkalizing effect on the bottom water. Showing that it is unlikely that for most approaches resurfacing bottom water, would lead to additional CO_2 uptake due to ocean afforestation.

Pre-processing the seaweed to increase the refractory nature of the organic matter is beneficial for three reasons. It increased carbon retention, has the least effect on ocean biogeochemistry and allows essential nutrient such as nitrate and phosphate to remain in the nutrient cycle.

This research and its model are the first step to understanding the potential and risks of ocean afforestation. Future research and CDR initiatives can continue on this research with in-situ experiments or coupling to climate model.

Data availability

Full code is available on GitHub: https://github.com/Merel-lanjouw/RADI_OceanAfforestation

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Appendices

Appendix 1: adjusted variables RADI

Notation	Description	Adjustment
z_res	Depth resolution [m]	Increased to avoid numerical errors
stoptime	Total simulation time [a]	Decreased to reduce run time, increased for long time effects
interval	Time steps [a]	Increased to avoid numerical errors
RC	Redfield ratio for carbon	Adjusted to fit OM
RN	Redfield ratio for nitrogen	-
RP	Redfield ratio for phosphorus	-

D_bio	Bioturbation coefficient [m2/a]	Adjusted to forced Foc
alpha	Irrigation coefficient [/a]	-
dO_2	Dissolved oxygen [mol/m3]	Adjusted to include new Foc
dalk	Total alkalinity [mol/m3]	-
$dtCO_2$	Dissolved inorganic carbon [mol/m3]	-
dCa	Dissolved calcium [mol/m3]	-
dtNO3	Dissolved inorganic nitrogen [mol/m3]	-
dtSO4	Dissolved inorganic sulphate [mol/m3]	-
dtPO4	Dissolved inorganic phosphorus [mol/m3]	-
dtNH4	Dissolved inorganic nitrogen [mol/m3]	-
dtH_2S	Dissolved inorganic sulphide [mol/m3]	-
dFe	Dissolved iron [mol/m3]	-
dMn	Dissolved manganese [mol/m3]	-
procs	Refractory particulate organic carbon [mol/m3]	-
psocs	Slow-decay particulate organic carbon [mol/m3]	-
pfoc	Fast-decay particulate organic carbon [mol/m3]	-
pcalcite	Calcite [mol/m3]	-
paragonite	Aragonite [mol/m3]	-
$pMnO_2$	Manganese (IV) oxide [mol/m3]	-
pFeOH3	Iron (III) hydroxide [mol/m3]	-
pclay	Clay* [mol/m3]	-
Foc	Flux of total organic carbon to the bottom [mol/m2/a]	No adjustment
Froc	Flux of refractory organic carbon to the bottom [mol/m2/a]	-

Fsoc	Flux of slow-decay organic carbon to the bottom [mol/m2/a]	-
Ffoc	Flux of fast-decay organic carbon to the bottom [mol/m2/a]	-
Focs	Foc for added POC [mol/m2/a]	New variable
Frocs	Froc for added POC [mol/m2/a]	-
Fsocs	Fsoc for added POC [mol/m2/a]	-
Ffocs	Ffoc for added POC [mol/m2/a]	-
dO_2w	Dissolved oxygen bottom waters [mol/m3]	Adjusted for sensitivity analysis

Appendix 2: species parameters

	Sargassum	Saccharina latissima	Macrocystis	Sugar cane bagasse
Wet biomass density	8,25 kg/m2	200 t wet weight ha-1 (Hughes et al., 2012)	14,4 kg/m rope (Gutierrez et al., 2006)	
Dry biomass density		20 t DW ha-1	1,656 kg/m	
WW:DW			0,115 (Wickham et al., 2019)	
Amount sunk				100 g/m2/a (D. Felker, personal communication, October 6, 2022)
Carbon content	40 g/kg WW	27,5% DW	30% DW	405 g/kg
Total carbon content	330,3 g/m2	550 g/m2	496,8 g C/m	40.5 g C/m2 (Melo et al., 2020)
Molar mass carbon	12,01 g/mol			12,01
Total carbon in mol	27,50 mol C/m2	45,80 mol C/m2	41,37 mol C/m	3.37 mol C/m2
Carbon sequestered (%)	11%		2,3% (Bayley, Marengo & Pelembe, 2017)	-
Potential sequestration		4.77 t CO_2·ha-1 (Sondak & Chung, 2015) 477 g CO_2/m2		
Molar weight CO_2	44,01 g/mol	44,01 g/mol		
Natural carbon flux	3,03 mol C/m2	10,84 mol C/m2	0,95 mol C/m2 (over 9 months)	
Artificial sinking flux	27,50 mol C/m2 (at once)	45,80 mol C/m2	41,37 mol C/m2 (at once)	3.37 mol C/m2 (at once)

C:N:P	797:47:1	630:70:1 (Lubsch, Lansbergen & Poelman, 2020)	222:11:1 (Atkinson & Smith, 1983)	405:20:3 (Frazão et al., 2020)
	Hu et al., 2021; Gouvêa et al., 2020; Gouvêa et al., 2021			

Ratio seaweed	0.9	0.7	0.5	0.3	0.1
Ratio wood	0.1	0.3	0.5	0.7	0.9
Bioturbation	only seaweed	only seaweed	only seaweed	only seaweed	only seaweed
Total amount (g)	500	500	500	500	500
Seaweed (g)	450	350	250	150	50
Wood (g)	50	150	250	350	450
Seaweed (mol C)	1.030	0.801	0.572	0.343	0.114
Wood (mol C)	2.082	6.245	10.408	14.571	18.734
Total (mol C)	3.112	7.046	10.980	14.915	18.849
Refractory fraction	0.127	0.321	0.515	0.709	0.903
Slow fraction	0.243	0.189	0.135	0.081	0.027
Fast fraction	0.630	0.490	0.350	0.210	0.070

Appendix 3: location parameters

Location	N. Atl. (H9) (Hales et al., 1994)	Southern O. (SM7) (Sayles et al., 2001)	Eq. Pac. (W2) (Hammond et al., 1996)	Orca basin
Depth	5210 m	3860 m	4370 m	2400 m
Bottom water conc				
Talk	2342			
CO_2	2186			
Temperature	2,2	0,84	1,4	
Salinity	34,9	34,696	34,69	215
Oxygen	266,6	215,7	159,7	0

Calcite saturation state	0.88	0,85	0,78	
Fluxes				
Calcite	0,2	0,25	0,22	
POC	0,18	0,14	0,2	
Clay	26	32	2	
Porosity				
Boundary layer	938 µm	715 µm	1 mm	