Methods to assess Blue Carbon Potential of Seaweed Culture at the North Sea: feasibility study

Desk study & Review workshop

DATE
March 2020

AUTHOR
Jeroen Veraart
Arjen de Groot
Cor Jacobs
Wilma Jans
Mandy Velthuis
Judith Klostermann

Review
A previous version of this memo was used as the basis for a review workshop (20 January 2020) with the participation of experts from the Noordzee Boerderij foundation and Wageningen Marine Research.

Table of contents

1 Introduction and approach

1.1 background

Our global climate is changing, and rising greenhouse gas emissions is one of the causes. The IPCC underpins the need to scale up and accelerate efforts to upscale and acceleration of far-reaching, multilevel and cross-sectoral climate mitigation and adaptation measures. Land use is known to determine the emission of the greenhouse gases from Dutch (agro)ecosystems. Marine and estuarine systems are also increasingly seen as an alternative location for food and sustainable energy production in the light of the increasing world population and the desire to reduce the climate footprint of food production on land (arable farming, livestock farming).

An interesting question is how marine food production (seaweed aquaculture) can be designed in such a way that the food chain (from primary production to consumer) becomes a net carbon sink. An important condition is also that marine food production is combined with the reinforcement of the ecological carrying capacity and biodiversity of the North Sea ecosystem. We focus on measures that are meant to relocate carbon from the short to the long cycle in which marine flora and fauna play an important role (This is our work definition of 'Blue Carbon').

Policymakers need instruments to verify the ‘Blue Carbon Sequestration Performance’ in order to assess the efforts of economic sectors to achieve a climate compatible and circular production of marine resources in view of national climate policies. At the same time, the annual sequestered carbon represents a potential market value for entrepreneurs.

1.2 Approach

This memo formulates guidelines for a monitoring & evaluation strategy that can provide future information on the ‘Blue Carbon Sequestration Performance’ of Seaweed aquaculture. We start with an exploration of the necessary innovations in existing monitoring techniques. We want to assess the added value of a monitoring and evaluation strategy that combines:
1) Sediment Traps & mesocosms;
2) E-DNA biomonitoring
3) Eddy Covariance measurements at Sea.

The assessment for each methodology uses the following criteria:
- Manageable / user-friendly (model/report tool)
- Technical Applicability (including opportunities)
- Scientific logic: *Do I measure the right thing?*
- Cost-effective
- Dutch Climate Policy needs
- Possibility to benchmark CO2 sequestration for seaweed entrepreneurs

2 System analysis: Carbon Fluxes at Seaweed farms

2.1 Introduction

In marine environments, carbon is constantly exchanged between the atmosphere and the water column. CO_2 dissolves in water, where it is in equilibrium with other inorganic molecules (carbonate and bicarbonate) which are together referred to as dissolved inorganic carbon (DIC). Yet, due to the presence of biological life, the blue carbon cycle is far more complex, containing fluxes between numerous forms of organic carbon, of which the most important are schematically visualized in Figure 1.

In marine systems, phytoplankton is the major contributor to primary productivity: the fixation of CO_2 into organic molecules via photosynthesis. This is especially true in eutrophic coastal ecosystems, where phytoplankton abundance and diversity are much higher than in the open sea (Tang et al. 2018). From the phytoplankton, carbon is transported and transformed through the biological food web and food chain. Grazing of phytoplankton mainly is done by non-automobile heterotrophic organisms, together referred to as the zooplankton. Both planktonic groups consist of a large variety of taxa that widely vary in size, morphology and function. In turn, zooplankton is eaten by larger animals (macrofauna), such as fish. Ultimately all these life forms die, and if incorporated into a higher trophic level, their remains result in particulate organic matter or carbon (POC) that sinks towards the sea bed. This flow of carbon through the food web towards the sea bed is often referred to as the biological carbon pump or biological deposition pump and forms the main mechanism for incorporation of blue carbon into the long carbon cycle.
Yet, only a fraction of the POC is incorporated in the sea bed. Most of the carbon contained in the particles becomes available as dissolved organic molecules (dissolved organic carbon or DOC) either due to direct leakage from biological cells, or via decomposition by a large variety of (micro)organisms (bacteria, but also fungi and protists). In fact, leakage to the DOC also occurs when carbon is being transferred between trophic stages in the biological food web, for instance when algal cells burst when being grazed by zooplankton or when small animals are killed and eaten by predators.
Most of the DOC is eventually further decomposed into inorganic molecules by microbes. However, a small but relevant fraction is transformed by microbes (mainly bacteria and archeae) to more stable organic molecules that may remain in the water column for hundreds or thousands of years as so-called recalcitrant dissolved organic carbon (RDOC), resulting in additional sequestration into the long carbon cycle (Jiao et al. 2010).

The introduction of a seaweed farm into the local ecosystem results in an even more complex blue carbon cycle, that in a way resembles that of a coastal system, containing one or more taxa of macroalgae as a second group of primary producers. Part of the carbon fixed in the macroalgae in a seaweed farm is eventually harvested. Although some of the remaining fraction is leaked to the DOC upon decay, a significant part is transported through the food web (e.g. via faunal grazing), contributing to the sequestration of carbon in the sea bed (Krause-Jensen et al. 2018). Yet, apart from this direct sequestration effect, the presence of macroalgae in the system may also influence the cycling of blue carbon by altering the local food web. Notably, their surface forms an important extra habitat for benthic organisms, which in turn form a food source for other organisms. As a result, seaweed farms may enhance the local biodiversity. Whether these changes in the local food web all together enhance or hamper carbon sequestration, remains largely unknown. While evidence exists that in non-harvested systems the presence of macroalgae may support carbon burial (Krause-Jensen et al. 2018), more research is needed to assess to what extent the construction of a commercial sea weed farm enhances the blue carbon sequestration performance of the local system.

Importantly, although Figure 1 presents a static situation only containing fluxes within the local ecosystem, water currents result in significant lateral influx and efflux of the dissolved carbon (DIC, DOC, RDOC) as well as the biological components and the POC. Yet, currently there is no established method to measure such lateral fluxes (Tang et al. 2018).

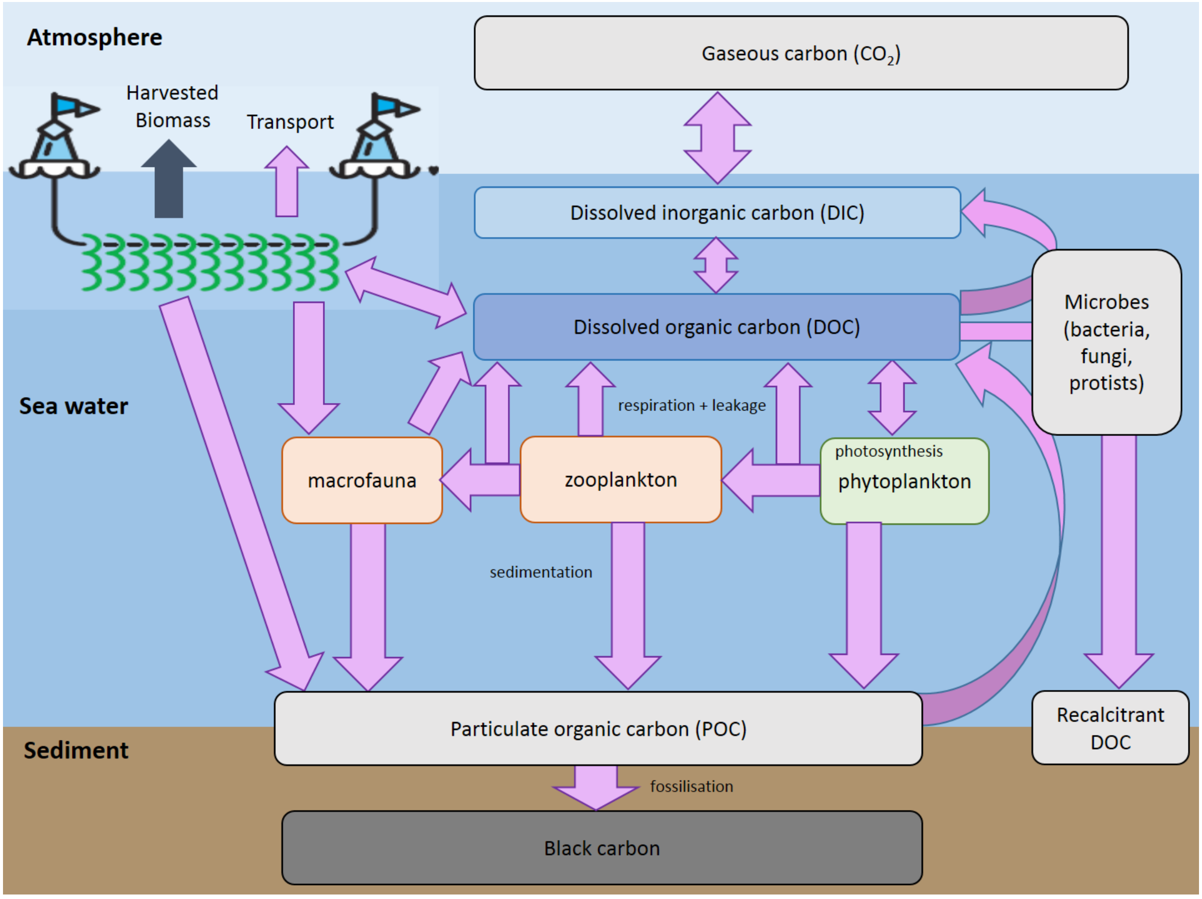


Figure 1*, Schematic overview of main fluxes of carbon in marine ecosystems containing a seaweed farm. NB: size of the arrows does not scale with the mass of carbon transported.*

Figure 1 shows the contours of how carbon flows can be influenced by seaweed cultivation based on expert judgment. This sketch is not complete, but it helps to think about the design of a monitoring and evaluation. strategy.

2.2 Baseline Blue Carbon and impact assessment

The impact of a seaweed farm on marine carbon fluxes can be assessed in several ways. Most of the carbon in the form of seaweed that is grown on the farm is harvested for commercial purposes. A method to assess the amount of CO2 taken up by the seaweed would be to determine the biomass and the carbon content of (a subsample from) the harvested seaweed. As one CO2 molecule provides one carbon atom for the seaweed-biomass, the harvested carbon in the seaweed biomass can be directly linked to its CO2-uptake. Related to this, it can be decided to not harvest part of the seaweed from the farm, but rather leave that material to be sedimented. This carbon then becomes part of the short-term carbon cycle (Hain et al., 2014). Most of this carbon will be consumed or degraded by marine organisms, while a small fraction sinks towards the sea bed where it can be stored as recalcitrant carbon in the long-term carbon cycle (figure 1).

Another important carbon flux on the seaweed farm is the sedimentation of organic carbon, either formed by the seaweed itself or by related organisms. The impact of the farm on the sedimentation flux can be assessed in a number of ways and a baseline is needed (figure 2):

- Comparing sedimentation fluxes at the farm and a reference site. When the seaweed is growing on a line between two buoys, a reference site could be a nearby buoy without seaweed on it.
- If the comparison between reference sites and seaweed farm is not practically feasible, an alternative could be time-for-space-substitutions. Traditionally done as a space-for-time-substitution, this method is commonly used to assess climate warming impacts on ecosystems (Kosten et al., 2012; De Frenne et al., 2013). However, this method could also work in the other way around, by comparing sedimentation fluxes at the seaweed farm before the growing season, during the growing season and after the harvest. Ideally, this method would involve a measurement before the instalment of a seaweed farm and would be best suited for newly start-ups in this type of farming. Nonetheless, it can be implemented on seaweed farms that are already established and still give indications on how the presence of seaweed impacts the sedimentation of carbon.
- Comparing sedimentation rates in the presence and absence of seaweed in mesocosm systems. Mesocosm experiments allow for the manipulation of a specific ecosystem component and assessing the impact of that component on the remainder of the (simplified) ecosystem (Sagarin et al., 2016). Mesocosms can thus be used to experimentally address the impact of the presence of seaweed on sedimentation and biodiversity. However, as these systems don't directly scale to the complexity in the field situation, care must be taken to extrapolate its findings.

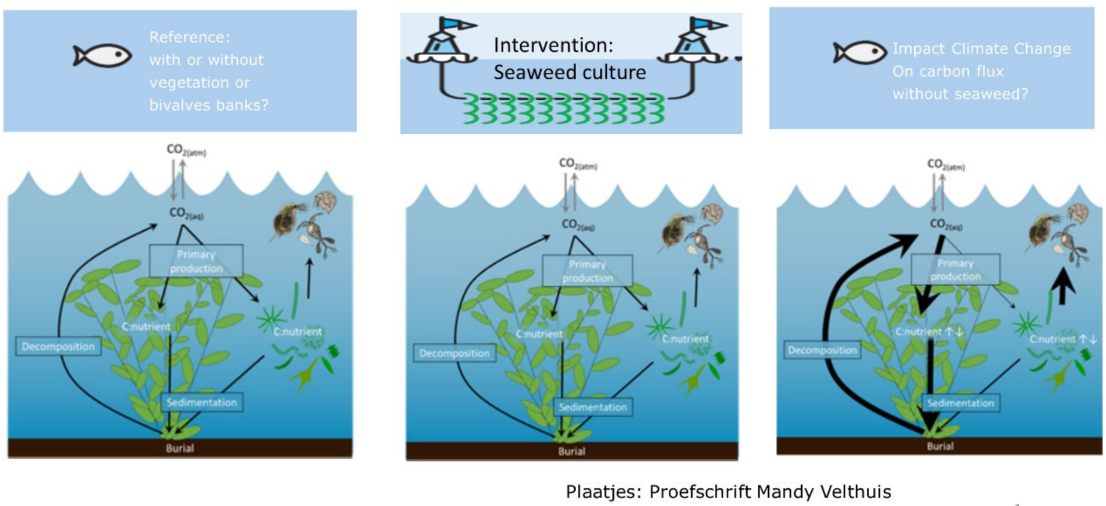


Figure 2*, What are useful reference situations and scenarios to discuss the impact of seaweed farms on the carbon cycle? (visual provided by Mandy Velthuis)*

2.3 Policy aspects and user needs

Policy instruments are needed to verify the 'Blue Carbon Sequestration Performance' in order to assess the efforts of economic sectors to achieve a climate compatible and circular production of marine resources in view of national climate policies. At the same time, the annual sequestered carbon represents a potential market value for entrepreneurs.

2.3.1 Dutch Climate policy

The total Dutch national greenhouse gas emissions amounted to 199 Mton CO_2-eq year^{-1} in 2017 (Ruyssenaars et al. 2019). Compared to 1990, the Netherlands achieved around 12% greenhouse gas emission reduction for all sectors in 2017. The reported emissions originate from the legal territory of the Netherlands. Technically, this also includes a 12-mile zone out from the coastline and inland water bodies. The annual national greenhouse gas reporting of the Netherlands includes, the Waddenzee, the Rhine-Meuse Estuaries in the South, lake IJssel and Lake Marker. They are part of the annual GHG emission inventory, however, with an emission factor assumed with a default value of zero (Arets et al., 2019). The used emission factors for open water, coastal wetlands, tidal marshes, seagrass meadows and aquaculture are currently reconsidered (IPCC, 2019).

The Dutch part of the North Sea has not been considered in this annual inventory. The relative contribution of economic activities in the Dutch part of the North Sea to the annual national greenhouse gas emissions is difficult to determine. Emissions come, for example, from navigation (fossil fuels), fisheries (storage cooling), construction (offshore wind, oil platforms) and mining. The water column and bottom of the North Sea and Wadden Sea also probably play a modest role in the exchange of greenhouse gases in the atmosphere (Nellemann et al., 2009).

Nellemann et al. (2009) reports a mean carbon burial rate of seagrass of 3 tonnes C ha^{-2}/yr^{-1} in natural ecosystems, however the bandwidth of uncertainty around this estimation of carbon capture is high (Teunis & Foekema, 2015; Foekema et al., 2018). A difference between seagrass and seaweed is that seaweed has no roots and therefore will capture less carbon in the soil after sedimentation.

Blue carbon can be defined as the carbon stored in marine and coastal ecosystems – in biomass, buried in sediments and sequestered from the atmosphere and ocean. Blue Carbon, as a whole (this is broader than only carbon capture to the marine soil), is considered as climate change mitigation measure in the OSPAR maritime area (OSPAR, 2015). Open seaweed farming systems can also be used a s resource for bioenergy with net carbon sequestration (Aitken et al., 2014). From studies using Life Cycle Analysis (LCA), some priorities within the environmental impacts can be derived. Still, there is considerable uncertainty regarding both the positive and negative environmental impacts of seaweed cultivation (Van den Burg et al., 2018).

Dutch policies primarily look at the North Sea as an alternative to land-based food production and onshore energy supply, whereby it is assumed that both can be achieved at sea with a lower carbon footprint. It should be noted that the sea is already highly productive (Van der Meer, 2020). Carbon reduction by offshore seaweed cultivation is also possible because animal feed production at land has a larger carbon footprint (Scholten, 2018).

The Dutch climate agreement (Klimaatberaad, 2019) mentions opportunities for the development of aquaculture (seaweed cultivation) in combination with nature development, the sequestration of greenhouse gases and the construction of offshore wind farms. No quantitative targets have been set, upscaling of seaweed cultivation combined with reduction of greenhouse gas emissions has been formulated as a knowledge and innovation challenge.

---

[1] To be able to compare this properly with other numbers about emissions, it is necessary to convert this number from C to CO2 and to CO2-eq.

2.3.2 Entrepreneurs

Carbon offsetting—receiving credit for reducing, avoiding, or sequestering carbon—has become part of the portfolio of solutions to mitigate carbon emissions, and thus climate change, through policy and voluntary markets, primarily by land-based re- or afforestation and preservation (Froelich et al, 2019; GDNK, 2018). However, land is limiting, creating interest in a rapidly growing aquatic farming sector of seaweed aquaculture. However, we have found no examples yet with sea farms. Carbon offset projects at land with a monetary value of around 5 € ton^{-1} CO2-eq according to (Hamrick and Gallant 2018), with this carbon price and the realized carbon sequestration at land the potential benefits for the land owner are approximately 30-120 € ha^{-1} jr^{-1}. In future the carbon price can become higher, see for example the current price developments in the Emission Trading System of the European Union (ETS). ETS is only a CO2-emission market for specified industries (aquaculture is not part of that). Within ETS a carbon price was used that ranged between 20 up to 30 euros per ton of avoided CO2 emissions in 2019.

3 Sediment traps

As indicated in chapter 3 (Figure 1), particulate organic carbon arrives at the sea bed by means of sedimentation. Sedimentation is the rate at which floating or suspended particulate particles sink and accumulate on the sediment. The sedimentation flux thus determines directly the export of carbon from the upper layers in the water and is important to consider in assessing the blue carbon potential of an ecosystem. A standard way of assessing sedimentation rates in the field is by placing a so-called sediment trap in the ecosystem and emptying the contents at regular time-intervals. This chapter summarizes current knowledge and feasibility on sedimentation rates for Blue Carbon purposes.

3.1 Scientific logic (Do I measure the right thing)

Sediment traps allow us to directly assess the amount of sedimented material (organic and inorganic) in situ. Depending on how often these traps will be sampled, it is possible to either estimate daily/weekly fluctuations in sedimentation rates or estimate an integrated sediment up build (as some of the material can already decompose while it sinks or while it sits on the bottom of the sediment trap). A downside of these traps is that the sediment trap removes physical contact between the deposited sediment and the sediment that is already present. This may reduce colonisation by organisms and excludes bioturbation. Therefore, the sediment deposition measured with the sediment trap does not equal carbon burial but gives us indications on how much material leaves the upper water layers. The efficiency of sediment traps can furthermore vary substantially between types (Nolte *et al.*, 2013) and care should be taken in selecting which type of sedimentation trap fits the research question and system best.

The amount of sedimented material caught in the sedimentation trap can vary depending on depth of deployment, as the material is degrading while it sinks out. In theory, sedimentation traps that are deployed at a greater depth, therefore approach the Blue Carbon potential of an ecosystem better. However, deploying a sedimentation trap at a large depth is challenging, especially in marine systems. Care must be taken when interpreting these types of results and could be overcome by modelling the degradation of sinking material (Hedges, 1992).

3.2 Manageable / user-friendly (model/report tool)

Depending on their scale, sedimentation traps are quite user-friendly, as they are relatively low-tech and easy deployable in the field. Most often these traps are deployed in the field and emptied at certain time-intervals. This involves relatively few man-hours. Depending on the system the sedimentation traps are deployed in, there can be an accessibility difficulty. If they are deployed in a remote area, the time- and transportation investment should also be considered (for instance if they must be reached by boat).

Sedimentation traps range in complexity, from very low-cost funnel traps to advanced time-series sediment traps. Low-cost funnel traps can be easy to construct and maintain. These types of traps can even be deployed in citizen-science projects, where citizens can make their own sedimentation traps with materials obtained from a hardware store.

3.3 Cost-effective

In contrast to water-air flux measurements, which capture the total carbon flux in the forms of respiration and photosynthesis, sedimentation traps are focused on the water-sediment carbon fluxes.

Whether a method is cost-effective or not, depends on the posed research question. The sedimentation traps method can be relatively low-cost. They need to be deployed and emptied at a certain point in time. The contents are either air- or oven dried and weighed. Possible additional analyses include carbon content determination, which is relevant in a blue carbon context.

4 Mesocosms

4.1 Scientific logic (Do I measure the right thing)

Mesocosm studies allow us to manipulate specific components of the ecosystem and study its implications for the blue carbon potential. For example, to address the effect of biodiversity or food-web complexity on carbon sedimentation, one could measure sedimentation rates in mesocosms with seagrass and with seagrass and its consumer. Alternatively, one could also address the effects of environmental changes such as eutrophication or climate warming on blue carbon potential of an ecosystem. As is the case with any experimental system, there are limitation to mesocosm studies. Though they can include a fair bit of complexity, they remain a simplified version of the real ecosystem and care must be taken when choosing the type of mesocosm system. In tidal ecosystems, for instance, using a mesocosms with stagnant water does not mimic the water movements organisms experience in situ. Rather, a tidal mesocosm system would then be more appropriate. More in-depth information on opportunities and challenges of using mesocosm systems for marine sciences can be found in (Sagarin *et al.*, 2016).

4.2 Cost-effective

Mesocosms need quite some man-hours to set-up and maintain. This of course does depend on the complexity of the specific mesocosm system. As mesocosms are usually set up in or close to laboratory facilities, they are often easily accessible. Mesocosms range in complexity from simple 'buckets' to advanced technical material (Verschoor et al., 2003; Velthuis et al., 2018) and depending on this complexity can require quite some expertise and facilities to run. An added advantage of mesocosm experiments is that they are quite popular for scientific collaborations. For example, some mesocosm systems are involved in European-wide consortia to share and jointly conduct experiments in these facilities. All in all, mesocosms studies can be quite costly. However, the amount of experimental control combined with the complexity that can be studied, make them very valuable tools for scientific projects.

5 E-DNA biomonitoring

As shown in section 3.1 most of the carbon within the sea water column is either present as dissolved organic molecules (DOC, dissolved organic carbon) or is fixed in biomass of organisms belonging to a complex food web including eukaryotes (especially phytoplankton, zooplankton, macrofauna and macroflora), as well as prokaryotes (bacteria). Carbon fixed in each of these food web components is either released to the DOC by leakage or decay, or eventually buried the sediment when dead remains (either organic or inorganic particles) sink into the sediment without being decayed. As shown in H3.1, carbon is also transferred between the different components of the biological food web. The composition of this food web strongly influences the ratio between efflux to the atmosphere and sequestration in the sediment and thereby the transfer to either the short or long carbon cycle.

(e)DNA biomonitoring potentially provides an efficient and flexible alternative to traditional morphological assessments of the taxonomic composition of the biological community. Here we briefly summarize the key aspects of the food web that could be monitored based on DNA, and the current status of this relatively new methodology.

5.1 Scientific logic (Do I measure the right thing)

While the focus of our study lies on potential relocation of carbon from the short to the long carbon cycle, and thus the total exchange of the food web with the DOC and the sediment, changes in these fluxes due to perturbations in the system (such as the introduction of a seaweed farm) will mainly run via changes in the composition of the biological food web.

While a small number of research programs, such as the LTER-MC (Long Term Ecological Research site MareChiara) have quantified all carbon biomass stocks and fluxes within the planktonic food web (for a specific study system), this may not be necessary for assessments of the effect of sea weed farms on the carbon sequestration performance of the local ecosystem. More relevant and realistic may be to monitor key characteristics of the food web that influence the fraction of carbon that is sequestered. This provides insights in the mechanisms that drive potential shifts in sequestration performance. In theory, changes in such characteristics can then be monitored as a proxy for direct changes in sequestration rates.

Previous studies have identified various key determinants of sedimentation rates. The composition of the phytoplanktonic community is of importance as it determines the primary production (fixation of CO_2 in the food web), but also because of its influence on the fate of carbon in higher trophic levels. The export ratio of the phytoplankton (fraction of the total primary production that is released as CO_2 to the atmosphere) has been shown to be strongly influenced by changes in the ratio between diatoms and smaller phytoplankton (Bopp et al. 2005). Diatoms are not only more effective in carbon uptake then e.g. dinoflagellates and coccoliths (Reinfelder 2010), but also release less carbon upon decay as diatom particulate matter has a relatively high sinking speed (Treguer & Pondaven 2000), which increases the depth at which this organic material is remineralized and thus the residence time of carbon in the sub-surface and deeper water layers. Moreover, as diatoms are grazed by both meso- and microzooplankton while nanophytoplankton is mainly grazed by microzooplankton, a larger fraction of diatoms in the phytoplankton is accompanied with a shift towards larger sized zooplankton, resulting in higher sinking rates also in this component. Studies on the mesoplankton, mostly using copepods as a model, have shown an increase in average individual size also within this group. In turn, increased copepod sizes form a more efficient nutrient source for macrofauna (fish), resulting in higher fish biomass stocks. Monitoring copepod taxonomic diversity provides useful insights in these trophic interaction, as copepod sizes have been shown to correlate negatively with copepod taxonomic diversity (Beaugrand et al. 2010). Finally, in general a higher food web complexity, measured as taxonomic or ideally functional diversity, results in larger losses of carbon to the DOC (Beaugrand et al. 2010).

All in all, monitoring may focus especially on taxonomic composition of the phytoplankton (relative abundance of diatoms) and copepod diversity. Yet, a broad screening of biodiversity will be useful in pilot studies, as this allows to test the relevance of a variety of potential proxies, including also community composition of fish and decomposers (protists, bacteria).

5.2 Technical Applicability (including opportunities)

(e)DNA metabarcoding is increasingly used as a method to determine taxonomic composition of biological communities. The method (summarized in Figure 3) is based on the analysis of a specific region of the genome (the barcode) which is known to differ among taxa. After DNA is extracted from the sample community, the copy number of this DNA region is multiplied for all taxa of which DNA is present in the sample, using PCR. High-throughput sequencing techniques are then used to determine the exact sequence code of each barcode copy. Finally, after a thorough quality screening, automated taxonomic identification of each of these codes is performed by comparison to a reference database containing sequence codes of as many potentially encountered taxa as possible. The result is a list of taxa present in the sample, along with their relative abundances in terms of DNA copies. This information then allows the calculation of diversity measures, as well as the detection of specific taxa of interest. Although biases during the PCR amplification phase may result in skewed relative abundances, hampering an exact quantification of taxa within a single sample, variation in observed relative abundances among samples has been shown to most often reflect true variation in relative biomasses of taxa in the sampled environment, thus allowing the determination of e.g. ratios between phytoplankton taxa.

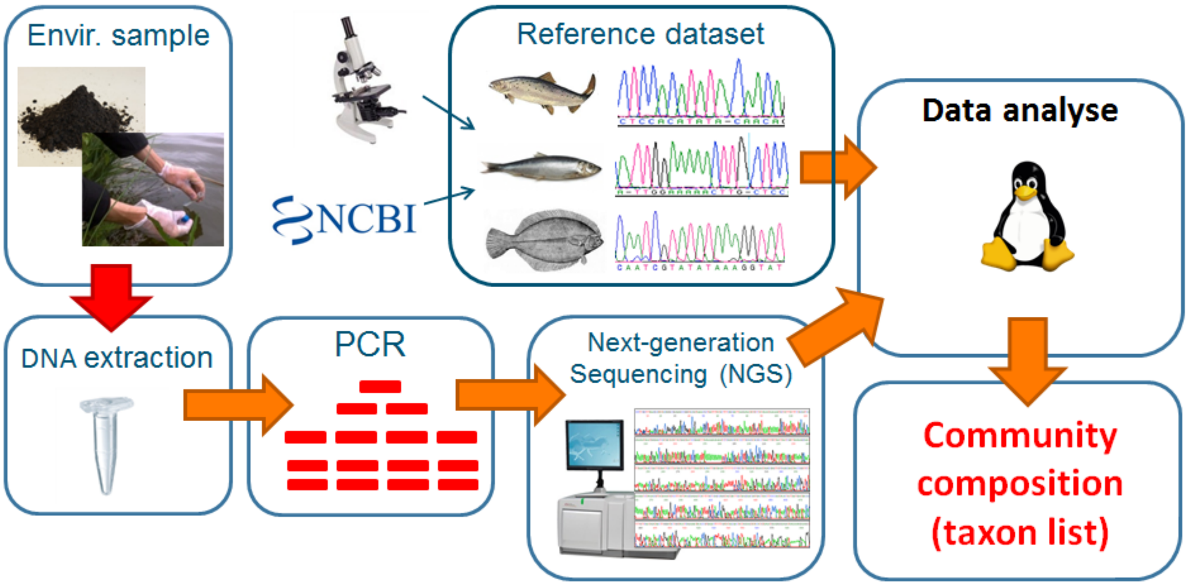


***Figure 3**, Schematic overview of a typical (e)DNA metabarcoding workflow*

Although only a limited number of studies are available so far that have used this workflow for detailed screening of planktonic and benthic communities in marine systems, results so-far are promising. Protocols for screening of eukaryotic communities in surface waters, including the selection of barcoding regions ('markers'), have been developed e.g. in the Tara Oceans project (e.g. Morard et al. 2018). Specialized protocols have been described for e.g. phytoplankton, macroalgae, zooplankton and fish.

Most studies have applied a multi-gene approach, using a region of the 18S rRNA as a backbone marker to provide a broad screening of the total eukaryotic diversity, while adding additional markers to zoom in to particular taxonomic groups (e.g. CO1 for all animals, 16S for copepods or 12S for fish).

Multiple studies have used a combination of 18S+CO1 for biomonitoring in the North Sea, including WUR-research specifically for sea weed farms (Bernard et al. 2019) and harbours (Slijkerman et al. 2017). While their protocols could be readily applied in pilot experiments, tailor-made methods may optimize efficiency for the metrics relevant in a blue-carbon context (zooming in on e.g. diatoms or copepods; see above), and may require the generation of additional reference data for the selected barcode(s) as well as specialized sampling and extraction protocols.

5.3 Manageable / user-friendly (model/report tool)

Traditional assessments of the large diversity of marine communities are time-consuming and require consultation of multiple taxonomic experts, each specialized in a taxonomic group. While such expertise is certainly essential during the development of DNA-based methods, such methods eventually can be used without highly-skilled taxonomic expertise, especially in case genetic or taxonomic diversity measures or ratios between may be used, in which case data analysis could ultimately be automatized to a large extent. This strongly increases the feasibility of biomonitoring of marine communities, especially since taxonomic expertise is becoming increasingly rare.

Ease of collection and transport of high-quality DNA samples depends on the sample type. Settle plates for monitoring of the benthic community need to be installed and removed by divers (e.g. Bernard et al. 2019), but upon removal can be transported to the lab for DNA extraction. Water samples can be collected more easily from a boat, e.g. via plankton net hauls, but may require on board filtration for volume reduction (e.g. Slijkerman et al. 2016). In both cases, sample storage during and after transport to the lab requires special attention to avoid DNA degradation. Samples are ideally transported and stored at sub-zero temperatures as soon as possible, and/or submerged in a buffer solution.

Future developments may allow on-site DNA analysis (e.g. using the handheld minION sequencer), thereby avoiding complex transport and storage protocols. Currently, (e)DNA analysis is however best performed in a specialized laboratory facility, to reduce the (high) risk of cross-contamination between samples. Both the laboratory analysis and the bioinformatic analysis of the resulting data is best performed by specifically trained personnel.

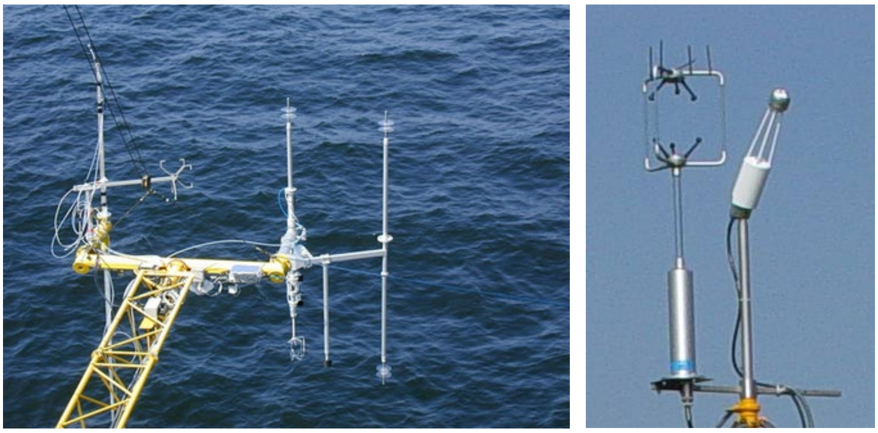
5.4 Cost-effective

Due to the reduction in labour by trained experts, DNA-based diversity monitoring is highly cost-effective compared to diversity traditional morphological identifications. As high-throughput sequencing methods allow for the simultaneous analysis of tens or even >100 samples, costs per sample are further reduced at larger sample sizes.

6 Eddy-Covariance

Large amounts of carbon are being exchanged between water bodies and the atmosphere through the air-water interface (see Figure 1). On a global scale, roughly 80 Gigatons of Carbon (GtC) is taken up as gaseous CO_2 and 78 GtC are emitted again from the water. The annual net uptake by the oceans is therefore roughly 2GtC, which is a significant part – about (20%) of the anthropogenic CO_2 emissions (IPCC 2013). However, the spatial and temporal differences are large. Notably in coastal zones, biogeochemical cycling can be quite intense since here, terrestrial, atmospheric and marine carbon cycles interact. Air-sea gas exchange is a major process affecting the coastal carbon cycle and it is therefore essential to have reliable estimates of this component of the carbon balance at sea (Bauer et al., 2013).

Traditional observations of air-sea exchange of carbon utilized indirect methods. Such methods estimate emission or uptake of CO_2 by multiplying observed or estimated CO_2 concentration differences between the water and the atmosphere with a so-called transfer velocity (Liss and Slater, 1974; Jähne and H. Haußecker, 1998). This transfer velocity has been the subject of many studies on air-sea gas exchange (Wanninkhof et al., 2009). It has usually been determined using other gases or compounds than CO_2 (e.g. Helium and SF_6, radioactive components). To this end, so-called scaling techniques need to be invoked. These render the indirectly determined transfer velocity applicable to CO_2. They rely on a comparison of physico-chemical properties of the compounds involved (notably gaseous diffusivity) and on theories of gaseous diffusion across the water-air interface (Wanninkhof et al., 2009). Obviously, such a scaling implies uncertainties in addition to the usual uncertainties pertinent to observations.



Picture: Left meteorological measurements at North Sea (right) and Eddy Covariance (left)

In the past few decades, a direct method has gained popularity: the so-called eddy covariance (EC) technique (Aubinet et al., 2012). This is a meteorological technique originally developed and applied over land but utilized more and more over water as well. To date, this technique has clearly proven its value for determination of gas exchange of over oceans, seas and lakes. In this chapter, we explore the possibility to utilize EC for determination of the air-sea CO_2 exchange over the North Sea.

6.1 Eddy Covariance (EC): a manageable and user-friendly measurement method

6.1.1 Principle

EC is a meteorological technique to measure vertical transport of matter – amongst other things - in the lower layers of the atmosphere. As such, CO_2 uptake or emission from land or water surfaces can be determined by EC. Although the mathematical derivation of the principles behind the technique is quite complicated (Foken et al., 2012), the physical interpretation is in fact straightforward.

Transport of a quantity by a given volume (a "package") of a medium like air is defined by (velocity) x (concentration). Thus, in order to determine vertical transport of CO_2 in air we would have to determine vertical air velocity (i.e., vertical wind speed) and CO_2 concentration of a control volume. It is just this, what EC does. Unfortunately, near the Earth's surface, the vertical wind speed is on average about zero and it is therefore nearly impossible to measure it with the required precision. However, large and measurable fluctuations occur thanks to turbulent eddies in the atmosphere ("parcels" of air going up and down all the time and taking care of the transport). Such air movements appear to be correlated with fluctuations of, for example, the CO_2 concentration. When the surface takes up CO_2, eddies deliver CO_2 to the surface. They are emptied a bit when reaching the surface and therefore, rising air coming from the surface will contain less CO_2 on average than downward moving air. The reverse reasoning holds if the surface emits CO_2. The resulting CO_2 concentration differences between the individual eddies can also be detected, as deviations from the average concentration. The implied correlation between the vertical wind speed and the CO_2 concentration is a direct measure of the vertical transport. It allows to use the principle that transport equals (velocity) x (concentration), with the control volume being individual eddies. Hence the name "Eddy Correlation" or "Eddy Covariance" (because the correlation is formally a covariance for CO2 transport).

To determine a reliable estimate of the total, net CO_2 exchange transport across a surface, an enough eddy needs to be sampled. Hence, in a typical EC setup high-frequency measurements of vertical wind speed and CO_2 concentrations are performed. Typically, about 10 measurements per second are performed (that is, measurement frequency is 10Hz), from which half-hourly to hourly averages of the CO_2 exchange are derived. Thus, a huge number of eddies and a large range of eddy sizes are sampled. Half-hourly to hourly averages assures that the measured CO_2 transport is predominantly related to turbulent transport, instead of to slow variations such as the daily solar cycle or moving meteorological systems at larger scales (e.g., fronts, low pressure areas). See literature for more details and in-depth information.

6.1.2 Advantages

The following scientific and sometimes also practical advantages of EC can be identified.

1) EC is direct

By definition, the method is direct (Aubinet et al., 2012; Foken 2008). It requires neither additional theories and approximations, nor other scaling techniques. For example, EC measures turbulence directly, while other techniques may require assumptions on turbulent development of the atmosphere; EC measures the net transport of CO_2 while other methods measure the transport of other gases and translate the results to CO_2 based on theories of gaseous air-sea exchange across the air-water interface and on comparison of physico-chemical properties (Wanninkhof et al., 2009).

2) EC is non-invasive

EC is applied at some height above the surface, leaving the surface itself undisturbed. As an example of an invasive method, we mention application of so-called chambers, which cover a surface, leading to a change in, for example, the light intensity at the surface or a physical disturbance like “digging a hole” or impeding wave development, leading to related uncertainty (e.g., Görres et al., 2014).

3) The method is quasi continuous and stand-alone

EC sites have to be erected with care. Once installed, the EC site needs some maintenance, depending on the environment and the instrument set applied. However, after installation and in-between service events it can run continuously and in a stand-alone mode. Data can be acquired day by day and night by night over prolonged periods. They can be stored locally or sent to remote servers on a regular basis. Automated processing of the EC raw samples may be done instantaneously or afterwards using special, freely available and user-friendly software, which has undergone scientific screening (Mauder et al., 2008). The former option allows sending more compact, processed datasets. The latter option is often used to safeguard raw data (high-frequency observations) to allow convenient accommodation of software updates, new insights regarding the processing of the data and additional process studies.

4) The footprint and timescale of EC are appropriate for process studies relevant to greenhouse gas exchange

At typical footprint size (area of the surface being observed) of EC is in the order of 100m x 100m to 1000m x 1000m, depending of the height of the system, surface properties and weather conditions. If average atmospheric flow patterns are undisturbed at the instrument location, effects of small surface features are averaged in a physical way (by the atmosphere). This is an advantage in many studies at the ecosystem scale. Although the initial averaging period is typically 30-60 minutes (ranging between 10 minutes and 2 hours; Foken, 2008) the results are easily aggregated to longer timescales, up to years, because of the automated, continuous nature of the method (Elbers et al., 2011; Ikawa and Oechel, 2015). Like illustrated in Figure 1, this implies that EC can fulfil a central role in greenhouse gas studies, from process studies and model validation to emission monitoring and verification (Hensen et al., 2010). This central role of micrometeorological techniques in general and of EC is visualized in Figure 1. The figure also illustrates that point scale measurements need a considerably greater effort to fulfil a similar role.

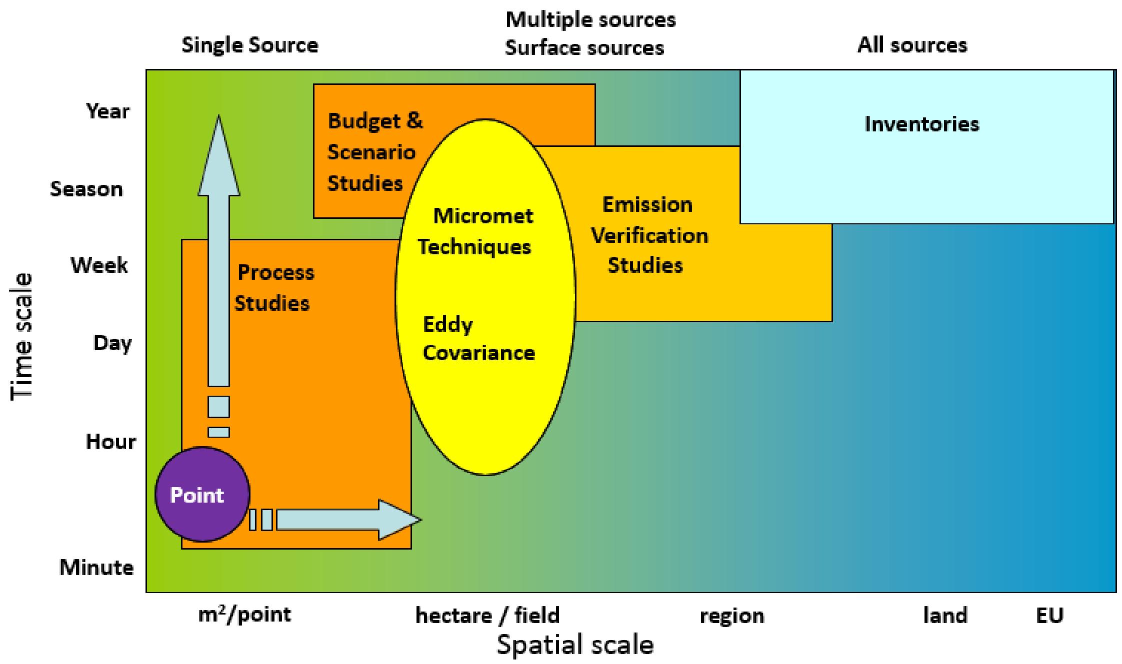


Figure 4. *Comparison of various Greenhouse gas exchange measurement techniques regarding their temporal and spatial scale. EC is typically executed at hectare and field scale and yields results at temporal scales from (less than) an hour to years. Adapted from Hensen et al. (2010).*

5) EC can be applied on many platforms

Platforms on which EC can be applied on various platforms such as in masts over land and on piers, onboard ships, on buoys and (other) moored platforms, on low-flying airplanes and on booms on stable platforms like oil and research platforms (see Figure 2 for some examples). The moving platforms including buoys require deployment of special instruments and software to account for their speed and other movements. Bulky platforms like ships and stable platforms at sea may require special corrections for the disturbance of atmospheric flow patterns (Blomquist et al., 2013; Butterworth and Miller, 2016; Foken et al., 2012; Oost et al., 1994). Development of techniques to apply such corrections has been rapid and such corrections have been shown to work well (see literature).

Figure 5. *Examples of platforms for EC measurements. From left to right: small, quasi-mobile mast in agricultural area; fixed mast in tropical forest; research airplane; boom at the former Sample site Noordwijk. Photos: Wageningen Environmental Research.*

6.1.3 Routine measurements with EC

Driven by the obvious scientific advantages and potential of EC to assist policy purposes like verification of emission reports and reporting methods, instrument and data processing software development has been extremely fast in the past few decades. Robust plug-and-play EC systems are available over land nowadays. They come with internationally accepted and standardized instrumentation and post-processing principles and software. They also come with utilities to transfer raw as well as (pre-) processed data (Aubinet et al., 2012). As a result of the rapid scientific and technical advance, the method has become readily accessible to a wide variety of communities outside the meteorological community. The rapid developments have resulted in quickly expanding observational networks based on EC, initially over land (e.g., FLUXNET and regional components; Baldocchi 2014). To date, oceanic counterparts linking up with terrestrial EC networks as well as with other oceanic monitoring networks are starting to develop as well (Steinhof et al., 2019).

6.1.4 Development of aquatic EC

Partly driven by the success of atmospheric EC measurements an aquatic equivalent has been pursued in recent years (Berg and Pace, 2017, and references cited therein). Although to date the technique has been applied mainly to measure O_2 uptake of systems like coral reefs and seagrass meadows, the technique can be valuable to study CO_2 exchange as well. First, O_2 and CO_2 exchange are strongly related through photosynthesis and respiration, implying that directly measured O_2 fluxes may give information on CO_2 fluxes – although indirect. This could provide valuable information in support of atmospheric EC measurements, especially since the underwater carbon system is a highly buffered one so that observations of gaseous CO_2 in water are difficult to interpret, in sea water (Abril, 2009). Second, near-surface O_2 measurements may allow robust evaluation of processes determining the transfer velocity (Berg and Pace, 2017).

6.1.5 Conclusion

It can be concluded that the EC technique has grown into a mature, user-friendly and widely accepted standard technique to measure exchange of CO_2 between the Earth's surface and the atmosphere, over land. Disadvantages can often be dealt with, except perhaps over extremely rough and heterogeneous surfaces like cities (Aubinet et al., 2012). Also, over the sea EC can fulfil a crucial role in scientific studies on CO_2 exchange. Development of EC in marine studies also been rapid, but here there are specific issues that have to be considered (Blomquist et al., 2013; Wanninkhof et al., 2009). This will be the subject of the next section.

6.2 Scientific issues: does EC measure the right thing over water?

During the development of the EC technique for application over land many scientific issues have arisen, but the main problems are now tackled in a standard way to get reliable and defensible outcomes of the EC measurements (Aubinet et al., 2012). We refer to the handbooks on micrometeorology and EC (e.g., Aubinet et al., 2012; Foken 2008) for issues like storage correction (EC fluxes need to represent exchange at the surface) gap filling (deal with incomplete datasets) and quality control and assessment. However, marine observations have some additional and unique problems, with a lack of consensus on their solutions (Blomquist et al., 2013). These are the subject of this section.

6.2.1 Small signals are prone to errors

Over water the CO_2 exchange is significant, but often quite small. To avoid large fractional errors extremely reliable and high-quality instruments and procedures are required. This should yield the desired signal-to-noise ratios even if the fluxes are small (Blomquist et al., 2013). During deployment of EC in marine environments it has become clear that several sources of error that may usually be ignored over land need correction over the sea because of the small fluxes. As a result, the corrections are sometimes larger than the measured fluxes and even can reverse the sign of the signal (Jacobs et al., 1999). Thus, the need for corrections should be avoided as much as possible. This is particularly true for so-called crosstalk with water vapour (the instrument detects water vapour as if it were CO_2; Kohsiek, 2000) and for density effects (Webb et al., 1980). These errors can largely be avoided by using so-called closed-path systems with driers (Blomquist et al., 2013).

6.2.2 Issues in a hostile environment

A general issue in a marine environment is the fact that the instrumentation will be exposed to salt and sometimes dust (Blomquist et al., 2013). This requires special precautions when setting up the EC equipment. Regular maintenance on at least a monthly basis will be mandatory (Steinhoff et al., 2019). Such maintenance requirements may put constraints on the choice of the location if unmanned stations are set up. The instruments need to be mounted high enough to avoid they are hit by waves (Butterworth et al., 2016). Data gaps due to technical issues and servicing are unavoidable and need to be filled to obtain the carbon balance at longer timescales (Papale, 2012). This might require advanced procedures like artificial neural networks that can also be applied over the sea (Rey-Sánchez et al., 2017), since the CO_2 exchange model is not as "straightforward" as over land.

6.2.3 Flow distortion and motion correction

If stable platforms, including masts located at or near the shore, cannot be deployed an EC equipment mounting platform such as buoys and (other) floating platforms including ships will have to be utilized. Such platforms are moving because of their speed, because of the influence of waves or both. This implies that special sensors such as accelerometers are needed to record such motions and to correct for the influence of motions on the measurements. To date, sensor packages and processing software are available to obtain high quality data on slow as well as on fast moving platforms (Butterworth et al., 2016; Vellinga et al., 2013). In some cases, platforms may be bulky (e.g. research vessels and platforms, oil platforms) and therefore lead to serious flow distortion which also requires correction (Butterworth et al., 2016; Oost et al., 1994).

6.2.4 Footprint issues

Both for process studies and for monitoring purposes the observations should match the system to be observed. This is not a trivial requirement in the case of EC. Typically, EC fluxes represent a larger area of 100m x 100m to 1000m x 1000m, depending on the surface and weather conditions (Rannik et al., 2012), the footprint. A larger footprint area can be an advantage if natural or physical averaging of the contribution of many spots in a heterogeneous environment is required. However, it can be a disadvantage if the area of interest is small in comparison with the footprint. Footprint analysis has become a standard part of the EC technique in order to properly interpret fluxes (Rannik et al., 2012), correct annual budgets for statistical sampling errors (Griebel et al., 2016) and to attribute or disaggregate observed carbon exchange (Hutjes et al., 2010).

Over moving water there is an extra complication since underwater footprint may be “displaced”. CO_2 produced elsewhere may reach the atmosphere in the EC footprint, while CO_2 produced in the footprint may be carried away before it reaches the air. This may be a problem particularly related to coastal zones, since these are quite heterogeneous, while the open ocean often may be considered much more homogeneous (Steinhof et al., 2019). If the flow of the water and the footprint are small in comparison with the horizontal size of the target system the right footprint will still be obtained (McGowan et al., 2016; Rey-Sanchez et al., 2017). Over the North Sea classical EC footprint analysis may have to consider water flow patterns (Jacobs et al., 2002).

6.2.5 Analysis of EC fluxes

It should be acknowledged that EC basically provides a net flux. This is enough to assess net carbon balances over hours to years. However, it does not allow to analyse the drivers and components of the carbon exchange. Such an analysis requires ancillary observations of meteorological conditions and carbon stocks and flows. Over land, much effort has been devoted to decomposition of the fluxes, ranging from efforts to distinguish release and uptake of CO2 (e.g., Laslop et al., 2012) to a more complete understanding of carbon flows (e.g., Jans et al., 2010). Ultimately, such analyses also result in a better understanding of the system under consideration. This may allow upscaling of carbon exchange from local observations to regional budgets, if combined with observations performed on platforms that also allow regional sampling and examination of spatial patterns (Hensen et al., 2010). Such platforms may include ships, airplanes and drones, tall towers and satellites.

6.2.6 Conclusion

It can be concluded that the EC can be applied in marine and coastal environments. Specific challenges occur in such environment, but strong efforts and quick technical developments are going on and allow to tackle possible problems with confidence. If special care is taken regarding setup, maintenance and interpretation of the data EC will be able to deliver robust and defensible carbon exchange data. If embedded in appropriate ancillary observations EC also allows process studies, including evaluation of models. If embedded in broader networks, EC can also help constructing regional carbon balances.

6.3 Technical Applicability (including opportunities)

Application of EC to monitor CO_2 exchange is technically feasible if the conditions are met (see 7.1 and 7.2). It will be useful to follow developments in the context of the Integrated Carbon Observation System for Oceans, ICOS-Oceans. ICOS guidelines for operation of marine EC stations and integration in broader networks allow better quality assurance and may permit access to various data sets, also aimed at regional carbon budgets (Steinhoff et al., 2019).

Selection of a suitable platform for monitoring purposes will be critical. Options could be:

- Existing masts and structures near the water; masts installed on piers and other locations near the coast. Main advantages are ease of access for maintenance and applicability of standard procedures to process EC data. Main disadvantage is that the footprint may be on land for extended periods of time.
- Moored platforms like buoys and other devices. This may be existing platforms or new ones to be installed. Main advantage may be that this option offers some flexibility to choose a suitable location, in case of new platforms also depending on legal boundary conditions and safety regulations. Disadvantages include maintenance issues and movement of floating platforms. Movement can be corrected for but requires a larger investment because of the extra instruments need and higher data processing costs.
- Existing structures in the North-Sea, such as wind turbines and structures built for sea farms, again depending on legal boundary conditions and safety regulations. The latter of these options may allow to choose the footprint area exactly in one of the special areas of interest. Movements may completely or largely be avoided and access for maintenance may be relatively easy. However, bulky platforms may lead to flow distortion. There may also be some special issues regarding mounting of the instruments.

Measurements at fixed locations yield data (quasi-) continuous in time. These can be used for process studies as indicated before and for assessment of local carbon budgets. Process studies as well as interpretation of the long-term budgets and their components require some additional measurements. Some of this information might be obtained with enough accuracy from already existing meteorological or oceanographic networks (e.g. run by the Royal Netherlands Meteorological Institute, KNMI, for meteorological information or by Rijkswaterstaat for observations on waves and water temperature).

- Acquisition of meteorological conditions needs to include at least wind speed and direction, temperature and humidity. Wind speed and direction can be obtained from the EC system. This is also true for temperature and humidity, but additional "slow" measurements are desirable. The basic measurements can be extended with radiation measurements, which are not commonly available in marine observation networks. In particular, because CO_2 is involved, solar radiation can give valuable information since photosynthesis is driven by light. Collecting information on the wave field, water temperature and salinity will be of great value for interpretation and extrapolation to other areas. Measurements of dissolved CO_2 and atmospheric CO_2 allow direct determination of the transfer velocity for CO_2, which supports upscaling to larger areas (see below).
- A development that may prove extremely valuable with regard to interpretation of EC data may be the aquatic EC technique. The technique has been proven to be applicable under water to the benthic zone for measuring oxygen fluxes between seafloor and overlying water and, e.g., around seaweed farms (Berg and Pace, 2017). Oxygen fluxes are extracted from raw measurements largely following the same principles as used in the atmosphere and can then typically be used as a proxy for carbon exchange because O_2 production and CO_2 consumption (and the reverse) are complementary in photosynthesis.
- Further interpretation and analysis may come from techniques discussed in the previous chapters. This integration between EC and such methods will be further discussed in the next chapter.

Observations based on EC remain limited in spatial extent. This limited footprint implies that it is not feasible to monitor the entire sea surface of even coastal area using this technique. So, determination of the carbon balance of areas much larger than – typically – 1x1 km^2 requires some way of extrapolation, preferably based on bio-physically plausible models. For such spatial upscaling purposes, the measurements at an EC site can be complemented with measurements on moving platforms, which not necessarily need to be EC measurements. For example, once a relationship between windspeed and transfer velocity has been established, observations of aqueous and atmospheric CO_2 content along with estimates of wind speed suffices to establish carbon budgets over larger areas (Takahashi et al., 1997).

- Satellites are able to determine important components of the carbon balance and so establish regional carbon budgets (e.g., Joshi et al., 2018; Yu et al., 2018). EC measurements may help to calibrate relationships between CO_2 exchange and sea surface properties, deployed in remote sensing techniques. Once established, remote sensing data may be used for upscaling (extrapolation) purposes, with EC stations being used as "anchor points" (ground truth).
- Small, low flying research airplanes may be equipped with EC instruments to measure CO_2 exchange over longer flight paths (Hutjes et al., 2010; Vellinga et al., 2013), thereby assisting spatial extrapolation. However, executing such flights may be subject to flight regulations and not be allowed everywhere. For example, some aircraft are not allowed to fly over the sea, which would restrict such observations to near-shore areas under favourable footprint conditions (wind blowing from the sea).
- Additional measurements for spatial extrapolation may also be conducted onboard ships, including commercial transport vessels and ferries. Usually, EC equipment is deployed on research vessels (Blomquist et al., 2013). If ships are equipped with EC instruments special sensors to detect movement are required and flow distortion should be corrected for. Apart from research vessels, commercial vessels such as ferries may be equipped with sensors to determine CO_2 concentration in water, seawater temperature, salinity and meteorological instruments. Meteorological observations have since long been deployed onboard Voluntary Observing Ships (VOS). Along similar lines, ICOS-ocean is developing a "Ship of Opportunity Program" (SOOP) for carbon (and more general: greenhouse gas) budget studies. This includes development of systems to observe physico-chemical water properties relevant for carbon exchange studies (Steinhoff et al., 2019).

6.4 Cost-effective

Given the principle of EC, it is obvious that application of the EC technique requires rather advanced instrumentation and therefore a considerable investment, depending in the system (Foken, 2008). In addition, the technique is mathematically complex and requires advanced processing software, especially on moving platforms. The raw (high frequency) data come in huge amounts and require careful post-processing, quality assessment and error handling.
The possibility to run EC systems quasi-continuously and in quasi-stand-alone mode in-between servicing events renders EC practically advantageous over other, more labour-intensive observational methods. Initial investments may therefore be compensated by labour-extensive operation of EC systems.
Over water, deployment of EC may be more costly if instrumentation needs to be applied on distant or moving platforms. A solution for the latter issue may be the use of freely available data existing observational networks or networks in development.

7 Conclusions and proposal for follow-up in 2020-2023

This report explored possibilities to assess the blue carbon potential of seaweed farms. After finishing the desk research, we organized a review workshop with practitioners from the North Sea Farm Foundation. The results of this review workshop have been used in formulating conclusions.

A key question for both science, climate policy and practice is how much carbon could be allocated from the short to the long carbon cycle. The workshop made clear that we must look broader than just only the sedimentation of seaweed plant residues to the soil. Previous studies estimated that, under conditions without harvesting, less than 3 tons of carbon per year per hectare is long-term captured in the soil of the sea. When harvesting seaweed this will be much less (<1%). Related to this, it can also be a strategy to develop a seaweed farming system where the yield is deliberately not harvested once every few years. In this alternative scenario a larger fraction sinks towards the sea bed where it can be stored as recalcitrant carbon in the long-term carbon cycle. Also, in this situation a part of the carbon from seaweed will be consumed or degraded by marine organisms and becomes part of the short-term carbon cycle (Hain et al., 2014). An important question is what the magnitude of this fraction is, and can it be influenced by management strategies at the seaweed farm?

Participants therefore emphasized that the follow-up research should focus on the question whether how much extra carbon can be long-term sequestered in associated biomass in the water column. Is it possible to increase the blue carbon potential by the development of multi-resource aquaculture systems where more than just seaweed is grown? And are the economic revenues of the potential carbon capture, expressed in carbon credits, enough to become part of a business model for future seaweed farms at the North Sea? Stichting Noordzee Boerderij is aiming for the development of extensive and diverse mixed sea farming systems. It is interesting to investigate whether these types of systems mean for carbon capture compared to monocultural seaweed systems. Is it possible to define a definition of a maximum sustainable yield at seaweed farms considering energy supply, blue carbon, food production and biodiversity?

We have explored opportunities and constraints of existing technologies: (1) Sediment Traps & mesocosms, (2) E-DNA biomonitoring and (3) Eddy Covariance measurements at Sea as research options to assess this fraction. Also, we have explored the possibilities to combine these technologies. The following conclusions are made:

- A baseline (the carbon sedimentation flux without a seaweed farm can be assessed in several ways, e.g. with (1) a reference site, (2) space-for-time-substitution or with mesocosm experiments.
- Sediment traps allow us to directly assess the amount of sedimented material (organic and inorganic) in situ. They are available from very low-cost funnel traps to advanced time-series sediment traps. However, it is also important to consider the conditions at the North Sea and the travel distances to the coast.
- Mesocosm studies allow us to manipulate specific components of the ecosystem and study its implications for the blue carbon potential. For example, one could measure sedimentation rates in mesocosms with seagrass and with seagrass and its consumer. Alternatively, one could also address the effects of environmental changes such as eutrophication or climate warming on blue carbon potential of an ecosystem. As is the case with any experimental system, there are limitation to mesocosm studies. In tidal ecosystems, for instance, using a mesocosms with stagnant water does not mimic the water movements organisms experience in situ. Rather, a tidal mesocosm system would then be more appropriate.
- Changes in the sedimentation rates are also influenced by changes in the composition of the biological food web as a result of a perturbation such as an introduction of a seaweed farm. E-dna monitoring is useful to assess those changes. E-dna, monitoring may focus especially on taxonomic composition of the phytoplankton (relative abundance of diatoms) and copepod diversity. Yet, a broad screening of biodiversity will be useful in pilot studies, as this allows to test the relevance of a variety of potential proxies, including also community composition of fish and decomposers

(protists, bacteria). Due to the reduction in labor by trained experts, DNA-based diversity monitoring is highly cost-effective compared to diversity traditional morphological identifications. As high-throughput sequencing methods allow for the simultaneous analysis of tens or even >100 samples, costs per sample are further reduced at larger sample sizes.

- Eddy Covariance (EC) can fulfil a crucial role in scientific studies on CO2 exchange in oceans and seas. However, there are specific issues that have to be considered given the specific conditions at the North Sea. If embedded in appropriate ancillary observations EC also allows process studies, including evaluation of models.
- A development that may prove extremely valuable regarding interpretation of EC data may be the aquatic EC technique. The technique has been proven to be applicable under water to the benthic zone for measuring oxygen fluxes between seafloor and overlying water and, e.g., around seaweed farms.

Policy aspects

- The Dutch climate agreement (Klimaatberaad, 2019) mentions opportunities for the development of aquaculture (seaweed cultivation) in combination with nature development, the sequestration of greenhouse gases and the construction of offshore wind farms. No quantitative targets have been set, upscaling of seaweed cultivation combined with reduction of greenhouse gas emissions has been formulated as a knowledge and innovation challenge.
- In 2019, the IPCC asked the countries that signed the Paris agreement, to review their greenhouse gas emissions reporting systems for open waters, coastal zones and aquaculture. It is therefore interesting to assess in future research how important aquaculture will be in the North Sea in the future.

User needs (entrepreneurs)

- Carbon offsetting—receiving credit for reducing, avoiding, or sequestering carbon—has become part of the portfolio of solutions to mitigate carbon emissions. Land is limiting, creating interest in a rapidly growing aquatic farming sector of seaweed aquaculture in which carbon offsetting is also possible. We have found no examples yet.
- Carbon offset projects at land create currently an average socio-economic value of around 5 € ton-1 CO2-eq, this is not yet enough for entrepreneurs. It is expected that this price will become higher in future, due to increasing impacts of climate change.
- Within the Emission Trading System (ETS) of the European Union (ETS) the carbon credit price ranged between 20-30 euro per ton CO2. However, ETS is only a carbon credit market for specified industries. Aquaculture is not part of that, but the industries that use seaweed as a raw material are.

Follow up in 2020

- Based on the results of this desk research and based on the feedback during the review workshop, it was decided to set up a mesocosm experiment, in collaboration with Wageningen Marine Research, with the objective to assess the long-term sequestration of carbon in lower trophic species in the water column in seaweed cultivation systems (2020-2021) by E-dna techniques.
- When the results of the mesocosm experiments are available, it is the intention to do additional field measurements (sediment traps) in collaboration with stichting Noordzee Boerderij.
- Explore the carbon offset potentials of seaweed farms together with Wageningen Economic Research

8 Literature

Abril, G. (2009). Comments on: ''Underwater measurements of carbon dioxide evolution in marine plant communities: A new method'' by J. Silva and R. Santos [Estuarine, Coastal and Shelf Science 78(2008) 827–830]. Estuarine, Coastal and Shelf Science, 82: 357–360.

Aitken, D., Bulboa, C., Godoy-Faundez, A., TurrionGomez, J. L., & Antizar-Ladislao, B. (2014). Lifecycle assessment of macroalgae cultivation and processing for biofuel production. Journal of Cleaner Production, 75, 45-56

Arets, E. J. M. M., J. W. H. van der Kolk, G. M. Hengeveld, J. P. Lesschen, H. Kramer, P. J. Kuikman, and M. J. Schelhaas. 2019. Greenhouse gas reporting of the LULUCF sector in the Netherlands - Methodological background, update 2019. In: Statutory Research Tasks Unit for Nature & the Environment (WOT Natuur & Milieu). Wageningen, p. 113.

Baldocchi, D. (2014). Measuring fluxes of trace gases and energy between ecosystems and the atmosphere—The state and future of the eddy covariance method. Global Change Biology, 20: 3600–3609. https://doi.org/10.1111/gcb.12649.

De, Frenne, P. , Graae, B. J., Rodríguez‐Sánchez, F. , Kolb, A. , Chabrerie, O. , Decocq, G. , De, Kort, H. , De, Schrijver, A. , Diekmann, M. , Eriksson, O. , Gruwez, R. , Hermy, M. , Lenoir, J. , Plue, J. , Coomes, D. A. and Verheyen, K. (2013), Latitudinal gradients as natural laboratories to infer species' responses to temperature. J Ecol, 101: 784-795. doi:10.1111/1365-2745.12074

Foekema, E., K. van de Wolfshaar, K. Elschot, and D. Debrot. 2018. Blue Carbon in Nederland. Beknopt overzicht voor beleidsmakers. Wageningen Marine Research, Ijmuiden, Brief rapportage aan PBL.

Froehlich , E., J. C. Afflerbach, M. Frazier, and B. S. Halpern. 2019. Blue Growth Potential to Mitigate Climate Change through Seaweed Offsetting. Curr Biol 29: 3087-3093.

Görres, C. M., L. Kutzbach, and L. Elsgaard (2014). Comparative modeling of annual CO_2 flux of temperate peat soils under permanent grassland management. Agric. Ecosyst. Environ., 186: 64-76.

GDNK (2018) Methode voor vaststelling van emissiereductie CO2-eq - CO2-emissiereductie via verhoging grondwaterpeil in veengebieden ('Valuta voor Veen'), Greendeal Nationale Koolstof Markt,

Griebel, A., Bennett, L.T., Metzen, D., Cleverly, J., Burba, G., Arndt, S.K. (2016). Effects of inhomogeneities within the flux footprint on the interpretation of seasonal, annual, and interannual ecosystem carbon exchange. Agric. For. Meteorol. 221: 50–60.

Hain, M.P., D.M. Sigman, G.H. Haug (2014), The biological pump in the past. Heinrich D. Holland, Karl K. Turekian (Eds.), Treatise in Geochemistry (2nd ed), 978-0-08-098300-4, Elsevier, Oxford (2014), pp. 485-517, 10.1016/B978-0-08-095975-7.00614-8

Hamrick K, Gallant M (2018) Voluntary Carbon Market Insights: 2018 Outlook and First-Quarter Trends. Ecosystem Marketplace, Forest Trend. Washington, USA

Hedges, J.I. (1992), Global biogeochemical cycles: progress and problems Mar. Chem. 39: 67-93.

Hensen, A., P.S. Kroon, A.J. Dolman, E.M. Veenendaal, J.H. Duyzer, J.A. Elbers, C.L. van Beek and J. Mosquera, (2010). Meten van broeikasgassen in het landschap. Landschap, 27, 57-65.

Hutjes, R.W.A., O.S. Vellinga, B. Gioli, and F. Miglietta (2010). Dis-aggregation of airborne flux measurements using footprint analysis. Agric. For. Meteorol., 150: 966-983.

IPCC (2013). *Climate Change 2013: The Physical Science Basis.* Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1535 pp.

IPCC (2019) 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories. Available from https://www.ipcc.ch/report/2019-refinement-to-the-2006-ipcc-guidelines-for-national-greenhouse-gas-inventories/.

Ikawa, H., and W. C. Oechel (2015). Temporal variations in air-sea CO_2 exchange near large kelp beds near San Diego, California, J. Geophys. Res. Oceans, 120: 50–63. doi:10.1002/ 2014JC010229.

Jacobs, C.M.J., J.F. Kjeld, P.D. Nightingale, R.C. Upstill-Goddard, S.E. Larsen and W.A. Oost (2002). Possible errors in CO_2 air-sea transfer velocity from deliberate tracer releases and eddy covariance measurements due to near-surface concentration gradients. J. Geophys. Res. C9, 107, 11-1 to 11-26, doi:10.1029/2001JC000983.

Jacobs, C.M.J., W. Kohsiek and W.A. Oost (1999). Air-sea fluxes and transfer velocity of CO_2 over the North Sea: results from ASGAMAGE. Tellus 51B: 629-641.

Jähne, B., and H. Haußecker (1998). Air-water gas exchange. Annu. Rev. Fluid Mech., 30: 443-468.

Jans, W.W.P, C.M.J. Jacobs, B. Kruijt, S. Barendse and E.J. Moors (2010). Carbon exchange of a maize (Zea mays L.) crop: influence of phenology. Agriculture, Ecosystem & Environment, 139, 316-324.

Joshi, I.D., Ward, N.D., D'Sa, E.J., Osburn, C.L., Bianchi, T.S., Oviedo-Vargas, D. (2018). Seasonal trends in surface pCO_2 and air-sea CO_2 fluxes in Apalachicola Bay, Florida, from VIIRS ocean color. Journal of Geophysical Research:Biogeosciences, 123, 2466–2484.

Klimaatberaad. 2019. Klimaatakkoord (versie 28 juni 2019). Den Haag, p. 237.

Kohsiek, W. (2000). Water vapour cross-sensitivity of open path H_2O/CO_2 sensors. J. Atmos. Ocean. Technol. 17: 299-311.

Kosten, S. , Huszar, V. L., Bécares, E. , Costa, L. S., van, Donk, E. , Hansson, L. , Jeppesen, E. , Kruk, C. , Lacerot, G. , Mazzeo, N. , De, Meester, L. , Moss, B. , Lürling, M. , Nõges, T. , Romo, S. and Scheffer, M. (2012), Warmer climates boost cyanobacterial dominance in shallow lakes. Glob. Change Biol., 18: 118-126. doi:10.1111/j.1365-2486.2011.02488.x

Liss, P.S. and P.G. Slater (1974). Fluxes of gases across the air-sea interface. Nature, 247: 181-184.

Mauder, M., Foken, T., Clement, R., Elbers, J.A., Eugster, W., Grünwald, T., Heusinkveld, B., Kolle, O. (2008). Quality control of CarboEurope flux data—part 2: inter-comparison of eddy-covariance software. Biogeosciences 5: 451–462.

McGowan, H.A., MacKellar, M.C., Gray, M.A. (2016). Direct measurements of air-sea CO_2 exchange over a coral reef. Geophys. Res. Lett., 43: 4602–4608. doi:10.1002/2016GL068772.

Nellemann, C., Corcoran, E., Duarte, C. M., Valdés, L., De Young, C., Fonseca, L. & Grimsditch, G. (Eds).(2009): Blue Carbon. The role of healthy oceans in binding carbon. A Rapid Response Assessment.United Nations Environment Programme, GRID-Arendal. Downloaded on August 14, 2015 at:http://bluecarbonportal.org/the-new-blue-carbon-homepage-2/document-inventory/downloadinfo/nellemann-et-al-2009-blue-carbon-the-role-of-healthy-oceans-in-binding-carbon/

Nolte S., Koppenaal E.C., Esselink P., Dijkema K.S., Schuerch M., De Groot A.V., Bakker J.P. & Temmerman S. (2013) Measuring sedimentation in tidal marshes: a review on methods and their applicability in biogeomorphological studies. Journal of Coastal Conservation, 17, 301-325.

Oost, W. A., Fairall, C. W., Edson, J. B., Smith, S. D., Anderson, R. J., Wills, J. A., Katsaros, K.B. and DeCosmo, J. (1994). Flow distortion calculations and their application in HEXMAX. Journal of Atmospheric and Oceanic Technology, 11: 366-386.

OSPAR (2015): Summary record of the 2015 Meeting of the Biodiversity Committee (BDC). Agenda Item 10 BDC 15/10/1-E . OSPAR Convention for the Protection of the Marine Environment of the North-East Atlantic. Meeting of the BDC, Cork, 2-6 March 2015. Downloaded on September 3rd, 2015 at: http://www.ospar.org/v_meetings/browse.asp

Papale, D. (2012). Data gap filling. In: Eddy Covariance, A Practical Guide to Measurement and Data Analysis (Eds. M. Aubinet, T. Vesala and D. Papale). Springer, Dordrecht: 159-172.

Rannik, U., Sogachev, A., Foken, T., Göckede, M., Kljun, N., Leclerc, M.Y. and Vesala, T. (2012). Footprint analysis. In: Eddy Covariance, A Practical Guide to Measurement and Data Analysis (Eds. M. Aubinet, T. Vesala and D. Papale). Springer, Dordrecht: 212-261.

Rey-Sánchez, A. C., G. Bohrer, T. H. Morin, D. Shlomo, G. Mirfenderesgi, H. Gildor, A. Genin, (2017). Evaporation and CO_2 fluxes in a coastal reef: an eddy covariance approach. Ecosystem Health and Sustainability, 3: 1392830.

Ruyssenaars, P. G., P. W. H. G. Coenen, P. J. Zijlema, E. J. M. M. Arets, K. Baas, R. Dröge, G. Geilenkirchen, M. 't Hoen, E. Honig, B. van Huet, E. P. van Huis, W. W. R. Koch, L. L. Lagerwerf, R. A. te Molder, J. A. Montfoort, C. J. Peek, J. Vonk, and M. C. van Zanten. 2019. Greenhouse gas emissions in the Netherlands 1990-2017. *In*: National Inventory Report 2019. RIVM -National Institute for Public Health and Environment, Bilthoven, the Netherlands.

Sagarin R.D., Adams J., Blanchette C.A., Brusca R.C., Chorover J., Cole J.E., Micheli F., Munguia-Vega A., Rochman C.M., Bonine K., Van Haren J. & Troch P.A. (2016) Between control and complexity:

opportunities and challenges for marine mesocosms. Frontiers in Ecology and the Environment, 14: 389-396.

Scholten, M. 2018. Technische Briefing Kringlooplandbouw. Wageningen, p. 14.

Steinhoff, T., and coauthors (2019). Constraining the Oceanic Uptake and Fluxes of Greenhouse Gases by Building an Ocean Network of Certified Stations: The Ocean Component of the Integrated Carbon Observation System, ICOS-Oceans. Frontiers in Marine Science, 6. DOI: 10.3389/fmars.2019.00544.

Takahashi, T., R.A. Feely, R.F. Weiss, R.H. Wanninkhof, D.W. Chipman, S.C. Sutherland, T.T. Takahashi (1997). Global air-sea flux of CO_2: An estimate based on measurements of sea–air pCO_2 difference. Proceedings of the National Academy of Sciences 94: 8292-8299.

Tamis, J. E., and E. M. Foekema. 2015. A review of blue carbon in the Netherlands. Wageningen Marine Research, Den Helder, p. 29.

van den Burg, S., Dagevos, H., Helmes, R., 2018. Sustainable seaweed value-chains - Economics, consumer attitudes and environmentalimpacts, Wageningn Ecocomic Research, Factsheet Proseaweed project, 8p. Availble at: https://edepot.wur.nl/471156

Van der Meer, J. 2020. Limits to food production from the sea. Nature Food 1: 762-764.

Vellinga, O. S., R. J. Dobosy, E. J. Dumas, B. Gioli, J. A. Elbers, and R. W. A. Hutjes (2013). Calibration and Quality Assurance of Flux Observations from a Small Research Aircraft. Journal of Atmospheric and Oceanic Technology, 30: 161-181.

Wanninkhof, R., Asher, W.E., Ho, D.T., Sweeney, C. and McGillis, W.R. (2009). Advances in Quantifying Air-Sea Gas Exchange and Environmental Forcing. Annu. Rev. Mar. Sci. 1: 213–44. Doi: 10.1146/annurev.marine.010908.163742.

Webb, E.K., Pearman, G.I., Leuning, R. (1980). Correction of flux measurements for density effects due to heat and water vapour transfer. Q.J.R. Meteorol. Soc. 106: 85-100.

Yu, X., Jiang, B., Li, B., Niu, X., Zhang, X., Liu, J. (2018). Retrieval of remotely sensed air–sea carbon flux in the Chinese Bohai Sea, Marine Georesources & Geotechnology, DOI: 10.1080/1064119X.2017.1412548.