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Development of a pilot 'European seafloor integrity account' assessing fishing pressure on seabed habitats

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Executive Summary

The aim of this study is to review the existing approaches to assess the impact of fishing-induced physical disturbance on seabed habitats and uses the outcome of such a review to develop a concept and method to calculate a pilot 'European seafloor integrity account' (SIA), which is linked to the assessment of marine ecosystem services. The review is almost entirely based on the process led by the International Council for the Exploration of the Seas (ICES) to provide guidance on the assessment of the state of seabed habitats, including the development and evaluation of indicators for fishing-induced pressure and its impact on these habitats. The pilot SIA has been calculated in the North Sea as 'proof of concept'. It is linked to the assessment of marine ecosystem services and aims at supporting Member States and the EU to achieve the 2020 goals on the Mapping and Assessment of Ecosystems and their Services (MAES) and the development of accounting systems under Action 5 of Target 2 of the EU Biodiversity Strategy to 2020 and, in particular, their post-2020 follow-up.

In the EU, ecosystem accounting is driven by two key policies: the EU Biodiversity Strategy to 2020 and the 7th EU Environmental Action Programme. They both include specific objectives towards protecting ecosystem services and natural capital. According to the MAES process, natural capital comprises both ecosystem capital and abiotic natural capital. The former is made up of the ecosystems, including the living organisms inhabiting them and their biological diversity, which is what makes ecosystems function and underpins their capacity to supply ecosystem services. The latter is made up of the abiotic assets of the planet and their flows.

Experimental Ecosystem Accounts (SEEA-EEA) are being developed as part of the 'System of Environmental-Economic Accounting' (SEEA) to show how to measure the ecosystem components of natural capital. Within SEA-EEA, the key accounting module that applies for the pilot SIA is the 'ecosystem condition account', which is closely related to the capacity of ecosystems to supply ecosystem services. In this study, the SEEA-EEA principles and considerations concerning the parameters defining ecosystem condition were interpreted and translated into the following requirements for the pilot SIA, which should:

Support policies with meaningful, objective and verifiable data, which are able to show degradation and/or recovery at policy-relevant time-scales.
In relation to the seabed, the EU Marine Strategy Framework Directive (MSFD) requires 'Good Environmental Status' (GES) to be achieved for benthic habitats (as part of the 'Biodiversity' Descriptor 1) and 'Sea-floor integrity' (Descriptor 6). According to the MSFD, seafloor integrity represents a state of seabed habitats "where structure and functions of the benthic ecosystem is not adversely affected". The criteria put forward by the MSFD to assess 'Sea-floor integrity' cover the "state", "pressure" and "impact" perspectives as these describe the overall status of each benthic habitat in terms of the proportion of the natural extent of the seafloor and its benthic broad habitat types that is, or not, impacted by the main anthropogenic pressures upon them: physical loss and physical disturbance. Linked to these perspectives, the pilot SIA reflects annual changes in the state of seabed habitats based on a fishing-induced degradation (here depletion) and a habitat-specific recovery of the benthic invertebrate community.

Be tightly linked to the ecosystem capacity and to the supply of ecosystem services.
Following the Common International Classification of Ecosystem Services (CICES), we distinguish between provisioning services, regulation and maintenance services and cultural services. The regulation and maintenance services are probably the most relevant for the pilot SIA because they have strong links to the benthic invertebrate community on which the account is based. These benthic invertebrate biota are involved in ecosystem processes and function such as bioturbation, nutrient cycling, reproductive output, secondary production, and so contribute to the ecosystem

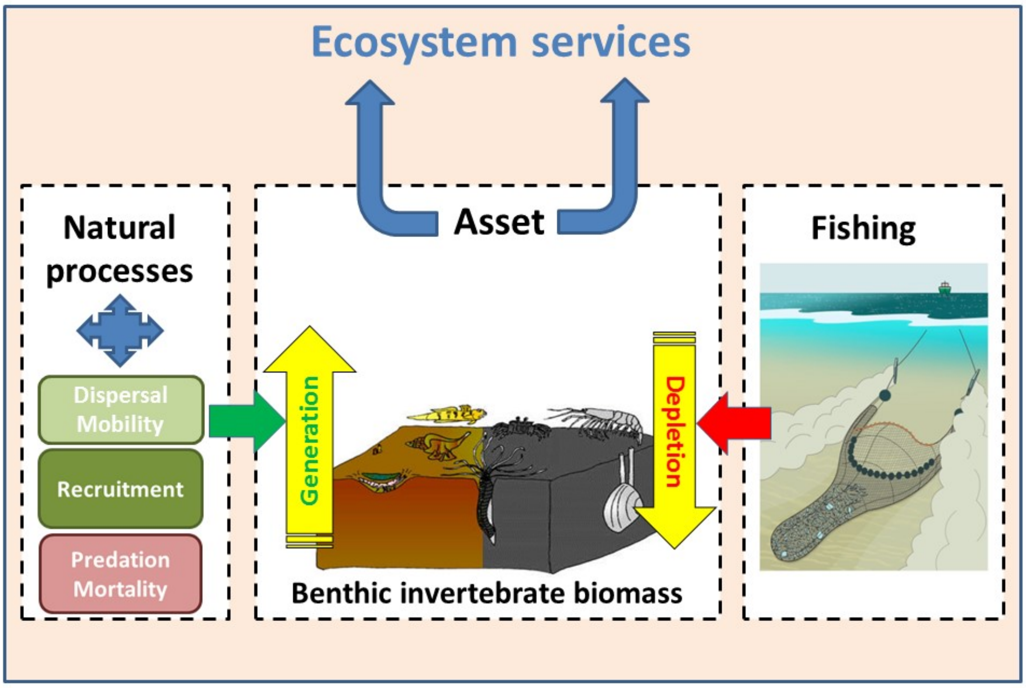
capacity to supply regulation and maintenance services such as Bioremediation; Filtration/sequestration, storage/accumulation; Decomposition and fixing processes; and Maintaining nursery populations and habitats.

Represent ecosystem health and/or its degradation, which is linked to the ecosystem's capability to achieve its fullest potential for service supply and is closely related to ecological integrity (or lack thereof). Ecosystem health should be expressed in physical units – possibly relative to some reference condition benchmark, e.g. no disturbance by human activities.
Being derived from the MSFD, seafloor integrity represents the health of seabed habitats and is expressed both in terms of structure and functioning, which are both tied to the (ecosystem capacity to) supply of ecosystem services. An appropriate method for the calculation of the pilot SIA should specifically cover the biotic part (here only the benthic invertebrate community, thus excluding plants and algae, due to the calculation method selected) as this is part of the ecosystem capital and can supply ecosystem services. The selected method to assess the state of seabed habitats impacted by the fishing pressure 'physical disturbance' calculates the biomass of the benthic invertebrate community relative to an undisturbed situation. This metric is considered a proxy for seafloor integrity and represents the asset on which the pilot SIA is based. From the condition aspects mentioned in the SEEA-EEA, the pilot SIA is most appropriate to cover the biodiversity aspect as, in an MSFD context, it is linked to the biodiversity of benthic habitats. In order to strengthen the link to biodiversity, the selected method allows the calculation of the metric for specific subsets of the benthic invertebrate community such as those differing in their sensitivity to fishing-induced physical disturbance. In this study those subsets were distinguished based on their longevity.

Reflect the impacts of (the main) human activities on the capacity of ecosystems to supply ecosystem services and, primarily, be able to inform on the performance of (fisheries) management to mitigate impacts from fishing-induced physical disturbance in order to conserve marine (benthic habitat) biodiversity.
Commercial fishing is considered the main human activity impacting on the state of the benthic invertebrate community. This community contributes to the capacity of seabed habitats to supply most of the regulation and maintenance and many of the cultural marine ecosystem services. The figure below shows the asset of the pilot SIA representing the capacity of the benthic invertebrate community to supply ecosystem services which is the result of an inflow (into it), i.e. its generation, based on various natural processes, and an outflow, i.e. its depletion, caused by the human activity, i.e. fishing, that generates the physical disturbance. The selected method calculates the flows based on, respectively, the characteristics of the EUNIS-3 habitat in terms of the composition of the benthic invertebrate community (which determines its potential to recover from the pressure) and the information of gear-specific fishing intensity. This allows the annual calculation of the SIA to reflect any management intervention that mitigates the fishing intensity and/or its spatial distribution.

The selection of the most appropriate method to calculate the pilot SIA was based on an ICES-led review process resulting in the selection of a method:

- that is mechanistic based on a logistic growth model, thereby allowing to show year-to-year changes and hence time-series.
- includes sensitivity aspects of the benthic invertebrate community allowing the explicit consideration of both their depletion (representing resistance) and recovery (representing resilience) aspects. The parametrisation of the depletion and recovery aspects is based on a recent global meta-analysis.
- calculates a metric (biomass relative to undisturbed conditions) sufficiently representative of the amount of functioning, still remaining in the benthic invertebrate community.



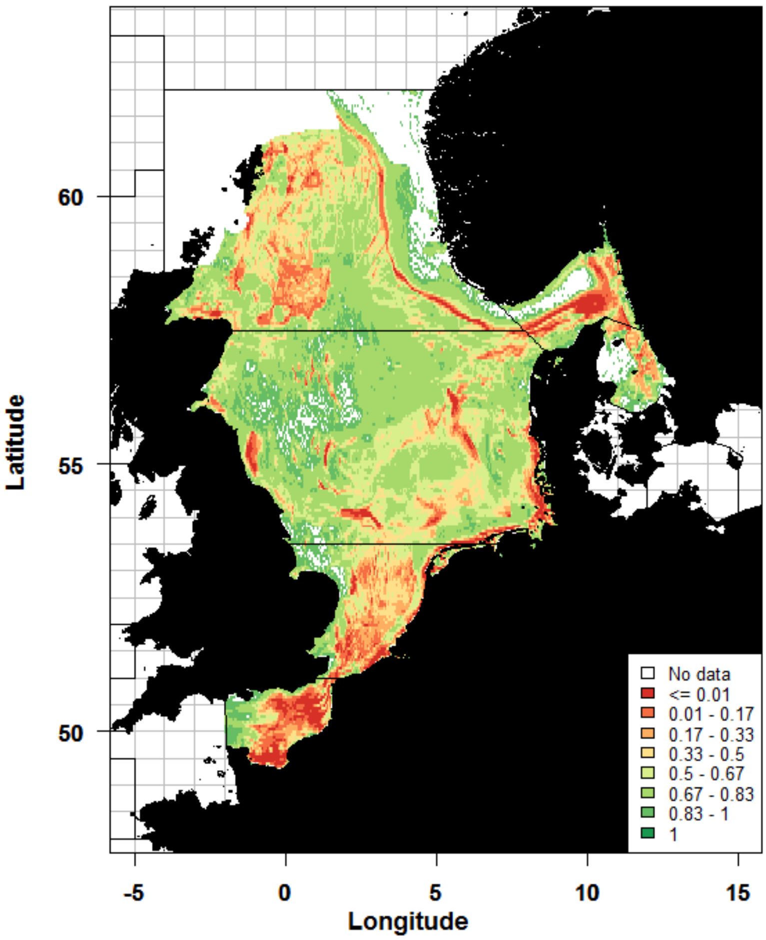
Basic processes determining the ecosystem asset (see Figure 4.1 main text)

As the result of these calculations the pilot SIA accounting table below shows a slight increase in the benthic invertebrate community, and so in the relevant North Sea seabed habitats' capacity to supply ecosystem services, relative to an undisturbed situation (100 %), both for the whole benthic invertebrate community and for each longevity class over 2009 – 2016. The capacity of the most sensitive part of the benthic invertebrate community, i.e. longevity class >10 years, is compromised more (at approximately 73 %) and recovers slower than the least sensitive part of 0 – 1 year which is at approximately 94 %.

Accounting table showing the annual asset of the SIA (see table 4.2 main text)

Longevity Class	2009	2010	2011	2012	2013	2014	2015	2016
0 – 1 year	92.2	93.6	94.2	94.6	94.8	94.9	94.9	95.1
1 – 3 years	88.9	89.8	90.3	90.6	91.0	91.1	91.3	91.5
3 – 10 years	80.9	81.0	81.2	81.4	81.7	81.8	82.0	82.2
> 10 years	72.8	72.8	72.9	72.9	73.1	73.1	73.3	73.3
Whole Community	80.6	80.8	81.1	81.3	81.5	81.6	81.8	82.0

The spatial distribution of the SIA asset in 2016 (figure below) shows areas with relatively low values in the SE, NE and NW North Sea and a large patch of higher SIA in the central North Sea.



Map of the spatial distribution of the asset of the pilot SIA (see Figure 4.3 main text)

The development and calculation of this pilot SIA has provided an account that:

- is representative of the state of seabed habitats from the impacts of fishing-induced physical disturbance;
- reflects the capacity to supply certain ecosystem services;
- is useful to inform policy on the performance of management actions to mitigate fishing impacts.

The limitations of the pilot SIA include that:

- It only assesses the state of a selection of seabed habitats with soft substrate based on the state of the benthic invertebrate community therein (hence excluding plants and algae). However, at least in this region, invertebrate fauna dominates the relevant soft-substrate habitats and plants and algae can be assumed to be inconsequential.
- It only reflects how these habitats are impacted by physical disturbance thus ignoring physical loss. It is likely, however, that both the structure and functioning of the relevant benthic habitats are primarily impacted by physical disturbance.
- This impact is caused by only one (albeit the most important) anthropogenic activity, i.e. commercial fisheries.

1 Introduction

The aim of this study is two-fold:

1. Review of existing approaches and development and description of a concept and method to assess the state of seabed habitats from fishing pressure:

i. Review of existing approaches (ICES Report of the Workshop on guidance on how pressure maps of fishing intensity contribute to an assessment of the state of seabed habitats (WKFBI), the revision of MSFD D6 and OSPAR BH3 indicator) and their applicability to assess the state of seabed habitats from fishing pressure.
ii. Development and description of a (concept and) method to assess the state of seabed habitats from fishing pressure. This involves:
    a. the identification of data requirements and the assessment of their availability, including spatial and temporal coverage;
    b. a consideration of potential policy-relevant impact thresholds;
    c. establishing links to/ensuring compatibility between the concept here and that underpinning the spatial and multi-metric indicator tool approaches for the assessment of cumulative impacts and pressures to be developed under ETC/ICM Task 1.6.2.d (pressure and impact assessment building on the 2016 Task 1.6.1.g).

2. Applying the method to assess the state of seabed habitats to the concept for developing a pilot 'European seafloor integrity account':

i. Consideration of how the method to assess the state of seabed habitats (from fishing pressure) matches the ecosystem accounting concept with the aim to develop and calculate a pilot 'European seafloor integrity account' in 2018;
ii. Description of the process towards the development of a pilot 'European seafloor integrity account' as part of developing an integrated EU ecosystem accounting system.

This work aims at supporting Member States and the EU achieving the 2020 goals on the Mapping and Assessment of Ecosystems and their Services (MAES) and the development of accounting systems under Action 5 of Target 2 of the EU Biodiversity Strategy to 2020 and, in particular, their post-2020 follow-up, as well as the implementation of the Marine Strategy Framework Directive and the Maritime Spatial Planning Directive.

In the following sections we introduce the topics that are at the basis for the calculation of the pilot 'European Seafloor Integrity Account' (SIA), i.e. the policy context (section 1.1), the review process of existing methods to assess fishing impact on seabed habitats (section 1.2) and the concept of ecosystem accounting (section 1.3). This information is then synthesized into our approach to calculate the pilot 'European Seafloor Integrity Account' (in section 1.4).

1.1 Policy context: 'Good Environmental Status' of seabed habitats

In relation to the seabed, the EU Marine Strategy Framework Directive (MSFD) (EC, 2008) requires 'Good Environmental Status' (GES) to be achieved as follows:

Descriptor 1: Biological diversity is maintained. The quality and occurrence of habitats [.....] are in line with prevailing physiographic, geographic and climatic conditions.

Descriptor 6: Sea-floor integrity is at a level that ensures that the structure and functions of the ecosystems are safeguarded and benthic ecosystems, in particular, are not adversely affected.

Other GES Descriptors, including Descriptor 2 ('Non-indigenous species'), Descriptor 3 ('Commercially-important fish and shellfish'), Descriptor 5 ('Eutrophication'), Descriptor 7 ('hydrographical conditions'), Descriptor 8 ('contaminants') and Descriptor 10 ('Litter'), also address aspects of seabed quality but will not be considered in this study.

Commission Decision (EC, 2017) sets out criteria and methodological standards defining GES in relation to the eleven MSFD Descriptors. Benthic habitats (as part of 'Biodiversity' Descriptor 1) and 'Sea-floor integrity' (Descriptor 6) are to be addressed together via a set of benthic broad habitat types, which correspond to the benthic habitat types in Level 2 of the EUNIS habitat classification as revised in 2016[1] (see Evans et al. (2016); Condé et al. (2018)). According to the MSFD, seafloor integrity represents a state of seabed habitats "where structure and functions of the benthic ecosystem is not adversely affected". The criteria to be used to assess 'Sea-floor integrity' are shown in Box 1.1. Out of those five criteria, D6C3 provides an "impact" perspective describing seafloor integrity in terms of what is impacted (e.g. adversely affected) by the pressures 'physical loss' (D6C1) and 'physical disturbance' (D6C2), whilst criteria D6C4 and D6C5 provide a "state" perspective, which describes the overall status of each benthic habitat in terms of the proportion of the natural extent of the seafloor and its benthic broad habitat types that is not lost (D6C4) or adversely affected (D6C5) by all anthropogenic pressures. D6C4 and D6C5, therefore, apply to both Descriptor 6, which is specifically about seafloor integrity, and the benthic habitats under Descriptor 1 (Biodiversity). This is actually specified under the 'Benthic habitats' theme's '*Specifications and standardised methods for monitoring and assessment relating to theme 'Benthic habitats''* in EC (2017).

[1] Habitat definitions and lower levels of the marine component of the EUNIS habitat classification are also undergoing a revision to be completed at the end of 2018

Box 1.1: Excerpt from the revised MSFD criteria and methodological standards defining 'good environmental status' for Descriptor 6 on 'Seafloor integrity' (EC, 2017) stating the relevant policy objectives relating to seabed habitats and how these are impacted by human activities.

Criteria elements	Criteria	Methodological standards
Physical loss of the seabed (including intertidal areas).	D6C1 — Primary: Spatial extent and distribution of physical loss (permanent change) of the natural seabed.	*Scale of assessment:* As used for assessment of the benthic broad habitat types under Descriptors 1 and 6. *Use of criteria:* The outcomes of assessment of criterion D6C1 (the distribution and an estimate of the extent of physical loss) shall be used to assess criteria D6C4 and D7C1. The outcomes of assessment of criterion D6C2 (the distribution and an estimate of the extent of physical disturbance pressures) shall be used to assess criterion D6C3. The outcomes of assessment of criterion D6C3 (an estimate of the extent of adverse effect by physical disturbance per habitat type in each assessment area) shall contribute to the assessment of criterion D6C5.
Physical disturbance to the seabed (including intertidal areas).	D6C2 — Primary: Spatial extent and distribution of physical disturbance pressures on the seabed.	
Benthic broad habitat types or other habitat types, as used under Descriptors 1 and 6.	D6C3 — Primary: Spatial extent of each habitat type which is adversely affected, through change in its biotic and abiotic structure and its functions (e.g. through changes in species composition and their relative abundance, absence of particularly sensitive or fragile species or species providing a key function, size structure of species), by physical disturbance. Member States shall establish threshold values for the adverse effects of physical disturbance, through regional or subregional cooperation.	

Criteria elements	Criteria	Methodological standards
Refer to Part I of this Annex for criteria D6C1, D6C2 and D6C3.		
Benthic broad habitat types as listed in Table 2 and if present in the region or subregion, and other habitat types as defined in the second paragraph. Member States may select, through regional or subregional cooperation, additional habitat types, according to the criteria laid down under 'specifications for the selection of species and habitats', and which may include habitat types listed under Directive 92/43/EEC or international agreements such as Regional Sea Conventions, for the purposes of: (a) assessing each broad habitat type under criterion D6C5; (b) assessing these habitat types. A single set of habitat types shall serve the purpose of assessments of both benthic habitats under Descriptor 1 and sea-floor integrity under Descriptor 6.	D6C4 — Primary: The extent of loss of the habitat type, resulting from anthropogenic pressures, does not exceed a specified proportion of the natural extent of the habitat type in the assessment area. Member States shall establish the maximum allowable extent of habitat loss as a proportion of the total natural extent of the habitat type, through cooperation at Union level, taking into account regional or subregional specificities. D6C5 — Primary: The extent of adverse effects from anthropogenic pressures on the condition of the habitat type, including alteration to its biotic and abiotic structure and its functions (e.g. its typical species composition and their relative abundance, absence of particularly sensitive or fragile species or species providing a key function, size structure of species), does not exceed a specified proportion of the natural extent of the habitat type in the assessment area.	*Scale of assessment:* Subdivision of region or subregion, reflecting biogeographic differences in species composition of the broad habitat type. *Use of criteria:* A single assessment per habitat type, using criteria D6C4 and D6C5, shall serve the purpose of assessments of both benthic habitats under Descriptor 1 and sea-floor integrity under Descriptor 6. The extent to which good environmental status has been achieved shall be expressed for each area assessed as: (a) for D6C4, an estimate of the proportion and extent of loss per habitat type and whether this has achieved the extent value set; (b) for D6C5, an estimate of the proportion and extent of adverse effects, including the proportion lost from point (a), per habitat type and whether this has achieved the extent value set; (c) overall status of the habitat type, using a method agreed at Union level based on points (a) and (b), and a list of broad habitat types in the assessment area that were not assessed.

In the above context, the term ‘habitat’ could have two distinct meanings:

- firstly, to refer to the environment used and occupied by a single species (termed 'habitat of a species' under Directive 92/43/EEC); in this case, the nature and spatial scale of the habitat can vary markedly according to the particular needs of the species across all stages of its life history (e.g. a seal or bird may need breeding, resting or feeding, as well as migratory areas which are very different in nature and location; some invertebrate species have a pelagic juvenile phase and a benthic adult phase);
- secondly, to refer to particular areas, which are characterized by specific communities of species (i.e. a multi-species concept of habitat); in this case the habitat comprises particular biotic and abiotic characteristics (and is often referred to as a biotope and termed 'natural habitats' under Directive 92/43/EEC), which make it distinguishable from surrounding habitat types. In contrast to the habitat of a single species, this use of the term habitat refers to something that is more uniform in its character, leading to the definition and classification of habitat types and the ability to produce maps of habitats. The EUNIS habitat classification provides a Europe-wide classification of marine (and terrestrial) habitats, *sensu* biotopes, in a 6-level (5-level for terrestrial) hierarchical system.

The criteria for D6 in the GES 2017 Decision refer to 'broad' and 'other' habitat types, in the sense of the second meaning of ‘habitat’ above, i.e. biotope. This second meaning of ‘habitat’ is, therefore, also adopted for this study. Thus, the benthic habitats addressed under the MSFD GES D1/D6 encompass both:

- biotic characteristics – the typical species composition and their relative abundance within the community;
- abiotic characteristics – the type of substrate, its topography and depth range and typical characteristics of the water above it, including its temperature, salinity, oxygenation, turbidity, wave and current regimes.

Notably the biotic characteristics are expected to change due to the impacts from anthropogenic pressures causing them to depart from the undisturbed situation (i.e. the reference conditions). The two relevant pressures that are specifically mentioned in this MSFD GES D1/D6 context (see Box 1.1) are:

- *Physical loss* shall be understood as a permanent change to the seabed which has lasted or is expected to last for a period of two reporting cycles (12 years) or more.
- *Physical disturbance* to seabed shall be understood as a change to the seabed from which it can recover if the activity causing the disturbance pressure ceases.

Additionally, in an MSFD context, physical disturbance is interpreted as encompassing more specific pressures such as “abrasion” and “changes in siltation” (EC, 2008) affecting the physical habitat but also “death or injury by collision”, which may affect the associated benthic invertebrates but is usually considered under “other physical disturbance” (OSPAR, 2014). In this study, all these specific pressures are included in the aggregate pressure “physical disturbance”. In contrast, physical loss is linked to sealing by man-made structures or solid waste disposal.

It follows that, in order to be policy-relevant, the pilot SIA should:

- Capture an aspect of the state of seabed habitats that is tightly linked to the structure and functioning of the benthic ecosystem. This implies capturing the biotic characteristics of the benthic ecosystem, i.e. the typical species composition and their relative abundance within the benthic community;

- Reflect how the biotic characteristics of the benthic ecosystem may be impacted by two pressures, i.e. physical loss and physical disturbance.
- Reflect how the impacts from any one of those pressures can cause the biotic characteristics of the benthic ecosystem to depart from an undisturbed situation.

Following from the definition of ‘physical loss’, which is understood as a permanent change, we should consider seabed habitats impacted by physical loss separate from those impacted by physical disturbance as only the latter can recover (i.e. within the policy-relevant timeframes, see also section 1.4). The “extent of loss of the habitat resulting from anthropogenic pressures” (see Box 1.1) is, thus, interpreted as the proportion of the seafloor not contributing to the functioning of seabed habitats. Because physical disturbance does allow part of the functioning to remain intact and some recovery when the pressure subsides, the focus of this study will be on this pressure (see also sections 1.4 and 4.1).

In distinguishing between the two pressures, i.e. physical loss and physical disturbance, the EC-MSCG (2018), i.e. the Group coordinating EU-level efforts for the implementation of the MSFD, has stated that “Further technical work is needed to provide operational definitions of these two terms, including which activities can lead to each pressure or to both pressures”. In anticipation of such an operational definition, for the development and calculation of the pilot SIA we have decided to focus on a single activity for which a method exists to quantify its main pressure affecting the seafloor, i.e. physical disturbance of seabed habitats by commercial fishing (see section 1.2). The existing method assesses the state of the invertebrate fauna within the benthic community because it covers a certain range of seabed habitats (see chapters 3 and 4). As a result, the SIA is calculated on a subset of the benthic community, i.e. the benthic invertebrate community, thus excluding plants and algae (see chapter 4).

1.2 The review of methods to assess fishing impact on seabed habitats

In search of a single activity for which a method exists to quantify fishing-induced physical disturbance of seabed habitats, we have reviewed the existing approaches to assess the state of these habitats in relation to the impact caused by the main fishing-induced pressure, i.e. physical disturbance. This review is almost entirely based on the ICES-led process to provide guidance on how pressure maps of fishing intensity contribute to an assessment of the state of seabed habitats, including the development and evaluation of regional benthic pressure and impact indicator(s) from bottom fishing. This process consisted of various workshops, namely WKFBI (ICES, 2016b), WKBENTH (ICES, 2017c), WKSTAKE (ICES, 2017b), WKTRADE (ICES, 2017a) and a reviewing process by WGECO and two Advice Drafting Groups, which resulted in an ICES advice sheet (see Annex 1). Chapters 2 and 3 introduce the various approaches and finish with a review of these approaches.

In line with the criteria and methodological standards defining the MSFD D6 on ‘Seafloor Integrity’ (EC, 2017) in Box 1.1, we distinguish between:

- the method to estimate fishing pressure (Chapter 2);
- the method to assess the state of broad scale seabed habitats and how this is impacted by fishing pressure (Chapter 3).

Fishing impact is assumed here to be determined by the interaction between fishing-induced physical disturbance from bottom-contacting fishing gear, and the sensitivity of the biotic element of the relevant broad-scale seabed habitats, in this case the benthic invertebrate community. Therefore, we consider the method to calculate fishing-induced physical disturbance separate from the method to calculate its impact on seabed habitats. As seafloor integrity represents a state of seabed habitats "where structure and functions of the benthic ecosystem is not adversely affected" (section 1.1), the pilot SIA should reflect the amount of benthic ecosystem structure and functioning as represented by the biomass of the benthic invertebrate community. The undisturbed situation is chosen as the reference where ecosystem structure and functioning are assumed to be optimal. The impact of fishing-induced physical disturbance then results in a decrease of the benthic invertebrate community biomass. The biomass that remains after this impact is what drives the functioning and, thus, what constitutes the pilot SIA (see section 1.4).

As the policy requirements (MSFD) pertaining to the state of the seafloor all involve the extent of the seafloor, or specific habitats affected by physical disturbance (and physical loss), all methods are based on a division of the seafloor into grid cells with specific spatial resolution. In addition, some other metric is required that describes the degree to which the seafloor is disturbed, together with a threshold that determines whether it is, thus, "adversely affected" by this disturbance or not. The latter, in turn, relates, and could be linked, to the policy objective of "Good Environmental Status" (GES) for D6; where only if the seafloor is adversely affected (and for which such a threshold would be required), does it count/contribute to the 'extent' reflected in D6C3 and D6C5 as those criteria measure the extent of habitats that are adversely affected by physical disturbance (Box 1.1). However, as there are currently no known thresholds determining what is "adversely affected", this link will not be pursued any further in the development of the pilot SIA.

1.3 Ecosystem accounting

1.3.1 Background information

The need for preserving the environment and for managing natural resources and ecosystems sustainably has been recognised for several decades (MA, 2005). This has given traction to the proposal by environmental economists and ecologists that we should consider earth's ecosystems as a type of 'natural capital' providing flows of ecosystem services, which needs to be managed well to be able to provide people with sustained flows of these services into the future (EEA, 2018 in prep).

In the EU, the concept of ecosystem accounting is driven by two key policies: the EU Biodiversity Strategy to 2020 (European Commission, 2011) and the 7th EU Environmental Action Programme (7th EAP) (European Commission, 2014). They both include specific objectives towards protecting ecosystem services and natural capital. The EU Biodiversity Strategy to 2020, in particular, requires, under Action 5 of its Target 2, the Mapping and Assessment of Ecosystems and their Services (MAES) and the development of accounting systems.

The following quotes illustrate well the longer-term visions set out in the above-mentioned EU policies, with regard to natural capital and its links to economic development and human well-being:

"By 2050, European Union biodiversity and the ecosystem services it provides — its natural capital — are protected, valued and appropriately restored for biodiversity's intrinsic value and for their essential contribution to human wellbeing and economic prosperity, and so that catastrophic changes caused by the loss of biodiversity are avoided."

Source: Our life insurance, our natural capital – an EU Biodiversity Strategy to 2020

"In 2050, we live well, within the planet's ecological limits. Our prosperity and healthy environment stem from an innovative, circular economy where nothing is wasted and where natural resources are managed sustainably, and biodiversity is protected, valued and restored in ways that enhance our society's resilience. Our low-carbon growth has long been decoupled from resource use, setting the pace for a global safe and sustainable society."
Source: 7th Environmental Action Programme

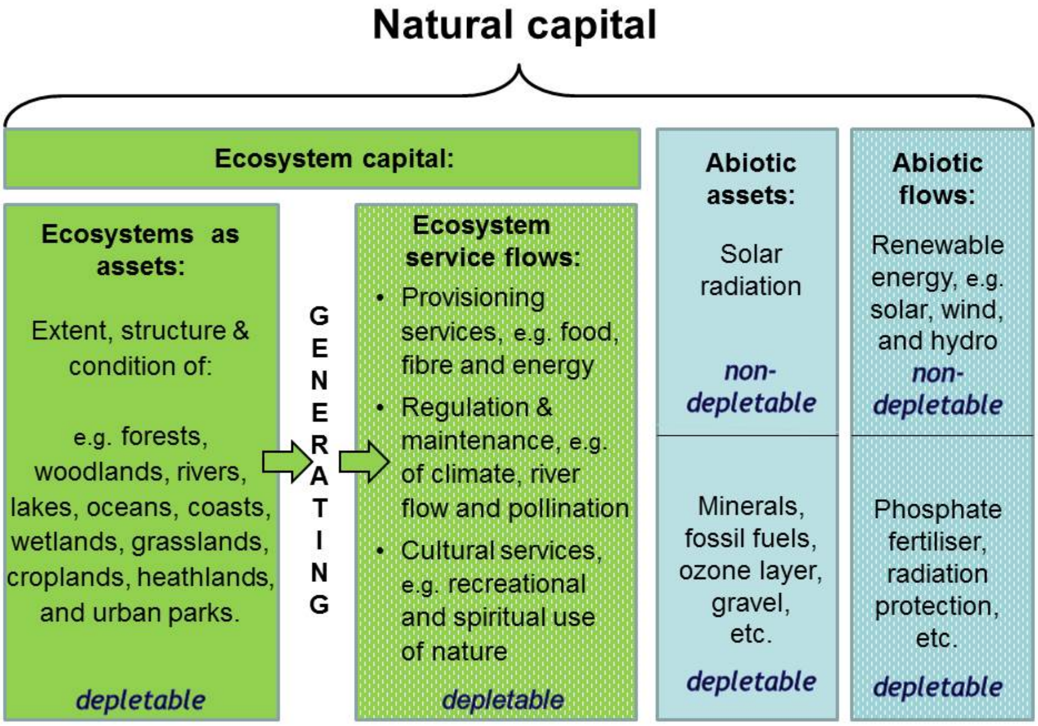
To help build the knowledge base for achieving these policy objectives, several shared projects were set up at EU level, including one to develop an integrated system for natural capital and ecosystem services accounting (KIP INCA). To note, however, that these policies as well as KIP INCA use the term "natural capital" to represent only ecosystems and their services, i.e. the core subject of ecosystem accounting as codified in the UN handbook on experimental ecosystem accounting, SEEA EEA (Anon, 2017), rather than also including the abiotic constituents of natural capital as defined in Maes (2013) (see Figure 1.1).

Thus, natural capital comprises both ecosystem capital and abiotic natural capital. The former is made up of the ecosystems, including the living organisms inhabiting them and their biological diversity, which is what makes ecosystems function and underpins their capacity to supply ecosystem services. The latter is made up of the abiotic assets of the planet and their flows. Either one, or both kinds of natural capital, provide people with exploitable and other resources and contributions to their lives, such as fossil fuels, minerals, fish, genes and atmospheric oxygen in the case of marine natural capital, and, thus, generate a flow of benefits via these ecosystem services and/or abiotic outputs.

Following the Common International Classification of Ecosystem Services (CICES), we distinguish between provisioning ecosystem services, regulation and maintenance ecosystem services, and cultural ecosystem services. As opposed to the provisioning services, the other two service categories are not linked specifically to marine biota and their outputs/materials that can be exchanged, or traded, or consumed, or used by people in, e.g., manufacturing (see (Haines-Young & Potschin, 2013)). And from these other two categories of services, the regulation and maintenance services are probably the most relevant for the pilot SIA because they have strong links to the benthic invertebrate community. These benthic biota are involved in ecosystem processes and function such as bioturbation, nutrient cycling, reproductive output, secondary production, and so contribute to the ecosystem capacity to supply services such as Bioremediation; Filtration/sequestration, storage/accumulation; Decomposition and fixing processes; and Maintaining nursery populations and habitats; which belong to the regulation and maintenance category[2] and can all be 'final' ecosystem services within certain contexts. Examples of cultural ecosystem services underpinned by benthic invertebrate biota are Scientific and Educational (see ETC/ICM (2019 in prep.)).

[2] Note this work started in 2017 and so we used version 4.3 of CICES, although this was revised and an updated version 5.1 was released in early 2018 (see https://cices.eu/)

Figure 1.1: Components of natural capital (from (EEA, 2018 in prep.), which updates it from Maes et al., 2013)



Accounting is an approach to structuring information that aims to provide an overview of, for example, income and expenses, and which gives complete and consistent results. This principle also underpins the System of National Accounts (SNA), which develops information on countries' Gross Domestic Product (GDP). This is a key figure for assessing economic progress and helps to understand the economic wealth of a nation. However, the wealth of a nation and the well-being of its people does not depend solely on the state of the economy, but also relies strongly on its natural resources and the services we derive from ecosystems. For this reason, statisticians, accountants and others have worked since the 1970s to create a complementary accounting system that covers ecosystem assets and the benefits we derive from them – this is the so-called 'System of Environmental-Economic Accounting' (SEEA). Experimental Ecosystem Accounts (SEEA-EEA) are being developed as part of SEEA to show how to measure the ecosystem components of natural capital, in terms of the state of ecosystems and their capacity to provide ecosystem services, as well as estimates the costs of protecting or repairing damage to these ecosystems.

Within SEA-EEA, the key accounting module that applies for the pilot SIA is the 'ecosystem condition account', which is closely related to the capacity of ecosystems to supply ecosystem services. There is increasing scientific literature (cf. scientific literature peer-reviewed by the Intergovernmental science-policy Platform on Biodiversity and Ecosystem Services – IPBES) demonstrating the close relationship between biodiversity, good ecosystem condition and long-term delivery of multiple ecosystem services. This is, especially, of regulation and maintenance as well as cultural services, since overuse/exploitation of provisioning services can act as a pressure on ecosystems and impact on services from these other categories, in addition to jeopardising the sustained supply of provisioning services themselves. The SEEA EEA handbook (Anon, 2017) suggests five aspects of condition that could be considered, namely vegetation, biodiversity, soil, water, carbon, in an example for a condition account for a single ecosystem unit. From these aspects of condition, the pilot SIA is most appropriate to cover the 'biodiversity' aspect as the state of benthic habitats is, *inter* *alia*, linked to 'marine biodiversity' under the MSFD, which is the policy context for the development of the SIA (see section 1.1).

Given the scope for experimentation provided by SEEA-EEA and the need to develop an approach to assess ecosystem condition that is suited to the European ecological and land use context, the common assessment framework developed under the MAES initiative for the assessment of ecosystems and their services under Action 5/Target 2 of the Biodiversity Strategy to 2020 (cf. Figure 2 in Maes et al., 2014), becomes the next obvious point to consider in developing the pilot SIA. For the purpose of MAES, "ecosystem condition" is usually synonymous for "ecosystem state" (Maes et al., 2013). It embraces legal concepts (e.g. conservation status under the Birds and Habitats Directives, ecological status under the Water Framework Directive and environmental status under the Marine Strategy Framework Directive) as well as other proxy descriptors related to state, pressures and biodiversity. Therefore, ecosystem condition is an important concept that should be used to assess trends and set targets related to the improvement of ecosystem health. Ecosystem health is closely related to the ecosystem's ecological integrity. Thus, ecosystem health can be summarized by a few categories of ecosystem properties, which relate to the maintenance of ecosystem functional diversity: "organization, autonomy and resistance to stress, vitality or vigour, and resilience"(Rapport et al., 1998; Rapport et al., 1999; Rapport et al., 2000; Rapport and Singh, 2006). The purpose of an ecosystem condition account should, therefore, be to produce a diagnosis of (some aspect of) ecosystem health, where health can be expressed relative to some reference condition benchmark. The development of such an ecosystem condition account, based on reference condition benchmarks, would create a common currency for ecosystem health. Potential benchmarks may include: "a pristine (or quasi-pristine) situation corresponding to no disturbance by human activities" (Weber, 2014).

1.3.2 Specific guidance to develop an ecosystem condition account

The Ecosystem Condition Account is a central component in SEEA-EEA and aims to track the 'condition' of ecosystems in a way that shows the improvement or deterioration in key ecological characteristics specific to individual (or groups of) ecosystems (Petersen, 2017). The SEEA EEA handbook (Anon, 2017) suggests five aspects of condition that could be considered (vegetation, biodiversity, soil, water, carbon) for a condition account. The pilot SIA is intended as an ecosystem condition account with biodiversity as its thematic focus. Its development is based on several sources of guidance.

Firstly, we consider the above-mentioned MAES initiative, which covers the links between ecosystem capital and well-being. Biodiversity is identified by MAES as a cross-cutting indicator of ecosystem condition (Maes, 2018). Within the EU, Member State obligations for the conservation and improvement of biodiversity are set out in various Directives, e.g. the Nature directives and, specifically for the marine environment, in the Marine Strategy Framework Directive. These directives all include provisions for regular reporting on the status of those aspects of biodiversity under their scope, i.e. of EU-level interest. (Petersen, 2017) provides a series of parameters relevant to assess ecosystem condition, which would then be relevant to build an ecosystem condition account, and which are reviewed here as follows:

I) The condition parameters chosen should match critical pressures on, and fundamental changes in, ecosystem condition identified in recent MAES work (this refers to Maes et al., 2013 and 2014).

II) As far as feasible condition parameters should be chosen that are applicable and comparable across all MAES ecosystem types, for example indicators related to biodiversity.

III) Where appropriate or necessary, ecosystem-specific condition parameters are to be included.

IV) The overall number of condition parameters per ecosystem type should not be too high (e.g. in the range of 3 – 5) to avoid complicating the construction and calculation of the overall account too much.

V) The condition parameters finally chosen should ideally be underpinned by data sets that allow a reliable quantitative analysis of trends at suitable spatial and temporal scale.

Secondly and similar to the 'integrated marine fish account' (Piet, 2017), the development of the pilot SIA was initially inspired by the approach put forward in the Ecosystem Natural Capital Accounts: A Quick Start Package (ENCA-QSP) (Weber, 2014) and then adjusted to the SEEA-EEA conceptual framework. As ENCA-QSP is an application necessary to operationalize SEEA-EEA, no major divergences are expected between the two. Thus, the relevant ecosystem accounting principles from the "priorities for the ecosystem natural capital accounts" (ENCA), as reflected in the Quick Start Package (QSP) (Weber, 2014), are also used to guide the development of the pilot SIA. The ENCA-QSP states that ecosystem accounts primarily aim at describing the impacts of human activities on the reproductive capacity of nature and their development should (at least) consider the principles we have included in Table 1.1.

Table 1.1. Relevant ecosystem accounting principles and their interpretation to guide the calculation of the pilot SIA

Ecosystem accounting principles	Interpretation of requirements
Meet the policy demand(s) • 1.06 Ecosystem accounts are statistical tools; they should not be tied to any particular political objective but, should support policies with meaningful, objective and verifiable data. • 1.07 Regarding macro-economic decisions, data need to be updated on at least an annual basis and should not be more than one year old. Time-series are also useful for understanding past trends, to feed models and to anticipate developments.	The account should be based on meaningful, objective and verifiable data and be able to provide a time-series that can be updated on an annual basis.
Be outcome-oriented • 1.08 Ecosystems differ and available data differ, but the fundamental diagnosis needed is the same: capability, degradation, steady-state or enhancement, accountability. At this Quick Start stage, relevance matters more than accuracy. It is important to define first what should be done in principle, and then, and only then, what can be done in practice.	The primary aim of the outcome should be 'relevance' making 'accuracy' secondary. The pilot SIA should inform on the ecosystem capacity to supply ecosystem services and how this changes over time. Its development should be approached from what can be done in principle not the current practicalities

Table 1.1. cont.

Ecosystem accounting principles	Interpretation of requirements
Use existing data available in countries and/or international databases • 1.09 Most of the data needed for producing a first set of accounts already exists. Some may be of insufficient quality, and most will require adjustment because they have been collected for various purposes, at various dates. The first accounts will certainly not be perfect but will meet the two main functions of any accounts: to inform on performance and to inform on the quality of the information.	Use existing data to create a pilot SIA that informs on • the performance of (fisheries) management to mitigate impacts from fishing-induced physical disturbance in order to conserve marine (benthic habitat) biodiversity • the quality of the available information on which it is based
First produce accounts of ecosystem capital capability and ecosystem services in physical units, then value ecosystem services and restoration costs • 1.12 As stated in the SEEA-EEA Introduction, "accounting for ecosystems in physical (i.e. non-monetary) terms is a key feature of the SEEA-EEA. (…) Approaches to accounting for ecosystems in monetary terms (…) are also described recognising that this raises additional complexities relating to valuation. In this regard measurement in monetary terms for ecosystem accounting purposes is generally dependent on the availability of information in physical terms since there are generally few observable market values for ecosystems and their services" (SEEA-EEA, para. 1.09).	The account should be expressed in physical units

The above SEEA-EEA principles and considerations concerning the condition parameters from Petersen (2017) were interpreted and translated into the following requirements for the pilot SIA, which should:

- be tightly linked to the ecosystem capacity to supply of ecosystem services, specifically the regulation and maintenance and cultural services.
- reflect the impacts of (the main) human activities on the capacity of ecosystems to supply ecosystem services.
- represent ecosystem health and/or its degradation, which is linked to (the reduction of) the ecosystem's capability to achieve its fullest potential for service supply and is closely related to ecological integrity (or lack thereof).
- express ecosystem health in physical units – possibly relative to some reference condition benchmark, e.g. no disturbance by human activities
- primarily be able to inform on the performance of (fisheries) management to mitigate impacts from fishing-induced physical disturbance in order to conserve marine (benthic habitat) biodiversity
- support policies with meaningful, objective and verifiable data, which are able to show degradation and/or recovery at policy-relevant time-scales.

1.4 Requirements to develop a Seafloor Integrity Account (SIA)

The pilot SIA will then be developed such that it is policy relevant (see requirements in section 1.1) and fulfils the accounting requirements in section 1.3. To that end the outcome of the review of methods to assess fishing impact on seabed habitats (introduced in section 1.2) is adopted because this has selected the most suitable method to assess such impacts (chapters 2 and 3), which will then be applied as proof of concept in one of the EU marine sub-regions, i.e. North Sea, for which adequate data are available to calculate the actual pilot SIA (chapter 4). Finally, this exercise is then evaluated in and concluded with a proposed way forward for the further process to calculate a European-level pilot SIA, i.e. applying to all four EU marine regions, as part of an integrated EU ecosystem accounting system (chapter 5).

The pilot SIA should reflect the condition of one of the components of marine biodiversity according to the MSFD, i.e. seabed habitats. As noted in section 1.1, in an MSFD context, seafloor integrity represents the health of those habitats, which is defined as "where structure and functions of the benthic ecosystem is not adversely affected". As the health of the seafloor is expressed both in terms of structure and functioning, and because the account should link to the (ecosystem capacity to) supply ecosystem services, which is determined by the presence and functioning of the relevant ecosystem components (see ETC/ICM, 2019 in prep.), it is apparent that the methodology underpinning the account should be able to capture both the structural aspects as well as the functioning of seabed habitats. When considering appropriate methods for the calculation of the pilot SIA and what it represents, we need to acknowledge that only the biotic part (e.g. the benthic invertebrate community), and not the abiotic part, should be considered as this is part of marine ecosystem capital and can supply marine ecosystem services.

The pilot SIA should then be able to reflect the status of the benthic invertebrate community relative to that of an undisturbed or pristine reference conditions, such that it captures how the adverse effects from any anthropogenic pressures cause it to depart from those reference conditions. Two anthropogenic pressures that may disturb the condition of the benthic invertebrate community are specifically mentioned in an MSFD policy context, i.e. physical loss and physical disturbance. Each pressure is caused by specific human activities. In the MSFD (2012-2013) reporting by Member States, the main activities reported as causing 'physical loss' at the EU level were linked to man-made structures (of which land claim, coastal defence and flood protection; port operations; and submarine cable and pipeline operations are mentioned the most) and solid waste disposal. The reporting on 'physical disturbance' clearly highlighted fishing as being the most important activity at the EU level; followed by dredging and port operations (EC, 2014).

Both conceptually, and for the calculation of the pilot SIA, the seafloor integrity lost (i.e. the amount of benthic ecosystem structure and functioning impacted permanently in terms of the relevant policy timeframe) due to past human activities will need to be distinguished from the human impacts on seafloor integrity due to physical disturbance, which the seafloor can still recover from when the pressure subsides.

Following from the definition of 'physical loss', which is understood as a permanent change, we should consider seabed habitats impacted by physical loss separate from those impacted by physical disturbance as only the latter can recover. This recovery would need to take place within the policy-relevant timeframes, such as 12 years or two MSFD 6-year cycles (see section 1.1), as policy is what normally requires the introduction of measures to prevent or mitigate such impacts by, e.g., limiting fishing intensity and/or its spatial distribution (see also section 4.1). The "extent of loss of the habitat resulting from anthropogenic pressures" (see Box 1.1) is, thus, interpreted as the proportion of the seafloor not contributing to the functioning of seabed habitats and hence to the supply of ecosystem services. As the pilot SIA is supposed to inform on (changes in) the state of the seabed habitats in terms of their functioning and their capacity to supply ecosystem services at policy-relevant timescales, a distinction is required between:

- the extent of seabed habitat that is lost and, therefore, does not contribute to the pilot SIA within the 12-year period selected here; and
- the extent of seabed habitat that is "only" disturbed and still contributing to a more or lesser degree to the pilot SIA and may show recovery within such a 12-year period if the pressure decreases (e.g. due to management intervention).

There is currently is no agreed operational definition of the 'physical loss' and 'physical disturbance' pressures that allows a categorisation of all the anthropogenic activities and their associated pressures into these two categories. For this reason, for the calculation of the pilot SIA and the need to assess physical disturbance on the seafloor, we have selected one human activity, i.e. commercial fisheries, which is known to be the primary cause of physical disturbance. Fishing may also be the cause of 'physical loss' if the sensitivity/vulnerability of a specific seabed habitat does not allow a recovery within the 12-year period that is used here to distinguish 'physical loss' from 'physical disturbance' (see section 1.1). However, for the calculation of a pilot SIA we have only considered those seabed habitats that can be expected to function and supply ecosystem services despite the anthropogenic pressures upon them. This exercise will also include an assessment of how representative this pilot SIA is.

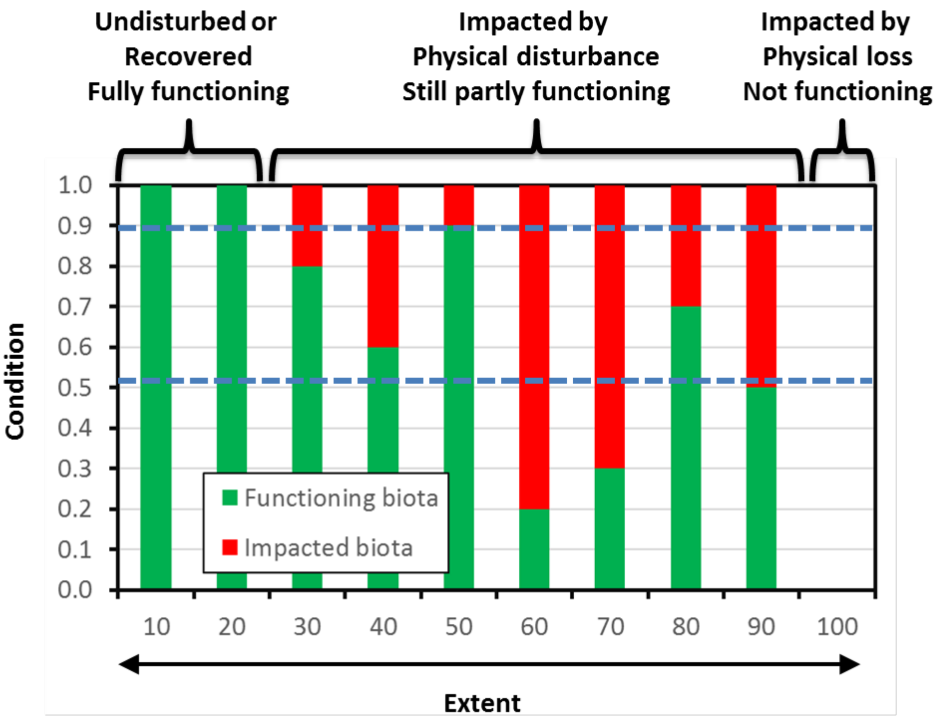
The relevance of the pilot SIA to EU policy is achieved because the state of seabed habitats is tightly linked to the concept of seafloor integrity within the MSFD (see sections 1.1 and 1.2). From a policy perspective, and following the MSFD, seafloor integrity should be expressed in terms of the spatial extent of the pressures, i.e. physical loss (D6C1) or physical disturbance (D6C2), and the specific seabed habitat types which are adversely affected (D6C3). In addition, there is the extent of seabed habitats that is not lost (D6C4), or not adversely affected from physical disturbance (D6C5), by all anthropogenic activities (see Box 1.1). All these criteria have in common that they are represented by a certain proportion of the total natural extent of the entire sub-region or of a given habitat type and require the setting up of thresholds determining what is "not lost" or "not adversely affected" in order to achieve the MSFD's "Good Environmental Status".

The pilot SIA is, thus, supposed to reflect the condition of seabed habitat(s) in terms of their functioning and their capacity to supply ecosystem services. The SIA metric, therefore, needs to describe the degree to which the benthic invertebrate community biomass is impacted by physical disturbance and, hence, the amount of functioning that still remains in that community. Pertaining to the selection of the methodologies to calculate the pilot SIA, this requires a distinction between the parts of the seabed habitat(s) that are:

A. pristine, undisturbed or fully recovered (and hence where the benthic invertebrate community is at carrying capacity (condition = 1), i.e. the maximum biomass that the undisturbed environment can sustain, and thus fully functioning). This category represents 20 % of the seabed habitat in Figure 1.2.
B. those that are disturbed but still functioning to a more or lesser degree (the benthic invertebrate community condition is anywhere between 0 – 1 depending on the level of disturbance). This category represents 70 % of the seabed habitat in Figure 1.2.
C. those that are "lost" (the benthic invertebrate community is not functioning, condition = 0). This category represents the remaining 10 % of the seabed habitat in Figure 1.2.

If this example (Figure 1.2) represents a specific marine region, then the overall condition is 0.67 in the 90 % part of that region that is not lost (Categories A and B above). If physical loss is also considered, and the remaining lost parts of the marine region are included (Category C above), then the condition is 0.6 but this now covers 100 % of the region. The usefulness of this metric in the accounting context is based on the assumption that there is a one-to-one relationship between the biomass, the functioning of the benthic ecosystem and its capacity to supply ecosystem services. We, thus, consider that such a condition metric (i.e. biomass of the benthic invertebrate community) is a good approximation of the seabed habitats' capacity to supply ecosystem services and should hence be what is represented by the SIA (see also Chapter 4).

Figure 1.2. Example of how a metric can express the condition of a specific seabed habitat (or of the entire seafloor of a marine region) in terms of its functioning depending on the impact of the 'physical loss' and 'physical disturbance' anthropogenic pressures.



As such the pilot SIA matches the MSFD's D6C3 and D6C5 best when physical disturbance is involved (see Section 1.2) and D6C4 in case of physical loss. However, where these criteria reflect the extent of the habitat that is, or is not, "adversely affected" or "lost", and in case of physical disturbance requires a threshold to make such a distinction, the SIA methodology has the advantage that benthic ecosystem functioning is expressed on a continuous scale, which does not require the application of any arbitrary threshold to determine when a habitat is "adversely affected". For example, using Figure 1.2, the application of a 90 % threshold would render 80 % of the marine region "adversely affected"; whereas a 50 % threshold would result in 50 % "adversely affected". This example shows that, for the same overall condition, the outcome of the assessment in terms of the extent of a region that "adversely affected" depends on the setting of a threshold. If the pilot SIA was made equal to this 'adversely affected' extent, rather than using the approach above (i.e. expressing benthic ecosystem functioning on a continuous scale), it would likely give a less accurate (and dependent on the threshold) estimate of the capacity of the benthic ecosystem to supply ecosystem services. Notwithstanding, as the available methods to assess fishing impacts (see section 1.2) can only calculate fishing-induced physical disturbance, the pilot SIA will only include the part of the seafloor that is not lost. In addition, as noted already, lost seafloor does not have the capacity to supply ecosystem services (see also Chapter 4).

2 Review methods to assess the fishing-induced physical disturbance

As explained in section 1.4, fishing is considered by far the most widespread human activity causing physical disturbance on seabed habitats. In a fisheries context, the 'physical disturbance' pressure is referred to as 'fishing intensity' and calculated as the swept area ratio. ICES (2016a) defines the swept area as the cumulative area contacted by fishing gear within a grid cell (i.e. a division of the seafloor with a specific spatial resolution) over one year. The swept area ratio is the swept area divided by the surface area of the grid cell.

In the methods considered here, the calculation of fishing pressure is based on a spatially resolved index of fishing intensity for mobile bottom contacting gear (i.e. trawls or dredges). Fishing intensity was, thus, defined as the area swept per unit area, i.e. the area of the seabed in contact with the fishing gear in relation to a surface area of the grid cell (ICES, 2015; Eigaard et al., 2017). For this, Vessel Monitoring through Satellite (VMS) data and fisheries logbook data[3] are required. In its raw format, VMS data are geographically distinct points, so-called "pings", providing information about the vessel position, instantaneous speed and heading. VMS transmits at regular intervals of approximately 2 hours, but with higher polling rates for some countries. VMS data points can be linked to logbook data in order to get additional information about the ship, the applied gear and eventually also the catch. Following some analytical steps to identify e.g. misreported pings, the vessel state (steaming, fishing or floating) has to be identified using the actual speed information. Only data, which were assumed to represent fishing activity, were then assigned to a grid with specific spatial resolution. Finally, national data were reported in a gridded and anonymized form summing the number of pings within each grid cell based on the time interval between successive pings, and including information about vessel flag country, gear code (equivalent to the Common Fisheries Policy/CFP Data Collection Framework level 4), fishing activity category (CFP Data Collection Framework level 6), average fishing speed, fishing hour, average vessel length, average kW, total landings weight and total value of all species caught. Therefore, estimates on the aggregated fishing time within each grid cell and métier (i.e. units to aggregate fishing activity, here based on gear type and target species[4]) are available for a specific time period based on VMS and fisheries logbook data.

Currently there are two initiatives that have managed to assemble datasets of international fishing fleets to produce fishing intensity maps covering (parts of) MSFD (sub-)regions as follows:

- Ongoing OSPAR request to ICES on VMS/Logbook data-call from 15th January 2016 covering the Northeast Atlantic (North Sea and Celtic Seas) and the Baltic Sea for the period 2009 – 2015. This dataset is based on a 0.05 x 0.05 degree grid, using the approach of C-square reference (Rees, 2003). However, due to variances in latitude, the extent of the 0.05º grid cell differs in total size across areas, from just under 14 km^2 in North East Scottish waters, to 21 km^2 in the Southern part of the Celtic Sea. Because of a legislative change, vessels of 12 – 15 m total length are only included in the estimates since 2012. The fishing intensity maps therefore only cover the years 2012 – 2015.
- The FP7 BENTHIS project[5] covering also (parts of) the Iberian peninsula and Mediterranean for the period 2010 – 2012. This dataset is based on a 1 x 1 minute resolution of approximately 2

[3] The EU requires the recording and reporting of data relating to fishing activity undertaken by EU vessels (and in EU waters) and to the landing and first sale of fishery products in the EU. These requirements are currently set out in various pieces of EU legislation: Council Regulations 2847/93, 1006/2008 and 1224/2009, and Commission Regulations 1077/2008 and 201/2010.
[4] https://datacollection.jrc.ec.europa.eu/wordef/fishing-activity-metier
[5] https://www.benthis.eu/en/benthis.htm

km^2 at 60°N. The project collected raw data from participant countries, which was analysed using an interpolation method to connect the VMS positions into trawl tracks (Eigaard et al., 2017).

Because of these differences, i.e. spatial resolution, time period, VMS positions versus trawl tracks) there is no straightforward comparison possible between the fishing intensity maps produced by these two initiatives.

The workflow to produce these fishing intensity maps is given in Figure 2.1 (Figure 6.2.1 in the WKBENTH report (ICES, 2017c)). In order to calculate swept-area values, certain assumptions about the spread of the gear, the extent of bottom contact and the fishing speed of the vessel needed to be made and thus, a number of working steps were necessary. The workflow distinguishes the different steps:

- First a full quality assessment of all submitted data was performed (Step 1). Submitted VMS datasets usually contained information on the gear based on standard DCF métiers (from EU logbooks, usually at the resolution of métier level 6) and the gear-specific fishing speed, but not on gear size and geometry.
- Therefore, vessel size-gear size relationships developed by the EU FP7 project BENTHIS project (Eigaard et al., 2016) or by the Joint Nature Conservation Committee (JNCC) (Church et al., 2016), were used to approximate the bottom contact (e.g. gear width). To do this, it was necessary to aggregate métier level 6 to lower and more meaningful gear groups, for which assumptions regarding the extend of bottom contact were robust (Step 2). If possible, the so-called "BENTHIS métiers" were used; otherwise the more general bottom contacting gear groups from JNCC were assigned.
- Following this, fishing effort (hours) was calculated and aggregated per c-square for each métier and year (Step 3).
- Fishing speeds were based on average speed values for each métier and grid cell submitted as part of the data call, or, where missing, a generalized estimate of speed was derived (Step 4).
- Similarly, vessel length or power were submitted through the data call, but where missing average vessel length/power values were assumed from the BENTHIS survey (Eigaard et al., 2016) or were derived based on a review done by JNCC (Step 5). Parameters necessary to fulfil steps 2, 4, and 5 are listed in Table 2.1 for BENTHIS métiers and table 2.2 for corresponding JNCC gear groups.
- The resulting bottom contact values (m) were finally used to calculate swept-areas (SA) per gear group, grid cell and year (Step 6).
- The swept-area information was additionally aggregated across fishing métiers for each gear class (otter trawl, beam trawl, dredge, demersal seine) with two layers, one for surface abrasion and one for subsurface abrasion (as proportion of the total area swept, see Table 2.1 and 2.2). To account for varying cell sizes of the GCS WGS84 grid, swept-area values were additionally divided by the grid cell area giving the swept-area ratio (SAR = number of times the cell was theoretically swept). Finally, effort and swept-area maps were generated at appropriate scales (Step 7 and 8).

Figure 2.1. Workflow for the production of fishing intensity maps from aggregated VMS data (0.05° x 0.05° C-square resolution) (from (ICES, 2016a)). All métiers and vessel size/ gear spread relationships were derived from (Eigaard et al., 2016).

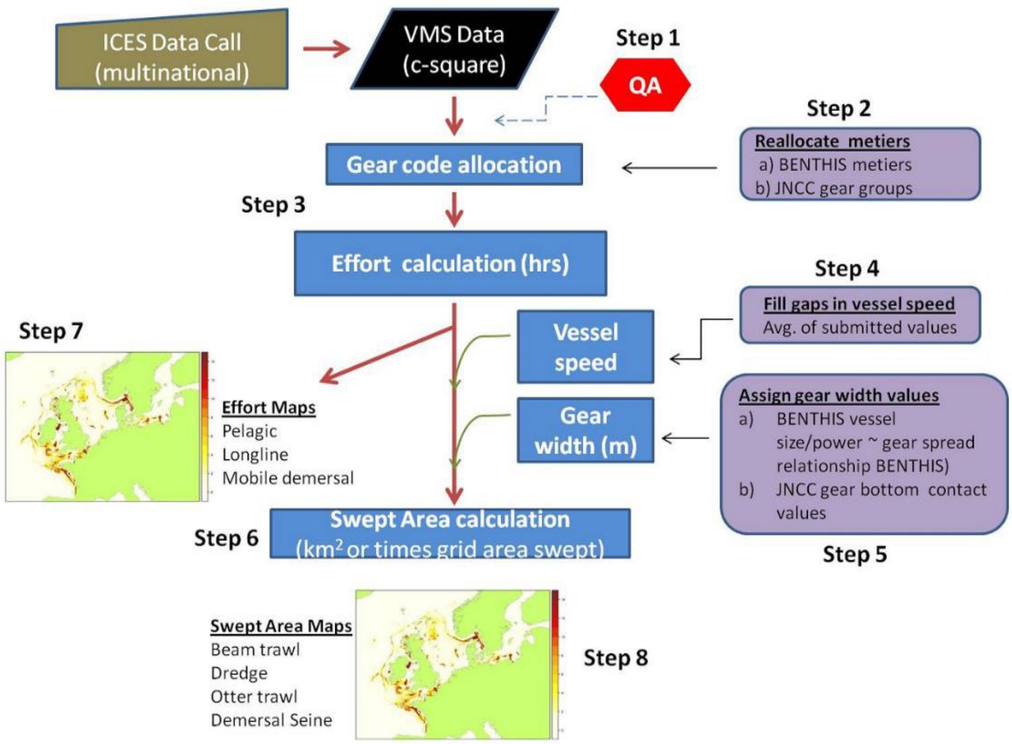


Table 2.1. Parameter estimates of the relationship between vessel size (as length (m) or power (kW)) and gear width, the average width of fishing gear causing abrasion (surface and subsurface), the corresponding proportion of subsurface abrasion, and the average fishing speed for each BENTHIS métier (derived from (Eigaard et al., 2016) and ICES 2016)

Gear class	Benthis metier	Model	Average gear width (m)	Subsurface proportion (%)	Fishing speed (knots)
Otter trawl	OT_CRU	$5.1039*(kW^{0.4690})$	78.92	32.1	2.5
	OT_DMF	$9.6054*(kW^{0.4337})$	105.47	7.8	3.1
	OT_MIX	$10.6608*(kW^{0.2921})$	61.37	14.7	2.8
	OT_MIX_CRU	$37.5272*(kW^{0.1490})$	105.12	29.2	3.0
	OT_MIX_DMF_BEN	3.2141*LOA+77.9812	156.31	8.6	2.9
	OT_MIX_DMF_PEL	$6.6371*(LOA^{0.7706})$	76.21	22	3.4
	OT_MIX_CRU_DMF	3.9273*LOA+35.8254	113.96	22.9	2.6
	OT_SPF	0.9652*LOA+68.3890	101.58	2.8	2.9
Beam trawl	TBB_CRU	$1.4812*(kW^{0.4578})$	17.15	52.2	3
	TBB_DMF	$0.6601*(kW^{0.5078})$	20.28	100	5.2
	TBB_MOL	$0.9530*(LOA^{0.7094})$	4.93	100	2.4
Dredge	DRB_MOL	$0.3142*(LOA^{1.2454})$	16.97	100	2.5
Demersal seines	SDN_DMF	$1948.8347*(kW^{0.2363})$	6536.64	5	NA
	SSC_DMF	$4461.2700*(LOA^{0.1176})$	6454.21	14	NA

Table 2.2. Estimates of fishing gear width causing abrasion (surface and subsurface) and the corresponding proportion of subsurface abrasion for each JNCC gear group (from ICES 2016a, Church et al. 2016)

JNCC gear group	Gear width	Subsurface proportion (%)	Fishing speed (knots)
Beam Trawl	18	100	4.5
Nephrops Trawl	60	3.33	3
Otter Trawl	60	5	3
Otter Trawl (Twin)	100	5	3
Otter Trawl (Other)	60	3.33	3
Boat Dredge	12	100	4
Pair Trawl and Seine	250	0.8	3

2.1 Maps of fishing intensity

Maps describing fishing pressure on benthic habitats are based on the fishing intensity (i.e. swept-area ratio SAR) estimates calculated as annual grid cell averages based on the above-mentioned two sources of information/initiatives, i.e. an ICES data call and the FP7 BENTHIS project.

The ICES data call covers the years 2009-2015 but for consistency only the period 2012 – 2015 is used (see below). When using the information per métier (see Table 2.1) or gear group (see Table 2.2.) surface and subsurface abrasion are considered separately as these involve different components of the benthic invertebrate community and hence different aspects of seafloor integrity. Both aspects are visualised for the three ICES ecoregions, i.e. Baltic Sea (Figure 2.2), Celtic Sea (Figure 2.3) and North Sea (Figure 2.4). Because of a legislative change, vessels of 12 – 15 m total length are only included in the estimates since 2012 which is the reason the maps are based on the average SARs only for the period 2012 – 2015 (see also section 2.1.2).

Figure 2.2. Fishing intensity expressed as average Swept Area Ratios (SAR) from the years 2012 – 2015 separated into surface (left) and subsurface abrasion (right) in the Baltic Sea. From ICES (2017c)

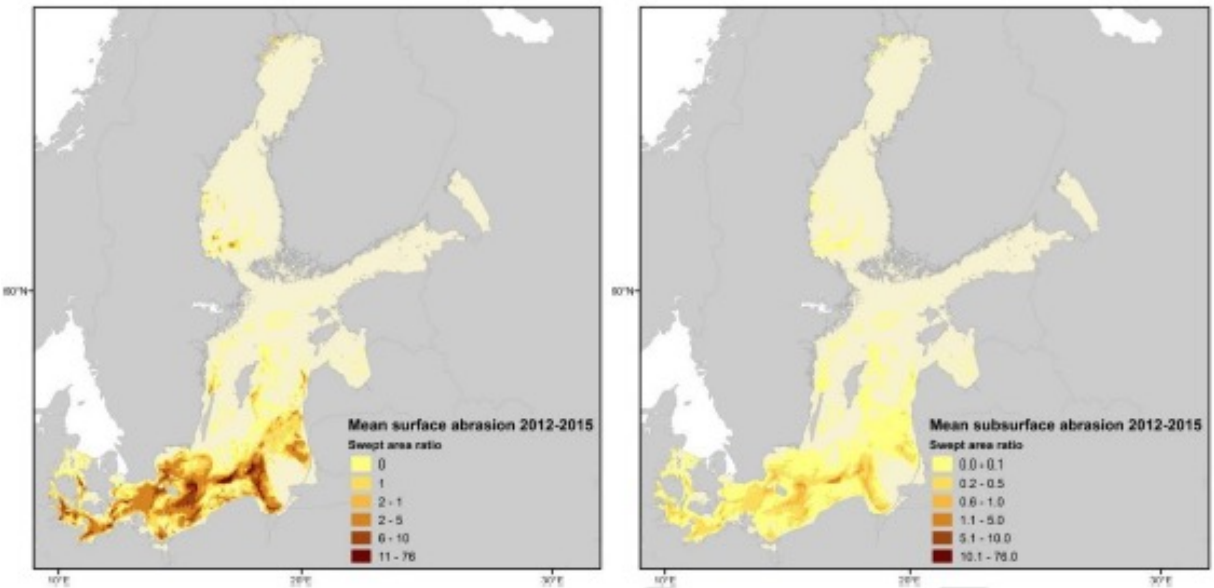


Figure 2.3. Fishing intensity expressed as average Swept Area Ratios (SAR) from the years 2012 – 2015 separated into surface (left) and subsurface abrasion (right) in the Celtic Sea. From ICES (2017c)

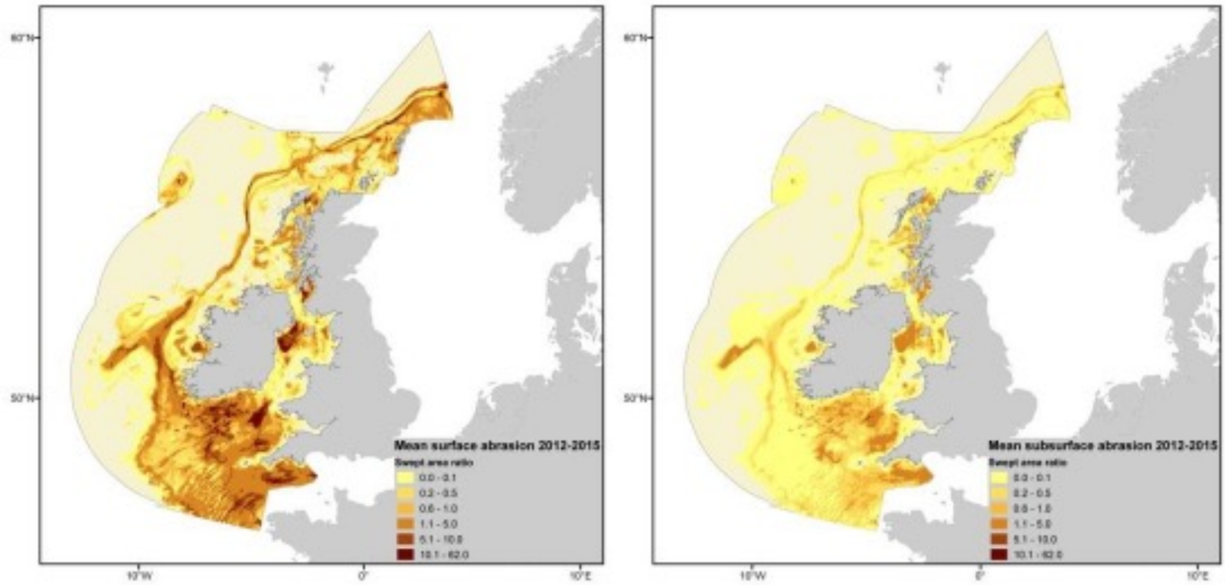
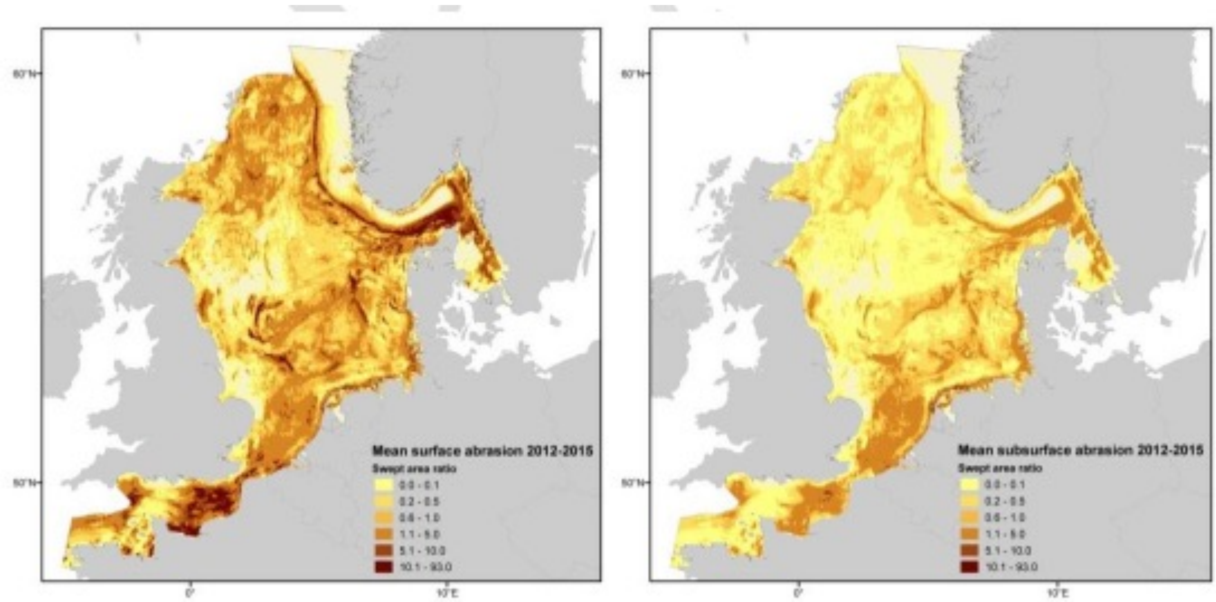
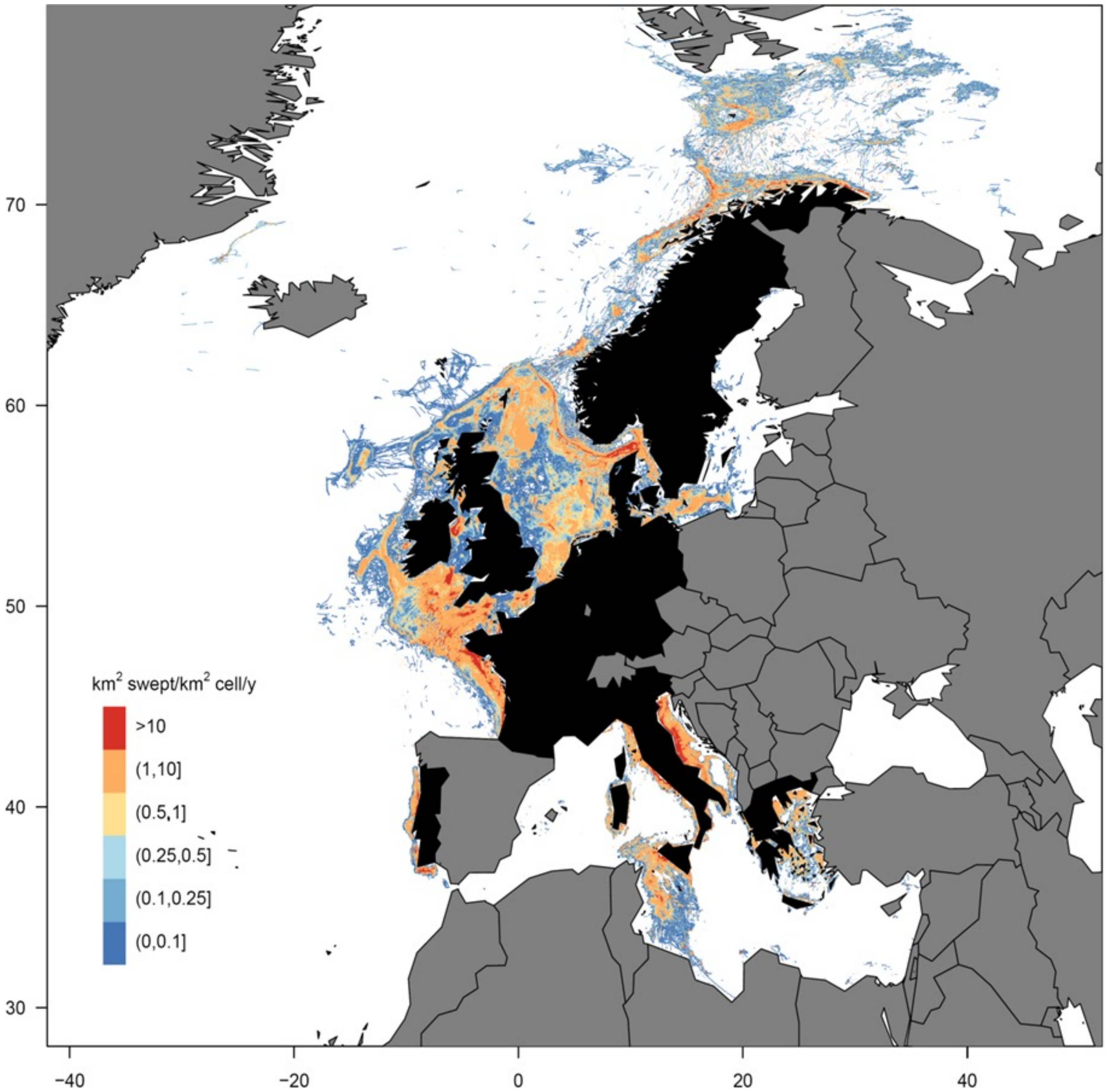


Figure 2.4. Fishing intensity expressed as Average Swept Area ratios (SAR) from the years 2012 – 2015 separated into surface (left) and subsurface abrasion (right) in the North Sea. From ICES (2017c)



The data from the FP7 BENTHIS project covers the period 2010 – 2012. This dataset is based on a 1 x 1 minute resolution of approximately 2 km^2 at 60^oN). This represents surface disturbance only and is based on all EU Member States and Norway in the project (see Figure 2.5).

Figure 2.5. Map of fishing intensity from the BENTHIS project expressed as average Swept Area Ratios (SAR) from the period 2010 – 2012. This map is based on a 1 x 1 minute resolution of approximately 2 km^2 at 60^{o}N). This represents surface disturbance only and is based on the EU Member States and Norway represented in the project (indicated in black). ***This is, therefore, not comprehensive but does show that Member States in different EU marine regions possess the information required to calculate fishing intensity*.**



2.2 Limitations of the selected method

Vessel monitoring systems are primarily intended for compliance and monitoring purposes in relation to the EU Fisheries Policy, and so the data collected were not specifically designed to enable fishing intensity mapping. As such, there remain some data quality issues and caveats with the ensuing fishing intensity maps. These have been identified by WGSFD (ICES 2016a) and the most important aspects are briefly listed below:

- The outputs can only reflect the data submitted and data from some countries were still missing (Spain, Iceland, Greenland, Faroe Islands, Russia) or some parameters, e.g. fishing speeds were not fully submitted. Looking at the quality control summaries of WGSFD (ICES 2016a), the outputs appear to be consistent over time, but fishing pressure in certain areas may have been underestimated.

- Up to 2011, only vessels larger than 15 meters were obliged to have VMS on board. In 2012 the legislation changed, and data from vessels larger than 12 meters became available thereby covering the previous 12 to 15 metre gap. However, due to differences between countries how vessel length categories were reported, it was not always possible to partition this segment and therefore make the data directly comparable before and after 2012. This is likely to be relevant when examining trends in effort for inshore areas as the smaller vessels mainly occur close to coasts.
- Similarly, in nearshore areas and for some countries, substantial fleets of smaller vessels not equipped with VMS exist (< 15 m prior to 2012, < 12 m thereafter). For these, only logbook data are available, which is at the spatial resolution of ICES rectangles, which have a resolution of 1° longitude and 30' latitude that is too coarse to be considered to assess the status of seabed habitats.
- For calculating fishing intensities, and distinguishing between surface and subsurface abrasion, gear widths and fishing speeds are used as input. Gear widths are based on Eigaard et al. (2016). Information on vessel lengths and engine power is available as an average per métier. If this information was missing, often crude assumptions on average vessel sizes and engine power had to be made in order to estimate gear widths. Fishing speeds were mostly available and, where missing, were replaced by average fishing speeds on the same or similar gear.
- Although standard routines (using R for statistical computing and the related VMStools package (Hintzen et al., 2012) were defined, aggregation methods and the identification of fishing activity from VMS data may still vary between countries.
- Gear coding in logbooks is not typically suited for quantitative estimations of seabed pressure, i.e. the exact gear type (width/spread and weight) is unknown. The calculation of swept areas and the corresponding distinction between surface and subsurface can, therefore, only be an approximation of the actual values.
- There may be issues with misreporting (e.g. gear groups), which would obviously affect the outcome of the calculations.
- Within the ICES process it was decided to aggregate the data at a spatial resolution of so-called c-squares (0.05 x 0.05 degree grid, about 15 km² at 60°N latitude), which was the result of a pragmatic compromise that circumvented potential privacy issues and, thus, allowed the Member States to provide their national data. This, however, is not necessarily the best resolution for the most accurate reflection of fishing intensity. At this spatial resolution the fishing intensity is expected to be overestimated.

3 Review methods to assess the impact of fishing-induced physical disturbance on seabed habitats

3.1 Introduction

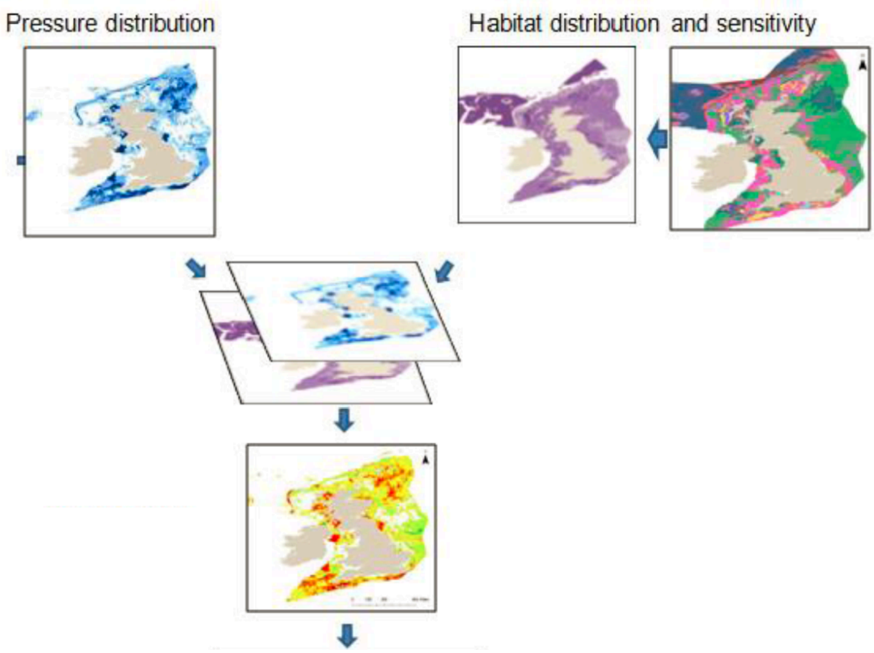
There are several methods to assess the state of the seabed habitats and how this changes (=impact) due to physical disturbance caused by fishing. These all have in common that the assessment is based on the combination of spatial maps of fishing intensity (describing the pressure) with spatial maps of seabed habitats, where different habitats may differ in their sensitivity to fishing (Figure 3.1). All assessments of (the impact on) the state of seabed habitats are based on the same habitat maps (see section 3.1) and fishing intensity maps (see section 2.1). Therefore, independently of the methodologies to estimate the state of the seabed habitats and how this is impacted by physical disturbance caused by fishing, the same issues apply pertaining to which geographic areas can be assessed, the spatial and temporal resolution of the fishing pressure, and/or habitat distribution data.

The methods we are considering to determine the impact of fishing-induced physical disturbance on seabed habitats, and developed for the assessment of seafloor integrity, were all presented and discussed in the ICES-led process described in section 1.3:

- OSPAR BH2 – Condition of Benthic Habitats communities
- OSPAR BH3 – Extent of physical damage to predominant and special habitats
- BENTHIS Longevity methodologies
- BENTHIS Population dynamic approaches

These methods are described in more detail in subsequent sections of this chapter.

Figure 3.1. Approach to determine the impact on seabed habitats from fishing pressure (i.e. physical disturbance) caused by overlapping the pressure distribution with the habitat distribution and an estimated habitat sensitivity (from ICES (2016a))

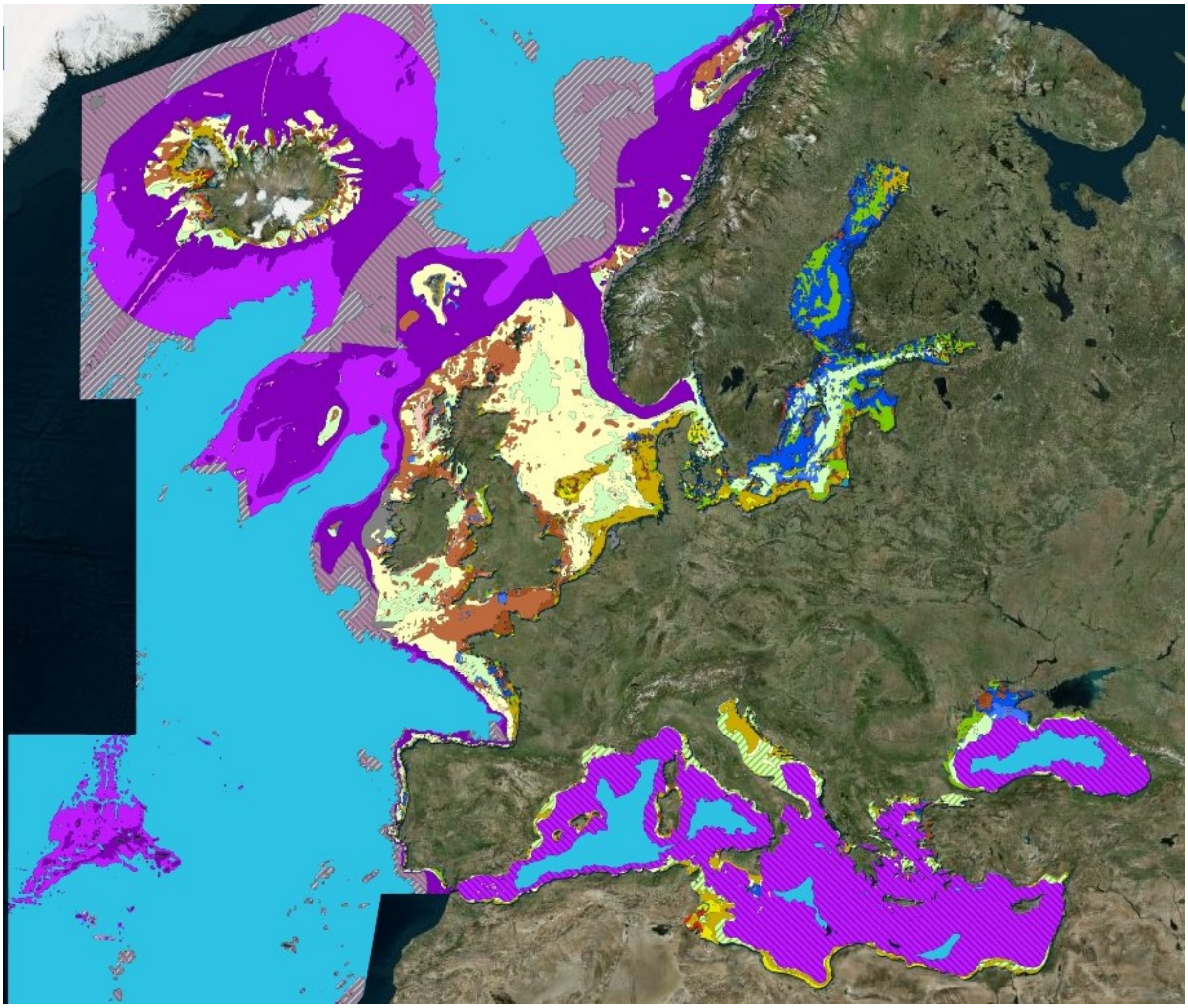


Impact map

3.1.1 Seabed habitat maps

Many habitat mapping studies are conducted throughout Europe, but none provide the coverage required for spatial assessments in all EU marine regions (see ICES 2016a and ICES 2017b). It was apparent that the 'seabed habitats' component – EUSeaMap – of the Marine Observation and Data Network (EMODnet)[6] met this specification and was the most appropriate source of marine spatial information on habitats available. This is, in particular, because it is the only EU-level consistent approach for the mapping of (broad scale) seabed habitats. The analysis undertaken here used the most up-to-date habitat map available for the assessment area (Figure 3.2).

Figure 3.2. EUSeaMap (EMODnet seabed habitat map, 18/6/2018)[7].



3.2 OSPAR BH2 approach

The OSPAR BH2 indicator is a common concept for the development of an umbrella of indices to assess the impact of each human pressure on the condition of each benthic habitat type, along a pressure-impact gradient. The aim is to inform management of human activities and improve the evidence and understanding of the relative effects of different pressures, e.g. fisheries, organic

[6] http://www.emodnet-seabedhabitats.eu/
[7] https://www.emodnet-seabedhabitats.eu/access-data/

enrichment, sedimentation, on benthic habitats and their communities. It is, therefore, not specifically intended for fishing pressure. One of the indices used to assess fisheries impacts was tested in the Southern North Sea. This index is based on a combination of indices evaluated through an index optimization tool: Benthic Multi-metric Index (BENMMI). The tool contains a suite of commonly used benthic indices, i.e. species richness per sample, Margalef diversity (D), SNA, Shannon index, PIE index (Probability of Interspecies Encounter), AMBI and ITI, which can be combined by the tool using Multi-Linear Regression and tested for their performance (sensitivity and precision) in regard to a pressure. The pressure data are introduced into the BENMMI tool combined with the benthos data for each specific sampling location. Of the indices included in this approach, only AMBI and ITI (the Infaunal Trophic Index) could provide any additional reference to functionality compared to the traditional indices focused on structural aspects such as species richness or density, i.e. abundance or biomass (see section 1.5).

The AMBI index (Borja et al. 2000) is based on ecological groups of species along a sensitivity-tolerance gradient, while the ITI index (Maurer et al. 1999, Word 1979) is a numerical representation of the distribution of dominant feeding groups of benthic fauna. In the index, species are assigned to four feeding groups encompassing feeding on suspended material to deposited material, translated into a range from 0 (only subsurface deposit feeding) to 100 % (only suspension feeding). It is noteworthy that for example predation, scavenging, parasitism and herbivory, additional feeding types of benthic invertebrates are not included in the index and thus only a subset of trophic interactions is possible.

Margalef diversity (D) (Margalef, 1958) has proven to be the index that performs best in terms of sensitivity and precision for fishing pressure, and thus the one index put forward to be used for the regional scale. The Margalef D provides insight into the impact on diversity from fishing, however it does not reflect functioning per se or link to any specific function, other than that a high diverse area has a higher probability to include a broader functional composition and functional resilience and resistance. The relationship between diversity and ecosystem function has been shown to be idiosyncratic (Emmerson et al., 2001; Bolam et al., 2002), and thus inferences for function based on this indicator are limited.

The ITI index shows the best sensitivity and precision for fisheries in certain areas (van Loon *et al.*, 2013), but has not been evaluated in the ICES review. The ITI index may theoretically provide a greater functional relevance, but, based on the feeding traits included, would most closely refer to the process of organic material cycling. Therefore, this index was considered not appropriate to assess the state of the seabed and how it is impacted by fishing.

3.3 OSPAR BH3 approach

This indicator is being developed under the OSPAR ICG-COBAM benthic expert group to assess the extent of physical damage to predominant and special habitats and has been adopted as a common indicator for the North Sea, Celtic Sea and Bay of Biscay/Iberian Peninsula. The work started in 2013 and has undergone several rounds of testing, consultation and reviews.

In this approach, sensitivity is based on the combined resistance (tolerance to impacts) and resilience (recoverability) of habitats based on observational and modelled data at species, biotope/EUNIS level 5 (or higher) and EUNIS Level 3. Sensitivity of ecosystem components, e.g. habitats and species, are determined by two aspects: the ability to withstand disturbance or stress (resistance or tolerance), and the ability and time needed to recover from a perturbation and return to the previous state (resilience or recoverability). A species or habitat with a high sensitivity is, therefore, one that has both a low resistance and low resilience. In contrast, a species or habitat with a low sensitivity is one with a high resistance and high resilience.

The distribution of disturbance categories per habitat type is calculated as nine levels of disturbance based on exposure matrices combining pressure intensity and habitat sensitivity per pressure type (Figure 3.3).

Figure 3.3. Weighted disturbance values of sensitivity categories over a temporal scale based on Sweeping Area Ratios (SARs) within a year. The values are applied per habitat type with each c-square. From ICES (2016a).

Disturbance		Habitat Sensitivity				
		1	2	3	4	5
Temporal extent of pressure	1	1	2	3	4	6
	2	1	2	4	6	7
	3	1	3	5	7	9
	4	1	4	6	8	9
	5	2	4	7	9	9

The BH3 approach is already put into practice and provides an initial assessment for the OSPAR 2017 Intermediate Assessment but uses a categorical approach that does not provide a continuous pressure – state relationship as recommended by ICES for any impact assessment (ICES, 2017c).

3.4 BENTHIS Longevity methodologies

The longevity approach assesses the impact of trawling on the benthic assemblage as a whole by considering the longevity of benthic invertebrates in relation to trawling intensity (Rijnsdorp et al., 2016a). It makes the assumption that taxa with a longevity that exceeds the average interval between two successive trawling events will be impacted by bottom trawling. By first establishing the relationship between the cumulative biomass and longevity in different sea floor habitats, defined by either the EUNIS classification system or by continuous environmental variables, the indicator of the trawling impact is estimated given the observed trawling intensity by grid cell.

There is ample evidence that bottom trawling shifts the species composition of benthos from long lived taxa to short lived taxa, suggesting that longevity may be used as a proxy of the sensitivity of the community to trawling pressure (Thrush et al., 2005). Since longevity is also related to other relevant life history characteristics such as the age at first reproduction and population growth rate, this information may be useful in developing indicators for trawling impact.

Within the BENTHIS project two longevity-based approaches were distinguished (ICES, 2017c):

- SBI where the trawling impact, and corresponding state of the seabed, can be estimated given the observed trawling intensity and the habitat-specific longevity distribution of the benthic invertebrate community.
- LL where the state of the seabed, i.e. seafloor integrity, is calculated as the ratio of the biomass of long-lived taxa to the un-trawled biomass using the longevity relationships fitted to the North Sea benthic invertebrate community.

3.4.1 Longevity community indicator (SBI)

In the first application of the BENTHIS longevity approach, the impact of bottom trawling was estimated assuming that taxa would potentially be impacted if the interval between two successive trawling events was shorter than their life span (Rijnsdorp et al. 2016). The interval between two successive trawling events can be estimated from the reciprocal of the swept area ratio (see Chapter 2). This method depends on the habitat-specific longevity distribution of the benthic invertebrate community. Once the relationship between the cumulative biomass and longevity is known, the trawling impact, and corresponding status of the sea floor, can be estimated given the observed trawling intensity in a grid cell. Grid cell estimates can be mapped or aggregated to calculate an index of trawling impact by habitat or management area. In the WKBENTH (ICES, 2017c) two indicators are distinguished:

- SBI1 (simple longevity approach) is estimated using the longevity distribution for the un-trawled situation and provides a worst-case situation as it assumes that all taxa trawled during their life span will be impacted. In Eigaard et al. (2017), the seabed integrity was estimated using this approach as the proportion of the biomass of benthic taxa where the trawling interval at the subsurface level exceeds their life span.
- SBI2 is estimated using the longevity distribution for the observed trawling intensity at each grid cell.

For this review, however, we consider the SBI as one method with different parametrisations depending on the trawling intensity. The suitability of this method is mainly determined by the output metric, which applies to both indicators, i.e. the proportion of the biomass of benthic taxa where the trawling interval at the subsurface level exceeds their life span.

3.4.2 Longevity long lived taxa (LL)

For the LL approach, the impact of trawling is assessed based on the long-lived taxa, more specifically the longevity of 10 years or more. The WKBENTH report (ICES, 2017c) distinguishes two LL methodologies, i.e. LL1 and LL2, but because the LL2 estimates the marginal impact (from one more sweep of the grid cell) it is not considered appropriate to assess the state of the seabed.

For the remaining approach LL1 (now referred to as LL) the state of the seabed, i.e. seafloor integrity, is calculated for each grid cell as the ratio of the biomass of long-lived taxa to the un-trawled biomass using the parameter estimates of the longevity relationships fitted to the North Sea benthic invertebrate community (Table 3.1). Trawling intensity showed a significant interaction with depth and tidal shear stress predicting a stronger decrease in long-lived biomass at increasing depth or decreasing tidal shear stress. In shallow areas and areas with a high shear stress, where the model predicted a positive effect of trawling on the biomass of long-lived taxa, the change in biomass was set at zero.

Table 3.1. North Sea-based parameter estimates of the selected mixed effect model of the cumulative biomass in relation with log(longevity) and the environmental variables log(depth, gravel%, log(trawling intensity) and log(tidal shear stress). (WKBENTH Table 6.2.2 (ICES, 2017c))

Fixed effects:

	Estimate	Std. Error	z value	Pr(>|z|)	
(Intercept)	-8.461840	0.787589	-10.744	< 2e-16	***
ll	3.391591	0.158234	21.434	< 2e-16	***
ldepth	0.888672	0.194269	4.574	4.77e-06	***
Gravel	0.013581	0.011573	1.173	0.24061	
lfreq	-0.700110	0.301009	-2.326	0.02002	*
lstress	-0.030685	0.117816	-0.260	0.79452	
ll:Gravel	-0.017213	0.006082	-2.830	0.00465	**
ldepth:lfreq	0.195986	0.083486	2.348	0.01890	*
lfreq:lstress	-0.089926	0.040885	-2.199	0.02784	*

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Because for the sediment characteristics and seabed stress no data layers were available at the resolution of the grid cell, the mean value estimated from the available benthic invertebrate community monitoring data set for each EUNIS-4 habitat type was assigned instead. For the grid cells of habitat types that were missing, an overall mean value was assigned.

3.5 BENTHIS Population dynamic approaches

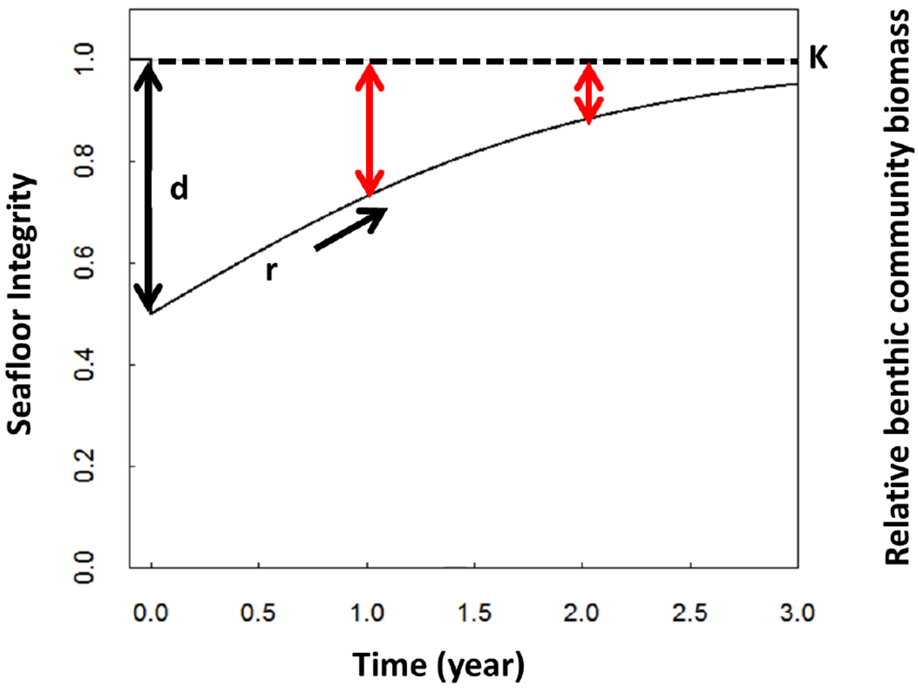
The BENTHIS project includes various approaches to determine the impact of fishing on seabed habitats, which have in common that they are based on a mechanistic understanding of the interaction of trawling with the benthic invertebrate community. This mechanism is determined by two parameters that describe the gear-specific sensitivity of the habitat, i.e. depletion and recovery, in combination with a métier-specific fishing intensity. The fishing intensity does not differ between approaches but the way the two sensitivity parameters are estimated does.

All population dynamic (PD) approaches have in common that according to (Pitcher et al., 2017) the benthic biomass B can be described using the logistic population growth model with a depletion rate d (fraction killed by a single trawl pass, specific to different gear-types) due to a trawling event and a recovery rate r (y-1):

$$dB/dt = rB(1-B/K) - dFB \qquad eq1$$

where dB/dt is the rate of change in biomass B in time t (years), K is an undisturbed situation with biomass at carrying capacity (i.e. the maximum biomass that the undisturbed environment can sustain indefinitely, given the food, habitat, water, and other necessities available), and F is fishing intensity (calculated as swept area per year in a grid cell divided by surface area of that grid cell, y^{-1}). The sensitivity of a habitat to different types of fishing is captured by the depletion rate d and the recovery rate r, which determines the time until recovery is achieved (Figure 3.4). Depending on the approach used to estimate these sensitivity parameters they can be habitat- and/or gear-specific.

Figure 3.4. Schematic of the parameters: gear-specific Depletion rate (d) and habitat-specific Recovery Rate (r), which determine the recovery time until K is reached. The benthic invertebrate community biomass is relative to an undisturbed situation (= carrying capacity K, biomass = 1), where impact after 1 and 2 years is indicated by the red arrows.



The logistic growth model provides an effective abstraction of the complex recovery dynamics of populations and communities and can be fitted to available data (Lambert et al. 2014). This model is identical to the Schaefer models commonly used in fisheries management when the data to implement full age or size-structured models are not available (Costello et al. 2016). If we assume that the recovery of biomass of biota B after trawling is described by the logistic growth equation, then the equilibrium solution can be used to estimate B as a fraction of carrying capacity K in an environment subject to chronic fishing disturbance (Pitcher et al. 2017):

$$B = 1 - F * d/r \qquad eq2$$

where F is trawling frequency, d is the depletion of biota caused by each trawl pass (expressed as a proportion), and r is rate of increase interpreted here as the recovery rate. Eq. 2 only requires estimates of F, d, and r to estimate relative abundance B/K. Eq. 2 suggests that r is constant but, in communities composed of species with a range of r values, trawling selects for species with faster life histories captured by short longevity, which are more resilient, and, therefore, r can be expected to increase with historic F. When calculating fishing impact, there are methodological possibilities to incorporate the composition of the biomass in terms of sensitivity categories, i.e. its profile, within a predominant habitat type. However, the available monitoring data often do not allow the determination of such categories. This limitation applies for the same habitat type within a sub-region, e.g. between the English Channel and the areas west of Scotland, as well as between (sub-) regions.

The two population dynamics approaches proposed so far are referred to as PD1 and PD2 as follows:

- The PD1 uses habitat-specific (EUNIS 3) estimates of the depletion and recovery parameters from Pitcher et al. (2017) based on a meta-analysis conducted by Collie et al. (2000). This meta-analysis was based on experimentally trawled areas in which the abundance of benthic fauna was measured in before/after, control/impact (= BACI) comparisons at different moments in time after trawling. These studies generally report the numerical abundance or biomass of benthic invertebrates in plots that were experimentally trawled one or more times at several points in time after trawling, in comparison to control plots that were not trawled. Based on this, seafloor integrity is estimated as the biomass relative to that of an undisturbed benthic invertebrate community.
- The PD2 only differs from the PD1 in terms of the estimation of the parameters depletion and recovery. This estimation has recently evolved from how it was initially reported as part of the ICES WKBENTH (ICES, 2017c) to the final presentation in the peer-reviewed paper (Hiddink et al., 2017). The PD1, and both PD2 approaches are presented below.

3.5.1 Population dynamics approach: PD1 parametrisation

Here the benthic invertebrate community is composed of a variety of taxa which differ in their population growth rates, the effect of trawling on the community biomass should be calculated as the sum of the biomass of the individual species. The r and K are likely correlated to the body-size of organisms, with smaller organisms having a larger r and a smaller K (Duplisea et al., 2002). Because the number of adult benthic species in a community decreases linearly with $\log_3$(weight) (Hiddink et al., 2006), we assume that both r and K have an exponential distribution ($\lambda e^{-\lambda x}$). Further we assume that there are no species interactions. Values of K and r were randomly chosen from the exponential distribution for 1000 species with rate of decline (λ) and mean = 1. K and r were then rescaled so that the sum of K within the community was summing to 1, and the mean of r being equal to the r in Table 3.2, and the sensitivity of each species was calculated.

For this PD approach we assume that seafloor integrity (SI) is represented by the benthic biomass relative to undisturbed conditions. This was calculated as the sum of the biomass of all individual taxa and divided by the benthic invertebrate community biomass in an undisturbed situation K:

$$SI = \sum (B_{taxa} / K_{taxa}) \qquad eq3$$

The seafloor integrity, therefore, depends on the gear-specific fishing intensity and the habitat-specific sensitivity.

Table 3.2. PD1 Depletion rate (*d*) and Recovery Rate (*r*) values (y^{-1}) for the different gear habitat combinations based on Pitcher et al. (2017) and a global meta-analysis of Collie et al. (2000). The *d* and *r* values are shown together with a set of sustainable trawling frequencies that are calculated based on these parameters and an arbitrary threshold representing "adversely affected" above which the benthic invertebrate community is assumed to have recovered.

Habitat	EUNIS	Gear			*Sustainable trawling frequency depending on potential threshold for "adversely affected"*			
			d	*r*	*80%*	*90%*	*95%*	*99%*
Biogenic		OT	0.39	3.03	0.48	0.18	0.08	0.02
Gravel	A5.1	OT	0.48	3.03	0.41	0.14	0.06	0.01
Sand	A5.2	OT	0.37	15.59	2.68	1.02	0.42	0.06
Mud	A5.3	OT	0.27	6.39	1.44	0.51	0.19	0.03
Biogenic		BT	0.45	3.03	0.4	0.16	0.07	0.01
Gravel	A5.1	BT	0.53	3.03	0.35	0.14	0.06	0.01
Sand	A5.2	BT	0.43	15.59	2.15	0.91	0.43	0.08
Mud	A5.3	BT	0.33	6.39	1.2	0.49	0.21	0.04
Biogenic		TD	0.67	3.03	0.26	0.1	0.04	0.01
Gravel	A5.1	TD	0.72	3.03	0.25	0.1	0.05	0.01
Sand	A5.2	TD	0.66	15.59	1.67	0.66	0.24	0.04
Mud	A5.3	TD	0.61	6.39	0.71	0.28	0.12	0.02

3.5.2 Population dynamics approach: PD2 parametrisation

This represents the latest developments on the parametrisation (i.e. depletion and recovery) of the population dynamics approach. For depletion, the preliminary gear-specific parameters, *d* and *P* (see Figure 3.5), presented in WKBENTH (ICES, 2017c) are identical to those in the accepted paper of Hiddink et al. (2017). For recovery, there is a slight discrepancy and we present both (see Figure 3.6 and Table 3.3).

3.5.2.1 Depletion

Depletion rates estimated from the experimental studies for biomass and abundance were not significantly different and hence the parameters apply to both biomass and abundance of the benthic invertebrate community. Estimates of depletion d and penetration depth P by gear type were very closely correlated (Fig. 10) (Pearson's r = 0.980, P = 0.020). Otter trawls (OTs) had the smallest impact, removing on average 6% of organisms per trawl pass and penetrating on average 2.4 cm into the sediment. Median penetration depths were 2.7 and 5.5 cm for beam trawls (BTs) and towed (scallop) dredges (TDs), respectively, and the corresponding median depletions per trawl pass were 14 and 20 %, respectively. Hydraulic dredges (HD)s had the largest impact, removing on average 41 % of organisms per pass and penetrating 16.1 cm. This resulted in Table 3.3 showing the median depletion and its (5 – 95%) range for otter trawls, beam trawls, towed dredges and hydraulic dredges matched to the EU gear types.

Figure 3.5. The relationship between the penetration depth (P) and depletion (d) of benthic invertebrate community biomass and abundance caused by a single trawl pass for different trawl gears (means ± SD): otter trawls (OTs), beam trawls (BTs), towed (scallop) dredges (TDs), and hydraulic dredges (HDs). From a global meta-analysis in Hiddink et al. (2017)

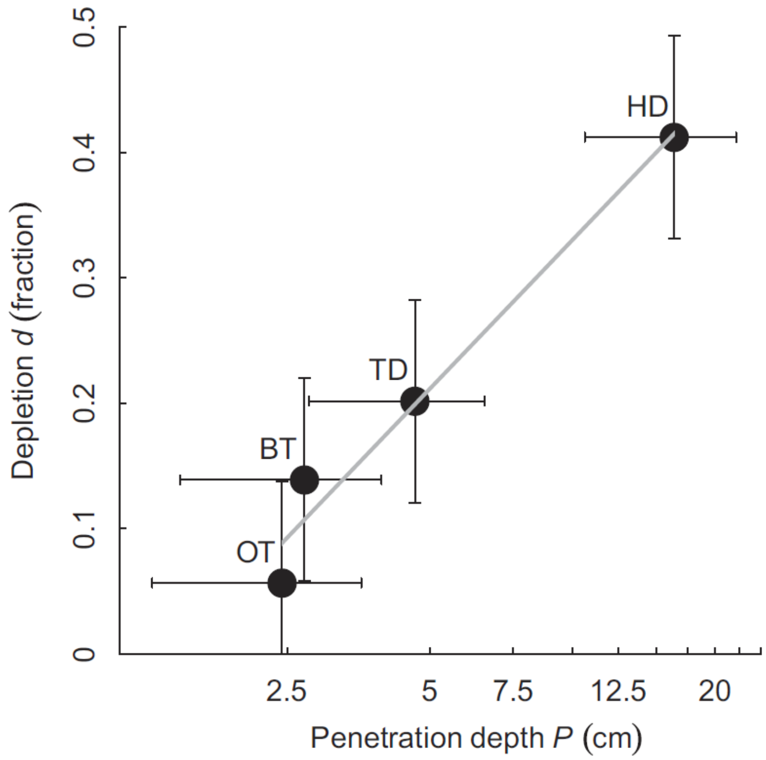


Table 3.3. Matching of gear types from a global meta-analysis in Hiddink et al. (2017) with EU gears, and estimates of depletion (d) for each gear type. (From ICES WKBENTH Table 6.2.4 (ICES, 2017c))

GEAR GROUP	EU GEAR CODE	DEPLETION *d*		
		5 %	Median	95 %
OT – otter trawl	OTB, OTT, PTB, SSC, OT, TBN, SDN	0.02	0.06	0.16
BT – beam trawl	TBB, TBS, TB	0.07	0.14	0.25
TD – towed dredge	DRB	0.13	0.20	0.30
HD – hydraulic dredge	HMD	0.35	0.41	0.48
Not grouped	FPO, GNS, PTM, GN, LHP, LLD, NA, OTM, GTR, TMS, PS, SPR, SV, SX, LHM			

3.5.2.2 Recovery

For the estimation of the PD2 recovery parameter we present two slightly different approaches, i.e. PD2a (Hiddink et al., 2017) and PD2b (Hiddink et al., 2018)

The PD2a is based on the application of a draft version of Hiddink et al. (2017) at the WKBENTH (ICES, 2017c), where the recovery rates were determined per longevity class and translated to the main habitat types based on the composition of the North Sea infauna benthic invertebrate community also from WKBENTH (ICES, 2017c) (see Figure 3.6 and Table 3.4). These longevity classes were taken from an international traits database based on expert judgment (Bolam et al., 2017). This results in the example below, where parameters are North Sea-specific taking the differences in recovery rates between taxa with different longevity explicitly into account. The relatively low recovery rates in the gravel habitat (A5.1) agree with the significant increase of the effect of trawling on the benthic invertebrate community (albeit in numbers of individuals) with increasing gravel content observed in Hiddink et al. (2017).

These parameters can be estimated for any other marine region providing sampling data are available that can be used to determine the composition of the benthic invertebrate community in terms of longevity classes.

Figure 3.6. North Sea-based cumulative biomass (proportion) – longevity (years) relationship as predicted by the generalised additive mixed effect model for four EUNIS-3 habitats at an annual trawling intensity of zero (full lines) and one (hatched lines). A5.1 – Coarse sediment, A5.2 – Sand; A5.3 – Mud; A5.4 – Mixed sediment (From WKBENTH Figure 6.2.3 (ICES 2017c))

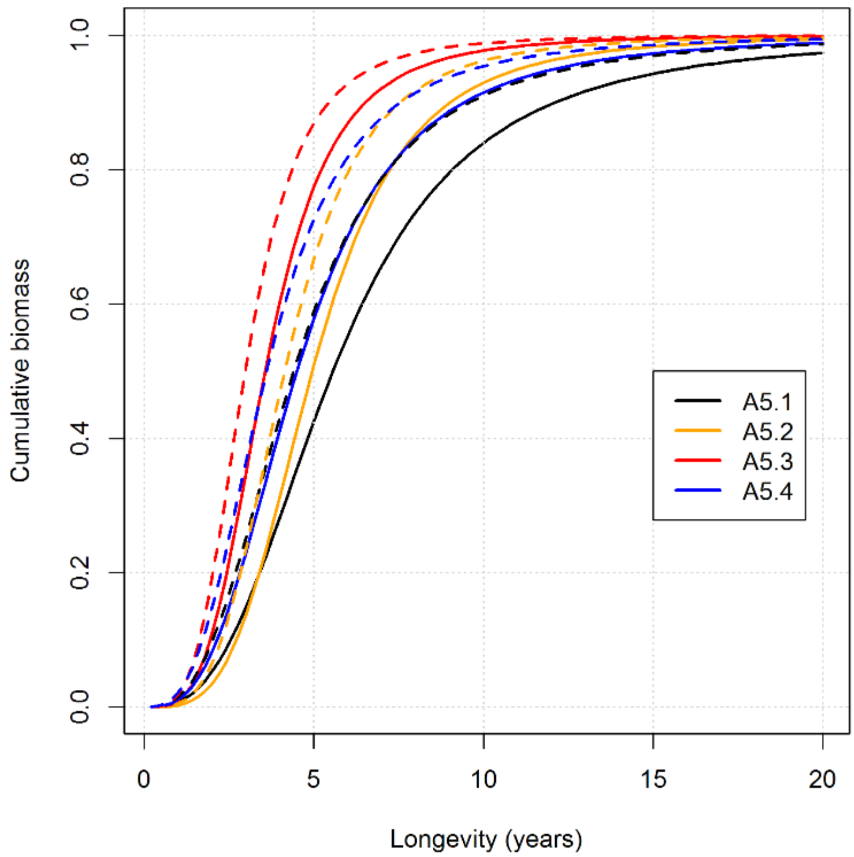


Table 3.4. North Sea-based biomass composition as % per longevity class (based on Figure 6.2.3. WKBENTH (ICES, 2017c)) and generic recovery rates per longevity class (Table 6.2.5 WKBENTH (ICES, 2017c)). Longevity classes are defined as 1 = (0 – 1 y), 3 = (1 – 3 y), 10 = (3 – 10 y) and 20 = (> 10 y). A5.1 – Coarse sediment, A5.2 – Sand; A5.3 – Mud; A5.4 – Mixed sediment

Habitat	Longevity class	% Biomass	r5 %	r50 %	r95 %
A5.1	1	0.7	0.31	1.24	4.59
	3	11.6	0.22	0.87	3.21
	10	68.9	0.12	0.47	1.76
	20	18.8	0.07	0.29	1.06
A5.2	1	0.2	0.31	1.24	4.59
	3	9.7	0.22	0.87	3.21
	10	80.0	0.12	0.47	1.76
	20	10.0	0.07	0.29	1.06
A5.3	1	0.8	0.31	1.24	4.59
	3	27.0	0.22	0.87	3.21
	10	69.1	0.12	0.47	1.76
	20	3.2	0.07	0.29	1.06
A5.4	1	0.9	0.31	1.24	4.59
	3	17.0	0.22	0.87	3.21
	10	71.3	0.12	0.47	1.76
	20	10.9	0.07	0.29	1.06

Based on the information in Tables 3.3 and 3.4, Table 3.5 was created, which includes three sensitivity classes: High (H), medium (M) and low (L). Table 3.5 is the basis for parametrisation of the depletion (d) and recovery rate (r) in the two formulas to calculate RT and B_t. For depletion, high sensitivity corresponds to the 95 % percentile and low sensitivity to the 5 % percentile in Table 3.3. For the recovery rates it is the inverse, i.e. high sensitivity corresponds to the 5 % percentile and low sensitivity to the 95 % percentile in Table 3.4. In order to be precautionary, this analysis was based on the high sensitivity because Hiddink et al. (2017) suggested that (at least for the recovery) a risk-averse approach should adopt this high sensitivity rather than the median (50 %).

Table 3.5. Generic PD2 Depletion rate (*d)* and PD2a Recovery Rate (*r* (*y*$^{-1}$*))* values for the different gear habitat combinations (based on Pitcher et al. (2017) and a global meta-analysis by Hiddink et al. (2017). For each parameter upper and lower 5 % bounds are provided in addition to the Median (50 %) to capture the range from High, Medium to Low sensitivity.

		Sensitivity Parameter					
EUNIS	Gear	Depletion d			Recovery r		
		H (0.95 %)	M (50 %)	L (5 %)	H (5 %)	M (50 %)	L (95 %)
A5.1	OT	0.16	0.06	0.02	0.123	0.487	1.813
A5.2	OT	0.16	0.06	0.02	0.126	0.495	1.848
A5.3	OT	0.16	0.06	0.02	0.148	0.583	2.170
A5.4	OT	0.16	0.06	0.02	0.133	0.525	1.955
A5.1	BT	0.25	0.14	0.07	0.123	0.487	1.813
A5.2	BT	0.25	0.14	0.07	0.126	0.495	1.848
A5.3	BT	0.25	0.14	0.07	0.148	0.583	2.170
A5.4	BT	0.25	0.14	0.07	0.133	0.525	1.955
A5.1	TD	0.30	0.20	0.13	0.123	0.487	1.813
A5.2	TD	0.30	0.20	0.13	0.126	0.495	1.848
A5.3	TD	0.30	0.20	0.13	0.148	0.583	2.170
A5.4	TD	0.30	0.20	0.13	0.133	0.525	1.955
A5.1	HD	0.48	0.41	0.35	0.123	0.487	1.813
A5.2	HD	0.48	0.41	0.35	0.126	0.495	1.848
A5.3	HD	0.48	0.41	0.35	0.148	0.583	2.170
A5.4	HD	0.48	0.41	0.35	0.133	0.525	1.955

The PD2b approach uses the recovery parameters as they occur in Hiddink et al. (2017) as it was published and has the advantage that it does not require any empirical data to characterise the benthic invertebrate community and so it can be applied in any marine region. That study presented a mean community recovery rate r of 0.82 y^{-1} when there was no trawling (5 – 95 % uncertainty intervals = 0.42 – 1.53) and the community was dominated by longer-living taxa (high longevity) which was probably applicable to real fishing grounds where trawling frequencies are usually in the range of 0 – 1 y^{-1} (Eigaard et al. (2017). Alternatively, the study presented a higher mean community recovery rate of 1.73 (5 – 95 % uncertainty intervals = 0.89 – 3.23) y^{-1} when the trawling frequency was high, i.e. 10 y^{-1}, favouring biota with faster life histories (and thus low longevity). The increase in recovery rate results from changes in community composition due to historic fishing, was relatively slight across ranges of trawling frequencies that dominate those on real fishing grounds. For example, the r estimate of 0.82 y^{-1} enables a community with a fraction depleted D = 0.5K recovery to 0.95K (T) in a median time of 3.6 y (5 – 95 % uncertainty intervals = 1.9 – 6.4 y).

3.6 Method comparison and selection

Here we summarize what we consider the main characteristics of the methods described in the literature for an assessment of the state of seabed habitats impacted by the fishing pressure physical disturbance (Table 3.6). The methods differ in how they estimate habitat sensitivity to this disturbance. Specifically pertaining to:

1. Which aspects of sensitivity they capture:

- Resistance (or tolerance): The ability of a receptor to tolerate a pressure without changing its character
- Resilience (or recoverability): The time needed to recover from a pressure, once that pressure has been alleviated

2. The main distinction between the methods is based on the parametrisation of these two aspects, where we distinguish between:

- Categorical methods, where the parametrisation is based on semi-quantitative approach involving expert judgement based on literature reviews, and expressed in terms of qualitative categories
- Statistical quantitative methods:
- Mechanistic quantitative methods differing in terms of parametrisation.

3. The metric to calculate seafloor integrity:

- Total biomass of the benthic invertebrate community
- Composition of the benthic invertebrate community
- An index of disturbance

One firm conclusion pertaining to the approaches came from the ICES (2016b) review group, which unanimously preferred the quantitative approaches, i.e. statistical or mechanistic, over the categorical approach, i.e. BH3. They identified several major problems in the categorical approaches that cannot easily be solved and, therefore, recommended that ICES puts more emphasis on proceeding impact assessments using quantitative approaches, rather than on the use of categorical approaches. Also from an accounting perspective, continuous numerical values should be preferred to categorical scores and hence we will not consider any categorical approaches for this purpose.

This leaves us with the mechanistic (Population dynamics: PD1 and PD2a and PD2b) and statistical (BH2, SBI and LL) approaches. Here the mechanistic approaches have the advantage of including both sensitivity aspects, as opposed to the statistical approaches based only on resilience (represented by recovery), because the explicit consideration of depletion (representing resistance) results in an impact that is specific to the fishing pressure "Physical disturbance". This lack of a specific relationship with fishing pressure applies even more for the BH2, which is based on generic sensitivity categories, providing yet another reason (in addition to it being a categorical approach) why this approach is less suitable for accounting purposes.

Table 3.6. Relevant characteristics of the methods to calculate the impact on seabed habitats of fishing-induced physical disturbance as proposed by WKBENTH (ICES, 2017c). The sensitivity aspect distinguishes between resistance (represented by depletion) and resilience (represented by recovery).

Methods	Approach and information used	Sensitivity aspect	Part of the community covered and calculated metric
BH2 was developed based on an approach that assesses sensitivity to several pressures (fisheries, organic enrichment, sedimentation, etc.). Margalef D is a biodiversity index that performs best in terms of sensitivity and precision for the pressure caused by fisheries and was used as the indicator.	Statistical requiring regional habitat-specific empirical data	None	Whole community, species richness based on abundance
BH3 creates a sensitivity layer indicating species or (when information on species level does not exist) habitats, defined to be sensitive to physical damage (fishing).	Categorical, based on expert judgement	Both	Subset: predominant species or special habitats, qualitative disturbance categories
SBI is estimated using the longevity distribution for the untrawled situation and provides a worst case situation as it assumes that taxa trawled during their lifespan will always be impacted.	Statistical requiring regional habitat-specific empirical data	Only Resilience/ Recovery	Proportion of the biomass of benthic taxa where the trawling interval at the subsurface level exceeds their life span
LL estimated the decrease in the biomass of long-lived taxa for each grid cell as a ratio of the untrawled biomass using the parameter estimates of the longevity relationships fitted. The method attempts to take account of depth and tidal shear stress.	Statistical requiring regional habitat-specific empirical data. Uses trait-based information.	Only Resilience/ Recovery	Subset, only biomass of long-lived taxa (> 10 years) relative to an undisturbed situation
PD1 depletion and recovery parameters are taken from Pitcher et al. (2017), based on data presented in Collie et al. (2000)	Mechanistic and dynamic based on meta-analysis	Both	Whole community biomass relative to an undisturbed situation
PD2a with regional habitat-specific parameters based on longevity distribution, based on WKBENTH (ICES, 2017c) and further improved in Hiddink et al. (2018)	Mechanistic and dynamic based on meta-analysis but requiring regional habitat-specific empirical data	Both	Whole community biomass relative to an undisturbed situation
PD2b with generic parameters independent of the habitat, based on Hiddink et al. (2017)	Mechanistic and dynamic based on meta-analysis	Both	Whole community biomass relative to an undisturbed situation

Another advantage when choosing between the mechanistic and statistical approaches is that the mechanistic approaches allow a dynamic application, i.e. showing year-to-year changes, as opposed to the statistical approaches, which only allow a static application over some specified period. Application of the mechanistic approaches would, therefore, allow carrying out annual assessments of the state of seabed habitats impacted by fishing, resulting in a time-series of the account. When it comes to considering the eventual application of the approaches to calculate the pilot SIA in all EU marine regions (see Chapter 5), we need to distinguish between the "Statistical requiring regional habitat-specific empirical data" approaches (BH2, SBI and LL) requiring empirical data (i.e. species- or at least traits-based composition of the benthic invertebrate community), which may often not be available, and the categorical or mechanistic approaches that only require habitat maps. In fact, the mechanistic PD2b does not even require habitat maps as the approach is gear-specific but not habitat-specific and, according to Hiddink et al. (2017), "supporting assessment of trawling impacts on unprecedented spatial scales" and with "global relevance". The PD2b can, therefore, even be applied in marine regions for which habitat maps are lacking as long as gear-specific information of the fishery is available. This was supported by the findings from the ICES-led process where most methods in Table 3.6 provided similar impact maps as the output was driven by fishing pressure rather than variations in sensitivity (apart from the LL longevity approach where the pattern was driven by depth).

Finally, there is the evaluation process that leads to the selection of the most appropriate metric to describe the state of the seabed habitat in terms of the state of its benthic invertebrate community.

- The qualitative disturbance categories (BH3) are the least useful as it is unclear what this represents, immediately followed by the "Proportion of the biomass of benthic taxa where the trawling interval at the subsurface level exceeds their life span" (SBI) as this reflects the sensitivity of seabed habitat, rather than its state which is what we are after and the result of how the pressure interacts with sensitivity.
- Then there are two metrics which track the impact on the benthic invertebrate community's composition in response to trawling, i.e. "species richness based on abundance" (BH2) and "biomass of long-lived taxa" (LL), and hence provide a proxy for the biodiversity aspect of the benthic invertebrate community. Both metrics however, are statistical approaches suffering from data availability issues and the fact that they only allow a static application instead of a dynamic one.
- Then there are the population dynamic approaches (PD) indicating how bottom trawling affects the biomass of the benthic invertebrate community using the "biomass relative to undisturbed conditions" as a proxy for the amount of ecosystem functioning (e.g. bioturbation, nutrient cycling, reproductive output, secondary production), still remaining in that community. If present, this functioning helps maintain not only the local community, i.e. a grid cell, as a whole, but the wider regional biodiversity (an important aspect of seafloor integrity) as well. This benthic invertebrate "biomass relative to undisturbed conditions" contributes to the habitat functioning aspect that (partly) determines seafloor integrity (see section 1.2) and is, therefore, the preferred metric for our accounting purposes (see section 1.5).

The overview of the different methods to calculate the state of seabed habitats impacted by the fishing pressure physical disturbance distinguishing their characteristics (Table 3.5) and the discussion of the relevance of these characteristics was the basis for selecting the preferred method to follow in this study (see Chapter 4). This method was not only expected to be suitable for an assessment of seafloor integrity but also from the perspective of natural capital accounting. As noted already, the PD methods appear to be the most suitable as they are:

- Mechanistic, thereby allowing to show year-to-year changes and hence time-series
- Include sensitivity aspects of the benthic invertebrate community allowing the explicit consideration of both their depletion (representing resistance) and recovery (representing resilience) aspects
- Calculating a metric sufficiently representative of the amount of functioning still remaining in the benthic invertebrate community

From these PD methods, both PD2 methods are based on the most recent and up-to-date meta-analysis. The PD2a has the advantage that it includes information on habitat sensitivity using longevity as a trait that allows some consideration of biodiversity issues. Instead, the PD2b has the advantage that it only requires fishing pressure data and, because of its limited data requirements, it is most likely to be suitable for application in all EU marine regions**. The calculation of the pilot SIA can, therefore, be based on the PD2 method, where for the recovery we apply the PD2a parametrisation if adequate habitat information is available and, otherwise, the PD2b parametrisation.**

Thus, for the application of the PD2 method the only requirement to apply the less sophisticated PD2b is the availability of VMS data at a sufficiently high resolution of all the main bottom trawling fleets distinguishing the different gear types, i.e. métiers. The recording of that data is mandatory under the CFP and, as such, each EU Member State (but also Norway and Iceland) should have these data. There are, however, privacy issues that need to be considered when making the data available. This may have consequences for the spatio-temporal resolution at which the data need to be aggregated to be used in this or any other studies, but should not prevent any Member State from making the data available. However, if adequate habitat maps are available, this would allow the application of the more sophisticated PD2a methodology to calculate the pilot SIA.

3.7 Application issues of the selected method

For the selected PD2 method (=PD2a and/or PD2b) we now consider some practical application/calculation issues.

3.7.1 Metric

The metric calculated to represent the state of seabed habitats impacted by the fishing pressure ‘physical disturbance’ is the biomass of the benthic invertebrate community relative to an undisturbed situation, and this metric is considered a proxy for seafloor integrity. Or in formula seafloor integrity = B/K with biomass B as a fraction of carrying capacity K (= maximum the undisturbed environment can sustain indefinitely, given the food, habitat, water, and other necessities available in the environment). In an environment subject to chronic fishing disturbance (Pitcher et al., 2017):

$$B = 1 - F * d/r \qquad eq2$$

where F is trawling frequency, d is the depletion of biota caused by each trawl pass (expressed as a proportion), and r is the recovery rate.

Thus, if the biomass of the benthic invertebrate community is equal to an undisturbed biomass (or at least not significantly different, see section 1.4 and the definition of “adversely affected” below), then seafloor integrity and the capacity of seabed habitats to supply ecosystem services is assumed maximal.

3.7.2 Change over time: annual assessments

The method required for an annual assessment of the state of the seabed should be able to provide annual seafloor integrity estimates and, for this, a more sophisticated method (but based on the logistic growth model introduced in section 3.5) is required. To that end the benthic biomass ($B_{g,t0}$) at a specific grid cell *g* at time $t_{0,}$ the first assessment year, was assumed to be determined by the historic fishing intensity *F'* assuming an equilibrium situation, which can be estimated by solving equation 2 over the period for which historic fishing was determined for each single taxon as in (Pitcher et al., 2017).

$$B_{g,t0} = 1 - F' * d/r \qquad eq3$$

The length of this historic period on which *F'* is based should be chosen such that it adequately represents the physical disturbance over a time-scale appropriate for that habitat. In practice, this may be limited by data availability. In an application of this approach for the North Sea by Piet (In prep.) they chose a period of five years, which should be adequate but a longer period is always preferred providing it adequately represents the current situation. In general, the length of the period should be attuned to that of the most sensitive habitat recovery time while avoiding any period in which major changes occurred that could have affected the spatial distribution of the fishery.

For an annual assessment cycle, fishing pressure needs to be calculated in annual time steps. If we assume that all fishing operations occur at the beginning of the assessment year t the benthic biomass caused by the depletion due to those fishing operations (thus without any recovery) $B'_{g,t1}$ in a grid cell *g* is given by:

$$B'_{g,t1} = B_{g,t0} * (1-d)^{F} \qquad eq4$$

According to Pitcher et al. (2017), the benthic biomass $B_{g,t}$ including recovery can be described according to:

$$B_{g,t} = B'_{g,t1} * K/[B'_{g,t1} + (K - B'_{g,t1}) * exp^{-rt}] \qquad eq5$$

and $B_{g,t1}$ at the end of that assessment year can be calculated for *t* = 1. Similarly, any subsequent year t = 2,3... can be calculated.

3.7.3 Incorporating the sensitivity of seabed habitats

Within the selected PD2 method, we distinguished between two parametrisations: the PD2a requiring information on the composition of the benthic invertebrate community in terms of longevity categories, and the PD2b which doesn't. Thus, we have one arguably superior method requiring additional data and another which can be applied with less requirements and is, therefore, more suitable for application across all EU marine waters.

In both cases, the application of the method does not depend on the outcome of the processes to determine a habitat typology and, thus, nor the ongoing, or any other, revision of the EUNIS categories[8]. Whatever the typology of habitats is applied, or however EUNIS categories are defined[9],

[8] The Level 2 of the EUNIS benthic habitat classification was revised in 2016 and the lower levels are still being reclassified and redefined up to the end of 2018. See Condé et al (2018).

the calculation of the pilot SIA is based on the matching of the parameters of the fairly crude habitat categories that determine habitat sensitivity to a habitat map that distinguishes those habitats based on some typology. As these categories for habitat sensitivity only distinguish between mud, sand, gravel (sometimes also biogenic substrate) the matching of habitat sensitivities to a habitat map should not prevent the application of this method. Still, it is worth checking against the revised EUNIS benthic habitat classification, when that is completed, to ensure that no adjustments are needed due to any reclassification or redefinition of the specific habitats considered.

3.7.4 Data limitations

Below we provide an overview of the data limitations and data quality issues that determine the feasibility of the state of the seabed habitats assessment, distinguishing between the data required to calculate the fishing-induced physical disturbance, i.e. the VMS data, and the data on broad-scale habitat maps and sensitivity as required to calculate its impact. An alternative to the VMS would be represented by the Automatic Identification System (AIS), which became compulsory in the EU in May 2014 for all fishing vessels of a length of over 15 meters. However, because it is still unclear whether AIS can provide representative high-resolution pressure maps and this system was not considered in the review process adopted in this study, it is not considered further.

Data limitations and data quality issues for assessing the **pressure**, i.e. fishing-induced physical disturbance:

- VMS data from vessels smaller than 12 m are lacking from the assessment. This introduces an underestimate in the assessment that is expected to be prominent in coastal areas of all regions but more so in case of e.g. the Mediterranean Sea or Black Sea.
- VMS data from certain countries, both within and outside the EU, may not become available (even though mandatory to collect them in the EU), which would underestimate the pressure in the areas fished by those countries. This is not believed to be a large issue in the Greater North Sea but is expected to be a bigger issue in marine regions with more non-EU countries bordering them, e.g. Mediterranean Sea and Black Sea.
- The calculation of fishing intensity, as well as of surface and subsurface abrasion, is inferred from a suite of vessel data, including vessel speed. However, fishing speed was not always supplied; in such cases, estimates of fishing speed were based on an average of the fishing speed values that were supplied.
- Estimates of fishing pressure are determined by the spatial resolution of the data. A higher spatial resolution is preferred but this is in practice prevented by privacy issues.

Data limitations and data quality issues for assessing the **impact** of the fishing-induced physical disturbance:

- Broad-scale seabed habitat maps may be both biased and uncertain, but the degree of this is often unknown and may vary between regions. This applies specifically for deeper waters owing to the relative lack of knowledge of biological features of the broad-scale seabed habitat types. For that reason, ICES only produces advice on impacts on seabed habitats shallower than 200 m. EUSeaMap provides information on confidence (Andersen, 2018) but at present there is no formal way to implement this information.
- Heterogeneity in the composition and total biomass of the benthic invertebrate community within the broad-scale habitats, i.e. at the level of grid cells, is not considered even though this is

[9] There is no 100 % alignment between EUNIS (2018) and EUSeaMap (2016). See Condé et al (2018).

very likely to occur and may affect the level of undisturbed biomass as well as the depletion and recovery parameters. To some extent this variation within the habitats may be addressed using benthic sampling data. The benthic samples, however, often do not include the entire community as especially epifauna may be missing. Benthic sample coverage is variable by region and by habitat.

- The sensitivity of the benthic invertebrate community in terms of depletion and recovery is most likely determined by many more traits than the longevity that is currently applied for recovery.

4 Developing a pilot 'European seafloor integrity account'

4.1 What is represented by the SIA

The need for preserving biodiversity, through managing human activities using natural resources and ecosystems sustainably, has given traction to the proposal that we should consider the earth's resources and ecosystems as a 'natural capital', which provides flows of abiotic outputs and ecosystem services (Figure 1.1), and their associated benefits, to people. When part of this natural capital, the ecosystem capital, is impacted by anthropogenic pressures it compromises the continued supply of ecosystem services on which we rely to meet our basic needs as well as to support our well-being and livelihoods/economy. This implies that all pressures acting upon, in this case, marine ecosystem capital need to be managed well in order to allow marine ecosystems to self-renew and sustain the supply of marine ecosystem services into the future. Pressures on marine ecosystems are indirect, as a result of using marine abiotic resources and outputs (e.g., oil, sand, navigation routes) or land and freshwater-based natural capital, or direct, as a result of using marine ecosystem services (e.g. wild animal seafood).

Experimental Ecosystem Accounts (SEEA-EEA) are being developed as part of the UN System of Environmental-Economic Accounting (SEEA) to show how to measure the ecosystem components of natural capital in terms of their state and their capacity to provide ecosystem services. The key accounting module that applies for the SIA is the ecosystem condition account and, specifically, its biodiversity aspect. This is because of the close relationship between biodiversity, good ecosystem condition and long-term delivery of multiple ecosystem services (not just provisioning but, possibly even more so, regulation and maintenance as well as cultural services).

The MSFD underlines that seabed habitats are an explicit part of marine biodiversity and ecosystem functioning (EC, 2017) and, hence, can supply ecosystem services. The seafloor integrity account (SIA) here, which considers the impact of fishing-induced physical disturbance on the state of seabed habitats is, therefore, well-placed as a potential ecosystem condition 'biodiversity' account (see section 1.4). As such, the SIA can inform policy makers on the performance of fisheries management to conserve this benthic habitat aspect of marine biodiversity. In this study to develop a pilot SIA, we focus on how fishing-induced physical disturbance impacts on certain, specific seabed habitats as a proof of concept illustrating how such an account can be calculated and used to inform policy.

The relevant policy context, i.e. MSFD, mentions two main pressures impacting the seafloor, i.e. physical disturbance and physical loss. However, for the purpose of calculating a pilot SIA we need to distinguish between those two pressures as these differ conceptually in how they impact seabed habitats specifically in relation to their relevance to inform policy. We assert that the impact of physical disturbance on the seabed is more relevant in the context of conserving marine ecosystem capital and sustaining the supply of ecosystem services. This is because physical disturbance impacts seabed habitats at much larger scales than physical loss Hyder et al. (2017), but also because recovery can occur at a time-frame relevant for MSFD reporting purposes (i.e. minimum two reporting cycles which equals 12 years, see section 1.2) once the pressure subsides. The SIA, therefore, focusses on fishing-induced physical disturbance as that can be managed to allow the recovery of the affected seabed habitats (by, for example, mitigating fishing intensity and/or its spatial distribution); while physical loss can only be prevented (given that there is no recovery from it).

The need to focus on (the recovery from) physical disturbance resulted in a specific selection of habitats for which the methods to assess seabed impacts from fishing-induced physical disturbance apply. Recent studies (see Chapters 2 and 3) have shown that only habitats with soft substrate (e.g. sand, mud, gravel) are the ones expected to recover from physical disturbance within policy-relevant time-frames. Thus, the pilot SIA will only be based on a range of habitats with soft substrate for which there is adequate knowledge to assess the impact of fishing-induced physical disturbance. In addition, the benthic community in the selected soft substrate habitats (see EUNIS habitats listed in, e.g., Table 3.5) is made up of invertebrate fauna. The limitations of the available methods to calculate the pilot SIA mean that the account is also affected by these limitations. As a result, the pilot SIA

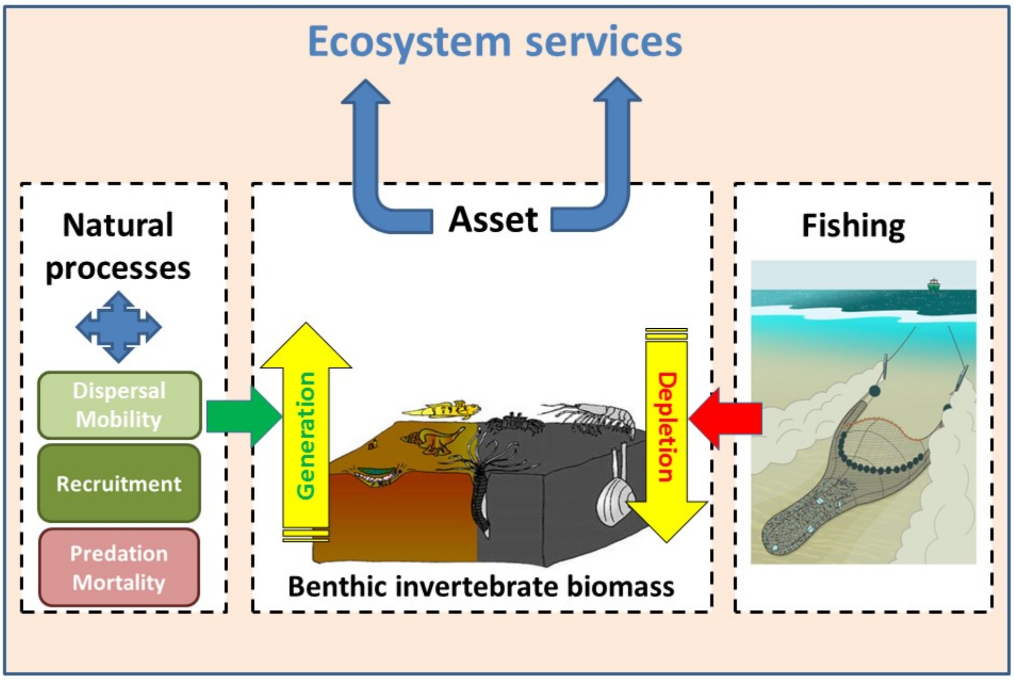
- only calculates the state of a range of seabed habitats with soft substrate,
- only includes the benthic invertebrate community (hence excluding plants and algae, the other biotic components), and
- only reflects how the benthic invertebrate community is impacted by physical disturbance as it is caused by
- only one (albeit the most important) anthropogenic activity, i.e. commercial fisheries.

The consequences of these conceptual and methodological limitations of the available methods are noted when considering the suitability of the pilot SIA to reflect seabed habitat(s) condition in a specific marine region.

4.2 The SIA in relation to the concept of (marine) ecosystem capital

The (marine) ecosystem capital here, in the context of the SIA, is represented by what is currently the best proxy available for assessing seafloor integrity, i.e. the state of soft-substrate seabed habitats impacted by the fishing pressure 'physical disturbance,' and where seafloor integrity is defined in the main policy framework, i.e. the MSFD. The SIA metric is the biomass of the benthic invertebrate community relative to an undisturbed situation, which now only applies to seabed habitats with soft substrates. This biomass is what determines the benthic invertebrate community's contribution to the supply of ecosystem services from these habitats. In an accounting context this proxy, therefore, represents the asset, which is the result of an inflow (into it), i.e. its generation, based on various natural processes, and an outflow, i.e. its depletion, caused by the human activity, i.e. fishing, that generates the physical disturbance (see Figure 4.1). Contrary to the Integrated Marine Fish Account (Piet, 2017), which specifically covers the provisioning marine ecosystem services, this outflow should not be considered an ecosystem flow as it is not related to the supply of the services the SIA intends to cover, i.e. regulation and maintenance and cultural services. The Integrated Marine Fish Account, however, is affected by the same anthropogenic activity, i.e. fishing, but targeting another ecosystem component, i.e. fish, in order to supply another ecosystem service, i.e. wild animal seafood provisioning. This implies that, at least conceptually, the benthic invertebrate community asset can be increased by mitigating its depletion without any consequences for the supply of the ecosystem service targeted by the fishing activity. Thus, the decrease of the benthic invertebrate community biomass due to physical disturbance, i.e. the outflow, is an unwanted consequence (i.e. environmental externality, see (EEA, 2015)) from fishing, which should be reduced as much as possible without compromising the catch opportunities responsible for the wild animal seafood provisioning service. Mitigation of the main activity causing physical disturbance on habitats with soft substrates, i.e. fishing, should, thus, result in their recovery, and so in an increase of the asset, i.e. benthic invertebrate biomass, which is what determines the contribution of the benthic invertebrate community to the capacity of those seabed habitats to supply regulation and maintenance, and cultural ecosystem services.

Figure 4.1 Basic processes determining the ecosystem asset in the focus of the pilot SIA, i.e. the biomass of the benthic invertebrate community, and how this asset is governed by natural processes contributing to its generation and recovery as well as by its depletion cause by the impacts from fishing-induced physical disturbance pressure. The asset is mainly considered from its capacity to supply ecosystem services, where if fishing pressure leads to the degradation of the condition of the ecosystem, its capacity to supply ecosystem services is reduced.



4.3 Approach to calculate the pilot SIA in the North Sea

The pilot SIA concept was tested in the North Sea based on the PD2 method, more specifically the PD2a variation (see Chapter 3), and the account was calculated for that EU marine sub-region. We used the pressure layer available through an OSPAR request on the production of spatial data layers of fishing intensity/pressure and provided by ICES (2018) covering the period 2009 – 2016[10]. The spatial resolution of the calculation is determined by that of the fishing intensity data, i.e. so-called c-squares (0.05 x 0.05 degree grids, about 15 km² at 60°N latitude). The EUSeaMap habitat map is available from EMODnet (https://www.emodnet-seabedhabitats.eu/access-data/download-data/).

The total surface area of the Greater North Sea is approximately $6.7*10^5$ km^2, of which most of the area (84 % of the whole North Sea, 95 % of the North Sea excluding the Deep-sea habitats) consists of the habitats covered by the pilot SIA, i.e. the soft-substrate seabed habitats EUNIS 5.1 – 5.4.

[10] http://www.ices.dk/sites/pub/publication%20reports/forms/defaultone.aspx?rootfolder=/sites/pub/publication+reports/data+outputs&folderctid=0x0120005daf18eb10daa049bbb066544d790785&view=%7B24a83160-91ce-481d-9f57-7e1a03f87b79%7D

Table 4.1. North Sea EUNIS benthic habitats, their surface area in km^2 and in proportion of the total North Sea (%) (surface areas from ICES (2017c)).

EUNIS habitats		km^2	%
A3.1	Atlantic and Mediterranean high energy infralittoral rock	3,119	0
A3.2	Atlantic and Mediterranean moderate energy infralittoral rock	1,978	0
A3.3	Atlantic and Mediterranean low energy infralittoral rock	82	0
A4.1	Atlantic and Mediterranean high energy circalittoral rock	2,050	0
A4.2	Atlantic and Mediterranean moderate energy circalittoral rock	11,956	2
A4.3	Atlantic and Mediterranean low energy circalittoral rock	7,525	1
A5.1	Sublittoral coarse sediment	91,461	14
A5.2	Sublittoral sand	366,852	55
A5.3	Sublittoral mud	69,862	10
A5.4	Sublittoral mixed sediments	33,493	5
A6.1	Deep-sea rock and artificial hard substrata	920	0
A6.2	Deep-sea mixed substrata	3,936	1
A6.4	Deep-sea muddy sand	9,179	1
A6.5	Deep-sea mud	51,998	8
NA	Data not available	14,789	2

The required biomass composition in terms of longevity classes (% per longevity class) was available for each of the selected soft-substrate seabed habitats (see Chapter 3 and Table 3.4). Each year and in each grid-cell, the benthic invertebrate biomass in those habitats B_t relative to undisturbed conditions (= carrying capacity *K*) at the beginning of a specific year *t,* decreases due to gear-specific fishing-induced depletion in that year *t*; while, at the same time, there is a habitat-specific recovery (as the consequence of the asset generation processes, see Figure 4.1). Together, this depletion and recovery determine the biomass at the end of that year, which is equal to the B_{t+1}. The biomass B_t in any particular year *t* can be calculated according to equations 4 and 5 in section 3.7.2. For the start of the first year of the series (2009 – 2016), we calculated the B_{2009}, assuming $B_{2008} = 1$ and *F* = mean F across the whole time-series. To translate the biomass of the benthic invertebrate community relative to undisturbed conditions into the pilot SIA, we turned the 0 – 1 values into % so that the SIA ranges from 0 – 100%.

The calculated biomass then represents the whole benthic invertebrate community or, to elaborate the biodiversity focus, we can also calculate the biomass distinguishing specific subsets of that community. For the calculation of the pilot SIA, we distinguished four longevity classes assuming this addresses the different sensitivities of the benthic invertebrate community to fishing-induced physical disturbance (sensu Rijnsdorp et al. (2018)). It is expected that more sensitive benthic communities, i.e. consisting of more long-lived species, suffer more from the same pressure than less sensitive benthic communities. This is a process that may ultimately affect biodiversity but, in this analysis here, it only results in slower recovery rates and, thus, a lower benthic invertebrate biomass for the more sensitive communities. Using Table 3.4, we calculated the biomass per longevity class (each with a different recovery rate). This provided us with the biomass relative to undisturbed conditions per year, per grid cell and per longevity class. As each grid cell can be attributed to a EUNIS habitat category, for which in the North Sea the composition in terms of % biomass per longevity class is known (see Table 3.4), we could calculate the weighted total biomass in each grid cell. The SIA can then be calculated per each of the selected EUNIS habitat as the mean across all the grid cells belonging to that habitat but also for the entire North Sea by weighting the habitat-specific SIA with the relative proportion of that habitat in the North Sea.

4.4 Results of the calculation of the pilot SIA in the North Sea

The SIA in the North Sea shows how the state of (selected soft-substrate) seabed habitats changes over time (2009 – 2016) and how natural and anthropogenic processes contribute to this as shown in Figure 4.2 and Tables 4.2 – 4.4. Changes over time are due to the inflow from natural processes, i.e. the asset generation also responsible for its recovery, is higher than the outflow, i.e. fishing-induced depletion. Figure 4.2 and Tables 4.2 – 4.4 also show how the two processes that determine the SIA change over time as the pressure and asset change. Thus, as the pressure decreases (by approximately 1 %.yr^{-1}), the inflow is bigger than the outflow and the SIA increases (by approximately 0.2 %.yr^{-1}). As the SIA increases, the same pressure will cause a bigger outflow in absolute terms as it removes the same proportion of an increasing asset. At the same time, the inflow decreases as the biomass is closer to the undisturbed level. Once the fishing pressure stabilizes at a specific level, the SIA will reach another equilibrium, where inflow and outflow are equal.

The SIA is composed of four longevity classes - L1 (0-1 years), L3 (1 – 3 years), L10 (3 – 10 years) and L20 (> 10 years) – of benthic invertebrates that differ in their capacity to recover and, hence, their sensitivity to additional mortality (i.e. not natural) such as caused by fishing-induced physical disturbance. From L1 to L20 the sensitivity increases. Figure 4.2 and Tables 4.2 – 4.4 show how the decreasing fishing pressure (Figure 4.2) causes the asset to change over time, both for the whole benthic invertebrate community and for each of the longevity classes separately. Table 4.2 shows how the historic fishing pressure resulted in an overall asset at 80.6 % of the undisturbed situation at the start of the time series in 2009, but with differences between the least sensitive part of the benthic invertebrate community (i.e. L1 at 92.2 % of the undisturbed situation) and the most sensitive part (i.e. L20 at 72.8 % of the undisturbed situation). Over the whole time period the least sensitive part of the asset, L1, subsequently increases by 0.4 %.yr^{-1}; whereas the most sensitive part, L20, only increases 0.1 %.yr^{-1}. This results in an overall asset at 82.0 % of the undisturbed situation at the end of the time series in 2016.

Table 4.3 shows an annual outflow of approximately 4.0% of the overall undisturbed asset due to depletion from fishing-induced physical disturbance, varying between approximately 6.7 % of the undisturbed L1 asset and approximately 2.5% of the undisturbed L20 asset.

Similarly, Table 4.4 shows an annual inflow of approximately 4.2 % of the overall undisturbed asset due to natural processes, varying between approximately 7.1 % of the undisturbed L1 asset and approximately 2.5 % of the undisturbed L20 asset. The slightly higher inflow compared to the outflow causes the increase in the asset. As the asset increases toward undisturbed levels (both overall as well as per longevity class), the inflow from natural processes decreases until it is equal to the outflow and a new equilibrium is established that corresponds to the lower fishing pressure.

Table 4.2. Accounting table showing the annual asset of the SIA (% relative to the undisturbed situation) for the whole benthic invertebrate community and for each longevity class, i.e. L1 (0 – 1 years), L3 (1 – 3 years), L10 (3-10 years) and L20 (> 10 years), in the North Sea's (selected soft-substrate) seabed habitats over 2009 – 2016

Longevity Class	2009	2010	2011	2012	2013	2014	2015	2016
L1	92.2	93.6	94.2	94.6	94.8	94.9	94.9	95.1
L3	88.9	89.8	90.3	90.6	91.0	91.1	91.3	91.5
L10	80.9	81.0	81.2	81.4	81.7	81.8	82.0	82.2
L20	72.8	72.8	72.9	72.9	73.1	73.1	73.3	73.3
Whole Community	80.6	80.8	81.1	81.3	81.5	81.6	81.8	82.0

Table 4.3. Accounting table showing the annual outflow of the SIA (% relative to the undisturbed situation) from fishing-induced depletion, for the whole benthic invertebrate community and for each longevity class, i.e. L1 (0 – 1 years), L3 (1 – 3 years), L10 (3 – 10 years) and L20 (> 10 years), in the North Sea's (selected soft-substrate) seabed habitats over 2009 – 2016

Longevity Class	2009	2010	2011	2012	2013	2014	2015	2016
L1	6.7	6.8	6.9	6.7	6.9	6.7	6.6	6.9
L3	5.8	5.8	5.8	5.7	5.9	5.7	5.7	5.9
L10	4.0	3.8	3.8	3.7	3.8	3.7	3.8	3.9
L20	2.5	2.4	2.4	2.3	2.4	2.3	2.5	2.6
Whole Community	4.1	4.0	3.9	3.8	4.0	3.8	3.9	4.1

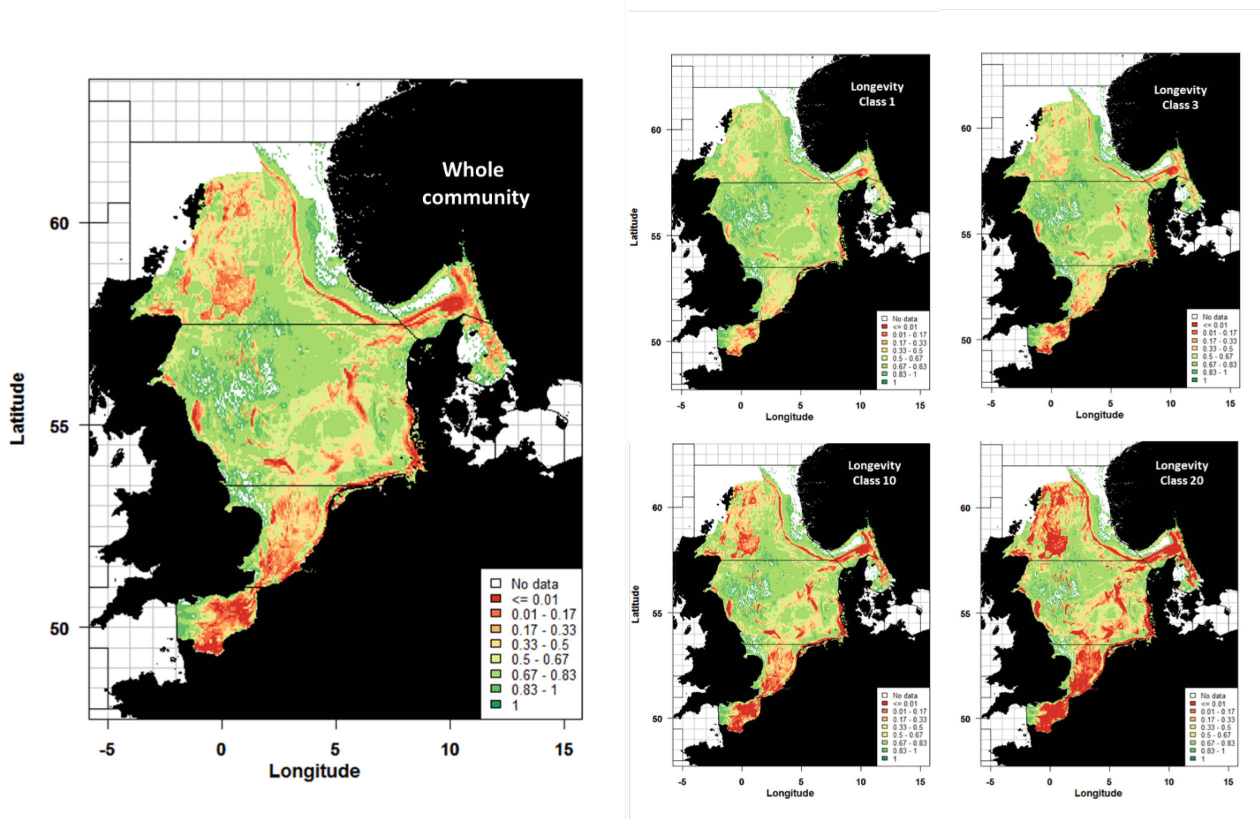
Table 4.4. Accounting table showing the annual inflow of the SIA (% relative to the undisturbed situation) from natural processes, i.e. those responsible for the generation and hence recovery, for the whole benthic invertebrate community and for each longevity class, i.e. L1 (0 – 1 years), L3 (1 – 3 years), L10 (3 – 10 years) and L20 (> 10 years), in the North Sea's (selected soft-substrate) seabed habitats over 2009 – 2016

Longevity Class	2009	2010	2011	2012	2013	2014	2015	2016
L1	8.2	7.4	7.2	7.0	6.9	6.8	6.7	6.8
L3	6.7	6.3	6.2	6.0	6.0	5.9	5.9	5.9
L10	4.1	4.0	4.0	4.0	3.9	3.9	4.0	4.0
L20	2.5	2.5	2.5	2.5	2.5	2.4	2.5	2.5
Whole Community	4.3	4.2	4.1	4.1	4.1	4.0	4.1	4.1

Maps of the spatial distribution of the SIA show areas with relatively low SIA values in the SE and NW North Sea and a large patch of higher SIA in the central North Sea (Figure 4.3). The same pattern is observed for each of the longevity classes separately but reflecting different absolute values.

Figure 4.2. Fishing-induced physical disturbance in Swept Area Ratio representing the frequency (year^{-1}) with which the (selected soft substrate) seabed habitats are fished in the North Sea (top left); the pilot SIA, consisting of four longevity/sensitivity classes, i.e. L1 (0 – 1 years), L3 (1 – 3 years), L10 (3 – 10 years) and L20 (> 10 years), (bottom left); and the processes of 'inflow' (bottom right) and 'outflow' (upper right) that together determine the SIA's change over time

Figure 4.3. Map of the spatial distribution of the asset of the pilot SIA in the North Sea in the year 2016 based on the whole benthic invertebrate community in (selected) soft substrates and also per longevity/sensitivity class. Values are divided by 100 so that the lowest category (red areas) indicates where the asset is < 1 % of undisturbed levels and the highest category represents an undisturbed asset. Values representing these categories were arbitrarily chosen with no other purpose than to distinguish areas with *relatively* higher SIA values from those with *relatively* lower SIA values.



4.5 Discussion on the suitability of the pilot SIA

Based on the development and calculation of this North Sea pilot SIA as a 'proof of concept', we discuss its suitability and its role in the context of assessing seafloor integrity proper. The suitability of the North Sea pilot SIA is discussed in terms of: (1) how representative it is to describe the state of all the North Sea seabed habitats and, specifically, of the benthic community therein resulting from the impact of fishing-induced physical disturbance, and (2) its potential current limitations in covering the effects of all (the main) anthropogenic activities and their pressures on the seafloor as would be needed to assess seafloor integrity proper. We also discuss (3) the suitability of the pilot SIA to inform policy on the state of seabed habitats in general and, more specifically, in relation to biodiversity issues or its capacity to supply ecosystem services, as well as (4) its application to other EU marine (sub-)regions.

4.5.1 Representative of the state of all seabed habitats

The pilot SIA was only calculated for a selection of the North Sea's soft-substrate habitats, i.e. excluding the deep-sea, but can be expanded to also include the deep-sea soft-substrate habitats. However, these selected habitats already represent 84 % of the whole North Sea (or 95 % without the deep-sea habitats in the Norwegian Trench). Moreover, these are also the habitats where most of the fisheries with mobile bottom contacting gear takes place (ICES, 2017c). Therefore, the pilot SIA as presented in this 'proof of concept' can already be considered sufficiently representative to reflect the impacts of fishing-induced physical disturbance on the North Sea's seabed habitats.

When considering the state of seabed habitats both in terms of the biota that determine the benthic ecosystem structure and functioning, how this is impacted by anthropogenic pressures (see section 4.5.2), and how this can be used to inform policy (see Section 4.5.3), the assumption has been that the benthic biota are made up exclusively of animals, i.e. the benthic invertebrate community, while this could also consist of plants and algae. EUNIS describes the sublittoral sediment (A5) as 'Sediment habitats in the sublittoral near shore zone (i.e. covering the infralittoral and circalittoral zones), typically extending from the extreme lower shore down to the edge of the bathyal zone (200 m)' where, according to Evans et al. (2016), both the infralittoral as well as the circalittoral zones are photic[11]. The occurrence of plants and algae, certainly in the part of the North Sea where the type of fishing causing physical disturbance occurs, is probably negligible and, therefore, not considered in the policy context relating to seafloor integrity, i.e. the MSFD (see sections 1.1 and 4.5.3), nor by the methods to calculate the state of seabed habitats from fishing-induced physical disturbance (see Chapter 3 and Sections 1.2 and 4.5.2). Still it is worth to consider this potential oversight as, in the context of the ecosystem capacity for service supply, it implies that only those services that can be supplied by the benthic invertebrate fauna are considered, and not those that can be supplied by plants and algae (e.g. the contribution of plants and algae to the Filtration/ sequestration, storage/accumulation service or the Flood protection service, which is supplied exclusively by plants and algae).

4.5.2 Representative of the main anthropogenic activities and their pressures

The pilot SIA only represents impacts of fishing-induced physical disturbance. For the North Sea, commercial fishing shows a % footprint on the seabed of slightly more than 50 % in the shallow (< 200 m) and approximately 25 % in the deep-water layers (> 200 m) (ICES, 2017c). The metric underpinning of the SIA, i.e., the biomass of the benthic invertebrate community (in selected soft substrates) compared to undisturbed conditions, is probably the best indicator of the extent of commercial fishing impacts showing that about half of the whole North Sea area is impacted by fishing.

Comparing the effects of fishing-induced physical disturbance on seabed habitats with those from other (physical) pressures, notably physical loss, from other anthropogenic activities would tell us how representative the North Sea pilot SIA is of all anthropogenic activities and their pressures. In order to do so, we used an inventory of all man-made structures in the North Sea (Hyder et al., 2017), which is based on a slightly different definition of the North Sea than the one used here but clearly shows that man-made structures cover a negligible part (0.2 %) of the natural seabed habitats in that sub-region (see Box 4.1). The comparison, therefore, shows that commercial fishing is by far the dominant activity affecting the North Sea's seabed habitats.

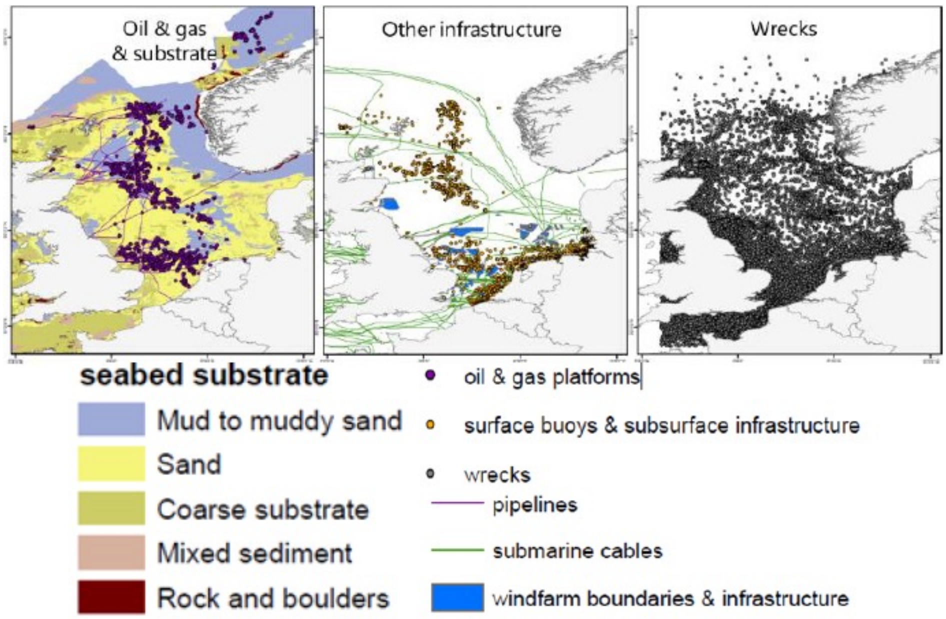
The methodology with which the pilot SIA is calculated only covers fishing-induced physical disturbance, arguably considered the only physical pressure impacting seabed habitats. This, therefore, excludes physical loss (fishing-induced or otherwise) should it occur in the North Sea. Whether fishing-induced physical loss occurs, and if so, what the extent of such a loss is, depends on the occurrence and extent of habitats which, if impacted by specific fisheries, would take longer than 12 years to recover. This period is the equivalent to two reporting cycles in the MSFD (EC, 2008) and is the threshold that is currently used to distinguish between physical disturbance and physical loss (see Chapter 1 and Section 4.1). If, indeed, such habitats exist, the question remains whether this implies that they can be assumed not to contribute to the SIA at all if they've been fished at least once, i.e. as their biotic component would not be there any longer. This would be consistent with the current definition/use of physical loss as caused by sealing from man-made structures (see Section 1.4), but it is arguably not representative of the actual

[11] To note, however, that the EUNIS definition of A5 here is the current one, whilst the classification and definition of the benthic habitats in the EUNIS Level 3 onwards is undergoing a revision up to the end of 2018, and Evans et al (2016) refers to the new Level 2 of the EUNIS benthic habitats as agreed in 2016.

situation where, for example, biogenic structures are damaged after the single passing of a trawl but still some functioning remains within them. Only after a certain degree of disturbance will the biogenic structures have completely disappeared and hence, they can be considered "lost" in the same way as the sealing pressure causes physical loss. Thus, from the perspective of conceptual rigour, it is probably better to assume that fishing only causes physical disturbance, albeit for some habitats the recovery time may exceed the current 12-year threshold. If the parameters that determine the fishing impact on those habitats become available, the pilot SIA could be expanded, so that it also includes those habitats.

While it would be possible to expand the pilot SIA so that it also includes other anthropogenic activities and their pressures, it appears that the current SIA, as tested in the North Sea, already succeeds in providing information on the state of the main seabed habitats and how they are impacted by the most important anthropogenic activity.

Box 4.1. Offshore man-made structure types and their proportion (%) of area coverage of the North Sea's natural substrates. The column "% of natural substrate" reflects how the man-made structures compare to the natural substrate of "Rock & boulders". Taken from Hyder et al. (2017).



Feature	Area (km^2)	% of total	% of natural substrate
Natural:	2,483,080	100	
Mud	796,654	32.1	
Sand	1,152,375	46.4	
Coarse substrate	410,273	16.5	
Mixed sediment	86,518	3.5	
Rock & boulders	37,261	1.5	
Man-made:	5,227	0.2	14.1
Oil & gas	81	0.0033	0.217
Wind turbines	7	0.0003	0.020
Pipelines	2,578	0.1038	6.919
Cables	2,774	0.1117	7.445
Wrecks	23	0.0009	0.061

4.5.3 Inform policy on the state of seabed habitats

The suitability of the pilot SIA depends strongly on its ability to inform policy on the state of seabed habitats in general as well as in relation to biodiversity issues or its capacity to supply ecosystem services. It follows on from Sections 4.5.1 and 4.5.2 that, even if the North Sea pilot SIA actually reflects the state of the benthic invertebrate community in selected soft-substrate seabed habitats resulting from impacts of fishing-induced physical disturbance, it could be taken to reflect the state of the whole benthic community, all seabed habitats and all human activities and pressures. The SIA is expressed in terms of the overall biomass of the benthic invertebrate community relative to undisturbed conditions. In addition, and in order to inform on biodiversity issues, we can also do this for a specific (more sensitive) subset of the benthic invertebrate community like the classes with longevities of > 20 or > 10.

Pertaining to the EU-policy relevance of the North Sea pilot SIA, this is mostly aligned with the MSFD Descriptor 1 on 'Biodiversity' although, because the SIA is spatially resolved, it is also relevant from an MSFD Descriptor 6, 'Seafloor integrity', perspective as it is linked to the extent of the seabed habitats potentially in 'good environmental status' (GES) once a threshold for GES is set. Applying a specific threshold, e.g. representing the biomass that remains when it is not 'adversely affected' (see Box 1.1) and which could be a political threshold determining GES for D6C3 and D6C5, would allow the calculation of the extent of the seafloor area that is "not adversely affected" and, hence, where the benthic ecosystem is assumed to be adequately functioning. However, such a threshold currently does not exist for the North Sea and neither for other EU marine (sub-)regions. For this reason and for the purposes of this study, we have explored an arbitrary set of thresholds linked to the sensitivity of the benthic invertebrate community (represented by each longevity class). Figure 4.4 shows the extent of the whole seafloor area that is above a certain threshold as follows:

- A least stringent threshold where the seabed is not adversely affected if only 50 % (T50) of the biomass remains. For the least sensitive part of the community (L1) this results in 99 % of the seafloor area not being adversely affected. For the most sensitive part (L20) this is 78 %.
- A moderately stringent threshold of 80 % (T80) of the biomass remaining, which results in respectively 94 % (L1) and 60 % (L20) of the seafloor area not being adversely affected.
- The most stringent threshold of 90 % (T90) of the biomass remaining, which results in respectively 86 % (L1) and 50 % (L20) of the seafloor area not being adversely affected.

Table 4.5 shows something similar but for each of the EUNIS habitats separately instead.

Figure 4.4. EU-policy relevance of the pilot SIA. Application of a specific threshold, i.e. T50, T80 or T90, corresponding to the biomass of the benthic invertebrate community (or a specific longevity/ sensitivity class, i.e. L1, L3, L10 or L20) "not adversely affected" by fishing-induced physical disturbance translates the pilot SIA into the extent of the seafloor "not adversely affected" as relevant under the MSFD. The extent is expressed as the proportion of the total area of the selected habitats with soft substrate, which covers only part of the total North Sea surface area.

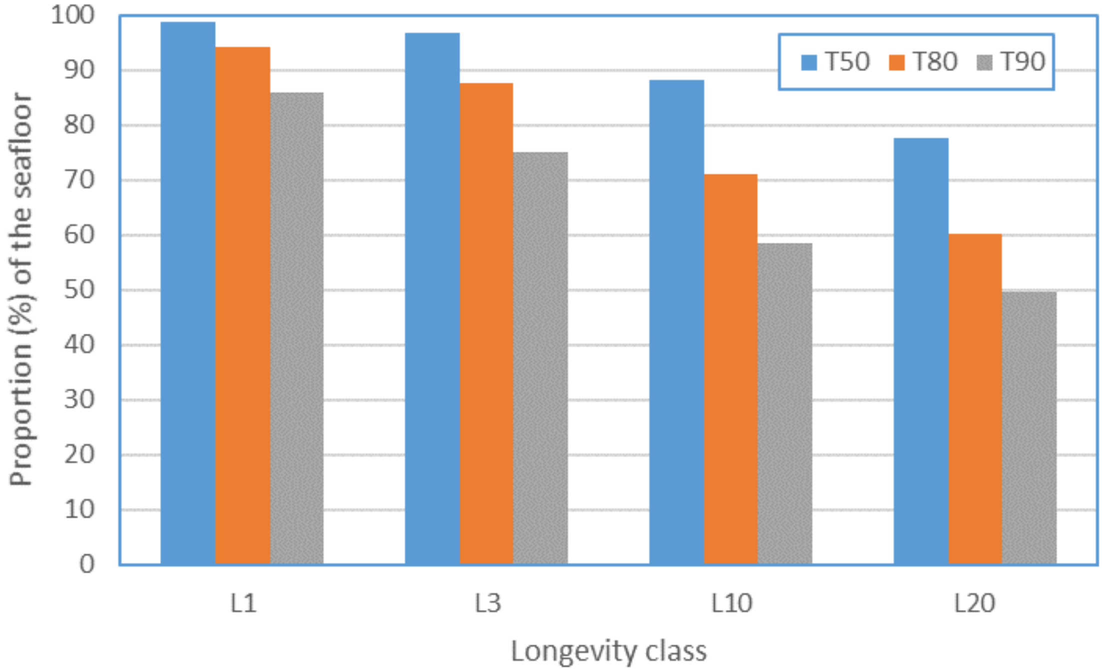


Table 4.5. EU-policy relevance of the pilot SIA. Similar to Figure 4.4 but now for each of the EUNIS habitats separately

EUNIS	Longevity	T50	T80	T90
A5.1	1	99	93	84
A5.1	3	96	86	71
A5.1	10	86	66	54
A5.1	20	74	55	45
A5.2	1	99	94	86
A5.2	3	96	87	75
A5.2	10	88	71	58
A5.2	20	78	60	49
A5.3	1	99	95	88
A5.3	3	98	89	77
A5.3	10	90	74	62
A5.3	20	81	64	54
A5.4	1	99	94	85
A5.4	3	96	87	74
A5.4	10	88	71	58
A5.4	20	79	60	49

As the setting of such a threshold is a political decision, we have not attempted to do so but have rather shown how such a threshold would determine the outcome of the analysis by showing the different outcomes with the use of different thresholds.

This study illustrates another issue with the application of this pilot SIA to inform on the state of seabed habitats. The pilot SIA calculated here for the North Sea "only" reflects the negative impacts from fishing-induced physical disturbance on the benthic invertebrate community in the selected soft-substrate seabed habitats. However, as noted already, it can be taken as being representative of the state of the whole benthic community in all seabed habitats from all anthropogenic pressures. Nevertheless, the pilot SIA could be further developed to improve its accuracy by also including the actual negative impacts from other pressures, i.e. physical loss. However, it should also be considered that what are often considered negative effects, i.e. sealing of the initial often soft-substrate seabed habitats with man-made structure, could just as well be considered a positive effect, i.e. the creation of additional hard substrate (see Hyder et al., 2017). This additional hard substrate may be supporting new communities of organisms that differ in their functioning and, hence, may be able to supply different ecosystem services, or even the same services as the organisms that have been lost. While it is currently unclear if this constitutes a net benefit in terms of the overall supply of ecosystem services it is likely that it would enhance biodiversity as hard substrate seabed is, at least in the North Sea, less common than soft-substrate seabed. Thus, in the North Sea, the majority of the seabed is mud and sand, with rocky shores in many places and some reefs. Offshore installations and other man-made structures (e.g. wrecks) may provide hard substrate that contributes towards the general ecosystem productivity and the connectedness of the network of hard substrate. These man-made structures, therefore, could be beneficiary to biodiversity albeit not "natural" as they are different from the seabed habitats that were there initially. This, in turn, brings up the issue of naturalness in relation to the time horizon. Part of the soft-substrate habitats, now considered natural, consisted of biogenic hard structures in the more distant past. Both the biogenic reefs in the past as well as the current man-made structures enhance biodiversity. However, it is unclear how these areas should be dealt with in the SIA context.

4.5.4 Application in other EU marine (sub-)regions

The North Sea is one of the most data-rich EU marine (sub-)regions and, as such, a good candidate to develop and calculate the pilot SIA. The required information may not be available for other EU marine regions or sub-regions, which would prevent the calculation of this account therein. Thus, even if it is mandatory to collect the data required to calculate fishing pressure for CFP enforcement purposes, the CFP does not apply in the same way across all EU marine regions and there is no easy access to this data for many reasons (see section 3.7.4). These reasons include that there is no central repository for this data, but they need to be requested from each Member State and then processed to cover a given marine (sub-)region as currently done by ICES for the North East Atlantic Ocean, including the Baltic Sea. Then, if the issue is that adequate habitat maps are not available, although EUSeaMap should be able to provide these, there is the possibility to apply the PD2b parametrisation, which calculates the same metric but now without any consideration of the habitat-specific recovery. Even though this results in some loss in accuracy, it still allows a comparison of the SIA across EU marine regions.

5 Evaluation and way forward

Following from sections 1.3 and 1.4, the relevant aspects of the asset, i.e. of the benthic invertebrate community biomass in (selected soft-sediment) seabed habitats, which determine both its sensitivity to fishing-induced physical disturbance and its capacity to supply ecosystem services are all captured by the pilot SIA as tested in the North Sea. Acknowledging the pilot SIA's limitations (see also Chapter 4), the evaluation of the performance of the current methodological approach against the relevant requirements (Table 5.1) shows this pilot SIA is worth to develop further.

Table 5.1. Accounting requirements based on SEEA-EEA and MAES (see Sections 1.3 and 1.4) and the evaluation of the selected approach to calculate the SIA against those requirements

SIA requirements	Evaluation of the selected approach
• reflect the impacts of (the main) human activities on the capacity of ecosystems to supply ecosystem services. • be tightly linked to the supply of ecosystem services, specifically the regulation and maintenance and cultural services.	Commercial fishing is considered the main human activity impacting on the state of the benthic invertebrate community. This community contributes to the capacity of seabed habitats to supply most of the regulation and maintenance and many of the cultural marine ecosystem services (see ETC/ICM, 2019 in prep). Benthic invertebrate biota are involved in the ecosystem processes and functions (e.g. bioturbation, nutrient cycling, reproductive output, secondary production) that underpin the ecosystem capacity to supply regulation and maintenance services (e.g. Bioremediation; Filtration/ sequestration, storage/accumulation; Decomposition and fixing processes; and Maintaining nursery populations and habitats). They can also underpin, as ecosystem structures, cultural ecosystem services (e.g. Scientific, Educational).

• be able to produce time-series in order to understand past trends.	For an accounting methodology to be suitable to deliver a time-series there are several requirements. It should be:
	• Mechanistic, calculating the appropriate SIA metric (i.e. total biomass of benthic invertebrates) using quantitative relationships based on a mechanistic understanding
	• Dynamic and determined by two processes which together drive the year-to-year variation and possible trends of the SIA metric:
	    ○ Depletion causing an outflow of the asset determined by how the physical disturbance caused by fishing interacts with seabed habitats. The relevant variables and parameters are fishing intensity *F* and the gear- and a habitat-specific depletion parameter *d*
	    ○ Generation (responsible for Recovery) causing an inflow into the asset determined by natural ecosystem processes. The relevant parameter is the habitat-specific recovery rate *r*

Table 5.1. cont.

SIA requirements	Evaluation of the selected approach
• represent ecosystem health which is the equivalent of the ecosystem's capability to achieve its fullest potential and is closely related to ecological integrity. • ecosystem health should be expressed in physical units possibly relative to some reference condition benchmark, e.g. no disturbance by human activities • primarily be able to inform on (some aspect of) ecosystem health and/or its degradation even if practical impediments (e.g. data availability) may currently prevent this. As such, an account need not be perfect but should meet its initial goals: to inform on performance and to inform on the quality of the information.	In an MSFD context, the health of the seabed habitats is captured as "seafloor integrity" and defined as "where structure and functions of the benthic ecosystem is not adversely affected". The SIA metric represents the biomass of the benthic invertebrate community (in selected soft-sediment substrates) relative to undisturbed conditions, which, by definition, should correspond to the fullest contribution of this community to the relevant seabed habitats' capacity for service supply. The current methods and their data requirements, thus, allows the SIA to inform on ecosystem health and its degradation due to commercial fishing-induced physical disturbance but practical impediments may hamper its implementation: • across all EU marine regions (see section 3.7.4) • representing the whole fishing fleet, i.e. small vessels are excluded (see section 3.7.4) • covering all seabed habitats even though the main relevant habitats are included (see sections 4.1 and 4.4) But despite these practicalities, and where feasible of being calculated, the SIA is able to inform policy developers and makers on the performance of fisheries management to mitigate the physical disturbance of the soft-substrate seabed habitats (for example by limiting fishing intensity and/or its spatial distribution) due to the main human activity exerting this pressure, i.e. commercial fisheries, and also provide a formal framework to inform on the quality of the information
• support policies with meaningful, objective and verifiable data.	The SIA as now defined is tightly linked to the MSFD biodiversity criteria related to the state of seabed habitats. The data comes from mandatory monitoring programs and standardized processing routines related to the implementation of the CFP.

The biomass of the benthic invertebrate community is probably the best proxy to represent the functioning of the selected soft-substrate seabed habitats and is what *tends* to determine the relevant benthic community's supply of ecosystem services as it excludes the contribution of the plants and algae that may occur in those habitats. The accuracy and relevance of the SIA could be further improved by expanding the range of habitats and the anthropogenic pressures included and considering the potential oversight caused by the omission of plants and algae. In order to improve the policy relevance of the SIA, specific structural aspects of the benthic invertebrate community could be considered such as species composition and/or size structure or functional aspects based on traits, as well as expanding it to include other biota. In time and as the knowledge base expands, the appropriate species-, size- or trait-specific specific details may be included into this account, so that it better reflects any one of the different perspectives aligned with one of the different accounting requirements (see Table 5.1) as follows:

- *Capacity to supply ecosystem services*. As this applies mainly to regulation and maintenance and cultural marine ecosystem services in their broadest sense, it is probably best represented by the total biomass of the benthic community as is currently the case. However, it may be possible to develop an account that represents a specific regulation and maintenance or cultural ecosystem service, or a set thereof, by selecting only those species (i.e. animal or plant and algae) known to contribute to that service or set. However, this would only be for as far as the possible service overlaps detected by ETC/ICM (2019 in prep.) allow and if the species composition is known of the animals and plants/algae that make up this community.

- *Achievement of EU policy objectives related to seafloor integrity*. All the relevant MSFD criteria defining GES for Descriptors 1 and 6 relate to the extent of the seafloor not 'adversely affected' but there is currently no further specification of any thresholds that would define 'adversely affected'. If such thresholds are established, such as by the recently set up Technical Groups on 'Thresholds' under the MSFD Common Implementation Strategy, it should be possible to translate the spatially resolved biomasses per grid cell into a measure of the 'extent' where biomass is above that threshold (see Section 4.5.3). Note, however, that choosing 'extent' as the metric would compromise its accuracy to reflect the seabed habitat's capacity to supply ecosystem services as was shown in the example of Section 1.4 (Figure 1.2)
- *Biodiversity conservation*. Leaving aside what is noted at the end of Section 4.5.3, to support biodiversity conservation the account should specifically reflect the state of the most sensitive part of the benthic invertebrate community as this is where biodiversity is most likely to be compromised. In this study, we used longevity for that purpose as the more long-lived species are more susceptible to be impacted by physical disturbance. To increase compliance to this accounting requirement, the account could go further and be based only on the most sensitive class (i.e. L20). As with the other two perspectives, a modification of the SIA in order to comply with this perspective would compromise its suitability for the other perspectives.

Thus, while relatively small modifications can be made to the methodology to calculate a SIA that better represents, specifically, any of the above perspectives, doing so would compromise its ability to represent the others. This pilot SIA calculated as the total biomass of the benthic invertebrate community in (selected) soft-substrates relative to undisturbed conditions is, therefore, probably, overall, the best account to reflect the state of seabed habitats from not only the impacts from fishing-induced physical disturbance but anthropogenic pressure in general. In time and guided by improved operational definitions of physical disturbance and physical loss (see Section 4.5.2), it should be possible to calculate an improved SIA (at least for the North Sea) that covers the effects of all anthropogenic pressures on all the seabed habitats and where both the animal as well as the plant/algal component of the benthic community are considered.

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