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Ecosystem-based carbon footprinting of marine engineering projects

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Dredging projects use large amounts of fuel, which leads to substantial carbon dioxide (CO_2) emissions. Until now, reducing the carbon footprint of dredging projects has mainly involved investigating the possibilities of dredging schemes and vessels that are more fuel efficient. A reduction in the order of 10–20% may be within reach, most of it is a win–win situation since fuel reduction will also reduce costs. A further reduction in carbon dioxide emissions may be possible on a project-by-project basis but will involve a trade-off between dredging costs and carbon dioxide emissions. Marine engineering projects also have an impact on primary production and formation of organic carbon and on sedimentation processes and burial of organic carbon in sediments. Both impacts influence carbon sequestration and can be a substantial or even overriding factor in the 'carbon footprint' of a project. The carbon footprint of a marine engineering project is often larger and more complex than previously anticipated. However, a more comprehensive carbon footprint also shows that a significant reduction in carbon dioxide emissions is possible when the designs and dredging and maintenance schemes stimulate sequestration of organic carbon in the wider environment.

1. Introduction

Dredging requires enormous amounts of energy and environmental policies require a reduction in related carbon dioxide (CO_2) emissions. Part of the dredging sector aims to reduce carbon dioxide emissions by 20% before 2020. The dredging industry is already working with more energy-efficient vessels that emit less carbon dioxide for every cubic metre excavated. However, maritime engineering projects can be more carbon dioxide efficient by allowing more efficient construction schemes or by creating the right conditions for sequestering carbon dioxide in the ecosystem where the project is constructed. The essence of an ecosystem-based approach is that the design phase takes into consideration carbon dioxide emissions and carbon dioxide sequestration processes in the coastal ecosystem.

The 'building with nature' (BwN) initiative includes the development of a programme that focuses on ecosystem-based carbon dioxide footprinting and design. The BwN initiative is committed to the integration of infrastructure, nature and society in new or alternative forms of engineering (see Ecoshape, 2014). Steps are currently being taken within BwN to develop a design tool that enables the calculation of the carbon dioxide footprint and to steer the design towards reducing it (Dekker *et al.*, 2014). To that end, a partnership has been formed between two dredging companies (Boskalis and Van Oord), non-governmental organisations (the North Sea Foundation and the Wetlands International Foundation), engineering and consulting firms (Arcadis, Royal HaskoningDHV and Witteveen + Bos) and Deltares, a Dutch institute for applied research in the field of water, subsurface and infrastructure. The goal is to be able to develop and construct maritime engineering projects that have a smaller carbon dioxide footprint over their entire life cycle than they would have with conventional design and construction methods.

2. Relevance of an ecosystem-based approach

2.1 The carbon dioxide emission potential of dredging material is substantial

In discussions on carbon dioxide emissions by the dredging industry, the emphasis so far is on emission by the equipment used. In most dredging schemes the carbon dioxide emission per cubic metre dredged may amount to 2–5 kg CO_2/m^3. This is for a dredging cycle that involves transport over 10–20 km. During the process of dredging, part of the fine sediments and attached organic carbon is released from the sediment. The total organic carbon content of sand used for nourishment amounts to 30–120 kg carbon dioxide equivalent. Recent research by Deltares shows that the potential carbon dioxide emissions of dredging sludge is very large (Veld, 2014). So the potential carbon dioxide emission of 1 m^3 of sand is much larger than the carbon dioxide emission as a result of dredging it. It is therefore important to consider the fate of organic matter in dredged materials. The release of fines including attached organic matter can be steered by the dredging method, which may have a large impact on the carbon dioxide balance of a project. The 'carbon footprint' can also be reduced by carefully selecting the location of the sand pit.

2.2 The carbon sequestration potential of marine ecosystems is large

Intertidal wetlands have the ability to sequester carbon dioxide (Laffoley and Grimsditch, 2009). There is a wide range in estimates as to how much. It depends on location, stage in succession and other factors such as climate and sedimentation rates. In the long run the total build-up of the sediment is the most relevant, because most intertidal areas such as a salt marsh or a mangrove forest will eventually reach a climax state and a biomass maximum. Over a period of 100 years a salt marsh may sequester as much as the equivalent of 400–1200 t CO_2/ha, which is much higher than emissions generated by building, for example, a salt marsh or a mangrove forest as part of a soft defence strategy. So if costs would not be a constraint, a design that uses salt marshes or mangroves usually has a smaller carbon footprint.

2.3 A sand pit can also sequester large amounts of organic carbon

Most marine engineering projects involve dredging for which sand is taken out of a pit. The sand pit will trap fine sediments and attached organic carbon if it is deep enough. Depending on sedimentation rates, the depth and form of the pit, a large proportion of the attached organic carbon is permanently trapped in sediments. The carbon sequestration by a sand pit can be significantly larger than that of an intertidal area, so it is an important component of the carbon footprint of a marine engineering project that involves dredging.

2.4 Fine sediments enable carbon sequestration but are in limited supply

A sand pit or newly created salt marsh may trap fine sediments that hence are not available to other parts of the intertidal area. If the availability of fine sediments is limited, building a salt marsh may lead to the erosion of another one, so the net carbon sequestration of building a salt marsh may be nil. It is therefore important to consider if this form of substitution may take place. Even if the new salt marsh is not competing with another salt marsh nearby, the fine sediments that are trapped by it would otherwise bury organic carbon in another deposition area, such as the continental shelf or even further away. As the availability of fine sediments is often limited, the difference in the way different parts of the coastal system are able to sequester organic carbon in a matrix of fine sediments is relevant. The efficiency with which different depositional areas use available fine sediments for trapping organic carbon can be expressed in a carbon/fluorine (C/F) ratio.

2.5 Phosphorus is needed for formation and sequestration of organic carbon

Phosphorus is essential for the formation of organic carbon and is often the most limiting factor in primary production. Without phosphorus there is no (organic) carbon sequestration. The fate of carbon and phosphorus varies between different deposition areas, a difference that is expressed as the carbon/phosphorus (C/P) ratio (Emeis *et al.*, 2000). The C/P ratio varies between 50 and 600 and is often higher in offshore depositional areas and higher in vegetated coastal wetlands. A higher C/P ratio implies a more efficient use of phosphorus in carbon sequestration. So trapping carbon dioxide in wetlands can be more but also less efficient than in other parts of the coastal system. Examples exist of newly created salt marshes that trap large amounts of organic carbon due to rapid sedimentation but at low C/P ratios. A design that allows for less rapid sedimentation would lead to higher C/P ratios and potentially much more organic carbon sequestration on the scale of the coastal system.

The aforementioned example shows several ecosystem-related impacts that are relevant to the carbon footprint of a marine engineering project. In the example a salt marsh was used, but similar kinds of processes take place in case other types of intertidal areas (e.g. mangrove forests, mud flats) would be created or impacted by a marine engineering project. There are more processes that influence primary production (other nutrients such as nitrogen, temperature, light) and carbon sequestration (e.g. soil-forming processes, the presence of sulfur and iron) (Pidgeon, 2012). Most of these processes result in specific C/P and C/F ratios that are not influenced by the project (e.g. temperature, light or the presence of iron and sulfur in depositional areas) or are less limiting to primary production, such as nitrogen.

3. The position of the project in the coastal ecosystem

Primary production (e.g. the formation of organic carbon), and sedimentation (e.g the burial of organic carbon), is key to carbon sequestration. For primary production, the amount of biologically available key nutrients such as phosphorus is essential. Phosphorus is in many environments a limiting factor to primary production and it is critical to assess the impact of a project on the availability of phosphorus.

Similarly, without fine sediments it would not be possible to sequester organic carbon for longer periods in sediments. Sand by itself can contain and sequester organic carbon, but only in limited quantities. A precondition for burial of organic carbon is anoxic conditions that prevent its further decay, a condition that is met in the case of a matrix of fine sediments. Fine sediments are often available in limited quantities. The exception is river deltas where large amounts of fine sediments reach the sea. It is therefore important to assess the impact of a project on the availability of fine sediments.

Fine sediments may find their final resting place on the continental shelf, if they are not withheld by marine wetlands (Jansen *et al.*, 2003). They may even end up in deeper parts of the ocean. Their final destination depends on the characteristics of the coastal system (Van der Zee *et al.*, 2002). A project that involves the construction of a salt marsh will sequester organic carbon in this marsh as a consequence of the interaction of primary production (e.g. algae, benthic algae, plant tissue) and sedimentation of fine sediments. It may also sequester fine sediments in organic carbon in the sand pit. However, the fine sediments would, without this project, contribute to the sequestration of organic carbon elsewhere, perhaps in another salt marsh nearby or on the continental shelf farther away. It is therefore important to scout for potential substitution processes that involve fine sediments.

3.1 Important components in the carbon footprint of a marine engineering project

A comprehensive carbon footprint of a marine engineering project needs to look at the following.

- Dredging: the carbon dioxide emission per cubic metre of sediment is determined by the size of vessel, the way sediment is dredged and placed into its new position and many other factors. The carbon dioxide emission related to the construction of dredging equipment is negligible compared to the fuel consumption. There are several options for optimising the carbon footprint on this level, with roles and responsibilities for both the contracting authority and the contractor.
- Construction: the carbon dioxide emission by constructing and construction materials. Most marine projects also include the use of harbour dams, groynes and so on, for which quarried stone and concrete is used. These building materials represent vast amounts of carbon dioxide emission. The carbon footprint of a project, such as the strengthening of a dike, can be greatly reduced if stone and concrete revetments can be reused, which can often be made possible by the design.
- Abstraction area/sand pit: the organic carbon sequestration related to the release and trapping of fine sediments and related organic carbon and phosphorus. The fines released and trapped will lead to changes further down-drift in the coastal system, furthering or reducing the formation of the intertidal area, the sedimentation rates in depositional areas and so on.
- Construction area/project area: often the original sea bed is replaced by a (wider) beach, dunes or land reclamation area. The project may lead to changes in coastal processes, such as longshore sediment transport that may affect and alter down-drift areas and change their carbon sequestration capacity.

4. Handling the complexity

Carbon is an important building block of life and is present in all organic life forms. It is present not only in tissue of plants, algae and marine organisms, but also in the shells of marine organisms. Carbon is present in different forms, and also the sequestration of carbon has different forms. The sea is an open system. This implies that sand, fine sediments, organic matter and nutrients move freely from one area to another. This movement is restricted for sand, but fine sediments and organic matter, especially in the form of algae, and also (dissolved) nutrients travel considerable distances. This implies that there are regional cause-and-effect chains that may need to be considered. Carbon cycles are strongly related to primary production and are therefore complex. There are, however, options to simplify this complexity.

4.1 Short and long cycles: focus on long-cyclic sequestration

A distinction can be made between short-cyclic forms of carbon sequestration in plants, animals and the humus of soils, and long-cyclic forms of sequestration that, in coastal systems, are mainly related to sedimentation. Short-cyclic forms show large variations in time and place and are difficult to monitor, to measure and to extrapolate to larger areas and time scales. For instance, the carbon uptake of a salt marsh depends on tides, seasons, salinity, nutrient input, vegetation type and more variables. Most of the variation takes place within a season or a tide, so in essence a short period of time. With time vegetation will reach a climax in which it is fully established and can no longer sequester more organic carbon in organic tissue. Further sequestration by fully grown marine wetlands depends on sedimentation and soil formation. The long-term sequestration capacity of, for example, a salt marsh, consists mainly of the organic carbon sequestered in its biomass in its climax state and the carbon sequestered in its sediments over a specific period. Both can be measured and calculated largely independent of the short-cyclic variation.

4.2 For substitution focus on sand, fines and phosphorus

There are many processes that govern primary production and carbon sequestration by sediments. It is proposed to focus on the following processes for regional assessments.

- Sand: sand contains little organic carbon, but it is an essential building block in many coastal systems. Most marine engineering projects that take place at sandy shores influence sand budgets and longshore processes, and the subsequent erosion and sedimentation may affect coastal wetlands, dunes and beaches as well as the nourishment needs of a project.
- Fines: as argued, fine sediments are needed for the long-cyclic sequestration of organic carbon in soils. Fines are abundant in river deltas but overall fines are only available in limited supply. Fines are also an essential building block for coastal wetlands, such as salt marshes, mudflats and mangroves. Projects change the availability of fines, their distribution and sedimentation.
- Phosphorus: of the nutrients that govern primary production, phosphorus is the most limiting. Projects that directly or indirectly alter the availability of phosphorus also alter primary production and therefore carbon sequestration.

The C/P ratio in sediments and soils is influenced by several processes. Over time the C/P ratio increases because phosphorus that is bound to organic matter is released from the soil more effectively than carbon. The release of phosphorus also strongly depends on the presence of sulfur and iron and is controlled by oxygen and microbiological activity. The organic C/P ratio differs depending on the sedimentation rate, being lower (near 200) in the case of fast sedimentation (>1 cm/year) and at very low sedimentation rates ($<0{\cdot}002$ cm/year). Intermediate sedimentation rates can have C/P ratios that are higher, up to 600 (see Ingall and van Cappellen, 1990). Very low sedimentation rates occur in deep sea environments. Very high sedimentation rates can be expected on the coastal shelf, near deltas and in estuaries, but also in sand pits. Frequent resuspension of bottom sediments also lowers C/P ratios.

4.3 Simplify by reasoning

The carbon footprint of a project is complex, but it is possible that the most complex parts are not relevant for a particular case. For example, when comparing two nourishment strategies, annual and periodical, one may argue that mainly the cubic metre efficiency of the nourishment scheme and the CO^2/m^3 efficiency of the equipment used are relevant if the same shallow sand pits are used in both schemes.

Regarding substitution there are basically three different situations.

- In coastal systems with potentially full replacement and substitution, the emission caused by dredging and constructing will be the paramount factor in the carbon footprint and in comparisons between alternative designs and dredging schemes. This is the simplest level of assessment.
- In coastal systems with little risk of replacement and substitution, dredging and construction schemes can be supplemented by the sequestration characteristics of sand pits and marine wetlands, if being part of the project.
- More complicated are those coastal systems in which only partial substitution is expected. Here all processes need to be taken into account and the carbon footprint will have a considerable bandwidth because especially offsite substitution is very difficult to assess and can often only be done qualitatively.

Furthermore, one may need to focus on those changes in the coastal system that endure over longer periods. So the emphasis should be on expected long-term equilibrium states of the coastal system.

5. Initial assessments of an ecosystem-based carbon footprint

5.1 Proposed initial calculation scheme

The BwN programme aims to develop a tool that allows the calculation of a more comprehensive carbon footprint that helps to identify the potential to reduce the carbon footprint by altering design, dredging schemes, pit location, and so on.

Figure 1 shows a simplified scheme for a carbon footprint for marine engineering projects. It distinguishes the direct carbon dioxide emission due to dredging and construction, including the emission related to the production of construction materials. Furthermore, a distinction is made between the abstraction site/pit site and the construction/project site. An important element is the substitution that may take place by

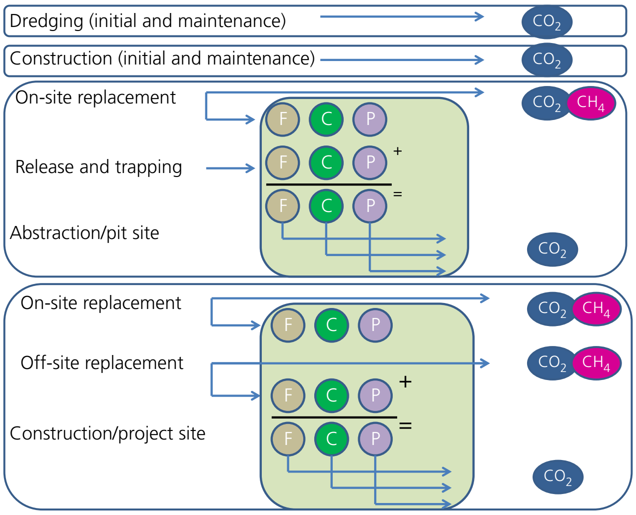

Figure 1. Calculation scheme: C, carbon; CO_2, carbon dioxide; CH_4, methane; F, fine sediments; P, phosphorus

following the fate of and impact on sand, fines and phosphorus.

Focus is on long-cyclic sequestration and on the role of fines and sedimentation processes. The far field substitution that takes place related to fines and phosphorus is the most complex. C/P and C/F ratios and other variables have been collected from the literature in order to obtain first impression of the sequestration capacity and efficiency of different types of depositional areas. Data are scarce and almost non-existent for sand pits. The plan is to collect more field data to fill in the gaps. Another information gap is the proportion of the fines that is trapped by depositional areas.

5.2 First assessments

This scheme was used for a first set of calculation sheets. Using these calculation sheets, different cases have been considered, such as the sand engine on the coast of Delfland and a new BwN pilot, the mud engine that is meant to stimulate salt marsh development locally in the Wadden Sea using dredged material.

The conceptualisation of a project over a 100-year period is an important and daunting step that requires extrapolating trends and also coastal policies. The issue of substitution is strongly governed by long-term and regional assumptions regarding the sand and fine sediment balances and of the availability of phosphorus. The complexity and uncertainty in the long term is very large, so it is proposed to consider intermediate stages for assessment.

The example of the sand engine shows that a design that enables the use of larger dredging equipment (due to sheer volume) and comparatively simple dredging schemes (e.g. with substantial bottom release) may lead to a reduction in the carbon footprint of coastal maintenance projects. It also shows the potentially important role of the sand pit in the overall carbon footprint. As its location and form influence the release and trapping of fines and related organic carbon and phosphorus, the sand pit merits more attention.

More understanding is needed at the sediment–water interface that determines C/F and C/P ratios in different kinds of depositional areas and marine habitats. For this sediment, sampling and analysis is necessary with an emphasis on long-cyclic sequestration processes and also of deeper sediment layers. Of great interest are the sedimentation characteristics of different forms of sand pits. Also different forms of organic matter need to be distinguished that have different decay rates.

Also the long-term hydrodynamics of various potential carbon sequestration sites are critical in order to define the permanency of long-cyclic carbon sequestration. The carbon sequestration of many years can be lost during an occasional fierce storm, not only in the form of salt marsh erosion but also by resuspension of settled fine sediments out of sand pits and from depositional areas on the continental shelf.

6. Next steps

Based on these first results additional steps are being taken by the programme in order to fill in relevant information gaps, validate the calculation scheme and to refine it. Furthermore, specific formats will be developed for different types of projects in different types of coastal environments. More information needs to be gathered for cases that appear to offer opportunities to alter positively the carbon footprint.

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