D1.2

Conceptual model of marine ecosystem functioning, supply of Ecosystem Services and interactions

WP n° and title	**WP1 – Mechanistic understanding of the ecosystem services supply side**
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Acronyms

WP	**Work Package**
ES	**Ecosystem Services**
ScAB	**Scientific Advisory Board**
ERA	**Environmental Risk Assessment**
BCS	**Belgian Continental Shelf**
OWF	**Offshore Wind Farm**

1. Executive summary

As part of Work Package (WP) 1 of the SUMES project, we aimed to gain a better understanding of the structures and processes underlying the supply of Ecosystem Services (ES) in temperate shallow shelf systems. This was done by creating conceptual models of the structures and processes that make up different compartments of the marine system and how these supply ES. We then merged these conceptual models, leading to a final model that represents the most relevant variables and mechanisms for ES supply in the marine ecosystem of shallow shelf areas. This gave us insight into the interactions between ES through the structures and processes of the biophysical system. The model was validated by consulting with experts from the SUMES Scientific Advisory Board (ScAB) in an interview setting. The conceptual model is an important outcome of WP1 of SUMES, and forms the basis to develop a quantitative model in WP3 that is specifically suitable for the Belgian Continental Shelf (BCS).

2. Introduction

As part of WP1 of the SUMES project, we aimed to gain a better understanding of the structures and processes that make up ecosystem functioning and that underlie the supply of ES, following the Ecosytem Services Cascade model (Haines-Young & Potschin, 2010). The marine environment can be seen as a multidimensional web of ecosystems that are interlinked by longitudinal, lateral, vertical and temporal dynamics (Fisher et al. 2009). These fluxes and dynamics define the places of supply of ES. The ES (provisioning, regulating and cultural) flow along these dynamics and result in distribution patterns of ES benefits. The objectives of WP1 are to gain insight into the mechanisms (structures, processes and interactions) that underlie the supply of ES and to identify the causes of changes in ecosystem functioning and ES supply related to economic activities by integrating Environmental Risk Assessment (ERA) into ES supply. These tasks are based on scientific and experimental studies related to general hydrodynamics, morphodynamics and ecological aspects in marine systems, including insights from models, descriptive research and monitoring.

In the construction of the conceptual model, the focus is on the supply of ES in temperate shallow shelf systems, excluding the intertidal zone. These boundaries were set because the processes occurring in the intertidal and coastal zones can be very different from the subtidal and would thus be better represented in separate models, which is outside the scope of the SUMES project. The conceptual model does not feature human activities and related stressors, but only the biophysical structures and processes and the ES they supply; The link with human stressors will be made at a later stage when ES supply is linked to ERA (WP4), that way the local to regional effects of a particular marine activity will be quantified. Thus, the scope of this deliverable is to develop a conceptual model of marine ecosystem processes, structures and functions that *potentially* supply ES, with a focus on their interlinkages. Because human activities were not considered at this stage, the *actual* supply cannot be derived from the conceptual model: For certain services, human activities are an essential factor in ES delivery, but this is outside of the scope of this deliverable (Figure 1). We also do not take into account forcing variables, such as meteorological conditions.

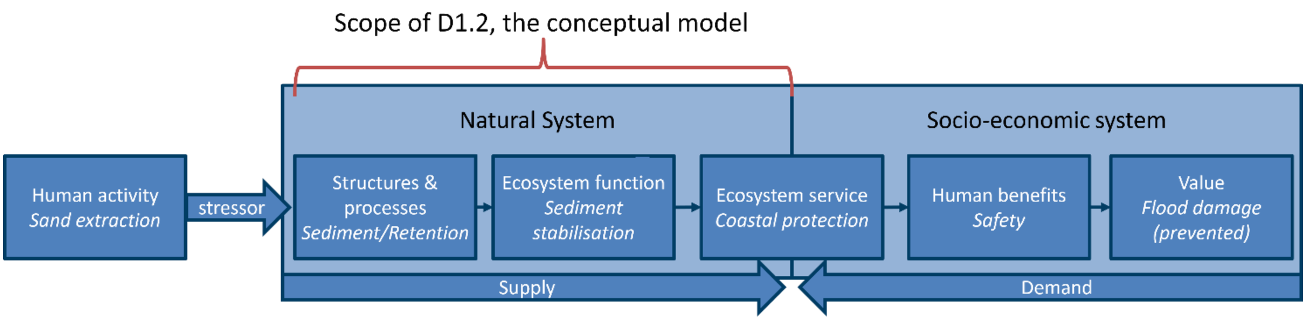

Figure 1: Ecosystem services cascade, with coastal protection as an example, showing the scope of D1.2, the conceptual model.

3. Methods

In order to create a conceptual model of the structures and processes underlying ES supply in a systematic way, we first selected relevant ES (Section 3.1). Then, we created models of ES supply for different compartments of the biophysical system, the evidence for which was stored in an evidence library (Section 3.2). These models were then merged to form the full conceptual model draft, which was validated with the input of ScAB members (Section 3.3).

3.1. Selection of ES

The selection was based on literature on ES that are (potentially) delivered in the BCS and similar temperate, shallow shelf systems (Table 1). This initial list, which was also used as a basis to select ES deemed important by stakeholders in a workshop (D2.2 *Ecosystem Services relevant for the Belgian Continental Shelf based on multi-actor lab*), consists of 14 ES. The rationale behind the composition of the initial list, including the references used to justify inclusion, can be found in D2.2, in Table 6 (Annex section). We added the service *pest control* to this initial list of ES, as literature showed this to be a relevant service in the BCS and similar systems (Lancelot et al., 2005; Broszeit et al., 2019).

Table 1: Ecosystem Services relevant for the BCS included in the initial list with their CICES equivalents.

Ecosystem Service	CICES equivalent/code	CICES classification level
Farmed aquatic plants	1.1.2 Cultivated aquatic plants for nutrition, material and energy	Group
Farmed aquatic animals	1.1.4 Reared aquatic animals for nutrition, materials or energy	Group
Wild aquatic animals	1.1.6 Wild animals (terrestrial and aquatic) for nutrition, materials or energy	Group
Mediation of wastes	2.1.1 Mediation of wastes or toxic substances of anthropogenic origin by living processes	Group
Coastal protection	Regulation of baseline flows and extreme events	Group
Nursery and habitat maintenance	2.2.2.3 Maintaining nursery populations and habitats (including gene pool protection)	Class
Pest control	2.2.3.1 Pest control (including invasive species)	Class
Climate regulation	2.2.6.1 Regulation of chemical composition of atmosphere and oceans	Class
Recreation	3.1.1 Physical and experiential interactions with the natural environment	Group
Scientific research	3.1.2.1 Characteristics of living systems that enable scientific investigation or the creation of traditional ecological knowledge	Class
Cultural heritage	3.1.2.3 Characteristics of living systems that are resonant in terms of culture or heritage	Class
Aesthetic value	3.1.2.4 Characteristics of living systems that enable aesthetic experiences	Class
Surface for navigation	4.2.X.X Other aqueous ecosystem outputs	Group
Sand and other minerals	4.3.1.2 Mineral substances used for material purposes	Class
Renewable offshore energy	4.3.2.3 Wind energy	Class

3.2. Models of ecosystem compartments

The marine system can be divided into several broad environmental compartments that can each be influenced by human activities. We started constructing conceptual models for the benthic and pelagic biochemical compartments (which include the lower food web and nutrient cycles) and a conceptual model for the upper food web. A separate model was constructed for the role of (cultured) bivalves (*suspension feeders* in the models) in the system, because of their unique position in both the biochemical and trophic compartments (Smaal et al., 2019).

In these models, the major structures and processes defining the system were represented, and linkages with potential supply of ES were indicated. By structures we mean all structures naturally present in the system, but these may also refer to man-made structures that have become an integral part of ecosystem functioning (e.g. man-made hard substrates). Forcing variables, such as meteorological conditions and nutrient input, were left out to keep the focus on the internal dynamics of the system. The conceptual models thus represent the state-of-the-art in a condensed and integrated manner. The models capture the response of the ES supply to changes in ecosystem structures and processes, following the rationale of the ES cascade. Our aim was to condense the information to broad variables and identify the most important ones in ES delivery, therefore not all variables were explicitly included in the models. The conceptual models of the different compartments are shown in the Annex section (Figure 5-Figure 7).

After the models were constructed for the main components of the system, they were merged into a single model. This was done to display the interlinkages between the different ecosystem compartments and to allow for the identification of interactions between ES through the structures and processes of the system. During and after merging of the compartment models, changes were still made to the structures and processes included based on the literature. A draft of the full conceptual model (M1.1) was due in July 2021.

The method used was based on the fourth step of the method by Van der Biest et al. (2020) for setting ecologically sensible objectives: 'For each habitat and ES, the processes that contribute to ES development, maintenance or delivery are identified.' Structures and processes that make up the ecosystem functioning of temperate shallow shelf systems were partly derived from Van der Biest et al. (2017). Besides this, we also used other sources to complete specific parts of the conceptual models. The sources used to construct the conceptual model were documented in an evidence library (Annex, Table 4Figure 4), as also done by Olander et al. (2018). Each link from the model, having an ID number, is documented in the library with:

- the link description (i.e. what process is represented);
- the evidence for the link, giving a summary of *how much* and *what types* of research support it;
- the strength of the evidence, from *high* to *none*. Here, we categorised the evidence strength based on the number of types of evidence, the consistency in the results, the methods used and the applicability to our area of interest (
- Table 2);
- other factors to be taken into account, such as nuances or situations under which the assumptions do not hold;
- the sources used, which offers a (non-exhaustive) list of studies that provide evidence for the link.

Table 2: Criteria used to judge the confidence level for the links in the conceptual model. From Olander et al. (2018).

Confidence level	Types of evidence	Consistency of results	Methods	Applicability
High	Multiple	Direction and magnitude of effects are consistent across sources, types of evidence, and contexts	Well documented and accepted	High
Moderate	Several	Some consistency	Some documentation, not fully accepted	Some
Fair	A few	Limited consistency	Limited documentation, emerging methods	Limited
Low	Limited, extrapolations	Inconsistent	Poor documentation or untested	Limited or none
None	None	Not applicable	Not applicable	Not applicable

Assessing the strength of evidence in a systematic and reproducible way is an important part of reviewing literature and gathering ecological data. As depicted in Figure 1Figure 2, the strength of evidence is not only determined by the amount of evidence available, but also by the level of consensus surrounding the subject. It's important to note that the evidence library is a living document that may be supplemented or adjusted throughout the SUMES project. In this way, it offers a useful reference for the literature on ecosystem functioning and ES supply. The document is stored online, and can be accessed through this link.

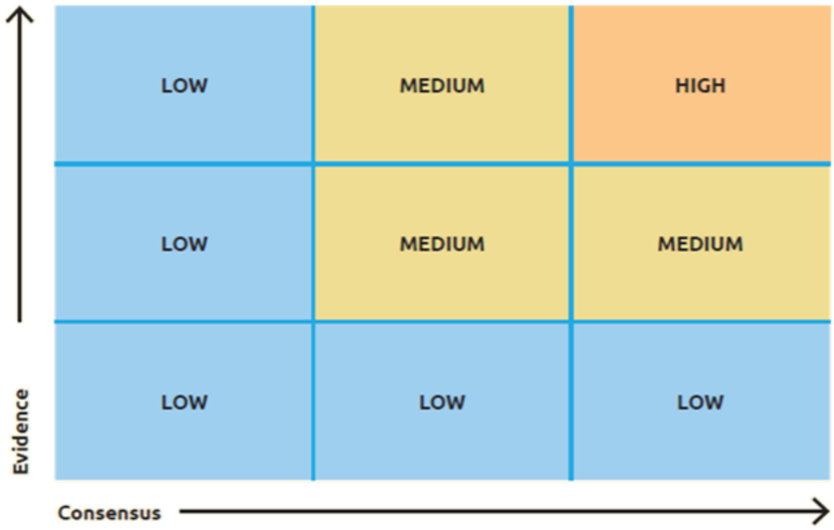

Figure 2: Graphic representation of the relationship between evidence and consensus, resulting in evidence strength. From Kroger et al., 2018.

3.3. Validation by scientific experts

The conceptual model was validated by scientific experts of the SUMES ScAB during interviews held in July 2021 (M1.2). The experts were consulted to review part of the conceptual model, which was mainly based on their professional expertise. In these interviews, the experts were asked to follow cause-effect chains through the conceptual model in order to identify missing or irrelevant components and faulty assumptions. This was done in three interviews, each with a specific focus: Jan Vanaverbeke (Royal Belgian Institute of Natural Sciences) and Gert van Hoey (ILVO) on benthic functioning, Sheila Heymans (European Marine Board and VLIZ) and Angel Borja (AZTI) on marine food webs, and Fiona Culhane (University of Plymouth) on marine ES supply. The draft model was updated after carefully considering the inputs from the scientific experts, resulting in the final conceptual model of ES supply.

4. Results

The conceptual draft model, which is solely based on literature, gives an overview of how the structures and processes in temperate shallow shelf systems can potentially contribute to the delivery of ES (Figure 3Figure 3). One of the main observations is the high degree of connectivity between the marine food web and the cycling of nutrients, where the lower food web serves to link the two. We also identified complex interactions between benthic organisms and their environment. This can be attributed to their immobile lifestyle compared to pelagic, free-living biota such as plankton and fish. Our conceptual model includes all categories of ES, regulating (e.g. *mediation of wastes*), provisioning (*e.g. wild aquatic animals*) and cultural (*recreation*). The cultural services are limited to *recreation*, because other cultural ES were either too system-specific or not linkeable to any ecosystem structures and processes. *Nursery and habitat maintenance* can be seen as a supporting service. ES can be delivered by both structures and processes in the system: for example, the service *sand and other minerals* is supplied by the presence of the structure *sediment*, whereas *mediation of wastes* is supplied by several processes that remove excess nutrients from the water column. The structures and processes are linked by (1) material flows indicate the movement and/or transformation of non-living materials from one group or process to another, like the burial of *organic nutrients and carbon* in the *nutrient and carbon stock* in the sediment, (2) trophic flows, which indicate the consumption of one living (trophic) group by another, like the consumption of phytoplankton by zooplankton, as well as the mortality of all living groups to the detrital structure and (3) influences, which indicate that one structure or process affects another without the presence of a flow of material or biomass, like the (negative) effect of increased turbidity on primary production. The lack of forcing variables means the model is focused solely on the behaviour generated within the system.

Table 1Table 3 gives an overview of the suggested changes to the draft conceptual model suggested by the experts. Most suggestions concerned the functioning of the benthic system, the food web and nutrient cycling, and were incorporated into either the conceptual model or the evidence library. After incorporating these changes, we arrived at our final conceptual model of ES supply (Figure 4). Initially, several ES were not included in the draft conceptual model for various reasons, but later on these were added to the final conceptual model without being linked to any structures or processes in the system. This was done because these services were found to be relevant in the BCS and similar systems, either by the stakeholders or by literature (or both), but their supply could not be attributed to any or all ecosystem components and were therefore left out of the draft conceptual model: For example, *renewable offshore energy* and *surface for navigation* were initially excluded because the supply of these services could not be linked to ecosystem structures or processes. *Scientific research* had been excluded because it is inherently linked to most of the structures/processes. We had excluded *cultural heritage* as an ES because it is highly specific to each system (for example, in a small portion of the BCS this may apply to traditional shrimp fishers, but there might be other traditions linked to other biotic groups in other areas). Lastly, we had excluded *aesthetic value* because none of the structures and processes in the conceptual model could impact this service. The abovementioned services are displayed in the final conceptual model (Figure 4) to ensure their inclusion later on in the SUMES project. Even though their interaction with the ecosystem is limited, they may interact with eachother or other human activities: For example, the construction of OWFs could impact the *aesthetic value* of the system. These potential interlinkages can be tackled in WP3 and WP4.

The final conceptual model gives a holistic overview of the mechanisms in the marine ecosystem by which ES are supplied and provides insight into which structures and processes are most important in the supply of ES: For instance, suspension feeders can be directly linked to the ES *farmed aquatic animals*, *pest control*, *coastal protection* and *climate regulation*, and influence the mediation of wastes indirectly. The upper foodweb is also instrumental in the supply of several ES, such as *recreation* and *wild aquatic animals*. Furthermore, it becomes clear that the benthic biota (suspension and deposit feeders) serve a pivotal role in connecting the pelagic and benthic systems, as well as the biological and chemical components. We divided the benthic biota into suspension feeders (e.g. mussels and anemones, mostly hard substrate, epibenthic organisms), deposit feeders (e.g. polychaetes, mostly soft substrate, endobenthic organisms) and macrofauna (e.g. crabs and echinoderms, mostly large-bodied, mobile predators). It is important to note that this distinction is a highly simplified view of benthic ecology: For instance, suspension feeders can be found both on hard and soft substrates. In the pelagic zone, primary production is an essential process, serving as the link between the chemical component and the foodweb (of which it is the basis). In the benthic, the diagenetic processes dominate the dynamics, and they influence the chemical composition of both the benthic and pelagic zones. These diagenetic processes are in their turn influenced by the presence of deposit and suspension feeders, as well as the sediment properties. The physical properties of the substrate also influence ES supply, as it may have an effect on *nursery and habitat maintenance* and *sand and other minerals* for extraction. It also affects the benthic biota and the diagenetic processes taking place in the sediment. It is worth noting that in many shallow shelf systems, including the BCS, natural hard substrates have mostly disappeared due to human activities (Lotze et al., 2006). However, man-made structures (like wind turbines) can also fulfil this role within the functioning of the ecosystem (Reubens et al., 2010). Therefore, it's very important to include hard subsrate in the conceptual model, especially because SUMES is aimed at investigating the effects of human activities and pressures. All in all, this model can be used as a comprehensive summary of the state of the art of ES supply in temperate shallow shelf systems like the BCS.

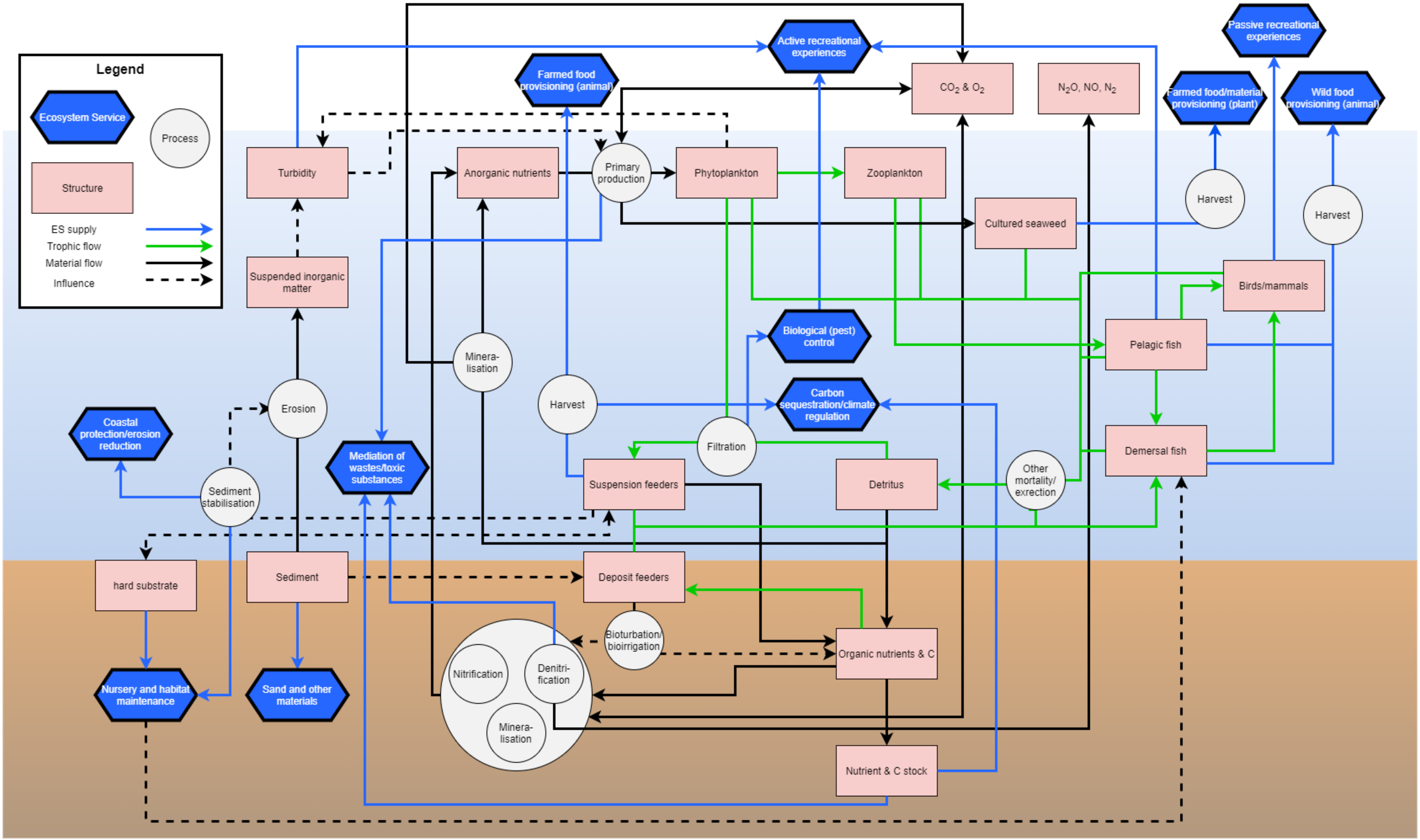

Figure 3: Draft of conceptual ecosystem services provisioning model (M1.1). Blue, red, and white boxes represent ES, structures and processes respectively. Blue arrows represent ES supply, green arrows represent trophic flows, black arrows material flows and dotted arrows represent influences.

Table 3: An overview of suggestions by the scientific experts and whether they were adopted into the conceptual model/evidence library

Interview no.	Subject	Expert suggestion	Adopted?
1	Benthic functioning	Include macrofauna (crustaceans, echinoderms, etc.) as a trophic group that feeds on suspension/deposit feeders and is predated on by demersal fish and is harvested.	Yes, in conceptual model
1	Benthic functioning	Include the ES of nursery and habitat maintenance for macrofauna.	Yes, in conceptual model
1	Benthic functioning	Include an effect of sediment on diagenetic processes: the type of sediment (mainly the fineness) influences the oxygen availability for processes in the sediment.	Yes, in conceptual model
1	Benthic functioning	Include an effect of biodeposition on sediment, as biodeposition leads to fining of the sediment.	Yes, in conceptual model
1	Benthic functioning	Include an effect of suspended inorganic matter on suspension feeders, as high concentrations of suspended matter can smother suspension feeding organisms.	Yes, in conceptual model
1	Benthic functioning	Include a flow of phytoplankton to detritus/organic nutrients and C in the sediment, as about 30% of primary production in the BCS is not transferred to the food web, but rather dies and settles.	Specified in the evidence library; link was already there as part of 'other mortality'
1	Benthic functioning	Long-term carbon storage is only relevant in areas where the sediment remains undisturbed by e.g. trawling or decommissioning of wind turbines.	Yes, nuanced link in evidence library
1	Benthic functioning	Nursery and habitat maintenance is only relevant when habitat leads to increased production, rather than merely attraction of marine organisms (attraction-production hypothesis).	Yes, nuanced link in evidence library
2	Food web	The diets of birds and marine mammals are sufficiently different to split them up into separate groups.	Yes, in the conceptual model
2	Food web	Suspension feeders are not only predated upon by macrofauna but also by demersal fish. To a lesser extent this may also be the case for deposit feeders.	Specified in evidence library
2	Nutrient cycling	Detritus is taken up by zooplankton in what is known as the 'microbial loop', where microbes break down larger pieces of detritus into particulate organic matter.	Yes, in the conceptual model
2	Nutrient cycling	Leave 'toxic substances' out of the ES 'Mediation of wastes/toxic substances', as our model is only aimed at excess nutrients and not other man-made pollutants such as heavy metals.	Yes, in the conceptual model
2	Legend	Change 'influence' to 'non-trophic mediation'.	Yes, in the conceptual model
3	Food web	Possibly include a link from macrofauna/deposit feeders to recreation, for e.g. crab diving and cockle harvesting.	No, relevance in BCS could not be shown
3	Food web	Possible contribution of the food web to carbon sequestration.	No, more sources required to confirm

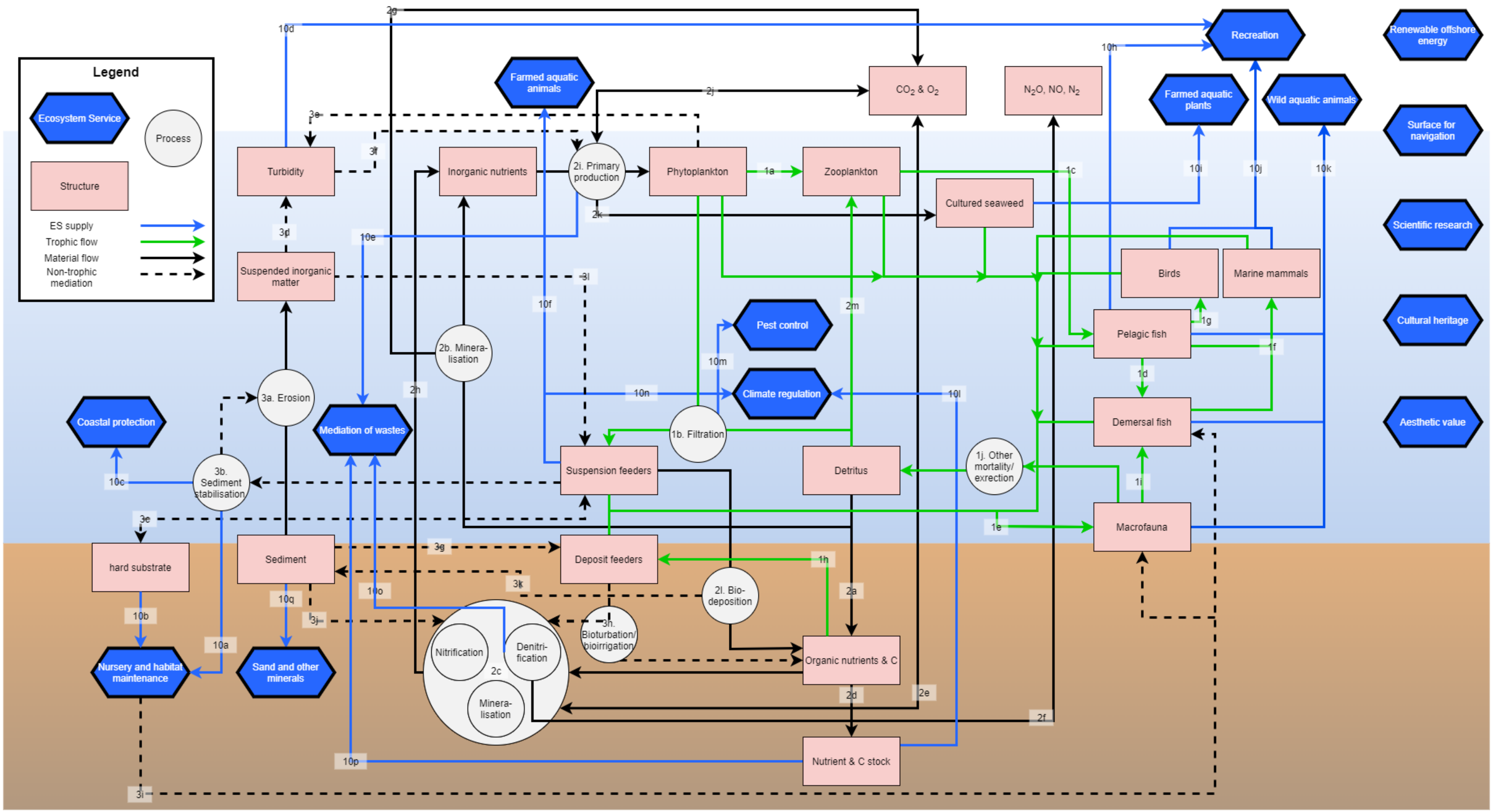

Figure 4: Conceptual model after model review with experts. Blue, red, and white boxes represent ES, structures and processes respectively. Blue arrows represent ES supply, green arrows represent trophic flows, black arrows material flows and dotted arrows represent non-trophic mediations. Each link is labelled with the ID used in the evidence library.

5. Further use in SUMES

The next step, as part of the conceptual integration of ERA with ES assessment, is to link the conceptual model to variables impacted by human activities, which will be investigated in an impact assessment performed by UGent-GhenToxLab. This will result in a more directional conceptual model for each (major) human intervention. Starting with the impact of the construction of an Offshore Wind Farm (OWF), identified as the showcase in WP4, we will identify the cause-effect chain based on the conceptual model, i.e. modelling the impact on the supply of ES. This will allow us to pinpoint the most important variables linking human activities or interventions to ES supply through ecosystem functioning. For this, we will follow the rules and guidelines for the design of Ecosystem Services Conceptual Models provided in *Building Ecosystem Services Conceptual Models* (Olander et al., 2018). Besides the first SUMES case study itself, OWFs, this exercise will also show the interactions between OWF and other human activities, such as the exclusion of fisheries (cfr. Advanced cases, WP4) and ES. As a first exploration of these interacting human activities, stakeholders were asked to visualise the interactions between ES and human activities (D2.2, Figure 9). The result of this provides a useful starting point for identifying linkages between human activities, the system's structures and processes, and ES.

The conceptual model created in this part of WP1, and the models incorporating human impacts, will be used at multiple stages of the SUMES project. Firstly, during the review and selection of quantitative models (D1.1), the conceptual model will be used as a criterium to assess whether the quantitative models cover relevant parts of the marine ecosystem. Secondly, the preliminary selection of indicators of ES supply that is part of WP1 (M1.3) will be done for the structures, processes, functions and services included in the conceptual model. Finally, the conceptual model is also the basis for the quantitative model that we aim to create in WP3. The model will be important at that stage, as it will help us to identify which variables are essential in ES supply and the interactions between ES.

This conceptual model offers a general overview of ES supplied in the subtidal area of the BCS and similar shallow shelf systems. For future uses within the project, we will make a selection of ES from this model. ES will be selected based on (1) whether they were identified by the stakeholders as important (D2.2) and (2) whether they are relevant for the SUMES case studies. Additionally, some ES from the initial list were not linked to any structures or processes in the biophysical system. Though these ES were excluded from the conceptual model, they may be of importance later in the project when the biophysical system is linked with human activities, because these could influence the supply of those ES.

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7. Annexes

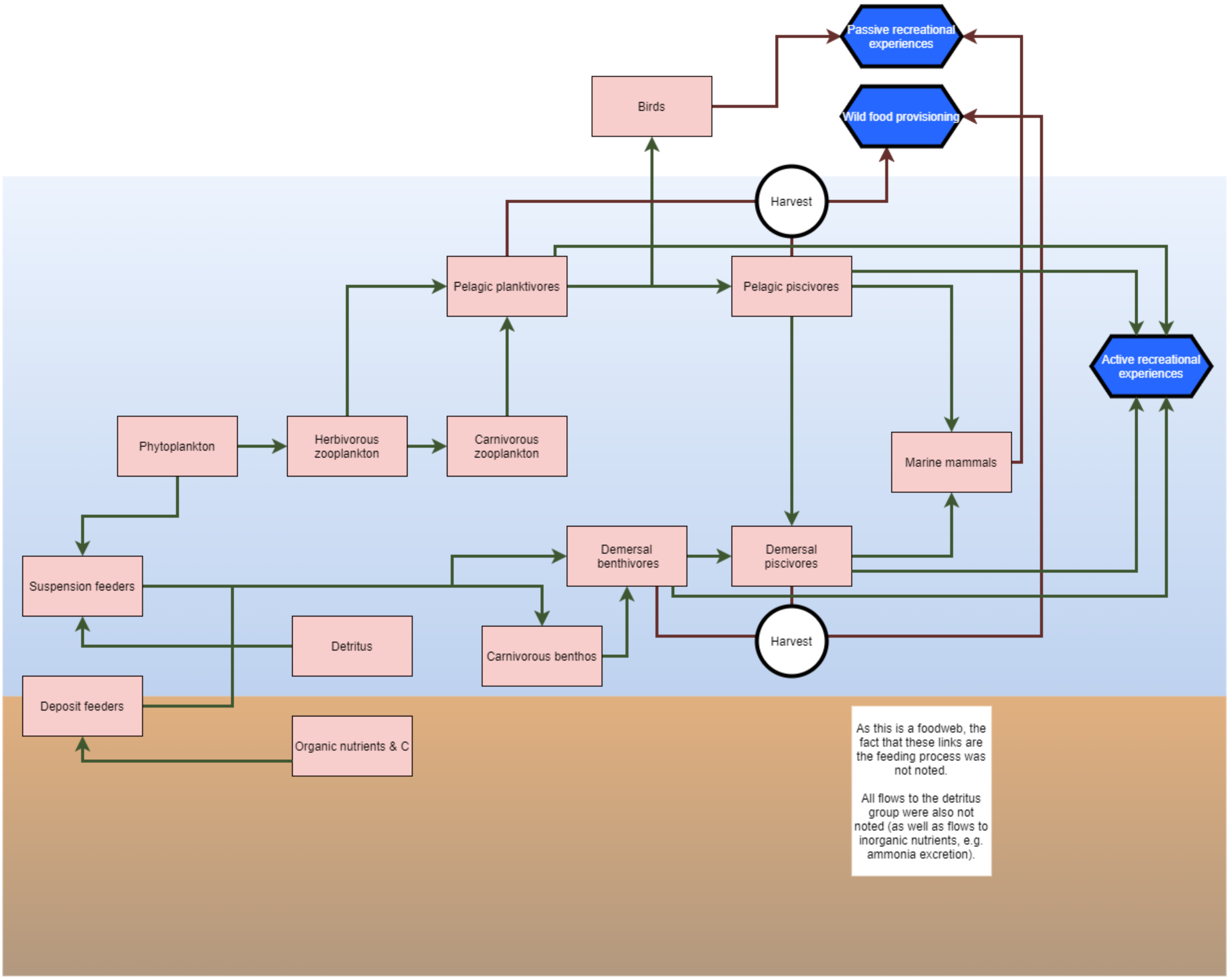

Figure 5: Draft conceptual model of the food web compartment. Red, white and blue boxes represent structures, processes and ecosystem services respectively. Arrows indicate flows and relationships.

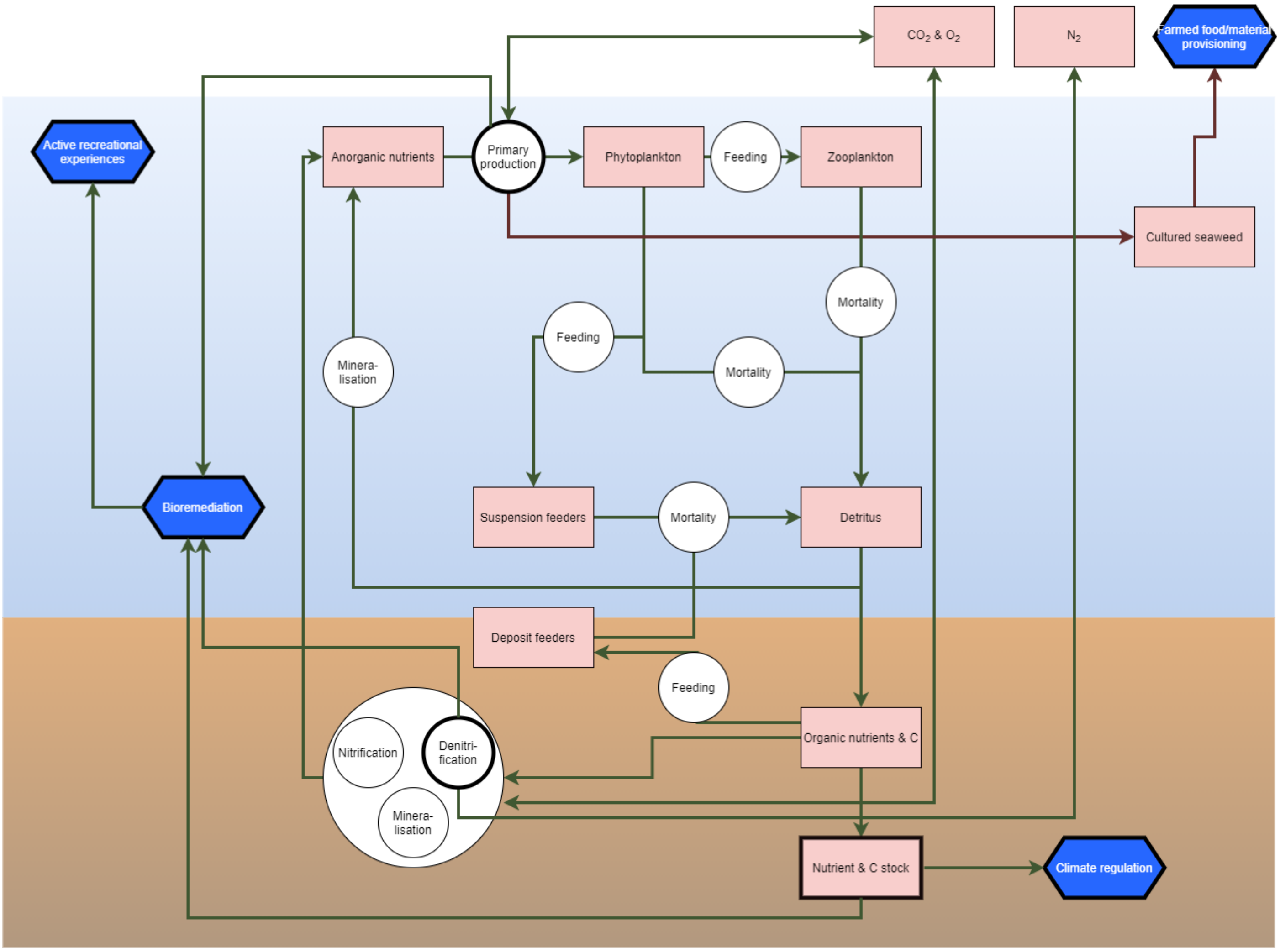

Figure 6: Draft conceptual model of the nutrient cycling compartment. Red, white and blue boxes represent structures, processes and ecosystem services respectively. Arrows indicate flows and relationships.

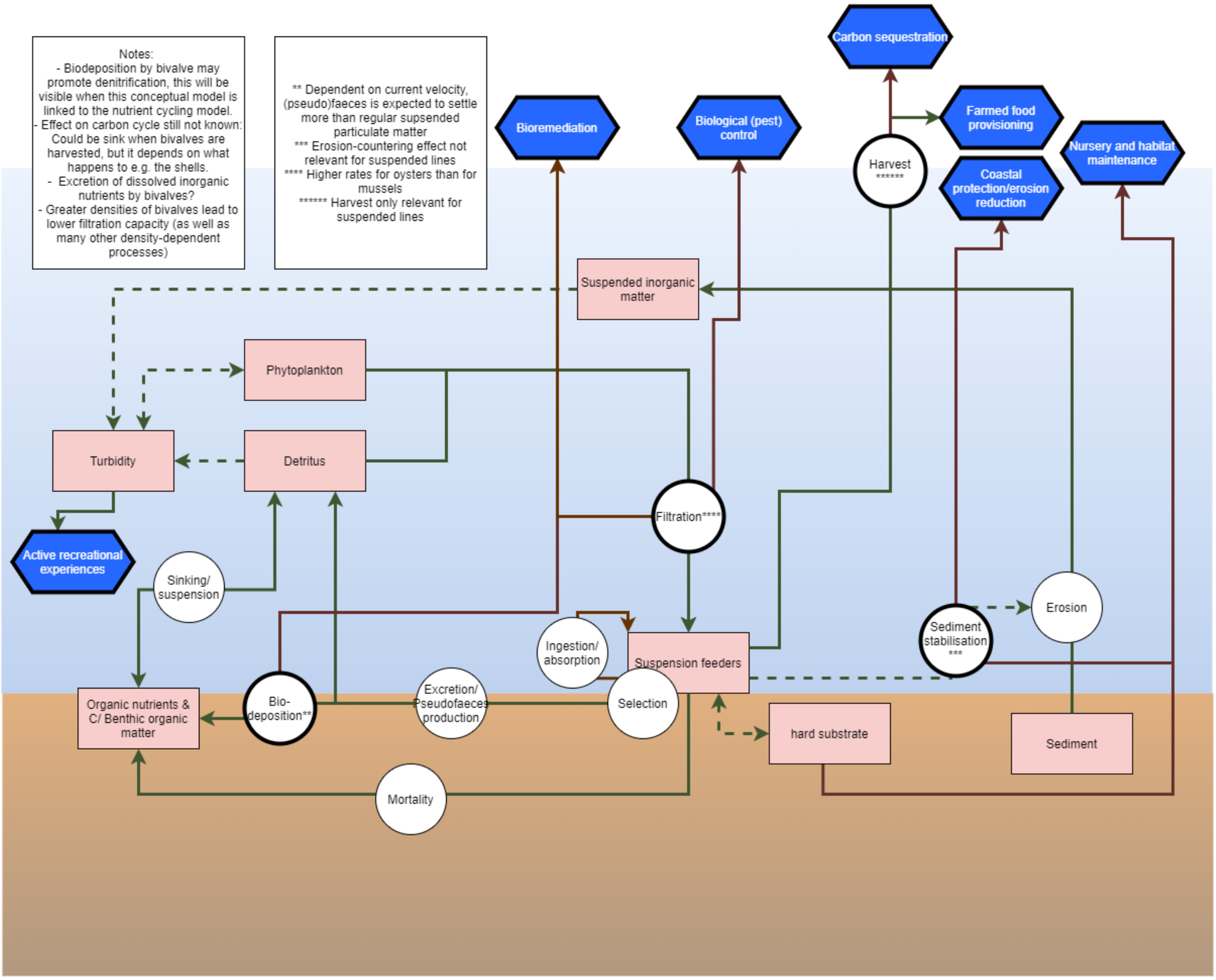

Figure 7: Draft conceptual model of processes related to bivalves. Red, white and blue boxes represent structures, processes and ecosystem services respectively. Arrows indicate flows and relationships.

Table 4: Evidence library, describing the links in the conceptual model, the summary and strength of the evidence found, other factors influencing the relationship and sources used to include it in the conceptual model. Not final, to be updated throughout the course of the project. *Sources not yet included in references.*

ID	Component	Description	Summary of evidence	Strength of evidence	Other factors	Sources
1a	Trophic interactions	Predation of phytoplankton by zooplankton	Long history of empirical research, modelling studies and lab studies show the importance of zooplankton grazing on phytoplankton densities	High	Phytoplankton is a diverse group that is variably grazed upon by multiple groups of zooplankton	Heath, 2012; Steele & Ruzicka, 2011; Lancelot et al., 2005

1b	Trophic interactions	Filtration of phytoplankton and detritus by suspension feeders	Research has shown that grazing of phytoplankton by suspension feeders can have significant impact on phytoplankton densities and primary production. Suspension feeders also feed on suspended organic matter.	High	This flow shows a simplification of the suspension feeding community, as well as phytoplankton, and detritus, as all these group are diverse. Grazing can be very variable. When phytoplankton densities become very high, this can have negative effects on suspension feeders. Greater densities of bivalves lead to lower filtration capacity (as well as many other density-dependent processes).	Heath, 2012; Smaal et al., 2019; Slavik et al., 2019; Ivanov et al., 2021; Mavraki et al., 2020
1c	Trophic interactions	Predation of zooplankton by pelagic fish	Many studies of fish diets and food web modelling have shown zooplankton to be the main food source for (small) pelagics.	High	Though this is the main food source for (small) pelagics, pelagic fish also feed on benthic organisms, phytoplankton, demersal fish and other pelagic fish (larvae).	Heath, 2012; Steele & Ruzicka, 2011
1d	Trophic interactions	Predation of pelagic fish by demersal fish	Dietary studies and food web modelling have shown that the average trophic level of (adult) demersal fish is higher than that of pelagics (in the North Sea), proving the importance of the flow of biomass from pelagic to demersal fish.	High	This flow is most relevant for adult demersals feeding on small pelagics and larvae. For early life stages it may not be relevant or may be reversed, but it becomes more important as fish mature (ontogenetic niche shift).	Heath, 2012; Steele & Ruzicka, 2011
1e	Trophic interactions	Predation of benthic suspension and deposit feeders by macrofauna.	Dietary studies and food web modelling have shown macrobenthic organisms to be the main food source of macrofauna.	High	The diverse communities of benthic organisms are variably predated upon by demersal macrofauna. Macrofauna are also known to be scavengers, feeding on detritus.	Heath, 2012; Steele & Ruzicka, 2011; Smaal et al., 2019
1f	Trophic interactions	Predation of fish by marine mammals	Dietary studies and food web modelling have shown the effects of predation by marine mammals on fish	High	-	Heath, 2012; Steele & Ruzicka, 2010
1g	Trophic interactions	Predation of pelagic fish by birds	Dietary studies and food web modelling have shown the effects of predation by birds and mammals on pelagic fish	High	Fish from discards is also a major source of food for birds. Marine mammals also feed on pelagic fish.	Heath, 2012; Steele & Ruzicka, 2011
1h	Trophic interactions	Uptake of organic nutrients and C in the benthos by deposit feeders	Dietary studies and food web modelling has shown the flow of benthic organic material to deposit feeders.	High	Deposit feeders feed on a wide range of organics in and on the sediment, originating from many different biological groups.	Heath, 2012; Steele & Ruzicka, 2011
1i	Trophic interactions	Predation of macrofauna by demersal fish	Dietary studies and food web modelling have shown the importance of macrofauna (crabs, echinoderms, etc.) as a food source for demersal fish	High	Demersal fish also feed directly on suspension feeders, and to a lesser extent also on deposit feeders.	Heath, 2012; Steele & Ruzicka, 2011

1j	Trophic interactions	Production of particulate organic matter (faeces and dead organisms) by marine organisms	Long history of biological research shows that organic matter in water column and on sea floor originates from marine organisms, both from death due to disease/old age and non-assimilated food (faeces). This is especially important in the BCS for phytoplankton, where about 30% of primary production is converted to detritus (not taken up in the food web).	High	-	Christensen, 2005
2a	Biogeochemical cycle	Flux of organic nutrients from the water column to the upper layer of the sediment via deposition of dead organic matter	Long history of biological research shows that part of the detritus reaches the seafloor without biodegradation	High	The amount of detritus that reaches the seafloor without degradation depends on the weight, shape, composition and density of the detritus	Lancelot et al., 2005; Soetaert et al., 1996
2b	Biogeochemical cycle	Degradation of dead particulate organic matter in the water column resulting in release of inorganic nutrients	Long history of biological research shows microbial degradation in the water column	High	The degree of mineralisation in the water column depends a.o. on the degradability of the organic matter, the sinking rate of detritus and resuspension of organic matter on the seafloor	Butenschön et al., 2016; Lancelot et al., 2005
2c	Biogeochemical cycle	Conversion of organic nutrients to organic and inorganic compounds through microbial activity in oxic and anoxic conditions in the sediment	Soil diagenetic experiments show changes in nutrient compounds in the soil and mediation by microbial activity	High	For simplicity, the complex bacterial communities responsible for these processes were left out of the	Lancelot et al., 2005; Soetaert et al., 1996; Billen, 1982
2d	Biogeochemical cycle	Transfer of organic nutrients to deeper soil layers where it remains buried on longer time scales	Soil diagenetic experiments show changes in concentrations of nutrient compounds throughout vertical soil profile	High	Bioturbation, bioirrigation and resuspension may affect the storage of nutrients in the sediment	Ivanov et al., 2021; Haas et al., 1997
2e	Biogeochemical cycle	Release of CO_2 from and consumption of O_2 in the sediment during mineralisation	Large evidence from soil diagenetic experiments	High	CO_2 and O_2 are soluble gases (dissolution in water column). Exchange with atmosphere is indirect	Braeckman et al., 2014
2f	Biogeochemical cycle	Release of N_2, NO and N_2O gas from the sediment during denitrification	Large evidence from soil diagenetic experiments. Less evidence for production mechanisms of the different gas types.	Moderate/High	Main product of denitrification is N_2. This is an insoluble gas resulting in direct exchange with atmosphere. In particular conditions, denitrification may leak N_2O which is a strong GHG.	Toussaint et al., 2021; Braeckman et al., 2014
2g	Biogeochemical cycle	Release of CO_2 from and consumption of O_2 in the water column during diagenetic processes	Large evidence from experiments	High	CO_2 and O_2 are soluble gases (dissolution in water column). Exchange with atmosphere is indirect	Provoost et al., 2013

2h	Biogeochemical cycle	Flux of inorganic nutrients from the sediment to the water column resulting from degradation of dead organic matter	Large evidence from soil diagenetic experiments	High	-	Toussaint et al., 2021; Butenschön et al., 2016; Lancelot et al., 2005
2i	Biogeochemical cycle	Conversion of inorganic nutrients to organic matter by phytoplankton	Long history of biological research	High	Primary production also depends on solar irradiance, temperature, pH and CO2 concentration besides inorganic nutrients	Butenschön et al., 2016; Lancelot et al. , 2005
2j	Biogeochemical cycle	Consumption of C02 and release of O2 by phytoplankton during primary production, resulting in fluxes between water column and atmosphere	Long history of biological research	High	CO2 and O2 are soluble gases (dissolution in water column). Exchange with atmosphere is indirect	Butenschön et al., 2016; Lancelot et al. , 2005
2k	Biogeochemical cycle	Conversion of inorganic nutrients to organic matter by seaweed	Limited research on seaweed in Belgian waters	Low	-	Value@Sea project, Aquavalue; Knoop J., De Clerck O.
2l	Biogeochemical cycle	Production of particulate organic matter (faeces and pseudofaeces) by marine organisms	A large number of field studies and models show the importance of biodeposition of (pseudo)faeces produced by suspension feeders on benthic nutrient content.	High	(Pseudo)faeces is first released into the water column. Dependent on current velocity, (pseudo)faeces is expected to settle more than regular suspended particulate matter, therefore this was not represented in the model.	Lancelot et al., 2005; Smaal et al. 2019
2m	Biogeochemical cycle	Breakdown of detritus by microbes in the water column, and uptake of the produced particulate/suspended organic matter by small zooplankton	Many models of marine nutrient cycling show the importance of the microbial loop for nutrient cycling in the water column.	High	-	Baird & Milne, 1981; Baird et al., 2019
3a	Physical environment	Erosion: the volume of sediment being suspended into the water column.	Hydrodynamical modelling studies have shown the importance of erosion in the highly dynamic Southern North Sea	High	Erosion rates are dependent on currents, grain size depth and many other factors.	Borsje et al., 2014;
3b	Physical environment	Colonization of suspension feeders leading to stabilisation of the sediment, decreasing erosion	Studies have shown that in high densities, certain bivalves can increase sediment stability.	Moderate	Evidence is limited to very high concentrations of bivalves. Erosion-countering effect not relevant for suspended lines.	Donadi et al., 2013; Smaal et al., 2019; Borsje et al., 2014
3c	Physical environment	Suspension feeders settle on hard substrate, certain groups provide hard substrate (mussels)	A large number of field studies, lab studies and modelling studies have shown the colonization of suspension feeders on hard substrates.	High	Not all suspension feeders provide hard substrate.	Smaal et al., 2019

3d	Physical environment	Suspended inorganic matter (sediment etc.) in the water column blocks light, increasing turbidity	A long history of field studies has shown the effect of suspended sediment on turbidity	High	-	Wang et al., 2020
3e	Physical environment	Phytoplankton blocks light, increasing turbidity	A long history of field studies has shown the effect of high concentrations of phytoplankton on turbidity	High	-	Lancelot et al., 2005
3f	Physical environment	The amount of light penetrating the water column influences primary production	The effect of turbidity on primary production is shown by many lab studies and modelling studies.	High	-	Lancelot et al., 2005
3g	Physical environment	The sediment type influences the deposit feeding community	In the Belgian part of the North Sea, the link between sediment types and biological community has been intensively studied.	Moderate	Sediment type is not only grain size, but also organic matter content and other traits.	Degraer et al., 2009; Breine et al., 2018
3h	Physical environment	Deposit feeders burrow and flush their burrows, influencing benthic conditions	The potential for bioturbation and bioirrigation of different benthic communities has been confirmed in multiple lab and field studies.	High/Moderate	Highly dependent on the benthic community.	Toussaint et al., 2021; Meysman et al., 2006; Wrede et al., 2018
3i	Physical environment	Certain demersal fish species and macrofaunal species inhabit hard structures and use them as shelter or nursery grounds	Nursery function of hard sediment has been shown (indirectly) through studies of the presence of fish eggs. The effect of hard substrate on macrofauna has been shown extensively. The relation between fish species and their habitats is studied extensively.	Moderate	Direct evidence for nursery function is hard to come by for many habitats. Because of the high mobility of fish, habitat relationships may exist but are usually not very strong. Only a service when production is increased, rather than habitats merely attracting species (attraction-production hypothesis).	Lauria et al., 2011; Lelièvre et al., 2014
3j	Physical environment	Sediment fineness determines the rate of diagenetic processes, as larger grain sizes allow for higher sediment oxygen concentrations.	Relatively strong knowledge base of empirical and modelling studies show the effect of sediment fineness on sediment chemistry.	Moderate/High	There is a dichotomy in the effect of permeability on oxygen concentration and sediment processes, where from a certain permeability, nutrient cycling increases drastically.	Toussaint et al., 2021
3k	Physical environment	Biodeposition leads to fining of the sediment.	Relatively well-known process in the shallow shelf systems, though the exact values are difficult to know.	Fair	-	Toussaint et al., 2021; Ivanov et al., 2021
3l	Physical environment	High concentrations of suspended inorganic matter influencing suspension feeder feeding.	Relatively well-known process in the shallow shelf systems, though the exact values are difficult to know.	Fair	-	Capelle, 2017

10a	Ecosystem Service supply	Sediment stabilization leading to increased diversity of benthic communities, which leads to the provision of nursery and habitat maintenance for fished species that inhabit and spawn in soft sediment habitats.	Shown for seagrasses, but not so much for BCS. Field studies prove that sediment stabilization leads to higher benthic diversity, but link to habitat/nursery service not yet shown. Theorized for *Lanice* reefs.	Low	-	Degraer et al., 2009; Borsje et al., 2014; Van der Zee et al., 2015
10b	Ecosystem Service supply	Hard substrate leading to the provision of nursery and habitat maintenance for species that inhabit and spawn in hard sediment habitats	Multiple studies dedicated to the effect of bivalve reefs on nursery/habitat maintenance. Theoretical studies on the effect of man-made hard structures.	Moderate	-	Smaal et al., 2019;
10c	Ecosystem Service supply	The stabilization of sediments leading to reduced wave energy, enhancing coastal protection	Extensively shown for bivalves in coastal waters, as well as *Lanice* reefs.	Moderate	-	Smaal et al., 2019; Van der Biest et al., 2017; Borsje et al., 2014
10d	Ecosystem Service supply	Higher turbidity reduces the possibility of certain active recreation, such as diving	Mainly qualitative evidence of the effect of turbidity, with various causes, on recreation	Fair	Likely plays a limited role because of the high natural turbidity in the North Sea.	O'Higgins & Gilbert, 2014
10e	Ecosystem Service supply	Take-up of excess nutrients through primary production, mediating wastes	Many modelling, field and lab studies show the take-up of nutrients by primary producers.	High	-	Van der Biest et al., 2017; Broszeit et al., 2019
10f	Ecosystem Service supply	Harvest of cultured bivalves providing food	In the BCS there is potential for bivalve aquaculture, and multiple test projects are being set up or have been completed in OWFs.	High	Harvest only relevant for suspended lines, not benthic reefs.	Smaal et al., 2019; UNITED project; Edulis project
10h	Ecosystem Service supply	Recreational fisheries enabled by certain fish species	Studies have been carried out into recreational fisheries in the BCS, also in relation to human activities	High	Some demersal fish may also be of interest for recreational fisheries. However, the majority is pelagic.	Van der Biest et al., 2017; Broszeit et al., 2019; Vandendriessche et al., 2013
10i	Ecosystem Service supply	Harvest of cultured seaweed providing food and materials	There is a consensus that that there is an opportunity for seaweed culture in the BCS, though currently there is only one test study.	Low	-	Van der Biest et al., 2017; UNITED project
10j	Ecosystem Service supply	Birds and marine mammals enabling passive recreation, namely bird and whale watching	Though information on the distribution of birds and marine mammals in the BCS is plentiful, the link with recreation is less known.	Fair	To which extent changes in bird and mammal abundance influence recreation is unknown.	Van der Biest et al., 2017; Broszeit et al., 2019

10k	Ecosystem Service supply	(Industrial) harvest of fish and crustaceans providing food	Many studies, specifically for the BCS as well.	High	Harvest of (benthic) crustaceans is currently limited in the BCS.	Van der Biest et al., 2017; Broszeit et al., 2019
10l	Ecosystem Service supply	Burial of organic material providing carbon sequestration/climate regulation	Carbon sequestration in the North Sea is minimal and mainly confined to specific areas (outside of the BCS).	Medium	Thought to not be important in highly dynamic shallow systems such as the BCS. Only relevant when sediment remains undisturbed.	Van der Biest et al., 2017; Haas et al., 1997; De Borger et al., 2021
10m	Ecosystem Service supply	Filtration of phytoplankton controlling (harmful) algal blooms	Many field and modelling studies show the potential of suspension feeders such as bivalves to control HABs	High	When the concentration of algae becomes too high, it can cause mass die-offs of bivalves when sedimentation of organic matter causes suffocation.	Van der Biest et al., 2017; Smaal et al., 2019; Slavik et al., 2019
10n	Ecosystem Service supply	Carbon sequestered in bivalve shells providing long term carbon storage/climate regulation	Shells from harvested bivalves usually end up in landfills, storing the carbon for a significant amount of time.	Moderate	Sequestration potential is dependent on the fate of the shells.	Smaal et al., 2019
10o	Ecosystem Service supply	Denitrification in the sediment, mediating wastes	Diagenetic processes in the sediment have shown to be very important in regulating nutrient concentrations in the water column, in field, lab and model studies	High	-	Van der Biest et al., 2017; Toussaint et al., 2021
10p	Ecosystem Service supply	Burial of excess nutrients mediating wastes	North Sea sediments have minimal capacity for N storage and this is mainly confined to specific areas (outside of the BCS), but act as P sink especially closer to the shore.	Medium	Thought to not be important in highly dynamic shallow systems such as the BCS.	Van der Biest et al., 2017; Haas et al., 1997; De Borger et al., 2021
10q	Ecosystem Service supply	Sediments extracted for materials	Marine sand extraction is an increasingly important economic activity in the BCS	High	-	Van der Biest et al., 2017; Wyns et al., 2021

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