Expert assessment of risks posed by climate change and anthropogenic activities to ecosystem services in the deep North Atlantic

Citation for published version:
Armstrong, CW, Vondolia, GK, Foley, NS, Henry, L-A, Needham, K & Ressurreicao, AM 2019, 'Expert assessment of risks posed by climate change and anthropogenic activities to ecosystem services in the deep North Atlantic', Frontiers in Marine Science.

Link:
Link to publication record in Edinburgh Research Explorer

Document Version:
Peer reviewed version

Published In:
Frontiers in Marine Science

General rights
Copyright for the publications made accessible via the Edinburgh Research Explorer is retained by the author(s) and / or other copyright owners and it is a condition of accessing these publications that users recognise and abide by the legal requirements associated with these rights.

Take down policy
The University of Edinburgh has made every reasonable effort to ensure that Edinburgh Research Explorer content complies with UK legislation. If you believe that the public display of this file breaches copyright please contact openaccess@ed.ac.uk providing details, and we will remove access to the work immediately and investigate your claim.
Expert assessment of risks posed by climate change and anthropogenic activities to ecosystem services in the deep North Atlantic

Claire W. Armstrong1*, Godwin K. Vondolia2, Naomi S. Foley3, Lea-Anne Henry4, Katherine Needham5, Adriana M. Ressurreicao6,7

1UiT The Arctic University of Norway, Norway, 2Norwegian Institute for Water Research (NIVA), Norway, 3National University of Ireland Galway, Ireland, 4University of Edinburgh, United Kingdom, 5University of Glasgow, United Kingdom, 6Centro OKEANOS, Universidade dos Açores, Portugal, 7Centro de Ciências do Mar (CCMAR), Portugal

Submitted to Journal:
Frontiers in Marine Science

Specialty Section:
Deep-Sea Environments and Ecology

Article type:
Original Research Article

Manuscript ID:
436900

Received on:
15 Nov 2018

Revised on:
28 Feb 2019

Frontiers website link:
www.frontiersin.org
Conflict of interest statement

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest

Author contribution statement

All authors were substantially involved in the survey development and data collection. Data analysis was mainly carried out by GV and CA, but all authors contributed to development of the results used. CA initiated the writing of the paper, but all authors contributed to the final product in significant ways, and provided approval for publication.

Keywords

ecosystem services, Climate Change, Anthropogenic impact, risk, deep sea, North Atlantic Ocean, Blue growth

Abstract

Word count: 309

Sustainable development of the ocean is a central policy objective in Europe through the Blue Growth Strategy and globally through parties to the Convention on Biological Diversity. Achieving sustainable exploitation of deep sea resources is challenged by the huge uncertainty around the many risks posed by human activities on these remote ecosystems and the goods and services they provide. We used a Delphi approach, an iterative expert-based survey process, to assess risks to ecosystem services in the North Atlantic Ocean from climate change (water temperature and ocean acidification), the blue economy (fishing, pollution, oil and gas activities, deep seabed mining, maritime and coastal tourism and blue biotechnology), and their cumulative effects. Ecosystem services from the deep sea identified through the Millennium Ecosystem Assessment framework were presented in an expert survey to assess the impacts of human drivers on these services. The results from this initial survey were analyzed and then presented in a second survey. The final results based on 55 expert responses indicated that pollution and temperature change each pose high risk to more than 28% of deep-sea ecosystem services whilst ocean acidification, and fisheries both pose high risk to more than 19% of the deep-sea ecosystem services. Services considered to be most at risk of being impacted by anthropogenic activities were biodiversity and habitat as supporting services, biodiversity as a cultural service, and fish and shellfish as provisioning services. Tourism and blue biotechnology were not seen to cause serious risk to any of the ecosystem services. The negative impacts from temperature change, ocean acidification, fishing, pollution, and oil and gas activities were deemed to be largely more probable than their positive impacts. These results expand our knowledge of how a broad set of deep-sea ecosystem services are impacted by human activities. Furthermore, the study provides input in relation to future priorities regarding research in the Atlantic deep sea.

Ethics statements

(Authors are required to state the ethical considerations of their study in the manuscript, including for cases where the study was exempt from ethical approval procedures)

Does the study presented in the manuscript involve human or animal subjects: Yes

Please provide the complete ethics statement for your manuscript. Note that the statement will be directly added to the manuscript file for peer-review, and should include the following information:

- Full name of the ethics committee that approved the study
- Consent procedure used for human participants or for animal owners
- Any additional considerations of the study in cases where vulnerable populations were involved, for example minors, persons with disabilities or endangered animal species

As per the Frontiers authors guidelines, you are required to use the following format for statements involving human subjects:
This study was carried out in accordance with the recommendations of [name of guidelines], [name of committee]. The protocol was approved by the [name of committee]. All subjects gave written informed consent in accordance with the Declaration of Helsinki.

For statements involving animal subjects, please use:
This study was carried out in accordance with the recommendations of 'name of guidelines, name of committee'. The protocol was approved by the 'name of committee'.
If the study was exempt from one or more of the above requirements, please provide a statement with the reason for the exemption(s).

Ensure that your statement is phrased in a complete way, with clear and concise sentences.

No personal information regarding the experts involved was collected, hence according to the requirements of the Norwegian Centre for Research Data (following their web-based check system), there was no requirement for special permission. All experts participated voluntarily by sending in their surveys manually.

Data availability statement

Generated Statement: The datasets generated for this study are available on request to the corresponding author.
Expert assessment of risks posed by climate change and anthropogenic activities to ecosystem services in the deep North Atlantic

Claire W. Armstrong¹, Godwin K. Vondolia¹,², Naomi Foley³, Lea-Anne Henry⁴, Katherine Needham⁵, Adriana Ressurreição⁶,⁷,⁸

¹UiT The Arctic University of Norway
²Norwegian Institute for Water Research
³National University of Ireland Galway
⁴University of Edinburgh
⁵University of Glasgow
⁶MARE – Marine and Environmental Sciences Centre, Horta, Portugal
⁷OKEANOS Centre, University of the Azores, Horta, Portugal
⁸CCMAR Centre of Marine Sciences, Faro, Portugal

Abstract
Sustainable development of the ocean is a central policy objective in Europe through the Blue Growth Strategy and globally through parties to the Convention on Biological Diversity. Achieving sustainable exploitation of deep sea resources is challenged by the huge uncertainty around the many risks posed by human activities on these remote ecosystems and the goods and services they provide. We used a Delphi approach, an iterative expert-based survey process, to assess risks to ecosystem services in the North Atlantic Ocean from climate change (water temperature and ocean acidification), the blue economy (fishing, pollution, oil and gas activities, deep seabed mining, maritime and coastal tourism and blue biotechnology), and their cumulative effects. Ecosystem services from the deep sea identified through the Millennium Ecosystem Assessment framework were presented in an expert survey to assess the impacts of human drivers on these services. The results from this initial survey were analyzed and then presented in a second survey. The final results based on 55 expert responses indicated that pollution and temperature change each pose high risk to more than 28% of deep-sea ecosystem services whilst ocean acidification, and fisheries both pose high risk to more than 19% of the deep-sea ecosystem services. Services considered to be most at risk of being impacted by anthropogenic activities were biodiversity and habitat as supporting services, biodiversity as a cultural service, and fish and shellfish as provisioning services. Tourism and blue biotechnology were not seen to cause serious risk to any of the ecosystem services. The negative impacts from temperature change, ocean acidification, fishing, pollution, and oil and gas activities were
deemed to be largely more probable than their positive impacts. These results expand our knowledge of how a broad set of deep-sea ecosystem services are impacted by human activities. Furthermore, the study provides input in relation to future priorities regarding research in the Atlantic deep sea.

**Keywords:** Ecosystem services, climate change, anthropogenic impacts, risk, deep sea, North Atlantic Ocean, Blue Growth.

**Acknowledgements:**

We thank members of the Horizon 2010 ATLAS - A Trans-AtLantic Assessment and deep-water ecosystem-based Spatial management plan for Europe, and SponGES - Deep-sea Sponge Grounds Ecosystems of the North Atlantic an integrated approach towards their preservation and sustainable exploitation, for their participation in the surveys. We would like to acknowledge the help of Joana Xavier, Hans Tore Rapp and Detmer Sipkema for facilitating the opportunity of presenting and applying the Delphi survey among the experts of the Horizon 2020 project SPONGES. AR acknowledges Fundação para a Ciência e Tecnologia (FCT), through postdoctoral grant (SFRH/BPD/102494/2014) and the strategic project UID/MAR/04292/2013 granted to MARE. We acknowledge funding from the European Union's Horizon 2020 Research and Innovation programme under grant agreement No. 678760 (ATLAS). This output reflects the authors’ views only and The European Union cannot be held responsible for any use that may be made of the information contained therein.
1. Introduction

Although our oceans and seas are “out of sight, out of mind” to much of society, we are becoming increasingly aware of the fact that marine ecosystems are highly impacted by climate change and our endeavours to exploit living and non-living marine resources (Halpern et al. 2008). Despite their remoteness and difficulty to access, the demise of the deep ocean is particularly noteworthy as it is the largest but least known biome on Earth. The deep North Atlantic Ocean has been studied for the last two centuries, and is now known to harbour biogeochemical cycles, e.g., cycling of primary production, carbon and nutrients from the ocean surface to the deep seafloor (Oevelen et al. 2009, Vanreusel et al. 2010, Beazley et al. 2013).

Complex three-dimensional ecosystems formed by cold-water corals, sponges, and topographically complex seamounts and hydrothermal vents not only support high and sometimes unique or endemic species, but these ecosystems also provide many ecosystem goods and services which contribute to maritime economic activities that underpin the socio-economic wellbeing of Atlantic nations and their citizens (Galparsoro, Borja, and Uyarra 2014). These services include nutrient cycling and the biological pump, waste absorption and detoxification, fisheries and other deep ocean industries, bioprospecting and a number of cultural services related to education and science, aesthetic and inspirational contributions (Thurber et al. 2014). There is a lack of environmental baselines and assessments in relation to human interactions with the deep sea, but research points to three main impact contributors; the earlier days’ disposal and dumping, current resource exploitation, and future climate change, impacting on natural resources and different habitat types as described in some detail by Ramirez-Llodra et al. (2011). Deep sea habitats and services have undoubtedly been degraded by disposal and resource exploitation, and are now further challenged by unprecedented rates of climate change that will see the deep North Atlantic experience reduced oxygen levels, food supply to the seafloor, lower pH and a rise in deep ocean temperatures (Sweetman et al. 2017).

In addition to climate change and historic types of resource exploitation dating back to antiquity (fisheries) and into the last century (oil and gas), the European Commission Blue Growth Strategy seeks to support sustainable growth in the North Atlantic across five sectors: aquaculture, maritime and coastal tourism, blue biotechnology, ocean energy and seabed mining (EC 2012). This strategy may pose a challenge to the business and policy objectives seeking to balance societal needs with environmental sustainability.
One way to consider the balance between the blue growth economic agenda and sustainability is to assess the potential impacts or risks posed by different forms of human activity on the ecosystem services provided by the deep sea. It may also be assumed that an assessment of impacts and risks will inform marine spatial planning (MSP). Marine spatial planning calls for due regard in relation to various pressures from human activities and climate change on marine ecosystems, their services and economic development (Ntona and Morgera 2018). These impacts affect and pose risks in relation to services that the ecosystems provide to humans. In order to assess any form of risk, consequences and probability of hazard occurrences need to be identified. There is a multitude of studies assessing risks of specific activities, such as oil spills, aquaculture or shipping on specific resources, environments, ecosystems or their functions in marine ecosystems (Soares and Teixeira 2001, Olita et al. 2012, Copp et al. 2016). However, there are few studies that integrate risk assessments and ecosystems services (see Nienstedt et al. (2012) for a terrestrial example), or at least these are mainly limited to discussion regarding the approach (Faber and van Wensem 2012, Galic et al. 2012). There are several reasons for this gap. For one, the assessment of risks in relation to natural environments or ecosystems is often very demanding in itself. Knowledge is limited (particularly so in the deep sea), and the consequences can be highly diverse as well as controversial. Bringing the risk analysis one step further, to ecosystem services, can, therefore, be even more challenging.

A second issue is; who are the experts that should assess the risk to ecosystem services? Although the scientific knowledge can provide expert input regarding risks to ecosystems, it is not clear which expert body can provide expertise in relation to ecosystem services, i.e., services from ecosystems that provide benefits to humans (MEA 2005). Many economists assess values connected to ecosystem services (TEEB 2010), but are they necessarily the experts to assess unvalued risks, i.e. risks to ecosystem service provision as such? Though social scientists, in general, have not criticized the concept of ecosystem services to the same degree as others from different disciplines have (Silvertown 2015, Morelli and Møller 2015), they cannot be said to completely embrace it (Sullivan 2010). Furthermore, social science in this domain has more often focused on the interaction between humans in nature, power structures and knowledge acquisition, rather than individual or societal beneficiary interactions with ecosystems. This is however changing, with input from social sciences and the humanities increasingly finding its place, for instance in the intergovernmental science-policy panel on biodiversity and ecosystem services (IPBES) (Stenseke and Larigauderie 2018). Nonetheless, our study links ecosystems and services via the risk aspect, making it acceptable to survey largely natural scientists.
Why is it of interest to assess risks to ecosystem services, rather than environments, ecosystems or ecosystem functions? Clearly, the drive within the EU for marine ecosystem-based management is central in the aim for a broader perspective on the use of marine resources (MSFD 2008). The concept of ecosystem services, which has in recent years increasingly appeared in research, but also in policy and management (see for instance the MAES: Mapping and Assessment of Ecosystems and their services, under Action 5 of the EU Biodiversity Strategy to 2020, and the EU Blue Growth Strategy) brings nature’s contributions to humans to the forefront. Assessing risks to these services brings the consequences of human drivers directly in contact with societal aspects, i.e. the risks are brought closer to the issues that managers and politicians are directly considering. Whereas risks to ecosystems and their functions are of course important, there is at least one layer of knowledge between the output of these kinds of assessments and the human dimensions that managers and policy makers relate to. In going directly to the ecosystem services, we bring the risks of human drivers closer to home. Though there is mounting scientific evidence of risks to ecosystems, the many linkages between ecosystems and the multitude of ecosystem services they provide are not always well known or clearly identified, and especially so in the deep sea. Identifying risks to ecosystem services that deep sea ecosystems supply illustrates more clearly the potential losses that society may experience if the human drivers of change in these environments are not taken into account. In addition, the deep sea is often both spatially and temporally distant to the services that humans value, it is, therefore, all the more important to identify the riskiest drivers, and from this provide input into where more work must be done to mitigate or adapt to the risks involved.

In this paper, we use a Delphi survey approach to assess risks to deep sea ecosystem services within the North Atlantic. This is in contrast to previous work which has considered effects on ecosystems and their functions (Ahnert and Borowski 2000), effects by single drivers (Gornitz et al. 1994) and the effects on ecosystem services in coastal areas (Hayes and Landis 2004), which has most often been the focus in the literature. The Delphi approach is an iterative expert-based survey approach in order to see whether perceptions may reach more consensus based on information about the choices of peers in a previous round of the survey. Due to the lack of specific experts in this matter, we have chosen to use a broad set of expertise to assess the risks to ecosystem services in the deep sea. Our Delphi study respondents are members of two EU Horizon 2020 projects, consisting of a large variety of mostly biological and oceanographic expertise in relation to the North Atlantic deep-sea. The experts span physical oceanography, ecosystem modelling, deep sea ecology and genetics, natural resource economics and social
science, as well as marine policy. We assess risks of human activities or drivers on ecosystem services in the deep sea, using expert elicited risk assessments in a Delphi format. The results expand our knowledge of how a broad set of ecosystem services from the deep-sea are perceived to be impacted by human activities. Furthermore, the study provides input in relation to future priorities regarding research in the North Atlantic. The remainder of the paper follows this structure: The methodologies are discussed in the next section. The results are presented in Section 3, with discussions and conclusions in Section 4.

2. Material and Methods

We used a Delphi survey to assess risks of human drivers to deep-sea ecosystem services. The Delphi method has its origins from the RAND Corporation in the 1950s and 1960s and was largely motivated by the need for improved forecasting and securing some form of judgement convergence (Dalkey 1968). Over the years it has been utilized in a multitude of different assessments spanning from health issues (Steen et al. 2014, Keller et al. 2015) to challenges in the pulp and paper industry (Toppinen et al. 2017). The method is largely used in order to obtain some form of opinion consensus, and yet avoiding the influence of dominant individuals. In recent years, Delphi surveys have also increasingly been applied to environmental issues, such as valuation (Strand et al. 2017), and especially in relation to issues where there is limited knowledge, either in relation to the ecology (Filyushkina et al. 2018) or the values (Scolozzi, Morri, and Santolini 2012, Filyushkina et al. 2018).

The Delphi method relies on a panel of experts to gather information; on a subject with limited knowledge. This expert opinion is gathered through an iterative, anonymous survey with feedback. The survey is sent around twice or more, and information regarding the results of the previous round is distributed in order to allow the experts to evaluate their assessment and to see if there may be some agreement or convergence regarding the issue surveyed. The objective is to allow information produced by an expert group to be evaluated, building consensus over time (see the stages in the Delphi approach in Table 1).

Table 1. Stages in the Delphi survey approach

| Steps | Description                          |
|-------|--------------------------------------|
| 1     | Definition of problem                |
| 2     | Selection of experts                 |
| 3     | Survey instrument development        |
| 4     | Testing of survey instrument         |
Distribute 1st survey
Analysis of 1st round results, and development of presentation for 2nd survey
Distribute 2nd survey
Analysis of 2nd round results, comparison to 1st round, develop report

Though the Delphi process is considered more reliable than a single survey, the method has been critiqued for group pressure, rather than knowledge development, leading to consensus in repeated surveys (Woudenberg 1991). The Delphi approach is however also roundly defended, especially in relation to complex issues (de Loë et al. 2016) and topics where information is not easy to come by (Landeta 2006). Also in other fields where surveys are used, giving respondents time to reflect, discuss and gather information, is seen as a way to secure responses that are more reliable (MacMillan, Hanley, and Lienhoop 2006).

Risk assessment survey

The risk assessment survey was developed based on literature on ecosystem services in the deep sea (Armstrong et al. 2012, Galparsoro, Borja, and Uyarra 2014, Thurber et al. 2014), and determination of relevant human drivers within the research group (see Table 2).

Ecosystem Services

Ecosystem services are described as those services that ecosystems provide for human wellbeing. There exist a number of different ecosystem service frameworks that have been developed over the last fifteen years. We apply the Millennium Ecosystem Assessment’s (MEA 2005) framework in our analysis (Figure 1). This framework includes supporting services that feed into the direct services to humans; the provisioning, regulating and cultural services. A number of newer frameworks, such as TEEB (The Economics of Ecosystems and Biodiversity), CICES (The Common International Classification of Ecosystem Services) and IPBES do not include supporting services explicitly in their service portfolio (TEEB 2010, CICES 2013, IPBES 2017). The motivation for not including the supporting services is largely due to the issue of double counting of values. When monetarily estimating the value of ecosystem services, supporting services cannot be valued separately, as their values are inherently included in the value of the direct services that they feed into. Since we do not undertake valuation in this study, double counting is not an issue we need to take into account. Furthermore, in our
study area, the deep sea, most ecosystem services are removed in time and space from humans, and hence very many services are of the supporting type (Armstrong et al. 2012).

Figure 1. Ecosystem services in the deep sea, using the Millennium Ecosystem Assessment framework.

Human Drivers

The human drivers of risk to ecosystems and their services were identified through discussions with experts and also include some of the key areas identified for development within the EU Blue Growth Strategy (Table 2) (aquaculture was not considered a risk to the study area).

Table 2. Human drivers identified for the Delphi survey risk assessment

| Identified Human Drivers         |
|---------------------------------|
| Temperature Change              |
| Ocean Acidification             |
| Fishing                         |
Defining Risk

Risk is the product of two entities, consisting of 1) some measure of the consequences of an occurrence and 2) the likelihood that the occurrence will take place. Usually, the occurrence is defined as some hazard. However, occurrences need not be hazards causing negative effects, though this is usually what we worry most about, and are most interested in identifying. In our case, the hazards are presented as a number of different human drivers or their combination, impacting on ecosystem services. These drivers need not always lead to negative effects on all ecosystem services and in some cases provide positive effects, or there may indeed be reasons to believe some drivers may have both positive and negative effects. Our study involves a large number of ecosystem services and human drivers across the North Atlantic Ocean. It is recognized that there is currently limited knowledge of the deep sea and this leads to increased uncertainty in the study. As such experts could note both positive and negative effects in our assessment. Hence the assessment allows for positive and negative effects, with a scale of 1-5 (from very low severity to very high severity), or alternatively neither being applicable for some drivers in relation to some ecosystem services. The likelihood of the effect occurring is also measured on a scale of 1-5 (very low probability to very high probability). Ideally we should have included probabilities and specified severities. However, in order to keep the survey as brief as possible, we kept to these simplifying descriptions. Such a presentation of risk may, however, be problematic, and must be used with caution (Cox Jr. 2008). We do not however estimate a risk measure, but rather present the graphical combination of likelihood and severity. Risk assessment, in general, can also be critiqued based on normative aspects and in relation to problems of aggregation (Stirling 1998). However, caution is largely suggested in relation to decision-making in high-risk situations. For the use of assessing risk aspects in relation to broad categories of ecosystem services, such as we are carrying out here, many of the cautions are less problematic.
It is, however, worth noting the choice of grid lines in the risk matrix (i.e. where the high, moderate and low risk is assigned) is highly subjective. Clearly, these lines should be determined by some aim to “minimize the maximum loss of misclassified risks” (Cox Jr 2008, p 510), but this requires a lot more knowledge regarding consequences than is available for our study, and is seldom problematized in risk assessments.

The Survey

An initial survey was developed and pre-tested. Following revisions to the survey, the first round of the Delphi ecosystem service risk assessment was held at the 2nd EU Horizon 2020 project ATLAS’ General Assembly in April 2017. The session included a brief introduction to the aims of the work, the Delphi method and ecosystem services. The participants were given explanatory material (see Appendix 1) and the survey in an Excel sheet via email (see Appendix 2). Anonymity was guaranteed, as no data was collected that could identify the respondents. All respondents could pull out of the survey at will. While some surveys were returned during the project meeting, the majority were submitted in the following weeks. A total of 30 surveys were submitted and included for analysis. The responses to the first round survey were analysed; figures were produced to present relevant results for the next round and a new survey, using results from the first survey, was developed using SurveyMonkey (https://www.surveymonkey.net/) (see Appendix 3 and 4 for the second survey and an example of the online survey). In our presentation of the results from the first survey, we show first the perceptions of negative effects, as these are of most interest in relation to
policy, research, mitigation and adaptation. We presented the risk reporting matrices in the fashion of likelihood and effect as shown in Figure 2, where the two axes are represented by rank numbers. This representation is not uncommon (see for instance FAO guidelines for Ecosystem Approach to Fisheries http://www.fao.org/fishery/eaf-net/eaftool/eaftool_4/en#EAFTool-EAFToolSynergy).

The second survey was distributed, by e-mail, to the ATLAS project members at the end of October 2017, and two reminders were sent out. By mid-November 20 surveys from participants who had taken part in the first round were received. In April 2018 a special session was held for all project members at the EU Horizon 2020 project SponGES’ General Assembly. The project members were asked to complete the second version of the Delphi ecosystem service risk assessment online, using SurveyMonkey. Prior to completing the survey, respondents received a brief presentation about the Delphi method, ecosystem services and structure of the survey including the results from the first survey. These initiatives resulted in a total of 55 responses. The results from the ATLAS second round and the SponGES assessment were pooled and analysed, and compared to the first round, as presented in the Results section below.

3. Results

The results presented focus on the second round of the Delphi survey. The first round was employed as an initial information gathering exercise which provided information for use in the second round. Results from the first round of the Delphi survey are available in Appendix 3 and equivalent results from the second round are presented in Appendix 5. We focus on the results from the second survey, which is reasonable given a Delphi approach, where the second survey includes more assessment by the respondents. In some cases the results may appear different in the two surveys, but we find hardly any statistically significant difference, and hence only present the figures from second survey in this section (see the appendices for results from the first survey).

In the following we present the results from two forms of risk; (1) the risk resulting from anthropogenic activities (human drivers) on each ecosystem service identified to the deep sea and (2) the perceived level of risk associated with each human driver. As discussed previously, both positive and negative effects were surveyed but in this section we focus on the negative effects.
Fifty-five (55) responses were received from experts participating in the ATLAS and SponGES projects to the second survey, out of which 47% (all from the ATLAS project) participated in the first round. For each ecosystem service, the number of human drivers that pose high, medium and low risks are identified. The median severity and the median likelihood of the negative effects are presented for all services and drivers as the data gathered is at the ordinal level. The high, medium and low risks connected to the negative effects of human drivers on different ecosystem services are presented in Figure 3. It is shown that habitat and biodiversity, both supporting ecosystem services, are at high risk from six out of nine human drivers. Biodiversity, when it is considered a cultural ecosystem service, is at high risk from five human drivers. The provisioning ecosystem service of fish/shellfish is at high risk from four of the human drivers. Resilience is at high risk from two human drivers while the remaining ecosystem services are at high risk from at most one human drivers, if any at all.
Figure 3: Ecosystem service risk levels from the negative effects of different human drivers. The x-axis represents the number of drivers within each risk category.

The ecosystem services at low risk from a high number of human drivers are waste disposal and raw materials (both provisioning ecosystem services) and a supporting ecosystem service of primary production. None of these three ecosystem services is at high risk from human drivers.
The second objective was to assess the level of risk associated with the human drivers specifically. In Figure 4 we illustrate the different human drivers, and how they impact on the 21 ecosystem services as regards high, medium and low risks. This is used to identify the anthropogenic activities (human drivers) that are perceived to have the highest level of risk to ecosystem services.

![Diagram showing human drivers risk levels upon ecosystem services]

In Figure 4, pollution and temperature change cause high risk to five ecosystem services. This means that pollution and temperature pose high risk to 28% each for the ecosystem services identified. Ocean acidification, fishing and the cumulative impacts cause high risk to four ecosystem services each. This corresponds to about 19% of the identified ecosystem services. These are followed by mining, causing high risk to three ecosystem services. Tourism and blue
biotechnology are not perceived to have any high risk impacts on ecosystem services, and oil/gas activities are only perceived to be high risk in relation to oil/gas/energy as provisioning services.

The rankings of human drivers remain the same in both the first and second surveys except for temperature change which replaces ocean acidification as the greatest risk in the second survey. In addition, the risks of the six high risk human drivers increase. For instance, in the first round, pollution posed high risk to four ecosystem services and this increases to six in the second survey. Adverse impacts of tourism remain the same but risk perceptions of blue biotechnology declined in the second survey. There is, however, no statistical difference between the average number of ecosystem services at high, medium and low risk in the first and second surveys as can be seen in Table 3. We also observe that the variation only declined in the second round for the medium risk case. This may be due to the difference in the number of participants who responded to the two rounds. It is worth noting that there is large variation in the high risk ecosystem services, as well as for the human drivers.

In Figure 5 the positive effects of the different human drivers on different ecosystem services are presented, in order to compare the expectation of positive versus negative effects of different human drivers. We chose not to develop a single risk measure (for instance by using the product of the two digits from effect and likelihood), despite this not being uncommon in the literature (Staples et al. 2014), as products of ranked measures may give spurious and therefore unreliable results when compared (Hubbard and Evans 2010, Cox Jr. 2008). Each separate figure shows the positive and negative effects, using green and red coloured bubbles, respectively. The size of the bubble illustrates how many services are represented at each point of likelihood and severity of effect. Here we observe that for temperature change, ocean acidification, pollution, fisheries, oil/gas activities and cumulative effects, the negative effects come at far higher risk levels than the positive. This can be seen from the red bubbles concentrating to the upper right of the figures, while the green are more to the left. For mining and tourism, this effect is less clear. We can observe that for blue biotechnology, the positive effects come at far higher risk levels than the negative.

**Comparison of the first and second survey, and respondent certainty**

Comparing the first and second surveys, risk perceptions regarding human drivers give some appearance of worsening in the second survey relative to the first (for graphical comparison,
see Figure 3 above for the second survey and Figure 4 in the Appendix 5 for the first survey).

The number of human drivers that pose high risk increases from three to six for biodiversity (as a supporting service), two to six for habitat, three to five for biodiversity (as a cultural service) and two to four for fish/shellfish. However, using simple t-tests we find no statistically significant difference between the average number of human drivers classified as high, medium and low risk to deep-sea ecosystem services identified in the first and second surveys as can be seen in Error! Reference source not found. We also observe that the variation only declined in the second round for the medium risk case. This may be due to the difference in participants in the two rounds. It is worth noting the large variation in the high risk human drivers.

Table 3. Mean number of human drivers posing high, medium and low risk to ecosystem services, and mean number of ecosystem services at high, medium and low risk from human drivers, in the first and second survey. Numbers in parenthesis are standard deviations. T-values of mean difference test between the two surveys.

| Human drivers | First survey | Second survey | T-values of mean difference test | Ecosystem services | First survey | Second survey | T-values of mean difference test |
|---------------|--------------|---------------|---------------------------------|-------------------|--------------|---------------|---------------------------------|
| **High risk** | 0.81(1.03)   | 1.33(2.06)    | -1.04                           | 2.00 (1.73)       | 3.11 (2.31) | -1.15         |
| **Medium risk** | 3.90(2.07)   | 4.57(1.75)    | 1.13                            | 10.44 (4.42)      | 8.55 (4.30) | 0.92          |
| **Low risk**  | 3.52(1.57)   | 3.72(2.23)    | -0.40                           | 8.33 (6.08)       | 9.33 (6.04) | -0.35         |

We also assessed whether perceptions differed from the first survey to the second regarding the average number of human drivers posing high risk to ecosystem services, for those services that are perceived to be at high risk from at least one human driver, as shown in Table 4. Using t-tests, we reject the null hypothesis that the two conditional means are different, at the 5% level.
Table 4. Conditional mean number of human drivers posing high risk to ecosystem services, for those services that are perceived to be at high risk from at least one human driver. Numbers in parenthesis are standard deviations. T-values of mean difference test between the two surveys.

|                      | First survey | Second survey | T-values of mean difference test |
|----------------------|--------------|---------------|----------------------------------|
| **High risk**        | 1.7 (0.8232726) | 2.8 (2.20101) | -1.4803                          |
| **Medium risk**      | 3.6 (1.074968) | 2.7 (2.162817)| 1.1784                           |
| **Low risk**         | 3.6 (1.429841) | 3.5 (3.02765) | 0.0944                           |

Although the rankings of ecosystem services in terms of high risk remain almost the same in both the first and second survey, there were some changes in rankings of ecosystem services that are low risk. Risk perceptions of human drivers to educational services increased in the second survey but waste absorption, carbon sequestration, chemicals/pharmaceuticals and nutrient cycling were ranked lower in the second survey than in the first survey. However, the ecosystem services’ risk levels show similarly small changes as observed for the human drivers (see Table 3).

After the risk assessment we asked about respondents’ certainty in their responses using a scale from 1 to 5 (with 1 being very uncertain and 5 being very certain). The median level of the certainty score is 3 for both surveys, but the average certainty increased slightly from 2.56 in the first survey to 2.82 in the second round. A t-test found not statistical difference (at 5% level) between the expressed certainty in the two surveys.

We also asked the respondents to identify which ecosystem services that they are certain about. The main ecosystem services identified here include biodiversity, climate regulation and habitat. The cascading effects of these on other ecosystem services especially under the supporting and regulating ecosystem services were also noted. Instead of ecosystem services,
Some of the respondents indicate the impacts of human drivers that they are certain about. The human drivers cited include temperature change, ocean acidification, mining, pollution, tourism, biotechnology and fishing.

We also offered the respondents an opportunity to identify which ecosystem services they were most certain about. Though not all respondents responded to this query, the main ecosystem services identified included biodiversity, climate regulation and habitat. Some of the ecosystem services that respondents are uncertain about how will be impacted by human drivers include carbon cycle, oceanographic and water circulation in addition to the combined effects of the undergoing changes in ecological functions on regulating services. Some of the respondents mention issues such as the ecosystem services framework, the political will to take actions that are required to address the effects of human drivers and the scoring and monetary valuation of these effects.
Figure 5. Risk assessment for different ecosystem services: Median likelihood, positive (green) and negative (red) median effect of different human impacts.
During the survey, we asked the experts to give opinions on the validity and usefulness of the ecosystem services framework to understanding human dependence on the marine environments. The general impressions from these responses indicate that the majority of the experts think that the ecosystem services framework is very useful. However, they also believe that it can be improved, especially strengthening the scientific basis of the framework. Some reservations are expressed about the intangible nature of some of the ecosystem services such as cultural and supporting services, as well as the fact that ecosystem service frameworks can mask the importance of natural processes and functions that underpin the framework itself. Some propose that other frameworks should be developed to provide alternative perspectives.

4. Discussion

The survey points to four perceived high risk human drivers: pollution, temperature change, ocean acidification and fisheries, in addition to the cumulative effects. These results are similar to the findings of Halpern et al. (2008), who, using a number of databases combined with an expert judgement based area assessment, showed how Northern Atlantic ecosystems, especially in the east, are highly impacted. The authors show that the climate drivers (sea temperature, UV and ocean acidification), impact the largest ocean areas. However, though fishing covers far less area, different aspects of fishing (different types of by-catch as well as habitat modification), were perceived to pose similar threat levels as that of the climate factors. Pollution was given far less attention in the Halpern et al. (2008) study than it is in our results. This may be due to of further knowledge about the extent of marine pollution over the last 10 years, or that pollution is perceived to have a greater impact on ecosystem services than on marine ecology, the latter which was the focus of the Halpern et al. (2008) study. Interstingly, in our study oil/gas and mining, are considered to be far less risky in relation to ecosystem services than the four main high risk drivers. Blue biotechnology and tourism are perceived to provide the greatest positive effects and likelihoods, with oil/gas and mining following them. In concluding, newer blue growth industries do not seem to involve the greatest risk to ecosystem services. Indeed, it seems to be the larger global problems of climate, pollution and fisheries that are perceived to pose the highest risks to marine ecosystem services.

The main contribution of this study is to focus on risk to ecosystem services, rather than marine ecology or ecosystems, which is what are usually studied. Here we observe that the most ecosystem services perceived to be most threatened, i.e. services with high risk levels in
relation to most human drivers, are fish and shellfish, biodiversity (both as a supporting and a
cultural service) and habitats. Provisioning (fish/shellfish), cultural (biodiversity) and
supporting services (biodiversity and habitats) are therefore believed to be at risk from the
largest number of human drivers. The only regulating service understood to be at risk was
climate regulation, due to temperature change. Indeed, supporting services were perceived to
be the most at risk. This is noteworthy, as when focusing on ecosystem services most of the
newer frameworks (TEEB 2010, CICES 2013, IPBES 2017) largely do not include supporting
ecosystem services, but rather focus on the final provisioning, regulating, and cultural services.
An important message is that if the focus is only given to the three ecosystem service types that
directly impact humans, we may clearly ignore important impacts and their risks. This is
particularly meaningful in the deep sea.

This study has a number of qualifications worth mentioning. One is that the numbers of
responses are limited, and having more respondents in the first version would have been
advantageous. Furthermore, organizing the likelihood in a different fashion, for instance in
probabilities rather than ranks, would allow a more multiplicative presentation (probability
multiplied by effect), though as mentioned earlier, this is not without its problems. Giving the
respondents more information would be good but must be evaluated against the time needed to
carry out the survey. Yet, more information in the second survey regarding the variance in the
results could have been informative. The survey is very large and demands a lot of the
respondents. One option could be to limit a follow-up survey to the most high risk drivers and
ecosystem services, in order to probe these further. Though a qualitative assessment of
respondent uncertainty was included, a more systematic uncertainty assessment related to risks
would benefit a future study, providing an extra input on knowledge gaps and further research
needs.

The study underlines a number of issues. For one, there seems to be large uncertainty about the
degree of high risk that different human drivers pose. Though pollution, temperature change,
ocean acidification and fisheries, and the cumulative effects are on average deemed to pose
high risk to a number of ecosystem services, there is substantial variation in this perception.
This points to a need for more study in relation to these drivers and their linkages to ecosystem
services. There is also considerable variation amongst the respondents regarding the ecosystem
services perceived to be at high risk. The fact that it is the high risk drivers and services that
show the greatest variation is concerning, and stresses the need for more research into the
pressures and their responses, especially in the deep sea. Furthermore, the focus on supporting
The fact that most of the respondents were natural scientists may be one explanation for this result, and points to the need for greater inclusion of other disciplinary fields in surveys that involve ecosystem services. However, it should not be surprising that supporting services are central services in the deep sea, and that their importance may well surpass many other services that receive more attention in shallower and coastal waters.

Achieving sustainable exploitation of deep sea resources is challenged by the huge uncertainty around the many risks posed by human activities on these remote ecosystems and the goods and services they provide. This study contributes to the blue growth development and marine spatial planning in the deep sea by identifying human activities and climate change effects that may have an impacts on ecosystem services. The identification of the levels of risk associated with different human activities, and the perceived level of risk to ecosystem services will help inform future development and potentially maintain ecosystems in the deep sea.
5. References

Ahnert, Ahmed, and Christian Borowski. 2000. "Environmental risk assessment of anthropogenic activity in the deep-sea." *Journal of Aquatic Ecosystem Stress and Recovery* 7 (4):299-315. doi: 10.1023/a:1009963912171.

Armstrong, Claire W., Naomi Foley, Rob Tinch, and Sybille van den Hove. 2012. "Services from the Deep: Steps towards valuation of deep sea goods and services." *Ecosystems Services* 2:2-13.

Beazley, Lindsay L., Ellen L. Kenchington, Francisco Javier Murillo, and María del Mar Sacau. 2013. "Deep-sea sponge grounds enhance diversity and abundance of epibenthic megafauna in the Northwest Atlantic." *ICES Journal of Marine Science* 70 (7):1471-1490. doi: 10.1093/icesjms/fst124.

CICES. 2013. "Common International Classification of Ecosystem Services." accessed 8 Aug http://cices.eu.

Copp, G. H., M. J. Godard, I. C. Russell, E. J. Peeler, F. Gherardi, E. Tricarico, L. Miossec, P. Goulletquer, D. Almeida, J. R. Britton, L. Vilizzi, J. Mumford, C. Williams, A. Reading, E. M. A. Rees, and R. Merino-Aguirre. 2016. "A preliminary evaluation of the European Non-native Species in Aquaculture Risk Assessment Scheme applied to species listed on Annex IV of the EU Alien Species Regulation." *Fisheries Management and Ecology* 23 (1):12-20. doi: 10.1111/fme.12076.

Cox Jr., Louis Anthony (Tony). 2008. "What's Wrong with Risk Matrices?" *Risk Analysis* 28 (2):497-512.

Dalkey, N. C. 1968. Predicting the future. Santa Monica, California: The Rand Corporation.

de Loë, Rob C., Natalya Melnychuk, Dan Murray, and Ryan Plummer. 2016. "Advancing the State of Policy Delphi Practice: A Systematic Review Evaluating Methodological Evolution, Innovation, and Opportunities." *Technological Forecasting and Social Change* 104 (Supplement C):78-88. doi: https://doi.org/10.1016/j.techfore.2015.12.009.

EC. 2012. Blue Growth; opportunities for marine and maritime sustainable growth. In *Communication from the Commission to the European parliament, the Council, the European Economic and Social Committee and the Committee of the Regions*. Brussels: European Commission.

Faber, J. H., and J. van Wensem. 2012. "Elaborations on the use of the ecosystem services concept for application in ecological risk assessment for soils." *Science of The Total Environment* 415 (Supplement C):3-8. doi: https://doi.org/10.1016/j.scitotenv.2011.05.059.

Filyushkina, Anna, Niels Strange, Magnus Löf, Eugene E. Ezebilo, and Mattias Boman. 2018. "Applying the Delphi method to assess impacts of forest management on biodiversity and habitat preservation." *Forest Ecology and Management* 409:179-189. doi: https://doi.org/10.1016/j.foreco.2017.10.022.

Galparsoro, Ibon, Angel Borja, and María Calvo Uyarra. 2014. "Mapping ecosystem services provided by benthic habitats in the European North Atlantic Ocean." *Frontiers in Marine Science* 1. doi: 10.3389/fmars.2014.00023.

Gornitz, Vivien M., Richard C. Daniels, Tammy W. White, and Kevin R. Birdwell. 1994. "The role of ecological models in linking ecological risk assessment to ecosystem services in agroecosystems." *Science of The Total Environment* 415 (Supplement C):93-100. doi: https://doi.org/10.1016/j.scitotenv.2011.05.065.

Halpern, Benjamin S., Shaun Walbridge, Kimberly A. Selkoe, Carrie V. Kappel, Fiorenza Micheli, Caterina D’Agrosa, John F. Bruno, Kenneth S. Casey, Colin Ebert, Helen E. Fox, Rod Fujita, Dennis Heinemann, Hunter S. Lenihan, Elizabeth M. P. Madin, Matthew T. Perry, Elizabeth R. Selig, Mark Spalding, Robert Steneck, and Reg Watson. 2008. "A Global Map of Human Impact on Marine Ecosystems." *Science* 319 (5865):948-952. doi: 10.1126/science.1149345.
Hayes, Emily Hart, and Wayne G. Landis. 2004. "Regional Ecological Risk Assessment of a Near Shore Marine Environment: Cherry Point, WA."

Hubbard, D., and D. Evans. 2010. "Problems with scoring methods and ordinal scales in risk assessment." IBM Journal of Research and Development 54 (3):2:1-2:10. doi: 10.1147/JRD.2010.2042914.

IPBES. 2017. Update on the classification of nature’s contributions to people by the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. In Plenary of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. Fifth session, edited by The Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. Bonn, Germany.

Keller, Heather H., James McCullough, Bridget Davidson, Elisabeth Vesnauer, Manon Laporte, Leah Gramlich, Johane Allard, Paule Bernier, Donald Duerksen, and Khursheed Jeejeebhoy. 2015. "The Integrated Nutrition Pathway for Acute Care (INPAC): Building consensus with a modified Delphi." Nutrition Journal 14 (1):63. doi: 10.1186/s12937-015-0051-y.

Landeta, Jon. 2006. "Current validity of the Delphi method in social sciences." Technological Forecasting and Social Change 73 (5):467-482. doi: https://doi.org/10.1016/j.techfore.2005.09.002.

MacMillan, Douglas, Nick Hanley, and Nele Lienhoop. 2006. "Contingent valuation: Environmental polling or preference engine?" Ecological Economics 60 (1):299-307. doi: https://doi.org/10.1016/j.ecolecon.2005.11.031.

MEA. 2005. Ecosystems and Human Well-being: Synthesis. Washington, DC: Millennium Ecosystem Assessment, Island Press.

Morelli, Federico, and Anders Pape Møller. 2015. "Concerns about the use of ecosystem services as a tool for nature conservation: From misleading concepts to providing a "price" for nature, but not a "value"." European Journal of Ecology 1 (1):68-70.

MSFD. 2008. Marine Strategy Framework Directive. European Union.

Nienstedt, Karin M., Theo C. M. Brock, Joke van Wensem, Mark Montforts, Andy Hart, Alf Aagaard, Anne Alix, Jos Boesten, Stephanie K. Bopp, Colin Brown, Ettore Capri, Valery Forbes, Herbert Köpp, Matthias Liess, Robert Luttik, Lorraine Maltby, José P. Sousa, Franz Streissl, and Anthony R. Hardy. 2012. "Development of a framework based on an ecosystem services approach for deriving specific protection goals for environmental risk assessment of pesticides." Science of The Total Environment 415 (Supplement C):31-38. doi: https://doi.org/10.1016/j.scitotenv.2011.05.057.

Ntona, Mara, and Elisa Morgera. 2018. "Connecting SDG 14 with the other Sustainable Development Goals through marine spatial planning." Marine Policy 93:214-222. doi: https://doi.org/10.1016/j.marpol.2017.06.020.

Oevelen, Dick van, Gerard Duineveld, Marc Lavaleye, Furu Mienis, Karline Soetaert, and Carlo H. R. Heip. 2009. "The cold-water coral community as hotspot of carbon cycling on continental margins: A food-web analysis from Rockall Bank (northeast Atlantic)." Limnology and Oceanography 54 (6):1829-1844. doi: 10.4319/lo.2009.54.6.1829.

Olita, Antonio, Andrea Cucco, Simone Simeone, Alberto Ribotti, Leopoldo Fazioli, Barbara Sorgente, and Roberto Sorgente. 2012. "Oil spill hazard and risk assessment for the shorelines of a Mediterranean coastal archipelago." Ocean & Coastal Management 57 (Supplement C):44-52. doi: https://doi.org/10.1016/j.ocecoaman.2011.11.006.

Ramirez-Llodra, Eva, Paul A. Tyler, Maria C. Baker, Odd Aksel Bergstad, Malcolm R. Clark, Elva Escobar, Lisa A. Levin, Lenaick Menot, Ashley A. Rowden, Craig R. Smith, and Cindy L. Van Dover. 2011. "Man and the Last Great Wilderness: Human Impact on the Deep Sea." PLoS ONE 6 (8):e22588. doi: 10.1371/journal.pone.0022588.
Scolozzi, Rocco, Elisa Morin, and Riccardo Santolini. 2012. "Delphi-based change assessment in ecosystem service values to support strategic spatial planning in Italian landscapes." *Ecological Indicators* 21:134-144. doi: [http://dx.doi.org/10.1016/j.ecoind.2011.07.019](http://dx.doi.org/10.1016/j.ecoind.2011.07.019).

Silvertown, Jonathan. 2015. "Have Ecosystem Services Been Oversold?" *Trends in Ecology & Evolution* 30 (11):641-648. doi: [http://dx.doi.org/10.1016/j.tree.2015.08.007](http://dx.doi.org/10.1016/j.tree.2015.08.007).

Soares, C. Guedes, and A. P. Teixeira. 2001. "Risk assessment in maritime transportation." *Reliability Engineering & System Safety* 74 (3):299-309. doi: [https://doi.org/10.1016/S0951-8320(01)00104-1](https://doi.org/10.1016/S0951-8320(01)00104-1).

Staples, D., R. Brainard, S. Capezzuoli, S. Funge-Smith, C. Grose, A. Heenan, R. Hermes, P. Maurin, M. Moews, C. O’Brien, and R. Pomeroy. 2014. Essential EAFM. Ecosystem Approach to Fisheries Management Training Course. Volume 1 - For Trainees. In *RAP Publication*. Bangkok, Thailand: FAO Regional Office for Asia and the Pacific.

Steen, Jenny T van der, Lukas Radbruch, Cees MPM Hertogh, Marike E de Boer, Julian C Hughes, Philip Larkin, Anneke I Francke, Saskia Jünger, Dianne Gove, Pam Firth, Raymond TCM Koopmans, Ladislav Volicer, and on behalf of the European Association for Palliative Care. 2014. "White paper defining optimal palliative care in older people with dementia: A Delphi study and recommendations from the European Association for Palliative Care." *Palliative Medicine* 28 (3):197-209. doi: 10.1177/0269216313493685.

Stenseke, Marie, and Anne Larigauderie. 2018. "The role, importance and challenges of social sciences and humanities in the work of the intergovernmental science-policy platform on biodiversity and ecosystem services (IPBES)." *Innovation: The European Journal of Social Science Research* 31 (sup1):S10-S14. doi: 10.1080/13511610.2017.1398076.

Stirling, Andrew. 1998. "Risk at a turning point?" *Journal of Risk Research* 1 (2):97-109.

Strand, Jon, Richard T. Carson, Stale Navrud, Ariel Ortiz-Bobea, and Jeffrey R. Vincent. 2017. "Using the Delphi method to value protection of the Amazon rainforest." *Ecological Economics* 131 (Supplement C):475-484. doi: [https://doi.org/10.1016/j.ecolecon.2016.09.028](https://doi.org/10.1016/j.ecolecon.2016.09.028).

Sullivan, Sian. 2010. "'Ecosystem Service Commodities' - A New Imperial Ecology? Implications for Animist Immanent Ecologies, with Deleuze and Guattari." *New Formations* 69 (69):111-128. doi: 10.3898/NEWF.69.06.2010.

Sweetman, A.K., A.R. Thurber, C.R. Smith, L.A. Levin, C.L. Wei, A.J. Gooday, D.O. Jones, M. Rex, M. Yasuhara, J. Ingels, H.A. Ruhl, C.A. Frieder, R. Donavaro, L. Würzberg, A. Baco, B.M. Grupe, A. Pasulka, K.S. Meyer, K.M. Dunlop, L.-A. Henry, and J.M. Roberts. 2017. "Major impacts of climate change on deep-sea benthic ecosystems." *Elementa: Science of the Anthropocene* 5 (4). doi: [http://doi.org/10.1525/elementa.203](http://doi.org/10.1525/elementa.203).

TEEB. 2010. *The Economics of Ecosystems and Biodiversity. Ecological and Economic Foundations*. London, Washington DC: Earthscan.

Thurber, A. R., A. K. Sweetman, B. E. Narayanaswamy, D. O. B. Jones, J. Ingels, and R. L. Hansman. 2014. "Ecosystem function and services provided by the deep sea." *Biogeosciences* 11 (14):3941-3963. doi: 10.5194/bg-11-3941-2014.

Toppinen, Anne, Satu Pätäri, Anni Tuppura, and Ari Jantunen. 2017. "The European pulp and paper industry in transition to a bio-economy: A Delphi study." *Futures* 88 (Supplement C):1-14. doi: [https://doi.org/10.1016/j.futures.2017.02.002](https://doi.org/10.1016/j.futures.2017.02.002).

Vanreusel, Ann, Gustavo Fonseca, Roberto Danovaro, Maria Cristina Da Silva, André M. Esteves, Tim Ferrero, Gunnar Gad, Valentina Galtsova, Cristina Gambi, Veronica Da Fonseca Genevois, Jeroen Ingels, Baban Ingle, Nikolaos Lampadariou, Bea Mercckx, Dmitry Milijutin, Maria Miljutina, Agnes Muthumbi, Sergio Netto, Daria Portnova, Teresa Radziejewska, Maarten Raes, Alexi Tchesunov, Jan Vanaverbeke, Saskia Van Gaever, Virág Venekey, Tania Nara Bezerra, Hannah Flint, John Copley, Ellen Pape, Daniela Zeppilli, Pedro Arbizu Martinez, and Joelle Galeron. 2010. "The contribution of deep-sea macrohabitat heterogeneity to global nematode diversity." *Marine Ecology* 31 (1):6-20. doi: 10.1111/j.1439-0485.2009.00352.x.
Appendix 1. Delphi survey explanatory material

Dear scientist,

As part of WP5 we are aiming to identify the **risks and pressures to ecosystem services** in the North Atlantic from existing and potential future economic activity. To achieve this we are carrying out a Delphi study among scientists to probe for information on risks to ecosystem services that the ocean provides.

The Delphi method relies on a panel of experts to gather information; this is often due to limited knowledge regarding the service or good. The technique gathers expert opinion, usually in an iterative, anonymous survey with feedback. The objective is to allow information produced by an expert group to be evaluated, building consensus over time.

The survey is therefore sent around twice or more. In the second round the information regarding the results of the first round are distributed in order to allow the expert to re-evaluate their previous assessment and to see if there may be some more agreement or convergence regarding the issue surveyed.

We realize that you may not have detailed knowledge regarding parts of the survey. Note however that the survey is an attempt to assess expert **opinion**, especially where knowledge is limited, as in the deep sea. This is therefore a survey of your personal opinion.

The risk assessment matrix is the central part of the survey, but the table of ecosystem services in case study areas, and the follow-up questions are also central to different deliverables in WP5.

Attached is an explanation of the survey.

**THE SURVEY EXPLAINED**

1. Please enter the relevant personal information.

Example:
2. Ecosystem services are listed along the side of the risk matrix and the table of case study ecosystem services. If you feel central services are missing, please add to the Other box.

| Ecosystem services:     | Provisioning               | Fish/shellfish             |
|-------------------------|----------------------------|---------------------------|
|                         | Oil/gas/energy             |                           |
|                         | Minerals                   |                           |
|                         | Chemicals/pharmaceuticals  |                           |
|                         | Waste disposal sites       |                           |
|                         | Raw materials              |                           |
|                         | Other…                     |                           |
|                         | Regulating                 | Climate regulation        |
|                         | Waste absorption/detoxification |                     |
|                         | Carbon sequestration/absorption |                 |
|                         | Biological control         |                           |
|                         | Other…                     |                           |
|                         | Cultural                   | Recreation/tourism         |
|                         | Educational                |                           |
|                         | Cultural heritage          | Existence/bequest         |
|                         | Biodiversity               |                           |
|                         | Other…                     |                           |
|                         | Supporting                 | Nutrient cycling / biological pump |
|                         | Habitat                    |                           |
|                         | Resilience                 | Primary production        |
|                         | Biodiversity               | Water circulation/exchange |
|                         | Other…                     |                           |
Note that in the risk assessment matrix we are asking you to refer to the North Atlantic overall (i.e. not just your case study area). Associated human pressures are shown in the top row of the matrix. Additional risks or pressures can be added to the ‘Other’ box at the end.

The first four human activity/impacts in the risk matrix:

| Temperature change | Ocean acidification | Fishing | Pollution |
|--------------------|---------------------|---------|-----------|
| Pos/Neg Effect Likelihood | Pos/Neg Effect Likelihood | Pos/Neg Effect Likelihood | Pos/Neg Effect Likelihood |

The different human activity/impacts are to be assessed using the three measures below:

- **Positive and/or negative effect** (+, -, or na, i.e. positive effect, negative effect or not applicable)
- **Long run effect - up to year 2100** (Number shows degree of severity of effect from 1 to 5 where 1 = very low to 5 = very high degree of severity)
- **Likelihood of effect occurring** (Number shows how probable it is that there will be an effect upon the ecosystem service 1 = very low to 5 = very high probability)

I.e. identify whether each activity / impact will have a positive or negative effect on the different ecosystem service. If you think there may be both positive and negative effects, then you can put this in on the separate lines in the relevant boxes (see example below).

Then rank both the effect and the likelihood of the effect occurring on scales of 1 to 5.

Example of filling in the matrix (note: If you think some activities/impacts are not applicable in relation to some ecosystem services, then just write na in the Pos/Neg box):

| Ecosystem services: Provisioning Fish/shellfish Oil/gas/energy | Pos/Neg | Effect | Likelihood | Pos/Neg | Effect | Likelihood | Pos/Neg | Effect | Likelihood |
|-------------------|---------|--------|-----------|---------|--------|-----------|---------|--------|-----------|
|                    | +       | 3      | 3         | -       | 4      | 5         | -       | 2      | 4         |
|                    | na      | na     | na        | na      | na     | na        |

After you have filled in the matrix, please assess your personal certainty with regard to your assessment (on a scale from 1 to 5), and state which aspects you are most certain and uncertain about.

Example:
In the Ecosystem service table, we ask you to state the case study area (or areas) you are referring to, and then tick the cell if the relevant ecosystem service is present.

Example using the LOVE and Azorean case study areas:

| Ecosystem services | Case study area: LOVE | Case study area: Azores |
|--------------------|-----------------------|-------------------------|
| Provisioning       | Fish/shellfish        | x                       |
|                    | Oil/gas/energy        | x                       |
|                    | Minerals              | x                       |
|                    | Chemical/Pharmaceuticals | x                   |
|                    | Waste disposal sites  | x                       |
|                    | Raw materials         | x                       |
|                    | Other…                |                         |
| Regulating         | Climate regulation    | x                       |
|                    | Waste absorption/detoxification | x                   |
|                    | Carbon sequestration/absorption | x       |
|                    | Biological regulation | x                       |
|                    | Other…                |                         |
| Cultural services  | Recreation            | x                       |

The final open-ended questions in the survey are valuable input for WPS, and give you an opportunity to comment.

Please remember to send to claire.armstrong@uit.no

Thank you very much!
Appendix 2. The Delphi survey – version 1

| Question                                                                 | Rating | Expert 1 | Expert 2 | Expert 3 |
|-------------------------------------------------------------------------|--------|----------|----------|----------|
| Q1                                                                       |        |          |          |          |
| Q2                                                                       |        |          |          |          |
| Q3                                                                       |        |          |          |          |
| Q4                                                                       |        |          |          |          |
| Q5                                                                       |        |          |          |          |
| Q6                                                                       |        |          |          |          |
| Q7                                                                       |        |          |          |          |
| Q8                                                                       |        |          |          |          |
| Q9                                                                       |        |          |          |          |
| Q10                                                                      |        |          |          |          |

In review...
In review

| Case Study Area | Yes | No | Not Sure |
|----------------|-----|----|----------|
| Ecosystem services | 0   | 0  | 0         |
| Provisions       | 0   | 0  | 0         |
| Non-use values   | 0   | 0  | 0         |
| Cultural values  | 0   | 0  | 0         |
| Other            | 0   | 0  | 0         |

| Questions | Yes | No | Not Sure |
|-----------|-----|----|----------|
| 01. Are there some aspects above that you feel very certain or uncertain about? | Very certain: | | Very uncertain: |
| 02. Please note the ecosystem services you believe to be present in one specific Atlas case study area of your choice. Name the case study area: | | | |
Appendix 3. Text in the 2nd Delphi survey about results from the 1st Delphi survey. Assessing the risk in the Delphi survey – first round

For Tables 1 and 2 below we computed median scores for all negative effects and likelihoods that experts scored for the ecosystem services in Round 1 of the ATLAS Delphi survey. These median scores were used to classify the effects and likelihoods into five classes ranging from “very low” effects and likelihoods to “very high” effects and likelihoods. The colour coding is given in the tables below.

### Table 1. The negative effect of human activities on ecosystem services

| EFFECT | Provisioning |
|--------|--------------|
|        | Fish/shellfish |
|        | Oil/gas/energy |
|        | Minerals |
|        | Chemicals/pharmaceuticals |
|        | Waste disposal sites |
|        | Raw materials |
|        | Regulating |
|        | Climate regulation |
|        | Waste absorption/detoxification |
|        | Carbon sequestration/absorption |
|        | Biological control |
|        | Cultural |
|        | Recreation/tourism |
|        | Educational |
|        | Cultural heritage |
|        | Evidence/Bequest |
|        | Biodiversity |
|        | Supporting |
|        | Nutrient cycling / biological pump |
|        | Habitat |
|        | Resilience |
|        | Primary production |
|        | Biodiversity |
|        | Water circulation/exchange |

| EFFECT | TEMP CHANGE | OCEAN ACID | FISHING | POLLUTION | OIL/GAS | MINING | TOURISM | BLUE BIOTECH | CUMULATIVE |
|--------|-------------|------------|---------|-----------|---------|--------|---------|--------------|------------|

| Classes | Effect/Likelihood | Colour |
|---------|-------------------|--------|
| Very low | 1.0 to 1.7 | green |
| Low     | greater than 1.7 to 2.5 | yellow |
| Medium  | greater than 2.1 to 3.5 | orange |
| High    | greater than 3.1 to 4.1 | red |
| Very high | greater than 4.1 to 5.0 | orange |

In review
Table 2 The likelihood of negative effects on ecosystem services

| Likelihood - median negative |
|-------------------------------|
| Provisioning                 |
| Fish/shellfish                |
| Oil/gas/energy                |
| Minerals                      |
| Chemicals/pharmaceuticals    |
| Waste disposal sites          |
| Raw materials                 |
| Regulating                   |
| Climate regulation           |
| Waste absorption/desorption   |
| Carbon sequestration/desorption|
| Biological control           |
| Cultural                      |
| Recreation/tourism            |
| Educational                   |
| Cultural heritage             |
| Existence/inheritance        |
| Biodiversity                  |
| Supporting                   |
| Nutrient cycling/biological pump| |
| Habitat                      |
| Resilience                   |
| Primary production           |
| Biodiversity                  |
| Water circulation/exchange    |

| Classes     | Effect/Likelihood | Colour |
|-------------|-------------------|--------|
| Very low    | 1.0 to 1.7        |        |
| Low         | greater than 1.7 to 2.5 |        |
| Medium      | greater than 2.5 to 3.3 |        |
| High        | greater than 3.3 to 4.1 |        |
| Very high   | greater than 4.1 to 5.0 |        |

Median Effect and Likelihood on all Ecosystem Services

In these bubble plots we graph the median effect and likelihood of all human impacts upon all ecosystem services. The sizes of the bubbles are determined by the number of services in each median category. The green bubbles are the number of services that are positively impacted, while the red are the services that are negatively impacted. For instance, when looking at the top left bubble plot, it presents the median effect and likelihood of temperature change on ecosystem services. Here we observe that there is a large number of services with a median of about 3 for both effect and likelihood, but a few services with high negative risk, i.e., the red bubble at point (4,4).

We created these plots by first dividing responses into positive and negative effects on ecosystem services. We then computed frequencies for each coordinate of effects and their corresponding likelihood scores. The coordinates of effects and likelihoods were plotted as bubbles and the sizes of the bubbles are determined by the frequencies. We performed the above two procedures for negative and positive effects separately.
Ecosystem Services Risk Assessment Matrix

The median scores we presented for both effects and likelihoods separately in Tables 1 and 2 above, were combined for risk assessment using the risk assessment matrix in Figure 2 below. In the risk assessment matrix, high effects and high likelihoods indicate high risk and low effect and low likelihoods indicate low risk. If we use a risk reporting matrix such as the one given in Figure 2 below, we find that there are only services at high risk level in our study where the median likelihood and effect are (4,4). I.e. there are no cases of the remaining red areas in the figure below.
Figure 2. Risk reporting matrix

Maximum high risk in the Delphi study

Risk level
- High
- Moderate
- Low

In review
### Appendix 4. Example page of SurveyMonkey 2\textsuperscript{nd} Delphi survey

#### Identifying Ecosystem Services and associated risks in the North Atlantic – ATLAS Delphi Survey Round 2

### 4. Impact of Ocean Acidification on the following ecosystem services

| Ecosystem Service                  | Acidified (Harming) | Positive Effect | Limitations of Positive | Negative Effect | Limitations of Negative |
|------------------------------------|---------------------|-----------------|--------------------------|----------------|-------------------------|
| Fish - invertebrate (Harming)      | $\bigcirc$          | $\bigcirc$      | $\bigcirc$               | $\bigcirc$     | $\bigcirc$              |
| Phytoplankton (Provisioning)       | $\bigcirc$          | $\bigcirc$      | $\bigcirc$               | $\bigcirc$     | $\bigcirc$              |
| Mineral (Provisioning)             | $\bigcirc$          | $\bigcirc$      | $\bigcirc$               | $\bigcirc$     | $\bigcirc$              |
| Oganic/benthic/terrestrial         | $\bigcirc$          | $\bigcirc$      | $\bigcirc$               | $\bigcirc$     | $\bigcirc$              |
| Waste disposal                     | $\bigcirc$          | $\bigcirc$      | $\bigcirc$               | $\bigcirc$     | $\bigcirc$              |
| Eel (Provisioning service)         | $\bigcirc$          | $\bigcirc$      | $\bigcirc$               | $\bigcirc$     | $\bigcirc$              |
| Carbon sequestration               | $\bigcirc$          | $\bigcirc$      | $\bigcirc$               | $\bigcirc$     | $\bigcirc$              |
| Aquatic wetland (Regulating service) | $\bigcirc$         | $\bigcirc$      | $\bigcirc$               | $\bigcirc$     | $\bigcirc$              |
| Terrestrial (Cultural service)     | $\bigcirc$          | $\bigcirc$      | $\bigcirc$               | $\bigcirc$     | $\bigcirc$              |
| Cultural heritage (Cultural service) | $\bigcirc$         | $\bigcirc$      | $\bigcirc$               | $\bigcirc$     | $\bigcirc$              |
| Ecotourism (Cultural service)      | $\bigcirc$          | $\bigcirc$      | $\bigcirc$               | $\bigcirc$     | $\bigcirc$              |
| Recreation (Cultural service)      | $\bigcirc$          | $\bigcirc$      | $\bigcirc$               | $\bigcirc$     | $\bigcirc$              |
| Total                              | $\bigcirc$          | $\bigcirc$      | $\bigcirc$               | $\bigcirc$     | $\bigcirc$              |

In review
Appendix 5. Figures from the 2nd Delphi survey, equivalent to those presented in the first survey (in Appendix 3), and figures from the first round equivalent Figures 3 and 4.
Figure 3. Negative effects of human drivers on ecosystem services, and their likelihoods. Cases where both likelihood and effect are level 4 is marked as red.
Figure 4: Ecosystem service risk levels from the negative effects of different human drivers from first survey (equivalent to Figure 3 from the second survey).
Figure 5: Human drivers risk levels upon ecosystem services. From the assessment of negative effects of human drivers on ecosystem services for first survey (equivalent to Figure 4 from the second survey).