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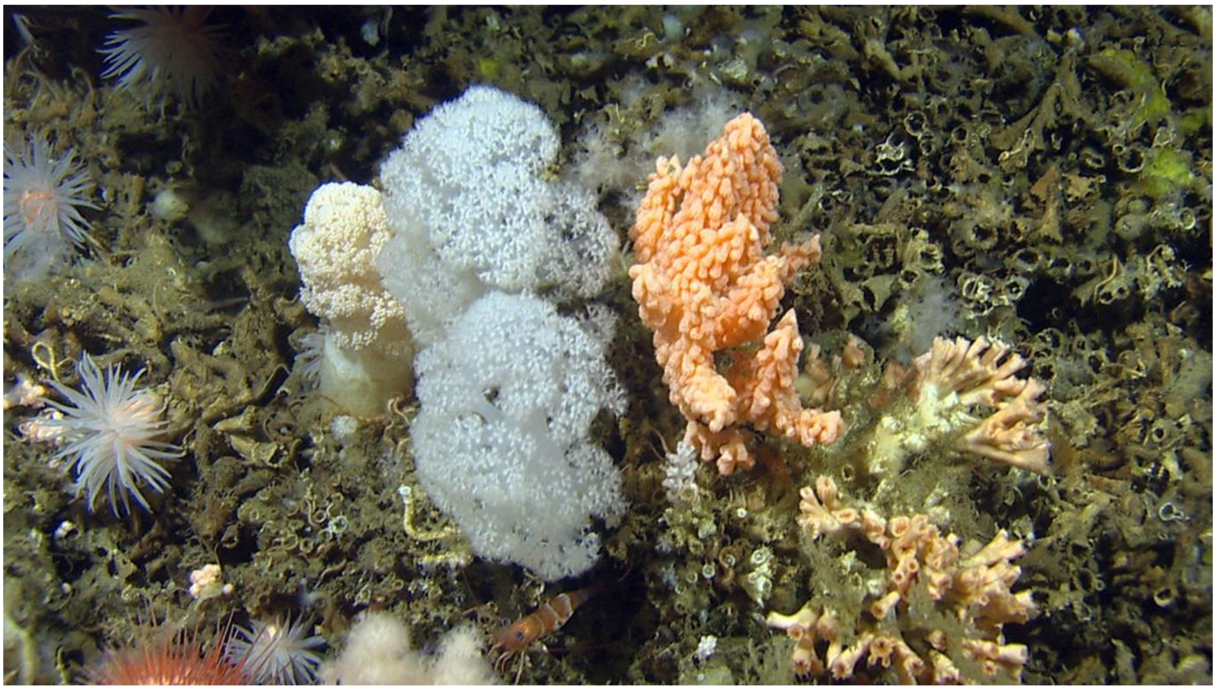
SOCIAL AND ECONOMIC ASSESSMENT OF OCEAN ACIDIFICATION - THE CASE OF COLD WATER CORAL



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TITLE:
SOCIAL AND ECONOMIC ASSESSMENT OF OCEAN ACIDIFICATION - THE CASE OF COLD WATER CORAL

Summary:

Management decisions must be taken despite large knowledge gaps regarding the impacts of ocean acidification on marine ecosystems. This report presents a framework for economic assessment and valuation of ocean acidification and its effects, illustrating how management can be informed by knowledge about ecosystem services and associated values. This can form the basis for decisions on adaptation or mitigation policies.
We give an overview of different management options. Application of the precautionary principle is also discussed.

The case of cold water corals is used to illustrate how the framework for economic valuation of ocean acidification can be applied. We identified five types of information needed to assess the socio-economic impact of ocean acidification on cold water corals and evaluated the status of knowledge of each of these types. It was concluded that the knowledge gaps made it impossible to assess the full impact of ocean acidification on cold water corals both qualitatively and quantitatively.

Due to the large uncertainties, expert opinion elicitations were used to determine likely direct physical, chemical and biological impacts of ocean acidification on cold water corals, resulting impacts on ecosystem functions and services, and possible mitigation and adaptation measures. The experts used a traffic light approach to assess their confidence regarding their suggestions. We sum up by recommending which knowledge gaps are most urgent to fill for a reasonable social and economic assessment of the effects of ocean acidification on CWCs.

While the methodology to use expert opinion for assessing impacts in a high-uncertainty setting needs to be refined, this study was valuable in identifying a framework for assessment to identify key knowledge gaps and give input to management. The experts also expressed that it was a useful exercise for them to see the relevance of their basic research into management.

Keywords: Ocean acidification, cold water corals, economic assessment, expert opinion elicitation

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Social and Economic Assessment of Ocean Acidification - the case of cold water coral

By

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Foreword

This report is product of a Fram centre project titled “Economic value and Ocean acidification”. The project has been part of the so-called ocean acidification “flagship” (research programme area) in the Fram centre. The flagship, like the Fram centre itself, is a multidisciplinary research environment.

We thank the flagship members for valuable input to the work reported here, directly or indirectly. We especially thank the participants at the expert elicitation workshop reported here.

We gratefully acknowledge financing from the FRAM Centre, UiT – The Arctic University of Norway, Norut and NIVA.

On behalf of the project group,

Jannike Falk-Andersson, Claire Armstrong and Eirik Mikkelsen

Tromsø, 05 January 2017

Summary

Management decisions must be taken despite large knowledge gaps regarding the impacts of ocean acidification on marine ecosystems. This report presents a framework for economic assessment and valuation of ocean acidification and its effects, illustrating how management can be informed by knowledge about ecosystem services and associated values. This can form the basis for decisions on adaptation or mitigation policies. Such policies can target different levels, from securing ecosystem functions to values related to ecosystems and their services to humans.

We give an overview of different management options, including the time and spatial scale they operate on, and what actors and types of policies are involved in their implementation. Application of the precautionary principle is also discussed, as this is a typical case of a complex environmental issue, both in terms of the social and natural systems impacted, which is characterised by large scientific uncertainty, potential non-linearity and thresholds.

The case of cold water corals is used to illustrate how the framework for economic valuation of ocean acidification can be applied. Cold water corals have been the focus of deep sea ecosystem service research, and we summarise current status with respect to the knowledge on their ecosystem services and associated values. Polar and sub-polar surface waters are projected to become undersaturated with respect to aragonite within the next 50 years, but model predictions suggest that the majority of the coral areas in the North Atlantic may remain in supersaturated waters, where carbonite shells are not dissolved. However, there is a lack of data on the Arctic Ocean. Regarding impacts of ocean acidification on cold water corals, the results are conflicting and there are large knowledge gaps in our understanding of impact on live corals, including indirect impacts through acidification-induced changes in the ecosystem.

We identified five types of information needed to assess the socio-economic impact of ocean acidification on cold water corals and evaluated the status of knowledge of each of these types. Knowledge on: 1) their distribution was rated low to medium, 2) their ecosystem services medium to high, 3) values related to the corals was rated as high for some services, but low for others, 4) the physical and biological impact of ocean acidification was rated low apart from dead coral dissolution, and 5) impact of ocean acidification on the ecosystem services was rated as low. It was concluded that the knowledge gaps made it impossible to assess the full impact of ocean acidification on cold water corals both qualitatively and quantitatively.

Due to the large uncertainties, expert opinion elicitations were used to determine likely direct physical, chemical and biological impacts of ocean acidification on cold water corals, resulting impacts on ecosystem functions and services, and possible mitigation and adaptation measures. The experts used a traffic light approach to assess their confidence regarding their suggestions. The direct negative impacts on live cold water corals were rated with low confidence, while for dead coral structures the confidence regarding negative impacts were high. The experts had highest confidence in adaptation measures (artificial reefs, marine protected areas and reduced fishing pressure) to

increase the resilience of the corals and the habitat services they provide. They had low confidence in geoengineering to reduce CO_2 levels.

We sum up by recommending which knowledge gaps are most urgent to fill for a reasonable social and economic assessment of the effects of ocean acidification on CWCs.

While the methodology to use expert opinion for assessing impacts in a high-uncertainty setting needs to be refined, this study was valuable in identifying a framework for assessment to identify key knowledge gaps and give input to management. The experts also expressed that it was a useful exercise for them to see the relevance of their basic research into management.

Acronyms

AMAP	Arctic Monitoring and Assessment Programme
CaCO3	Calcium carbonate
CO2	Carbon dioxide
CWC	Cold water corals
MEA	Millennium Ecosystem Assessment
RP	Revealed Preference
SP	Stated Preference
TEV	Total economic value
UNESCO	United Nations Educational, Scientific and Cultural Organization
WTP	Willingness to pay

1 INTRODUCTION: SOCIAL AND ECONOMIC ASSESSMENT OF OCEAN ACIDIFICATION

In this report we present a framework for identification and valuation of ecosystem services in the context of ocean acidification, and show how this can be relevant in guiding policy.

The report modifies and expands upon the report "The Economics of Ocean Acidification – a scoping study" (Armstrong, Holen et al. (2012)). We first present a general framework for identification and valuation of ecosystem services and summarise the ecosystem services and impacts of ocean acidification identified in the previous report. Next, we discuss the different management options available in dealing with the challenge of climate change in general. The framework for identification and valuation of ecosystem services is applied to the case of cold water corals (CWC), with a focus on CWC in Norwegian waters. The application to CWC contains both a presentation of previous valuation work conducted on CWC, the specific methods to assess and value the impacts of ocean acidification on CWC, and a discussion of the limitations of these methods. After setting the stage by reviewing what is known about CWC distribution, ecosystem services and valuation of these, CWCs are discussed in the context of ocean acidification. Expert opinion regarding ocean acidification and impacts on CWC ecosystem functions, services and policy issues is also included. Finally, policy options in terms of adaptation and mitigation in the context of CWC and ocean acidification is discussed and knowledge gaps and proposed directions for future research in this field are identified.

The report is meant to give a broad introduction to social and economic aspects of ocean acidification with a non-specialist academic readership in mind.

2 FRAMEWORK FOR IDENTIFICATION AND VALUATION OF ECOSYSTEM SERVICES

The science of identification and valuation of ecosystem services and their benefits has been developed as a response to degradation of ecosystems, in order to increase awareness of their importance to human welfare. Improved understanding of the links between ecosystems, policy and human wellbeing is hoped to aid in decision making and halt the current depletion of natural capital (MEA 2005). Ocean acidification represents a special, but not unique, case of human induced environmental change where management decisions must be made based on limited knowledge. Both the local and global impacts of altered pH in the ocean are uncertain.

In the following we present a framework for economic valuation of ocean acidification illustrating how management can be informed by knowledge about ecosystem services and their value. This is part of a larger process of understanding welfare changes due to increased CO_2 levels. Information about the economic consequences of higher CO_2 levels can provide input for adaptation and/or mitigation[1] policies (Figure 1).

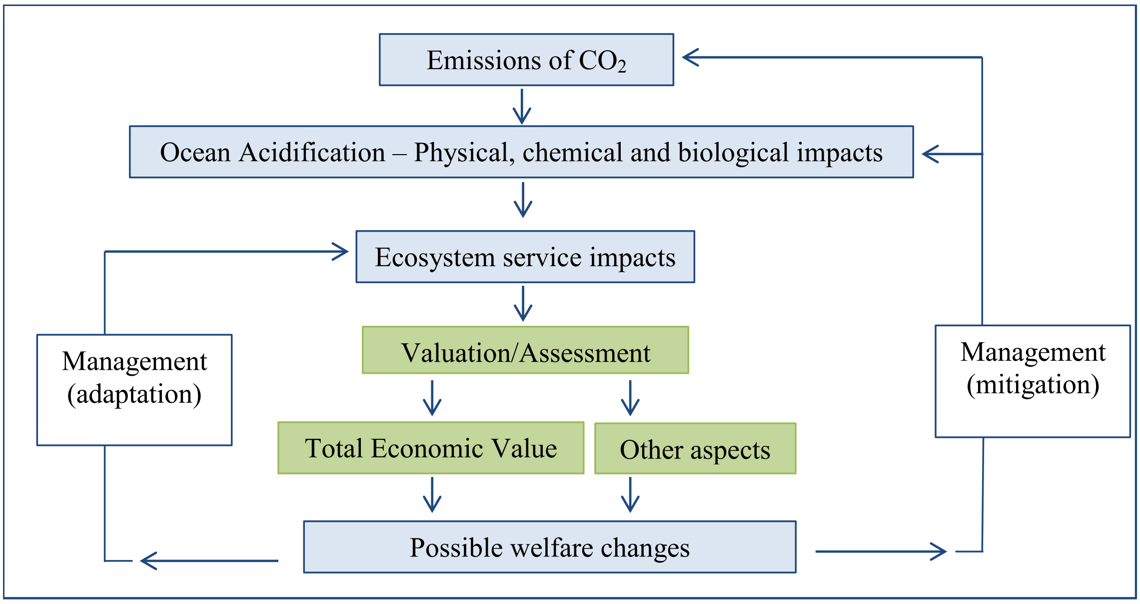

Figure 1: Impact pathway of ocean acidification illustrating how knowledge of the potential benefits and costs of CO_2 emissions may feed into management in terms of mitigation and/or adaptation (white boxes). Blue boxes are input/output, green boxes represents assessment/valuation methods and systems

The framework includes the three general recommendations that have been emphasised in reports and policy documents on ocean acidification: 1) stabilisation or reduction of atmospheric CO_2 levels; 2) preservation of ecosystem resilience by reducing non-CO_2-related threats; and 3) improved understanding of the physical, chemical and biological responses of the ocean to increased CO_2 (Rau, McLeod et al. 2012). The first point requires mitigation strategies and involves reduction of CO_2 emissions or enhancing carbon sinks, through for example targeted geo-engineering to affect ocean acidification directly. Adaptation, captured in the second point, focuses on ways to reduce or

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[1] **Mitigation:** An anthropogenic intervention to reduce the *sources* or enhance the *sinks* of *greenhouse gases*. **Adaptation:** Adjustment in natural or human systems in response to actual or expected climatic *stimuli* or their effects, which moderates harm or exploits beneficial opportunities IPCC (2007). Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. . M. L. Parry, Canziani, O.F., Palutikof, J.P., van der Linden, P.J. and Hanson, C.E. Cambridge**:** 976.

minimise any impacts of change from ocean acidification either through strengthening the capacity of the ecosystem to withstand change and/or the ability of societies to accommodate or handle changes (Hamin and Gurran 2009, Barange, Cheung et al. 2010, Rau, McLeod et al. 2012). The third point is not only about knowledge of biophysical responses, but extends to knowledge about the impact of biophysical changes on human welfare through valuation of ecosystem services.

The first step in a valuation process is to estimate physical and biological effects of increased CO_2 emissions on ecosystem functions[1] and translate this to impacts on ecosystem services. The Millennium Ecosystem Assessment framework (MEA 2005) illustrates the link between ecosystem and human well-being through identification of services that the ecosystem provides. These ecosystem services include *provisioning*, *regulating*, *cultural* and *supporting* services.

Changes in the flow of ecosystem services may impact human well-being in terms of basic material for a good life, health, social relations, security and freedom of choice and action.

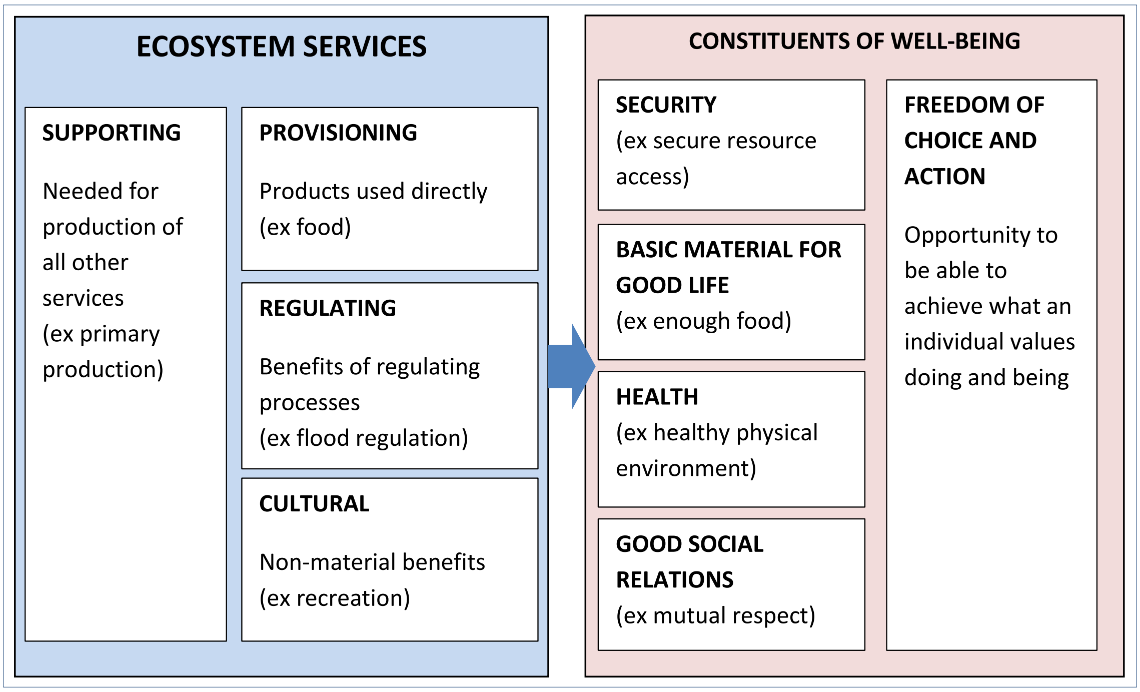

Figure 2: Ecosystem services contribute to human well-being (MA 2005)

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[1] Ecosystem functions is defined as "a subset of the interactions between ecosystem structure and processes that underpin the capacity of an ecosystem to provide goods and services" Kumar, P. (2010). The Economics of ecosystems and biodiversity: ecological and economic foundations. London, England, Earthscan.

The benefits and costs of these impacts on services are identified, demonstrated and, where possible, estimated using valuation techniques. In the *total economic value* (TEV) *framework* (Pearce 1994), welfare changes derived from individual preferences are organised systematically from use-values and non-use values. The TEV framework focuses on utilitarian values, which are the basis of traditional economic theory. These consist of direct use values (for example the value of corals mined for ornamental use), indirect use values (for example the benefits of corals as habitat for fish), option values (for example the willingness to pay to enjoy corals in the future) and non-use values (value of knowing that something exists and desire to bequest it to future generations). Figure 2 also illustrates that some values, for example the intrinsic right to exist and concerns for doing the right thing (Spash 2006), are not captured within the utilitarian value framework.

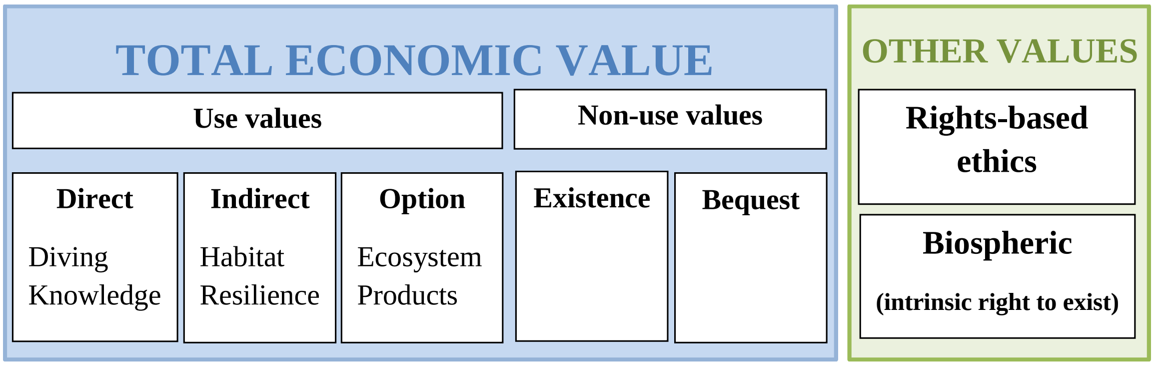


Figure 3: Total Economic Value (left) and values not included in TEV (right). Modified from Falk-Andersson, Foley et al. (2015).

The list of limitations connected to the valuation of ecosystem services in Armstrong, Holen et al. (2012) (see Table 1) emphasises the large uncertainties connected to the natural science knowledge on the impact of ocean acidification. Indeed, the estimated economic effects of ocean acidification may vary from positive to negative for many services, due to large uncertainties. Uncertainty increases as we move up the inverse pyramid of evaluating impacts (Figure 4). In the case of CWC, uncertainty increases as we move from evaluating impact on individual corals, to colonies of polyps, to the role corals have as habitat for fish and finally for commercial fish stocks.

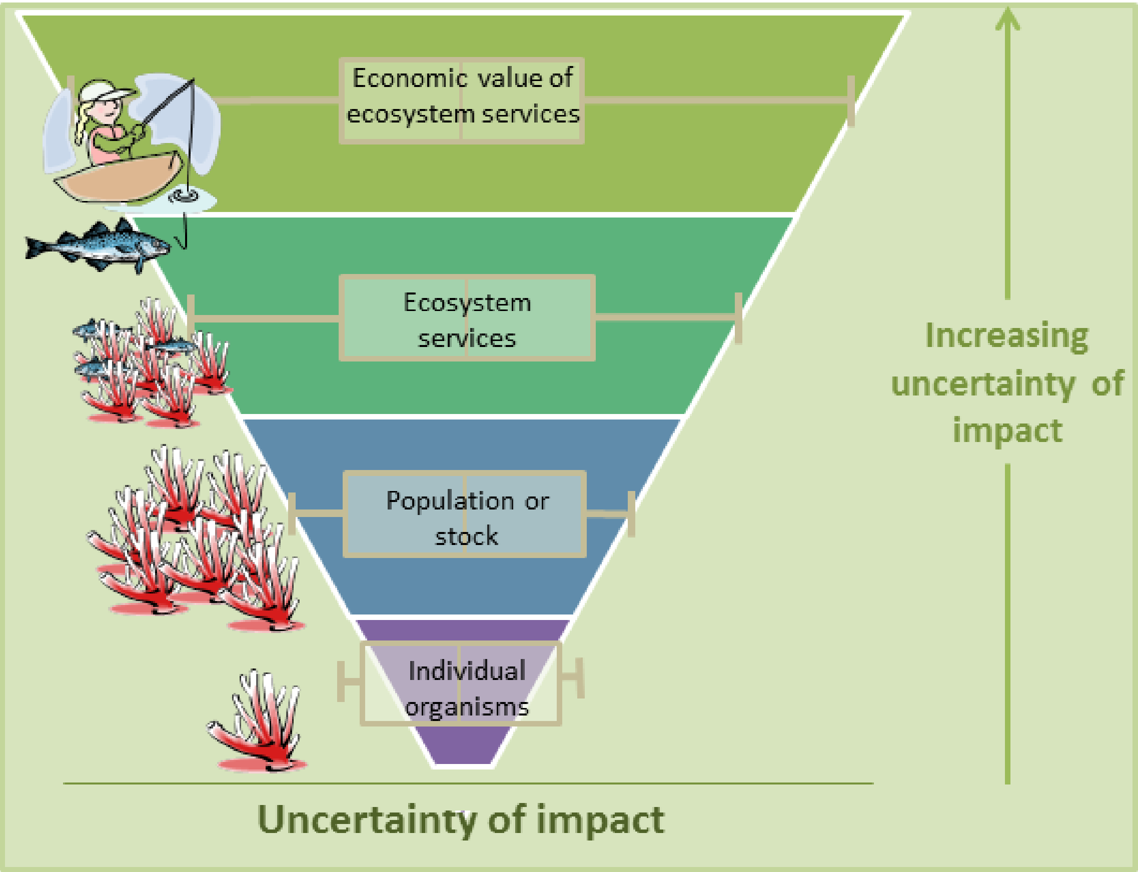
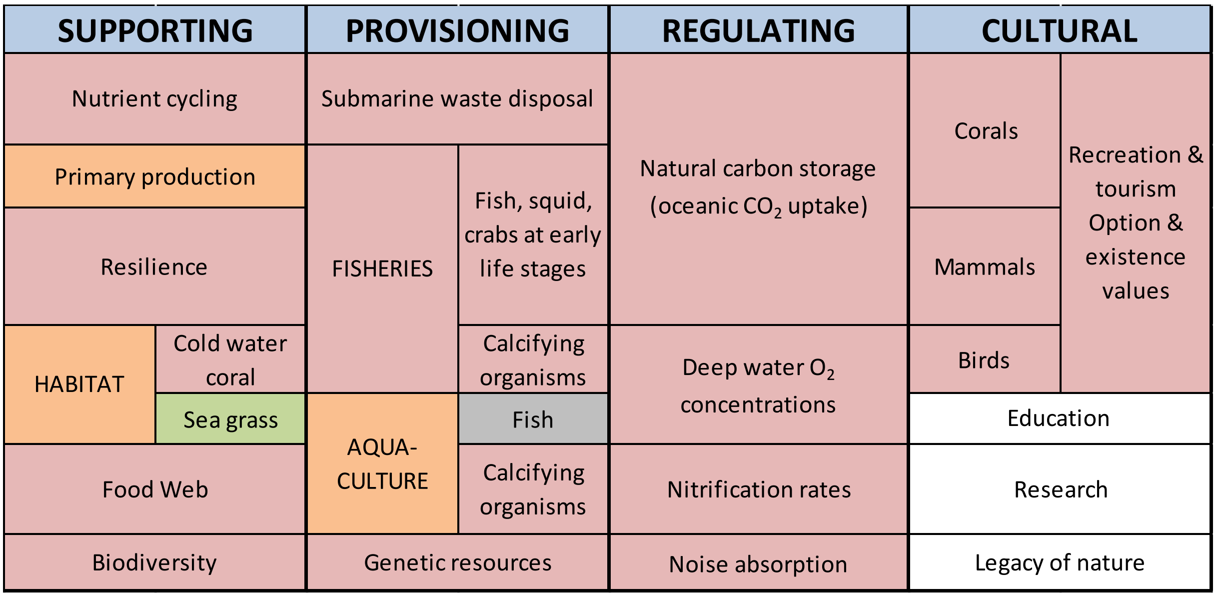


Figure 4: The inverse pyramid of evaluating the positive or negative impact of ocean acidification. This illustrates that the uncertainty of estimating impacts increases as we move up from effects on individual organisms to economic value of ecosystem services.

The impacts of ocean acidification can range from negative to positive, including no impact. The economic review of the impacts of ocean acidification in Norwegian waters conducted by Armstrong, Holen et al. (2012) is summarised in Table 1. The review is a partial analysis, neither taking account of substitution effects, nor alternative second best alternatives for example through changes in human consumption. There is very likely a bias in the literature towards studies on provisioning services. Furthermore, the resolution of the study also affects the analysis of ecosystem services. In the overview of impacts of ocean acidification on the ecosystem as a whole, cold water coral is listed as a supporting service providing habitat. The in-depth analysis of CWC to follow illustrates that the individual resources themselves may provide a number of ecosystem services, which may vary over time, space and users.

Table 1: Summary of ecosystem service impacts of Ocean Acidification as identified in Armstrong et al 2012. Purple = negative, green = positive, grey = no effect, orange = mixed effects. Services where information was too limited to suggest impact are marked white



SUPPORTING		PROVISIONING		REGULATING	CULTURAL	
Nutrient cycling		Submarine waste disposal		Natural carbon storage (oceanic CO_2 uptake)	Corals	Recreation & tourism Option & existence values
Primary production		FISHERIES	Fish, squid, crabs at early life stages			
Resilience					Mammals	
HABITAT	Cold water coral		Calcifying organisms	Deep water O_2 concentrations	Birds	
	Sea grass	AQUA-CULTURE	Fish		Education	
Food Web			Calcifying organisms	Nitrification rates	Research	
Biodiversity		Genetic resources		Noise absorption	Legacy of nature	

Furthermore, Armstrong, Holen et al. (2012) stress that the limitations on valuing ecosystem services become particularly apparent when ecosystems approach critical thresholds and/or in the case of irreversibility. In addition, identifying and capturing preferences with respect to management of natural resources is often complicated by missing markets, asymmetries, and multiple stakeholders often with conflicting interests (Armstrong and van den Hove 2008, Glenn, Wattage et al. 2010, Falk-Andersson, Foley et al. 2015).

3 MANAGEMENT OPTIONS: MITIGATION, ADAPTATION OR SUFFERING

Ocean acidification represents serious management challenges to mankind. In dealing with climate change, three main options are usually presented. They are mitigation, adaptation and suffering (Hultman, Hassenzahl et al. 2010). These three main options are also largely relevant as regards ocean acidification, and hence we discuss them in more depth in the following. Those wanting input on practical measures to prepare national or regional policies to adapt or mitigate ocean acidification, particularly for coastal environments, should consult (Strong, Kroeker et al. 2014).

While climate change mitigation includes efforts that reduce greenhouse gas emissions or enhance their sinks, adaptation measures are efforts to reduce vulnerability to or effects of the impacts of climate change (Kok and de Coninck 2007). Billé, Kelly et al. (2013) classify management and policy options to deal with ocean acidification into four main categories: preventing ocean acidification; strengthening ecosystem resilience; adapting human activities; and repairing damages. Within these categories they discuss a number of options, which we will briefly go through here.

The potential conflict between mitigation and adaptation strategies is well documented in the climate change literature (see e.g.Klein, Schipper et al. (2005), Hamin and Gurran (2009) for examples). The two approaches differ in three different ways which could explain the sources of these conflict (Klein, Schipper et al. 2005).

Firstly, they operate at different temporal and spatial scales. While benefits of mitigation today will only be evident in several decades because of the time lag in global climate systems, adaptation should be apparent in the near future. Furthermore, mitigation has global benefits, while adaptation is typically applied locally.

Secondly, they differ in the extent to which we can determine, compare and aggregate costs and benefits related to them. Mitigation options can be compared in terms of costs and CO_2 reductions achieved, and thus in their cost-effectiveness. The benefits of adaptation, however, are more difficult to express in a single metric, which makes comparisons between adaptation options difficult.

Thirdly, mitigation and adaptation strategies differ in terms of the actors and types of policies that are involved in implementation. Mitigation involves a limited number of well organised sectors that are closely linked to national planning and policy making, that take medium to long-term investment decisions. These are primarily energy and transportation sectors in industrialised countries as well as energy and forestry sectors in developing countries, in addition to the agricultural sector. For adaptation, however, a large variety of sectors is involved, spanning fisheries, aquaculture, tourism, water supply, urban planning and nature conservation. The decision levels range from individual to national, and though clearly this may vary, Klein, Schipper et al. (2005) think that climate change is generally not of immediate concern for these actors. Furthermore, while the impacts of climate change can be large, there is limited incentive to incorporate adaptation into decision-making. This because medium to long-term planning is not encouraged by policy or due to market failures, responsibilities for action are unclear, or because adaptation is concerned with collective goods (for example ecosystem integrity) (Klein, Schipper et al. 2005).

3.1 MITIGATION

Billé, Kelly et al. (2013) point to four different ways to mitigate ocean acidification. The first is to limit the emissions of CO_2 to the atmosphere, and the second to enhance the sinks of CO_2. The two other mitigation options relate to other (potential) causes of ocean acidification, namely local anthropogenic pollution apart from CO_2, that exacerbate the effects of ocean acidification at smaller spatial scales, and that methane currently trapped in methane hydrates below the ocean floor may be heated, convert to gas and escape into the ocean where it will react to create CO_2.

Limiting the emissions of carbon dioxide to the atmosphere is the main challenge we face to reduce climate change. It is seen as having the greatest potential, together with removal of carbon dioxide from the atmosphere. Techniques proposed to remove CO_2

from the atmosphere include fertilization of the oceans with iron to boost plankton growth and CO_2 uptake, and direct scrubbing of the air (Robock 2008, Victor, Morgan et al. 2009, Hultman, Hassenzahl et al. 2010).

It has been argued that geoengineering may give us systems to mitigate climate change impacts, and that the cost of this will be small compared to the costs of reducing CO_2 emissions and the cost of the effects of global warming (Barrett 2008). Defence shields, for example established by launching particles into the atmosphere that reflect sunlight back into space and thus cool the earth, could protect against climatic changes that threaten ecosystems and people (Barrett 2008, Victor, Morgan et al. 2009). Increased atmospheric reflection is regarded as the most promising and cost-effective geoengineering strategy to cool the planet. However, side effects of geoengineering technology could be catastrophic (see for example Robock (2008)). Increased reflection of sunlight would not mitigate CO_2 as a cause of ocean acidification, but it could by lowering the chance that methane from methane hydrates gets released.

Research on geoengineering is limited for a number of reasons. The experiments required are controversial and our understanding of climate system responses is poor. Furthermore, scientists fear that development of such techniques could reduce governments' incentives to invest in emission-reduction and that funds may be diverted from climate-science research and abatement technologies (Robock 2008, Victor, Morgan et al. 2009).

The importance of reducing other pollutants that contribute to local coastal ocean acidification is not clear (Billé, Kelly et al. 2013), but it could be significant. Billé, Kelly et al. (2013) also discuss ways to increase ocean pH, by adding chemicals like calcium carbonate. This is the technique that has been used to counter acidification of lakes due to acid rain. The feasibility of such measures to counter ocean acidification is unclear.

3.2 ADAPTATION

While mitigation has been the primary focus of climate policy so far, it is increasingly recognised that adaptation is needed to reduce future suffering (Hultman, Hassenzahl et al. 2010). Despite growing awareness of the scale of potential impacts and related costs, it is seen as unrealistic to assume that humans will take the necessary steps to stabilize atmospheric CO_2 at a level that will reduce or prevent on-going damages (Rau, McLeod et al. 2012). Billé, Kelly et al. (2013) define adaptation to ocean acidification "as the adjustment of natural or human systems in response to present and future acidification or to its effects, in order to mitigate the damage or to exploit beneficial opportunities."

Trying to increase the resilience of natural systems to ocean acidification is one type of adaptation. Resilience consists of two parts. It is the ability of an ecosystem to absorb a disturbance without getting large changes in its ecosystem functions, and it is the ability to restore itself to its original condition after having been disturbed Billé, Kelly et al. (2013). Resilience is expected to be higher with higher biological diversity (Folke, Carpenter et al. 2004). Policies that enhance diversity could thus increase ecosystem resilience to ocean acidification. Such policies could be based on Marine Protected Areas (Billé, Kelly et al. 2013).

The concept of adaptive management has been developed recognizing that ecosystems are not necessarily resilient. Regime shifts have been documented in numerous ecosystems in the marine realm, such as kelp forests and coral reefs (see Folke, Carpenter et al. (2004) for a review), and have influenced the ability of ecosystems to generate services. Key drivers of oceanic regime shifts are abiotic and biotic processes, as well as alterations of structural habitat, such as CWC (deYoung, Barange et al. 2008). Likelihood of regime shifts increases when humans reduce the resilience of ecosystems, for example through pollution or removal of key functional groups, or as a combination of pressures. Reducing other stressors could thus increase the resilience of ecosystems to ocean acidification (Billé, Kelly et al. 2013), either to keep the resilience within what is deemed safe limits, or buying time to find other methods to deal with ocean acidification and its effects.

The resilience concept extended to human systems is the capacity to accommodate or adapt successfully to external threats (Hamin and Gurran 2009). The focus in adaptive management has been to build resilience into both ecological and social systems (Folke, Carpenter et al. 2004, deYoung, Barange et al. 2008). Both adaptation and mitigation strategies can achieve resilience through reduced vulnerability, and thereby reduced biophysical, social and economic risks associated with climate change (Hamin and Gurran 2009). This includes the ability to exploit new opportunities in the stressed environment (Hultman, Hassenzahl et al. 2010).

Billé, Kelly et al. (2013) describe examples of human/social adaptation to ocean acidification, and discuss barriers and potentials for such adaptation based on climate changes studies. Depending on the issue at hand, very many various measures and strategies could be relevant.

Limited knowledge of drivers for change and internal ecosystem dynamics are recognised as barriers to understanding regime shifts and thereby also how management should deal with them. Interdisciplinary simulation studies have looked at optimal adaptive management strategies for marine fisheries that undergo regime shifts. These studies recommend changing harvest rates when there are indications that a regime shift has occurred, rather than waiting until the productivity level of the new regime has been verified (deYoung, Barange et al. 2008).

Alternatively, conventional single-species management dealing with short-term fluctuations, could be combined with a long term management strategy driving fleet capacity and investment cycles (deYoung, Barange et al. 2008). They also stress the need to analyse climate change scenarios in a two-way coupled system including both the human and the ecological dimension. Focus should not only be on estimating biophysical changes and the consequences for human societies, but also the responses of human societies to climate change, and subsequent feedback to the biophysical world (Barange, Cheung et al. 2010).

The final options that Billé, Kelly et al. (2013) discuss are to actively restore degraded ecosystems, or to tailor local ecosystems in anticipation of how ocean acidification might impact the local environment. Around tropical coral reefs, that has a different ecology to CWC, algae and seaweeds show promising ability to reduce the local process of acidification. It has also been proposed that selectively bred lines of acidification-tolerant strains of target species be used in restoration efforts (op. cit.).

3.3 THE PRECAUTIONARY PRINCIPLE

In response to the many challenges involved in risk analysis, including when assessing climate change, approaches that seek to embed traditional risk analysis in a wider societal decision-making setting have been developed. These acknowledge that our ability to understand and predict complex systems is limited and embrace the precautionary principle that states that scientific uncertainty should not prevent action if plausible consequences are severe or irreversible (UNESCO 2005, Hultman, Hassenzahl et al. 2010). The precautionary principle applies to issues that are complex, both with respect to social and natural systems, and are characterised by non-linearity and thresholds. Furthermore, it applies to cases where it is not possible to quantify scientific uncertainty (UNESCO 2005).

Finding an economically feasible way to implement the principle has been identified as important in reconciling competing points of views. Incorporating the precautionary approach into cost-benefit analysis to balance economic growth and environmental protection has been proposed as one solution (Kuntz-Duriseti 2004, Fenichel, Tsao et al. 2008). In this context, valuation of option values (what it is worth giving up today to keep future uncertain options available) and quasi-option values (the value of future information which can become available by delaying an irreversible development) becomes relevant (Perman, Ma et al. 2011). Such approaches include evaluating strategies under alternative and uncertain future payoff scenarios. Rather than focusing on optimising assets or payoffs, the main concern is the needs of vulnerable populations, achieving vulnerability reductions through strategic threat management, and making informed judgements about uncertain outcomes using best available quantitative tools (Hultman, Hassenzahl et al. 2010).

Regardless of the approach applied to capture option values, they are all influenced by human perceptions of risk. That risk perceptions are based on individual perceptions and values of the communities/ organizations in which they are framed has been expressed as a major limitation to risk analysis (Hultman, Hassenzahl et al. 2010). However, the precautionary principle as reviewed in UNESCO (2005) opens up for using people's perceptions in guiding policy. This is also in line with the argument that when facing large uncertainties, ethical judgement must supplement formal analysis in order to find a socially acceptable level of environmental impact (Perrings and Pearce 1994).

3.4 MULTIPLE STRESSORS

Climate change and ocean acidification may be affecting the existence and functioning of organisms, species and ecosystems. But they are typically not the only stressors. Pollution, (over-) harvesting, and habitat alteration are other examples (e.g. Breitburg and Riedel (2005), Darling and Côté (2008), Gurney, Melbourne-Thomas et al. (2013), Ban, Graham et al. (2014)). The new climate change related stressors may exacerbate the effects of the more traditional stressors.

To deal with the effects of the new stressors one option is to ameliorate the existing stressors (Keller, Gleason et al. 2009). Where marine protected areas have been used to protect against the traditional stressors, other management options include protecting potentially resilient areas, developing networks of MPAs, and integrating the various climate change stressors into MPA planning, management, and evaluation (ibid.)

MPA networks are generally accepted as an improvement over individual MPAs to address multiple threats to the marine environment. MPA networks are considered a potentially effective management approach for conserving marine biodiversity, they should be established in conjunction with other management strategies, such as fisheries regulations (Keller, Gleason et al. 2009).

4 SOCIAL AND ECONOMIC IMPACT OF OCEAN ACIDIFICATION: THE CASE OF COLD WATER CORALS

Exploration of deep-water environments the last few decades have revealed that corals are not only a tropical phenomenon, and that cold water corals (CWC) are found in cold, dark, and largely deep water of all the world’s oceans. This includes the high latitude regions where most studies of these structures have been carried out so far. Figure 5 shows distribution of CWC along the Norwegian coast as well as protected CWC areas. The latter includes the worlds’ largest known reef to date, found outside Røst in Lofoten. It is about 35 km long and 3 km wide (Freiwald, Fosså et al. 2004). Cold water corals consist of colonies of polyps connected by a common calcium carbonate frame that form complex three-dimensional structures. These colonies, connected by the skeleton the polyps makes, consist of both living and dead coral and range from a few metres in diameter to huge reef complexes (Freiwald, Fosså et al. 2004). This complexity gives support to highly biodiverse communities and provides important nursery habitats for many fish species, including commercial stocks.

While bottom trawling has so far been the main threat to cold water corals, ocean acidification may be the next on the list. Ecosystems in high latitude regions are believed to be particularly vulnerable to ocean acidification since cold water has a higher capacity to absorb carbon dioxide (AMAP 2014).

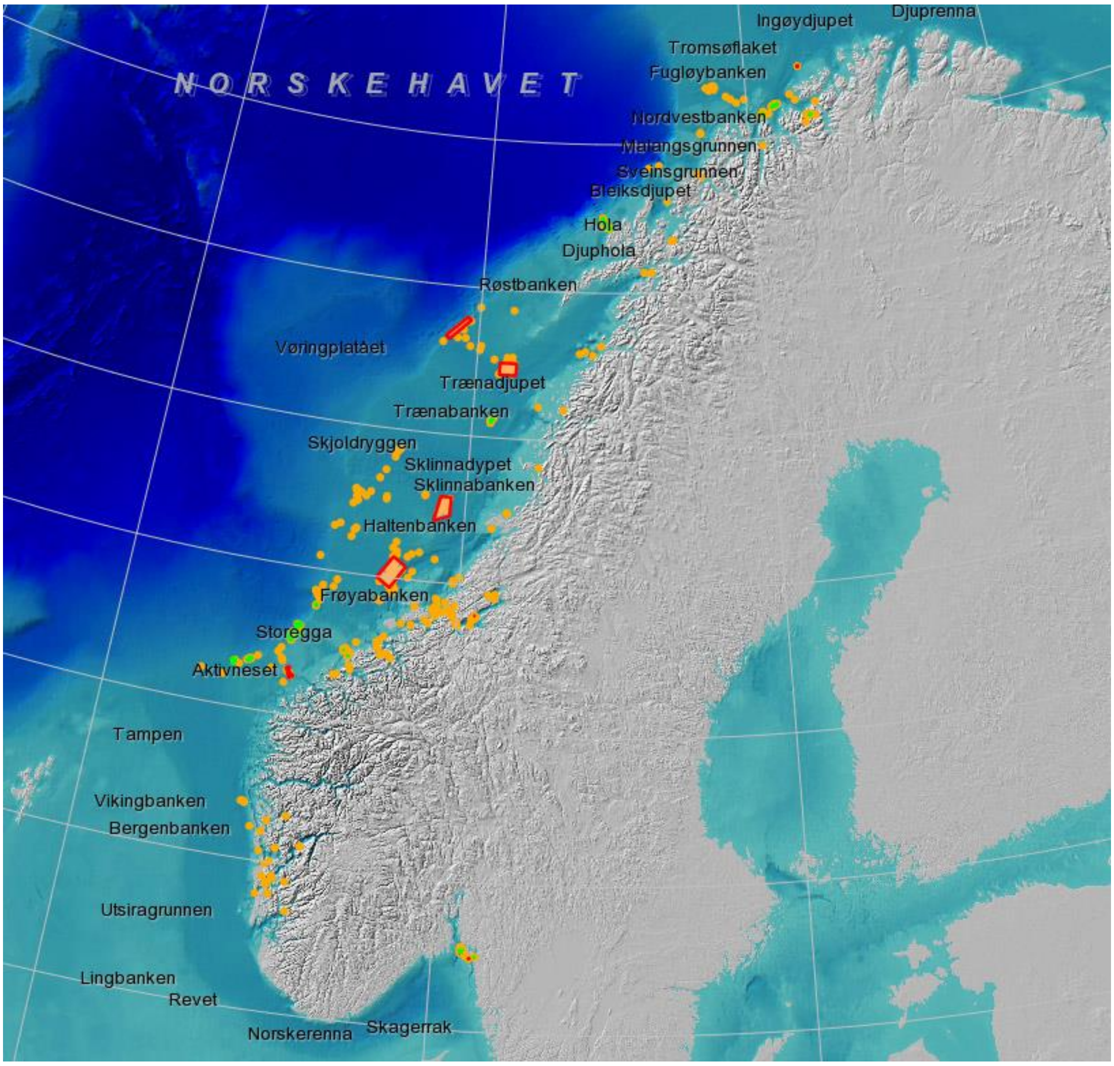


Figure 5: Cold water corals found in Norwegian waters. Coral reefs are marked in orange, areas where corals have been identified are marked in green, while red marks protected CWC areas (map from mareano.no). Note that the reefs in the figure are placement markings, not actual area coverage.

To assess the social and economic impact of ocean acidification on cold water coral there are (at least) five main types of information that are needed:

1) Cold water coral distribution
2) Ecosystem services of cold water corals
3) Valuation of cold water coral ecosystem services
4) The physical, biological and chemical impact of ocean acidification on cold water coral functioning
5) The impact of ocean acidification on ecosystem services from cold water corals

We will go through these in turn in the following. Since most of the research on CWC has been on stony coral (*scleractinians*) that make a hard skeleton, as opposed to soft corals[1], we will focus on the former in this report.

4.1 COLD WATER CORAL DISTRIBUTION

Due to the high cost of sampling and surveying in the deep sea, the wider assessment of the distribution of cold water coral globally is currently mostly based on habitat suitability modelling (Davies, Wisshak et al. 2008, Davies and Guinotte 2011, Yesson, Taylor et al. 2012). These studies give an indication of coverage, which again can be used in the assessment of the economic impacts of ocean acidification. As of yet, however, there is no overall estimate of cold water coral coverage, though some studies point to percentage habitat suitability coverage in specific ocean areas, of some cold water coral species (Yesson, Taylor et al. 2012).

The map in Figure 5 shows where CWC has been verified along the Norwegian coast, which means that their presence has been confirmed by scientists using under-water cameras. Multi-beam echo-sounder registrations indicate that there may be ten times as many occurrences of CWC as those confirmed (Buhl-Mortensen).

4.2 ECOSYSTEM SERVICES OF COLD WATER CORALS

Figure 6 summarises ecosystem services provided by CWC as identified in Falk-Andersson, Foley et al. (2015). While there are a few cases of mining and collection of corals to make jewellery (Grigg 2002), the main provisioning services are believed to be related to the potential they represent as raw materials for industrial and pharmaceutical uses (Foley, van Rensburg et al. 2010). Their ability to survive in the dark under conditions of extreme temperature and pressure suggest that they may have such commercial potential (Arico and Salpin 2005, Armstrong, Foley et al. 2010).

CWC have been suggested to offer regulating services, including carbon sequestration, which would be a climate gas mitigation benefit (Foley, van Rensburg et al. 2010). Unpublished work suggests that CO_2 released through the corals' respiration may result in a net release of carbon (Fosså, J.H. Norwegian Institute of Marine Research, pers. comm.). The study of White, Wolff et al. (2012) found that CWC turn over a large proportion of annual shelf carbon in the Norwegian Sea, and concluded that destruction of CWC may therefore significantly affect the carbon cycling in the North Atlantic.

Identified cultural services of CWC include recreational diving, but only applied to the unique case of Trondheim fjord where they are found at a depth of 39 meters. In the future, however, CWC may be visited by using submersibles. Films and books can also

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[1] Octocorals do not form reef, but can form assemblages of corals that are commonly referred to as "coral gardens" or "coral forests" Yesson, C., M. L. Taylor, D. P. Tittensor, A. J. Davies, J. Guinotte, A. Baco, J. Black, J. M. Hall-Spencer and A. D. Rogers (2012). "Global habitat suitability of cold-water octocorals." Journal of Biogeography **39**(7): 1278-1292..

make CWC available to a wider audience indirectly (Foley, van Rensburg et al. 2010). The charismatic nature of these creatures is also a cultural service (Armstrong and van den Hove 2008) and people have expressed that they would like CWC to be preserved for future benefits to themselves (option value) as well as future generations (bequest value), and because of their existence value independent of human use (Glenn, Wattage et al. 2010, Falk-Andersson, Foley et al. 2015). CWC also represent educational and scientific cultural ecosystem services, including that they provide archives of data that can give information on past climate change (Lutringer, Blamart et al. 2005, Puglise, Brock et al. 2005).

Supporting ecosystem services of CWC include habitat, biodiversity and resilience (Freiwald, Fosså et al. 2004, Foley, van Rensburg et al. 2010). Corals seem to attract fish, that in turn also attract fishers (Husebø, Nøttestad et al. 2002, Armstrong and van den Hove 2008). Changes in habitat services from CWC could affect the provisioning ecosystem services from other species, as shown for redfish (Foley et al. 2010).

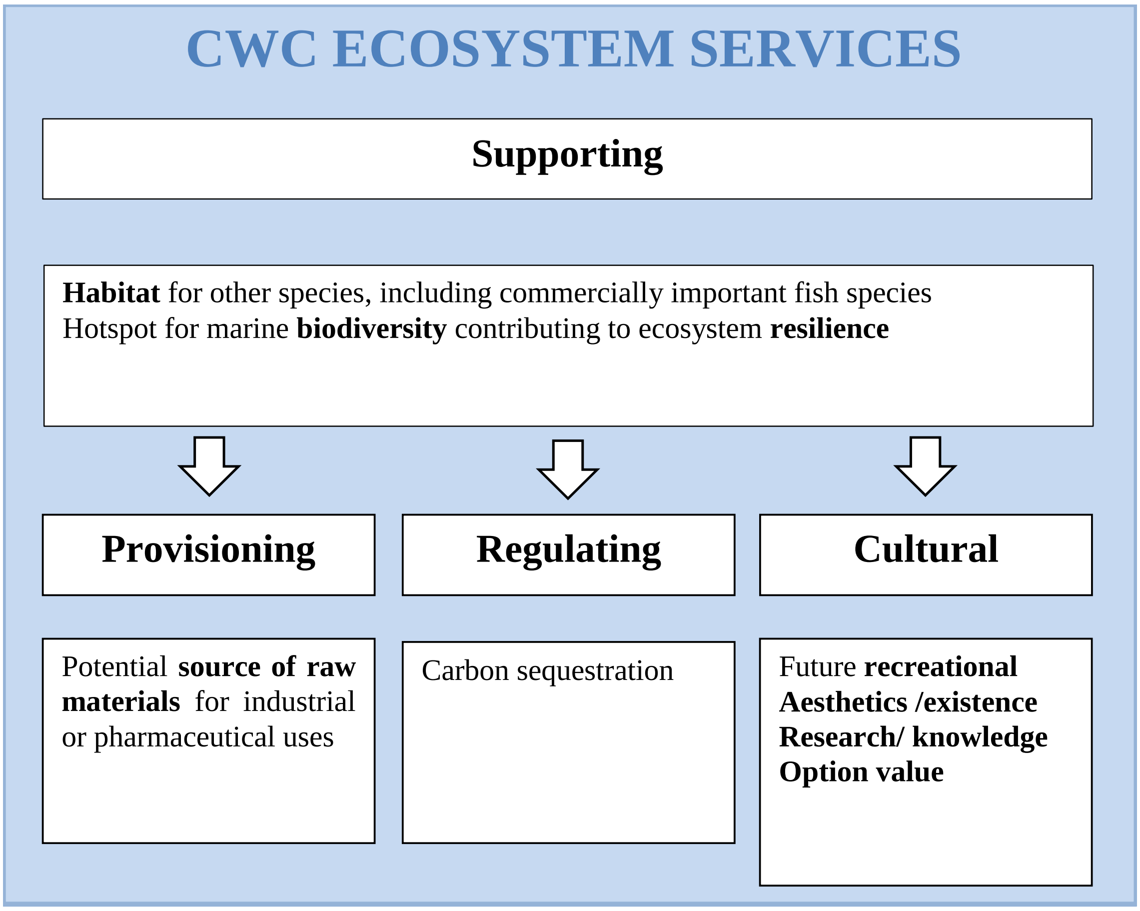

Figure 6: Ecosystem services of cold water corals. Modified from Falk-Andersson, Foley et al. (2015).

4.3 VALUATION OF COLD WATER CORAL ECOSYSTEM SERVICES

While the existence of CWC has been known to fishers and biologists for over 200 years, it was not until 1982 when Statoil captured them on video that they become known to the broader public. Once their existence became known to the Norwegian public through the media, protective measures were rapidly implemented. This was despite the restrictions such protection might represent for the two main marine industries in Norway (fishing and oil/gas exploration) and limited knowledge of their functional values (Armstrong and van den Hove 2008). Establishment of marine protected areas restricted fishing on a number of reefs and new regulations on fishing activities made it illegal to purposefully damage CWC.

Both fishers and biologists have had theories for the role of corals in the ecosystem, particularly as being nurseries and hiding places for fish, but this has not been confirmed (Kutti, Bergstad et al. 2014). Environmental organisations, backed by public support, have also been pressing for CWC protection (Foley, van Rensburg et al. 2010). This suggests that non-use and option values were and are important foundations supporting protection of CWC.

Option and quasi-option values have been listed as particularly important values for CWC, potentially justifying precautionary measures in managing the ocean floor. Given their slow growth, any damage is in effect irreversible within a time frame relevant to humans (Foley, van Rensburg et al. 2010, Falk-Andersson, Foley et al. 2015). A document calling for a halt of activities damaging CWC in order to give scientists a chance to learn more about their uses was signed in 2004 by 1136 scientists from around the world (Tsao 2004). This was a signal to policy makers of the value of protecting future information from CWCs by delaying an irreversible action today (quasi-option-value). In the context of ocean acidification, the issue of irreversibility is even more relevant.

Protecting CWC would also allow for more time to investigate the benefits these structures may provide both functionally and in terms of genetic information. This would benefit fishing communities, given that they provide habitat services or aggregate fish populations, as well as scientific communities involved in for example medicinal and pharmaceutical research. In Norway, coastal fishers have argued against other fishers that bottom trawl, also reflecting that this group of fishers would like to protect the quasi option values CWC represents (Armstrong and van den Hove 2008, Foley, van Rensburg et al. 2010).

The economic value of ecosystem services can be captured using market analysis (revealed preferences) and non-market valuation techniques (stated preferences). Ecosystem services of CWC are generally not traded, or revealed, in the market. Non-market valuation techniques have therefore been used to get a proxy of their economic value. These techniques can also be applied to capture non-market use values of CWC, such as scientific, aesthetic and educational use (Foley, van Rensburg et al. 2010). Armstrong et al (2012) give an overview of environmental valuation techniques based on individual preferences, which we reproduce here in Table 2.

Table 2: Environmental Valuation Techniques based on individual preferences, from (Armstrong, Holen et al. 2012).

	Indirect	Direct
Revealed preference (RP)	Travel Cost method Hedonic Price analysis Averting Behaviour	Production Function (Market prices) Replacement Costs Mitigation Costs
Stated Preferences (SP)	Choice Experiments	Contingent Valuation

Choice experiments, a stated preference method, have been applied to elicit public preferences for protection of CWC in Ireland (Glenn, Wattage et al. 2010). In a postal survey, respondents were asked to choose their preferred combination of various levels of fishing activities (all fishing - ban trawling - ban all fishing), area of protection (status quo - all known corals - all areas there are thought to be corals) and costs in terms of annual tax (€0 – €1 – €10). The willingness to pay to conserve CWC was not determined with statistical significance, but respondents did show a strong preference for a ban on bottom trawling where corals were thought to exist. The motivation for protection was that "they provide direct uses such as raw materials for biomedical industry, essential fish habitat and as a carbon sink that supports climate change" (direct use value, chosen by 87% of respondents), "so that I can personally have the option to use or see them in the future" (option value, 61%), "for the benefit of my children and future generations" (bequest value, 90%) and because they have "a right to exist, although I don't intent to use or see them" (existence value, 84%). Note that also non-use values as bequest and existence value were central motives for why people wanted protection (Glenn, Wattage et al. 2010).

A focus group study in Norway (Falk-Andersson, Foley et al. 2015) also found a preference for protection of CWC. In discussions their importance as habitat for fish (indirect use value) was highlighted, but ability to see the corals and their pure existence were also mentioned by some as reasons justifying protection. A survey complimenting the discussions in the focus group study reflected some of the same attitudes as found in Glenn, Wattage et al. (2010). Bequest values (89%) and the intrinsic right to exist (83%) were given high ratings with respect to why CWC should be protected, followed by option values due to current uncertainties regarding the potential values they represents (82%), indirect use-values with their role as fish habitat (74%) and regulators of climate (61%), while direct use value as raw materials in biochemical industries (33%) were lower rated (Falk-Andersson, Foley et al. 2015). A Norwegian survey using a discrete choice experiments confirmed these attitudes and found that the Norwegian public are willing to pay for protection of CWC, even if this involves limiting areas for both fisheries and petroleum industries (LaRiviere, Czajkowski et al. 2014, Aanesen, Armstrong et al. 2015).

Since recreational diving on CWC is not common and tours using submersibles is only a potential industry, the travel cost method is not relevant for valuation of CWC ecosystem services (Foley, van Rensburg et al. 2010).

The production function approach has been applied to quantify functional values associated with CWC in terms of habitat, assuming that CWC is an essential habitat[1] for redfish (*Sebastes*) (Foley, Kahui et al. 2010). Statistical analysis suggested an annual loss in commercial harvest between 11% and 29% due to an estimated 30-50% decline of coral in Norwegian waters. This is equal to an annual loss of 68-110 tonnes redfish harvest, or between NOK 445,700 and NOK 718,282 for each km^2 of CWC lost. According to the model, both carrying capacity and the intrinsic growth rate of the stock is influenced by available CWC habitat (Foley, Kahui et al. 2010). While the model fit was best when assuming that CWC was an essential habitat, compared to facultative[2], it may still not be crucial to the survival of redfish. Thus, one cannot assume that loss of CWC following ocean acidification will lead to extinction of redfish. The indirect use value of CWC as habitat is regarded by many as the strongest single economic argument for protection of CWC, as commercial fishing is an important industry (Foley, van Rensburg et al. 2010).

However, willingness to pay (WTP) to protect CWC is also of a significant magnitude. Aanesen, Armstrong et al. (2015) report Norwegian households' average annual WTP for increasing the protected areas of CWC in Norwegian waters from today's 2445 km2 to either 5000 or 10 000 km2. The reported WTP comes from a discrete choice experiment where respondents consider their willingness to pay for increasing the area protected. They consider the size of total area protected (as today; 2445 km2, or increase to 5000 or 10 000 km2), whether CWC is important as a habitat for fish, and whether the area to be protected is attractive for oil/gas activities and/or fisheries.

The marginal WTP to increase the conserved area from 2445 km2 to 5000 or 10 000 km2 is in the range €53-67/year per household[3] when everything else is kept at the reference level. The reference level in the study is when the CWC areas to be protected are "partly" important as habitat for fish and "partly" attractive for oil/gas activities and fisheries. With 2.35 million households in Norway this corresponds to a total WTP to increase CWC conservation from today's 2445 km2 in the range of € 20,716 – 48,748 per km2 (=NOK 186,445 – 438,728 at 9 NOK/€). As also people outside Norway may have a WTP for the conservation of cold water corals in Norwegian waters the WTP reported should be taken as a lower bound.

If the extra CWC areas to be protected are "important" as habitat for fish the WTP for conserving them increases with € 166.1 per household per year, compared to the reference situation. Similarly, if the extra CWC areas are "attractive" for oil/gas

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[1] An essential fish habitat is defined as "those waters and substrate necessary to fish for spawning, breeding, feeding, or growth to maturity" Anonymous (1996). The Sustainable Fisheries Act of 1996, USA.

[2] A facultative habitat enhances the stock, but is not essential for survival.

[3] Based on marginal WTP figures from Table 3 for "MXL model" in Aanesen et al. (2015) The MXL model's figures are preferred as this model is more realistic with its assumption of heterogeneous preferences among households. The other model they tested, the MNL-model, assumes homogeneous preferences among the households.

activities the WTP for conservation increases with € 16.3 per household and year compared to the "partly" reference situation. One might expect that higher attractiveness of the areas for industrial activities would reduce the overall WTP for CWC conservation, as conservation mean giving up present or future income or other benefits from the industrial activities. If that was the case then the reported marginal WTP should be negative. When it actually is positive in Aanesen et al.'s study it could be interpreted as the respondents seeing extra need for conservation measures the more attractive the CWC areas are for industry activities that potentially damage cold water coral. Also if the CWC areas are "attractive" for fishing (compared to the "partial" reference sitation) the WTP for CWC conservation increases, with €39.1 per household and year.

Table 3: Summary of ecosystem service values of cold water corals, modified from Foley, van Rensburg et al. (2010).

	Direct use	Indirect use	Option use	Non-use
Goods/assets				
Genetic resources	xx		○○○	
Raw materials/ornaments	●●			
Services				
Climate change regulator		○ xx		
Habitat	xx	●● xxx		
Aesthetic enjoyment	○ xxx			
Recreation	○			
Science and education	○○			
Attributes/diversity				
Cultural heritage (bequest value)				xxx
Intrinsic worth (existence value)				xxx
Uncertainty wrt value (quasi option value)			xxx	

● = economic values available in peer-reviewed literature; ● = low; ●● = medium; ●●● = high; ○ = no economic values available in peer reviewed literature, but economic values probable; ○ = low; ○○ = medium; ○○○ = high; x = no economic value available, but stakeholder opinions expressed suggest that the value is rated; x = low; xx = medium; xxx = high.

The valuation studies conducted so far on CWC have been set within the framework of marine protected areas (MPAs) as a means to capture people's preferences for securing future existence of CWC. Thus, the stakeholders potentially affected by MPAs have been identified as fishers, and, to some extent industries related to oil/gas exploration. Fishers in many countries are associated with marginalised coastal communities that have strong social and political support, as also indicated in the valuation studies on CWC described above. This may explain the more reluctant support for precautionary measures in the case of CWC compared to cases such as GM foods (Nelson 2001), hazardous waste (Hadden 1991) or marine mining (Mason, Paxton et al. 2010) involving large, often international companies.

In the case of ocean acidification the actions that may contribute to degeneration of corals are not related to specific industries or groups, but are a result of the combined pressures a high CO_2 world exerts on the ecosystem. The specific trade-offs that are presented to stakeholders may affect the outcome of a valuation study. Results from the valuation studies on CWC conducted with respect to fisheries regulations to date may therefore not be directly transferrable to an ocean acidification context. Valuation studies should explicitly include ocean acidification's effects on CWC for robust conclusions to be drawn on this.

While the values of ecosystem services related to CWC are relatively unknown, tropical coral reefs and their direct and indirect use values are better assessed and understood. Brander, Rehdanz et al. (2012) present a study on the economic impact of ocean acidification on tropical coral reefs around the world. They modelled changes in tropical coral reef area from ocean acidification. Economic values were then derived by conducting a meta-analysis of available literature, giving a value per reef area. The results from this study on tropical corals cannot be directly transferred to the effects of ocean acidification on CWC, since the two types of corals do not support the same services. In particular, tropical reefs are important for tourism and recreation, and this has been a major element in valuation studies of these resources.

4.4 COLD WATER CORAL IN THE CONTEXT OF OCEAN ACIDIFICATION

The review on distribution of cold water corals, the ecosystem services they offer and attempts to capture these in economic terms, illustrates that while a range of services has been identified, quantification and valuation adds complexity and increases uncertainty. Furthermore, the context in which CWC ecosystem services are explored matter for how valuation studies should be implemented. As stressed above, the focus of CWC valuation studies has been the physical impact of fishing gear on coral and whether further protection measures, for example marine protected areas, should be implemented at a national level. In the context of ocean acidification the scale of the problem is different as acidification of the oceans does not follow national boundaries. Mitigating measures should therefore be implemented at the international level, but adaptive measures should still be taken at a national level. The following sections will concentrate on cold-water corals in the context of ocean acidification, starting with the impact of ocean acidification on cold water coral calcification and physical and biological functioning.

4.4.1 OCEAN ACIDIFICATION AND CALCIFICATION

About 30% of the CO_2 released in the atmosphere by humans has been taken up by the oceans. This has resulted in increased concentration of hydrogen ions (H^+), which has led to reductions in pH and in the number of carbonate ions (CO_2^{3-}) in the sea (Orr, Fabry et al. 2005). Corals use aragonite, the mineral form of calcium carbonate, to build their calcium carbonate ($CaCO_3$) skeletons. In lab experiments, a reduction in carbonate ions has resulted in lower calcification rates in tropical reef builders. A similar response in CWC could be expected (Guinotte, Orr et al. 2006).

The *aragonite saturation horizon* is the limit between saturation and undersaturation with respect to aragonite. The horizon is the limit between where marine organisms will form biogenic[1] calcium carbonate, and where calcium carbonate will dissolve unless the organisms have some protective mechanisms (Figure 6, Box 1) (Guinotte and Fabry 2008). At shallower depths than the horizon calcium carbonate is formed, and at deeper depths it is dissolved. The horizon is expected to move shallower with increasing atmospheric CO_2 concentrations (Guinotte, Orr et al. 2006), limiting the zone where live cold water coral can form calcium carbonate and dead coral will exist over time. Colder waters hold more CO_2 and are therefore more acidic than warmer waters. It has been hypothesised that the low carbonate saturation state in cold environments contributes to the slow growth/ calcification rates of cold water corals, making them particularly vulnerable to ocean acidification. The distribution of CWC seems to coincide with the depth of the aragonite saturation horizon ranging from below 2000m to 200m depths (Guinotte and Fabry 2008, Cooley and Doney 2009).

Polar and sub polar surface waters have been projected to become undersaturated with respect to aragonite within the next 50 years (Orr, Fabry et al. 2005). Guinotte, Orr et al. (2006) project by the end of the century 70% of the waters where today's cold water corals are could be undersaturated with respect to aragonite (Guinotte, Orr et al. 2006). The majority of the coral areas that may remain in supersaturated waters will be located in the North Atlantic. This is the region where most of the bioherm[2]-forming CWC have been found so far, suggesting that Norwegian, as well as other Arctic CWC may not suffer. However, Guinotte, Orr et al. (2006) do not have data for the Arctic Ocean in their analysis, making predictions for this region difficult.

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[2] Bioherms are defined as ancient organic reef- or mound-like forms built by marine invertebrates such as corals. Britannica, E. (2013). Bioherm. Online Academic Edition. http://www.britannica.com/EBchecked/topic/65947/bioherm, Encyclopædia Britannica Inc..

Box 1: Cold and warm water corals and ocean acidification

The concentration of carbonate ions (CO_3^{2-}) determines whether organisms are able to produce calcium carbonate ($CaCO_3$) shells and plates. If the surrounding water is saturated with these ions, calcium carbonate will form, if not these structures will dissolve. There are two natural forms of crystal carbonate, of which aragonite is one, and which determines whether stone-building (*scleratinian)* cold water corals can produce calcium carbonate skeleton.

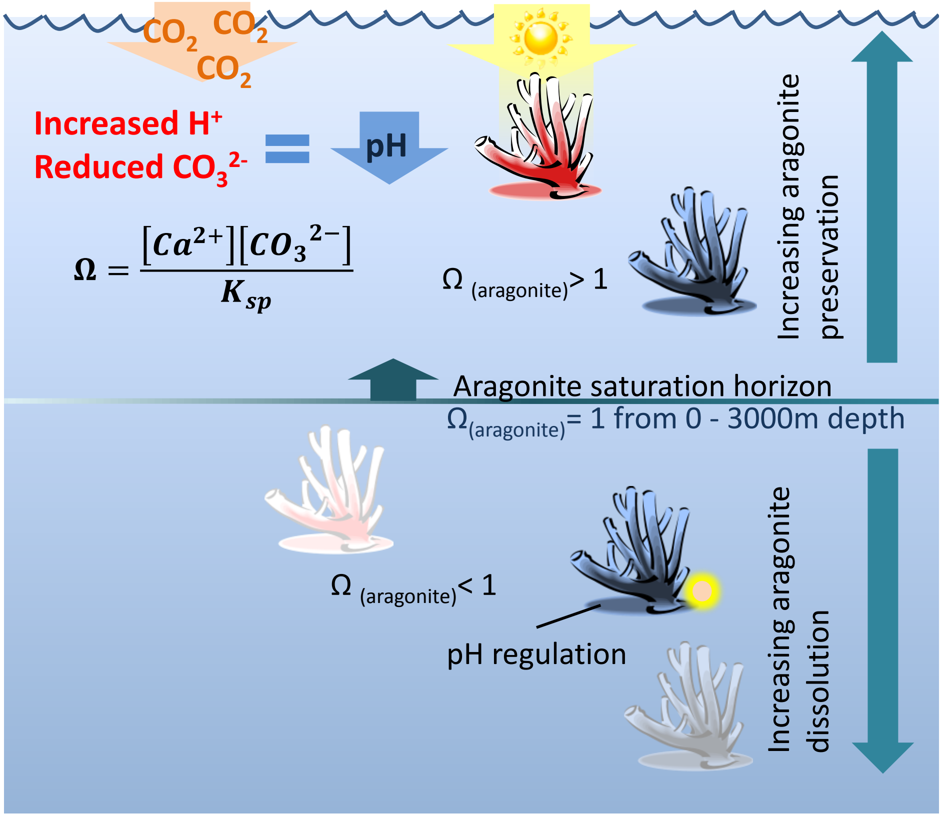


Figure 7: Calcification of tropical (red) and cold water corals (blue), and their dependence on the saturation horizon of aragonite, affected by ocean acidification.

The equation in the figure above describes how the saturation state (Ω) of Aragonite is a product of the concentrations of the ions Ca^{2+} and CO_3^{2-} divided by the solubility product K_{sp} for Ca^{2+} and CO_3^{2-} when the mineral is at equilibrium (neither forming nor dissolving). Uptake of anthropogenic CO_2 from the atmosphere into seawater increases the number of hydrogen ions H^+, which lowers pH, and reduces available CO_3^{2-} ions, and thereby reduces Ω. This has an impact on marine calcifiers as it makes it more difficult and/or requires more energy for them to form their shells and plates (Guinotte and Fabry 2008).The aragonite saturation horizon (Ω=1) is a result of temperature, pressure and depth. This depth differs globally, but is significantly shallower for the more soluble aragonite compared to for calcite (Feely et al 2004). Due to increasing uptake of CO_2 from the atmosphere by the oceans, the aragonite saturation horizon is moving shallower as indicated by the arrow on the saturation horizon. Cold water corals seems to be able to increase the carbonate saturation at the site of calcification (pH regulation), which enables them to calcify at, and in some cases below, the aragonite saturation horizon (McCulloch, Trotter et al. 2012).

Outside the coast of Norway the stony coral *Lophelia pertusa* forms large bioherm structures, consisting of younger corals growing on the skeletons of their ancestors. Both outside the Norwegian coast and elsewhere in the North Atlantic the aragonite saturation horizon is very deep (> 2000 m) compared to in the North Pacific. In the North Pacific deep water surveys have not revealed bioherms, and while there are some solitary colonies of stony corals close to the aragonite saturation horizon the corals are dominated by octocorals (soft corals) and stylasterids that use calcite, a less soluble form of calcium carbonate ($CaCO_3$), to build their skeletons (Guinotte, Orr et al. 2006).

Given that CWC live close to the aragonite saturation horizon, apart from a few exceptions such as in the Trondheim Fjord in Norway, they may have adapted to these low carbon saturation states which again could make them less vulnerable to ocean acidification (McCullock et al 2012), as we will look further into in the next section.

4.4.2 PHYSICAL AND BIOLOGICAL IMPACT OF OCEAN ACIDIFICATION ON COLD WATER CORAL

The ability of CWC to form complex calcareous structures, like reefs, is believed to give them a number of advantages. This includes elevating live corals into better flow conditions, increasing access to food, nutrients and well-oxygenated waters, provide anchoring against hydrodynamic forces, increase competitiveness for space and provide protection. Reproductive success of the corals has also been found to be positively correlated with the size of the reef (Kleypas, Feely et al. 2006, Kleypas and Langdon 2006).

In addition to being important to secure the functioning of the corals themselves, the reef structures have important functions in the ecosystem, including creation of complex spatial habitats and depth gradients that support high biodiversity. Additionally, the coral structures have an impact on the local hydrodynamic regime (Kleypas, Feely et al. 2006).

The physiology of marine organisms will in general be affected by ocean acidification through acid-base imbalance and reduced capacity to transport oxygen. As explained above, calcifying organisms such as CWC are expected to be particularly susceptible to ocean acidification because their ability to produce calcareous structures is directly affected by the carbonate chemistry of the sea. Reductions in calcium carbonate saturation in the sea water affect calcification rates negatively and carbonate dissolution rates positively (Guinotte, Orr et al. 2006, Kleypas, Feely et al. 2006, Fabry, Seibel et al. 2008). The living parts of the coral (the polyps) which are able to grow, are coated with a protective tissue, whereas the dead coral skeleton, forming the bioherm is directly exposed to chemical and biological erosion. Thus, it is assumed that when no longer covered by a protective tissue, the bioherm starts dissolving. For *Lophelia pertusa*, the reef building coral species along the Norwegian cost, only the last few centimetres of a colony branch are covered by living tissue (Beuck 2005).

Coral calcifiers are able to increase the carbonate saturation state at the site of calcification, located in between the polyp and the underlying skeleton, thereby counteracting the effects of reduced carbonate saturation in surrounding waters. This enables them to calcify at, and in some cases below, the aragonite saturation horizon, although at an energetic cost which explains their slow growth rate. Due to this it has been suggested that CWC are more resilient to ocean acidification than previously assumed (McCullock et al 2012).

Studies of the possible effect of ocean acidification on CWC have shown conflicting results. It is important to consider the effects both on the live and dead coral. In a short term study, lower pH resulted in reduced calcification for *Lophelia pertusa*, especially in young polyps (Maier, Hegeman et al. 2009). Form and Riebesell (2012), however, found in a slightly longer-term experiment that the CWC species adapted to acidified conditions and sustained net growth, and even showed positive response, in waters sub-saturated with aragonite. They suggested that CWC are able to adapt to ocean acidification, but stressed that sensitivity of CWC in early life stages or older parts of the coral framework may affect the totality of a reef.

Maier, Schubert et al. (2013) later questioned the conclusion of acclimation by Form and Riebesell (2012), based on the methods applied. Maier, Schubert et al. (2013) found that net calcification of CWCs (*Lophelia pertusa* and *Madrepora oculata* in the Mediterranean) was unaffected by pCO_2 levels projected at the end of this century. Furthermore, they noted that calcification rates were twice as high under pre-industrial CO_2 levels, compared to current and projected levels. This indicates that calcification rates of CWC have already declined drastically. They concluded that there are large unknowns with respect to the ability of CWC to sustain calcification rates under the current fast changes in CO_2 as well as expected CO_2 levels.

In a short term study of the impact of increased CO_2 levels, cold water coral *Lophelia pertusa* maintained calcification rates, but showed declining respiration rates. This suggest that that the coral has to use energy reserves to maintain calcification rates, which can be detrimental in the long-run (Hennige, Wicks et al. 2013).

There are large knowledge gaps and conflicting hypotheses in understanding the full impact of ocean acidification on live CWC. For instance, warming of the deep oceans has been proposed to enhance calcification rates (McCulloch, Trotter et al. 2012), thus allowing the corals to grow faster, but also cause higher energy demands which again may reduce growth (Form and Riebesell 2012).

Food availability is believed to be an important factor affecting CWC growth rates since up-regulation of pH at the calcification site is energy intensive (Form and Riebesell 2012, McCulloch, Trotter et al. 2012, Maier, Schubert et al. 2013). Being filter feeders they depend on organic matter and zooplankton that fall from the surface or are carried with ocean currents. CWC are found in areas with high surface primary productivity, suggesting that food falling from the surface may be particularly important. Many of the planktonic species that form the bottom of the marine food web build their $CaCO_3$ shells using carbonate ions. Thus, a more acidic ocean may reduce surface water phyto- and zooplankton production, which again can affect CWC negatively (Guinotte, Orr et al. 2006). Therfore, more holistic studies are needed to account for whole organism responses of CWC under more acidic conditions, including on fitness, defence, growth, feeding and reproduction.

The chemical erosion of the dead part of the corals may also slow down with global warming as high temperatures reduce the physicochemical dissolution capacity of calcium carbonate in seawater (Mehrbach, Culberson et al. 1973). Older parts of the coral framework may dissolute in undersaturated waters, causing the overall reef structure to weaken. Early life stages may also be more sensitive to ocean acidification (Form and Riebesell 2012, McCulloch, Trotter et al. 2012, Maier, Schubert et al. 2013).

Corals are also expected to be affected by the combined effects of human induced changes in carbonate saturation state, temperature, light and nutrients, levels of dissolved oxygen and supply of organic particles. There are only a few studies on combined effects, and none relating to CWC (Kleypas, Feely et al. 2006, Kleypas and Langdon 2006, Form and Riebesell 2012, Maier, Schubert et al. 2013).

4.4.3 THE IMPACT OF OCEAN ACIDIFICATION ON COLD WATER CORAL FUNCTION

If cold water corals are reduced due to ocean acidification, we would expect some of the same effects on ecosystem functioning and ecosystem services as the effects described when corals are reduced due to other reasons. To assess the impacts of ocean acidification is however difficult. To complicate the picture further, the total impact on the ecosystem and the services corals provide will be the sum of many interrelated processes, as for example the combined impact of changes in formation and dissolution of carbonate structures and response of bioeroders that chemically or mechanically erode hard substrates such as coral reefs (Kleypas and Langdon 2006).

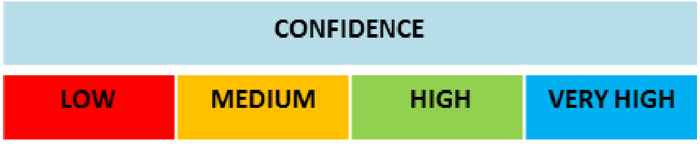
This review has so far revealed a number of potential losses due to reduced coral cover, but has not come across studies on possible benefits. However, we know that upon encountering corals, fishing gear can get lost and/or destroyed. Reductions in CWC could reduce the costs associated with this. There has been a strong focus on the negative impact of bottom trawling on benthic communities, but a suggested positive impact of trawling is that the disturbance may promote smaller benthic species with faster life cycles (Jennings, Dinmore et al. 2001, Hiddink, Rijnsdorp et al. 2008). Increased benthic production could benefit consumers, including fish populations harvested for human consumption. Thus reduced CWC coverage followed by a trawling practice equating to the intensive agriculture we find on land may “farm the sea” and result in higher fish productions. Empirical studies are, however, not conclusive and in general the total picture suggests that destruction of benthic organisms and habitat has an overall negative effect (Jennings, Dinmore et al. 2001, Hiddink, Rijnsdorp et al. 2008).

4.5 EXPERT OPINION ELICITATION REGARDING IMPACT OF OCEAN ACIDIFICATION ON COLD WATER CORAL FUNCTION AND SERVICES

Due to the large uncertainties regarding CWC ecosystem function as well as service impacts from ocean acidification we chose to carry out an expert opinion elicitation. The aim was to get the experts’ judgement of what impacts are likely. We expect that the experts' opinions are based on their knowledge of published peer-reviewed literature, grey literature, their knowledge of own and others' research in progress, as well as their best judgement of possible effects based on general competence in biology, chemistry and ecology. The elicitation was done at the Fram Centre Ocean Acidification Flagship meeting 21 October 2013 in Tromsø, Norway. The flagship meeting included a broad set of expertise on ocean acidification (see participant list in appendix).

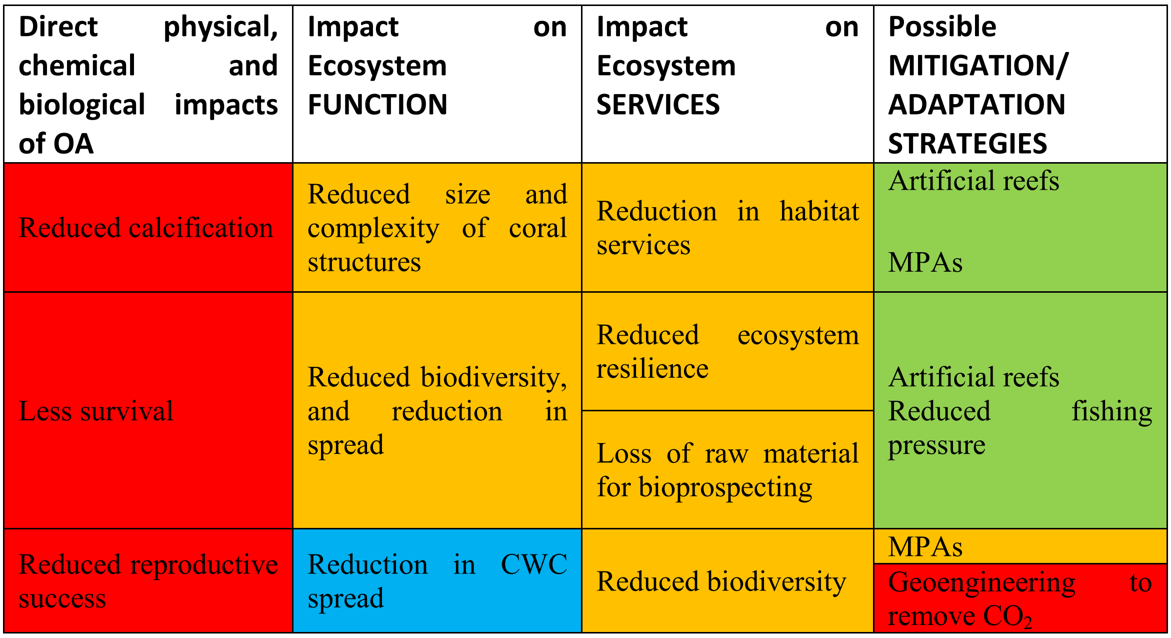
We presented in plenary the Millennium Ecosystem Assessment framework and the issues we wanted discussed, whereupon we divided the scientists present into three groups with varied areas of expertise. The groups were asked to suggest direct physical, chemical and biological impacts of ocean acidification, the impacts of this on ecosystem functions and services, as well as possible mitigation/adaptation strategies. The participants were asked to assess their confidence regarding their suggestions as low, medium, high or very high, following a traffic light approach (see illustration below).

The output from this expert opinion elicitation regarding cold water coral is presented in the tables below, for living and dead coral, and at 800 and 1200 ppm CO_2 in the atmosphere.



CONFIDENCE			
LOW	MEDIUM	HIGH	VERY HIGH

Table 4: Expert elicitation results for impacts and possible mitigation/adaptation strategies for living cold water coral at 800 ppm atmospheric CO_2



Direct physical, chemical and biological impacts of OA	**Impact on Ecosystem FUNCTION**	**Impact on Ecosystem SERVICES**	**Possible MITIGATION/ ADAPTATION STRATEGIES**
Reduced calcification	Reduced size and complexity of coral structures	Reduction in habitat services	Artificial reefs MPAs
Less survival	Reduced biodiversity, and reduction in spread	Reduced ecosystem resilience	Artificial reefs Reduced fishing pressure
		Loss of raw material for bioprospecting	
Reduced reproductive success	Reduction in CWC spread	Reduced biodiversity	MPAs Geoengineering to remove CO_2

Table 5: Expert elicitation results for impacts and possible mitigation/adaptation strategies for living cold water coral at 1200 ppm atmospheric CO_2

Direct physical, chemical and biological impacts of OA	Impact on Ecosystem FUNCTION	Impact on Ecosystem SERVICES	Possible MITIGATION/ ADAPTATION STRATEGIES
Reduced calcification	Reduced size and complexity of coral structures	Reduction in habitat service	Artificial reefs MPAs
Survival	Reduced biodiversity, and reduction in spread	Reduced ecosystem resillience	Artificial reefs
		Loss of raw material for bioprospecting	Reduced fishing pressure
Reduced reproductive success	Reduction in CWC spread	Reduced biodiversity	MPAs
			Geoingeneering to remove CO_2

Table 6: Expert elicitation results for impacts and possible mitigation/adaptation strategies for dead cold water coral at 800 ppm atmospheric CO_2

Direct physical, chemical and biological impacts of OA	Impact on Ecosystem FUNCTION	Impact on Ecosystem SERVICES	Possible MITIGATION/ ADAPTATION STRATEGIES
Increased dissolution	Reduced size and complexity of coral structures	Reduction in habitat service	Artificial reefs MPAs
		Reduced ecosystem resilience	Artificial reefs
		Loss of raw material for bioprospecting	Reduced fishing pressure
		Reduced biodiversity	MPAs
			Geoingeneering to remove CO_2

Table 7: Expert elicitation results for impacts and possible mitigation/adaptation strategies for dead cold water coral at 1200 ppm atmospheric CO_2

Direct physical, chemical and biological impacts of OA	Impact on Ecosystem FUNCTION	Impact on Ecosystem SERVICES	Possible MITIGATION/ ADAPTATION STRATEGIES
Increased dissolution	Reduced size and complexity of coral structures	Reduction in habitat service	Artificial reefs MPAs
	Reduced associated biodiversity	Reduced ecosystem resillience Loss of raw material for bioprospecting	Artificial reefs Reduced fishing pressure
		Reduced biodiversity	MPAs Geoingeneering to remove CO_2

We note that the possible direct physical, chemical and biological impacts of OA on cold water corals are stated with only low or medium confidence for the living cold water coral, but with high or very high confidence for the dead cold water coral. The confidence level increases with higher CO_2-concentrations. The mentioned direct impacts on both living and dead coral are all expected to be negative, but outright extinction is not expected.

The impacts on ecosystem functions are generally stated with higher confidence than the direct physical, chemical and biological impacts, but remember that the ecosystem function impacts stated are dependent on the direct impacts of OA on CWC. Also all mentioned impacts here are expected to be negative. Reduction in CWC spread due to reduced reproductive success of living CWC is expected with very high confidence at both 800 and 1200 ppm CO_2. The direct impacts on dead CWC are expected to give reduced size and complexity of coral structures with high or very high confidence. It is interesting to note that the impact on ecosystem function on dead corals due to reduced size and complexity of coral structure is rated with higher confidence at 800 compared to 1200 ppm CO_2. Since the experts were not asked to document their evaluations, nor to re-visit them given what seems like inconsistencies in evaluations, we do not know why these impacts were evaluated differently.

The impacts on ecosystem services are negative in a variety of ways, and all stated with medium confidence.

While the experts made comments to what type of impact they could expect, we do not know why different levels were rated with the different levels of confidence. Difference in confidence levels could be due to factors such as few or no studies, quality of performed studies (e.g. experimental setup, number of samples), or confidence in scaling up from impacts on individuals to populations both in time and space, and finally to ecosystem functions and services. Future expert elicitations should include such information to avoid evaluations being "black boxes" and secure that the evaluations are transparent and can be updated when more knowledge is available. When presenting the traffic light illustrations of elicitations, it could be useful to differentiate whether uncertainty is due to lack of studies or quality of current knowledge. Furthermore, allowing more time for the experts to check the literature and compare and discuss evaluations made in groups versus individually could also impact results.

We will return to the expert opinion on management options later.

4.6 SUMMING UP ON SOCIAL AND ECONOMIC IMPACT OF OCEAN ACIDIFICATION ON COLD WATER CORAL

We noted at the start of this case study that to assess the economic impact of ocean acidification on cold water coral there are (at least) five main types of information needed, that we now have covered in the previous sections:

1) Cold water coral distribution
2) Ecosystem services of cold water corals
3) Valuation of cold water coral ecosystem services
4) The physical, biological and chemical impact of ocean acidification on cold water coral functioning
5) The impact of ocean acidification on ecosystem services from cold water corals

The findings from the previous sections are summed up in the table below, including central references.

Table 8: Status of knowledge for assessing impacts of ocean acidification on cold water coral, with central references

Theme	Present knowledge	Central references
1) Cold water coral distribution	Still largely unknown. 3.5-17% of global oceans may be suitable for some CWCs. Calcite saturation state is likely a key limiting factor, based on habitat suitability modelling. There is disagreement on how OA may affect the distribution and there is a lack of data on projected changes of the aragonite saturation horizon for the Arctic Ocean. Norwegian distribution of CWCs is relatively well mapped, yet occurrence may be ten times higher than confirmed, based on echo sounder registrations.	Yesson, Taylor et al. (2012) Guinotte, Orr et al. (2006), McCulloch, Trotter et al. (2012) Buhl-Mortensen (2014)
2) Ecosystem services of cold water corals	A number of services CWCs provide have been identified. Except for an estimate of the effect of the supporting ecosystem services by CWC for Redfish outside Ireland, none of the ecosystem services are quantified or very well described. Currently, it seems that supporting ecosystem services are the most important ones (habitat services), but while the existence value of habitat has been documented, the importance of CWC as habitat has not been quantified. The cultural aesthetics/existence service of CWC also seems important. Future significant ecosystem services may be provisioning of raw materials for industrial or pharmaceutical uses, and cultural services including recreation and research/ knowledge. Some ornamental use of CWC has been documented	Freiwald, Fosså et al. (2004) Falk-Andersson, Foley et al. (2015) Armstrong, Foley et al. (2010) Foley, van Rensburg et al. (2010) White, Wolff et al. (2012) Armstrong and van den Hove (2008) Arico and Salpin (2005) Lutringer, Blamart et al. (2005) Puglise, Brock et al. (2005)

3) Valuation of cold water coral ecosystem services	Explicit valuation of ecosystem services from CWCs is done for the supporting services for redfish in Norway and outside Iceland. Willingness to pay for protection or conservation of CWCs for their existence as well as the supporting services as habitat for commercial and non-commercial fish (provisioning and cultural services), has been investigated in a choice experiment in Norway (published) and Ireland (unpublished). Interest in protecting CWC has also been investigated in a focus group study in Norway, highlighting habitat values (supporting services), non-use and intrinsic values (cultural services). Thus, despite a lack of knowledge regarding their actual importance as habitat, we can with confidence say that people value CWC for their habitat services. Interests and engagement by NGOs and others for the protection and conservation of CWC can be seen as an implicit expression of their value. Coastal fishers in Norway have argued to protect the quasi option values CWC represents. None of these values have been attempted quantified.	Foley, Kahui et al. (2010) Armstrong, Foley et al. (2016) Glenn, Wattage et al. (2010) Aanesen, Armstrong et al. (2015) LaRiviere, Czajkowski et al. (2014) Falk-Andersson, Foley et al. (2015) Armstrong and van den Hove (2008) Foley, Kahui et al. (2010)

4) The physical and biological impact of ocean acidification on cold water coral	<u>Live coral</u>: ambiguous results from various short-term and long term experiments of the impacts of pCO2, temperature and pH, ranging from negative to positive impacts on growth rates. Still, the reviewed studies seem to indicate less dire effects upon these resources than for instance tropical coral. There is very little knowledge regarding the effects of multiple stressors. *Expert opinion* is that there will be negative effects on living CWCs at 800 and 1200 ppm CO_2, but the confidence is low to medium on this. Confidence is medium to very high that this will give reduced size and complexity of coral structures, and reduced spread of CWC. <u>Dead coral</u>: No quantitative estimates of possible dissolution rates exist for CWCs in peer reviewed literature. Dissolution rates observed for tropical and sub-tropical corals range nearly 5 orders of magnitude. The *expert opinion* elicitation states high to very high confidence on increased dissolution of dead CWC at 800 and 1200 ppm CO_2, and also on reduced size and complexity of the coral structures.	Maier, Hegeman et al. (2009) Hennige, Wicks et al. (2013) McCulloch, Trotter et al. (2012) Form and Riebesell (2012) Andersson and Gledhill (2013)
5) The impact of ocean acidification on ecosystem services from cold water corals	No quantitative estimates exist in peer-reviewed literature of how the ecosystem services from CWCs may be affected by OA. *Expert opinion* from our elicitation is medium confidence for the effects of OA on both living and dead coral at 800 and 1200 ppm CO_2 giving reduction in habitat services, reduced ecosystem resilience, loss of raw material for bioprospecting, and reduced biodiversity.	

The knowledge status in Table 8 can also be represented graphically, as below in Table 9. There, the status of knowledge is indicated for both qualitative status/effects and quantified status/effects. A traffic-light colour coding is used to indicate *either the availability of data on the different aspects, or the level of confidence on the knowledge*.

The colour coding is conservative. This means that the colour code for data availability or confidence level that indicates the lowest knowledge level is chosen. For example, if "some data" exists for a certain aspect (yellow colour), but there is low confidence about the validity or reliability of the data (red colour), the indicator colour used in the table will be red. The evaluation of status of knowledge at one level is independent on the evaluation in the next level. Thus, although there is some confidence in ecosystem services and associated values of CWC, the impact of ocean acidification on these is rated with low confidence due to a lack of knowledge on how acidification affects CWCs.

Table 9: Graphical representation of status of knowledge for assessing impacts of ocean acidification on cold water corals.

🟥	No data/low confidence
🟨	Some data/medium confidence
🟩	Data exist/high confidence

		Status of knowledge	
		Qualitative	**Quantitative**
1) Cold water coral distribution			
	Distribution	🟨	🟨
	CWC volume	🟥	🟥
2) Ecosystem services of cold water corals			
	Supporting: Habitat services	🟩	🟨
	Provisioning	🟨	🟨
	Regulating: Carbon sequestration	🟨	🟨
	Cultural	🟩	🟨
3) Valuation of cold water coral ecosystem services			
	Supporting: Habitat services	🟩	🟩
	Provisioning	🟥	🟥
	Regulating: Carbon sequestration	🟥	🟥
	Cultural	🟩	🟩
4) The physical and biological impact of ocean acidification on cold water coral			
	Live corals' growth and survival	🟥	🟥
	Dead coral dissolution	🟩	🟥
5) The impact of ocean acidification on ecosystem services and values from cold water corals			
	Supporting: Habitat services, resilience	🟨	🟥
	Provisioning	🟥	🟥
	Regulating: Carbon sequestration	🟥	🟥
	Cultural	🟨	🟥

The knowledge gaps, with level four and five being a particular bottle neck, are clearly too big to do a quantitative assessment of social and economic consequences of ocean acidification on cold water corals. This is the case for any effects of ocean acidification on dead or live coral, and thereby any possible impact from these effects on ecosystem functions and services. Due to a number of research projects on the ecosystem services and associated values of cold water corals, the knowledge of level 2 and 3 is relatively good. However, there is a problem of scaling up the valuation studies to a global level, as they have been specific to just a few countries. Furthermore, the values related to habitat services are dependent on the CWC actually being important habitat for commercially important fish.

The only impacts that can be stated with some confidence are the negative effects from ocean acidification on dead coral leading to negative effects on habitat services and cultural ecosystem services. These are indicated in the table above with the yellow colour for the status of qualitative knowledge under *5) The impact of ocean acidification on ecosystem services and values from cold water corals* for *Habitat services* and *cultural* services. This is chosen based on the combination of high/ very high confidence in dead corals being affected by OA, and corresponding medium confidence on the impact on ecosystem services from this. For all other possible impacts (under point 5) the status of knowledge/confidence is low for both qualitative and quantitative impacts.

The lack of, or uncertainty of knowledge identified above make it impossible to assess the full impact of ocean acidification on CWC, qualitatively or quantitatively. The mapping and assessment which have been performed can, however, be useful for guiding future research and for management. We will now turn to this

4.7 MANAGEMENT OF COLD WATER CORAL

In the expert elicitation referred to earlier we also asked the experts to state their opinion on possible mitigation and adaptation strategies related to ocean acidification. The possible adaptation/ mitigation strategies that the experts' have highest confidence in are the use of artificial reefs, marine protected areas (MPAs), and reducing fishing pressure for fish species affected. Geoengineering to reduce CO_2 is considered a useful measure only with low confidence.

In the following we discuss management of cold water corals under increasing ocean acidification. As presented in Figure 1, such management can involve both mitigation[1], i.e. intervention to enhance the sinks of CO_2 or reduce the sources of CO_2 or acidification, and adaptation, i.e. actions to moderate harm or exploit beneficial opportunities in response to ocean acidification. Furthermore, there may even be trade-offs between these two approaches (Kane and Shogren 2000). In the following we will discuss mitigation and adaptation separately, focusing on the latter, with different aims and actions for cold water coral conservation listed in Table 10. Adaptation in the face of ocean acidification can focus on ecosystem *function*, i.e. physical, chemical and biological attributes that contribute to the self-maintenance of an ecosystem, or the ecosystem *service*, i.e. the for humans beneficial outcomes of ecosystem functions. These services contribute to human welfare, which can also be targeted directly with regard to adaptation. Hence, at a functional level an adaptation example could be that of geoengineering. For example development of physical structures that can contribute to

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[1] Note that there is a difference between climate mitigation and ocean acidification mitigation, as the former only focuses on CO_2, while the latter also includes reducing acidification.

replacing the function that dead coral structures have in terms of lifting the live part of the reef into favourable environmental conditions[1]. At a service level adaption could be protection of habitat through fisheries regulations, hence reducing the aggregate stress of multiple pressures. Finally, adaption to secure human welfare could involve growing CWC in artificial settings to maintain existence values. Clearly, there is a close link between ecosystem functions, services and benefits, hence securing functions may also secure services and benefits. Table 10 summarises the aims and actions connected to mitigation and adaptation strategies for preserving cold water coral functions, services and values, given ocean acidification.

Table 10: The aims and actions connected to mitigation and adaptation strategies for preserving cold water coral functions, services and values, given ocean acidification.

	Aim:	**Action:**
Mitigation	Reduce CO_2 emissions	Policy/change public behaviour
	Increase carbon sequestration	Policy/public expenditure/research
	Reduce acidification	Geo-engineering /research
Adaptation	Protect CWC function	Manage to increase resilience /Geo- and Genetic engineering
	Protect CWC services	Management/ Geo- and Genetic engineering
	Protect human benefits from CWC services	Genetic engineering/change public perceptions

A number of geo-engineering solutions have been proposed to mitigate acidification. This includes adding carbonates or silicates to the ocean, and various ways to preserve or enhance the ocean's biological and chemical capacity to form or sequester CO_2. Geo-engineering techniques have been tried out on tropical corals where buoyant shade cloths provide artificial shading. Other techniques proposed to reduce thermal stress and promote growth include the use of low-voltage direct current and wave- or tidal-powered artificial upwelling bringing cool, nutrient rich waters to the corals. Major limitations, however, include the ability to address the geographical scope of the

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[1] We recognise that the effect of such measures is not very credible, for example since other environmental conditions may change with elevation and costs may be very high. However, there are examples of rehabilitation of tropical coral reefs (see for example Spuregon, J. (1998). "The socio-economic costs and benefits of coastal habitat rehabilitaiton and creation." Marine Pollution Bulletin **37**: 373-382.)

problem and the potential for unforeseen negative ecological impacts (Rau, McLeod et al. 2012).

Adaptive management actions proposed to increase resilience of tropical coral reefs include protecting herbivorous fish and other top predators, manage water quality and generally minimise anthropogenic stress (Veron, Hoegh-Guldberg et al. 2009). Regardless of which actions are taken these cannot offer long-term protection of corals if CO_2 levels pass critical thresholds and corals respond negatively to acidification (Veron, Hoegh-Guldberg et al. 2009). However, as discussed earlier, the consequences of ocean acidification for cold water corals are not well known as of yet. Furthermore, multiple stressors may strengthen or weaken each other's effects (Griffith, Fulton et al. 2012). In addition to acidification, the ecosystem services that cold water corals supply are threatened by other human activities such as bottom trawling, oil and gas exploitation, cable laying, and research activities. These activities may reduce the resilience of cold water corals in the face of ocean acidification, and are hence of interest in relation to applying adaptation strategies in order to secure the flow of services provided by CWC. This illustrates that there are trade-offs between exploitation of different services. In order to maximise human welfare delivered by ecosystem services, there must be an assessment of what is lost and what is gained when priorities are made regarding one service versus another, and this is where valuation comes in.

Survival of corals, and their ecosystem functions, is believed to be highly dependent on the natural resistance existing in the gene pools today, as the speed at which climate change is happening is too rapid for any evolutionary process. Coral reefs are highly biodiverse habitats (Roberts, McClean et al. 2002; Freiwald, Fossa et al. 2004), and while it may be possible to replace some of the functions of CWC for example by constructing artificial reefs that can serve as habitat for some species, these will not be able to fully replace all the processes that contribute to the high biodiversity of corals, which again is the foundation for production of ecosystem goods and services. Protective culturing, selective breeding and genetic engineering are adaptation techniques proposed to assist resilience of corals. However, up-scaling this management strategy to include all impacted organisms is unrealistic (Rau, McLeod et al. 2012).

There may be possibilities for adaptation as regards cultural services in the shape of for instance aesthetic enjoyment; in the same way that cultured landscapes have replaced natural landscapes many places on terrestrial earth, clearly cultured seascapes might function in a similar way. Hence semi- or non-natural genetically engineered acidification-robust coral reefs could compensate for the loss of natural coral reefs. Whether these cultured seascapes will be second –best options involving costs connected to loss of existence values, or whether they alternatively can replace natural seascape benefits, will depend on human perceptions, which also may change over time.

5 FUTURE RESEARCH ON IMPACTS OF OA ON CWC

Our review and identification of the current status of knowledge and the knowledge requirements to analyse the social and economic impact of ocean acidification on cold water corals should be used to guide future research and research priorities.

Prioritising future research to handle knowledge gaps on issues like this can be viewed as part of risk management (Jones, Patwardhan et al. 2014). To do this properly, a number of factors should be considered, including the physical and environmental state and possible change, the state and potential economic and social change that could follow from the changes in the natural environment, and also the possible measures at hand to try to deal with the changes that can occur – and their costs (Jones, Patwardhan et al. 2014) (Meyer, Becker et al. 2013). This corresponds to considering exposure to natural change, social and economic vulnerability, and institutional vulnerability / adaptive capacity.

While an understanding of the possible geophysical changes can be seen as the foundation for any comprehensive risk assessment here, the knowledge gaps about them may not necessarily be the most urgent gaps to fill for risk management decisions. If preventive or precautionary measures are cheap and available one should not wait for knowledge gaps to be filled before implementing them. If possible measures are costly or have uncertain effects, one wants to determine the environmental and economic and social risks with larger accuracy before making a decision to implement such measures. If social and economic vulnerability is small, even for relatively large potential exposure to natural change, one is likely reluctant to invest much in knowledge acquisition or other risk-reducing measures. Research to fill knowledge gaps should not only be targeted at getting the necessary information to make complete risk assessments, but also to make it easier to decide whether some risks can be given lower priority regarding “full investigation”. Thus, regular assessments of what knowledge gaps to prioritise should be an important part of any iterative risk management process. Iterative risk management is especially appropriate under large uncertainty, long time frames, potential for learning over time, and influence of climate, biophysical and socioeconomic changes (Jones et al. 2013). With uncertainties inevitable, a precautionary attitude should nevertheless always be present.

Table 9 presents a simplified view of the current status of knowledge on the state and possible biogeophysical, social and economic impacts of ocean acidification in relation to CWC. As we have not carried out a comprehensive assessment of management options, so our assessment of research priorities is limited by this. With this caveat, we see the areas below as the most urgent for future research leading to a reasonable social and economic assessment of the effects of ocean acidification on CWCs. It should be noted that having reached a certain level of knowledge for some areas now does not necessarily mean it will be possible to expand from that level easily.

- Distribution and volume of CWC (level 1 in Table 9); Fundamental knowledge required for any such assessment. This is needed as a reference point for management, and a guideline for marine operations to avoid damage to the corals.

- Live corals' growth and survival (level 4): Fundamental knowledge is required regarding the biology of the corals as a baseline for impact studies.
- Dead corals' dissolution rates, and possible break-down of reefs into parts (level 4). Fundamental knowledge is required to understand the impact ocean acidification may have on the structural function of dead corals.
- Habitat services (level 2). There is a need for both ecological research on coral reef size/quality and link with ecological functions, especially linked to commercial fish species, and economic research to value these links. While the qualitative understanding is good, and there is some quantitative understanding of this link, the indirect value related to commercial fish stocks from CWC habitat is important to quantify due to the economic and social importance of the fisheries.
- The impact of ocean acidification on ecosystem services from cold water corals (level 5). The knowledge gap on impact of OA on CWC (level 4) is a major limiting factor for assessing impact despite relatively good information on the ecosystem services of cold water corals.

Other works that explicitly or indirectly give recommendations on which knowledge gaps to fill regarding ocean acidification in general include (Williamson, Turley et al. 2013) and (Gattuso, Mach et al. 2013). The latter has an expert opinion survey on the knowledge about ocean acidification, status, development, socio-economic impacts and mitigation measures. The statements about OA that the experts are asked to assess in Gattuso, Mach et al. (2013) are rather broad in their formulation, and there is little specifically related to cold-water corals.

6 CONCLUSION

This synthesis of the impact of ocean acidification on cold water corals and the ecosystem services they provide illustrates the different areas and levels of knowledge that needs to be established and linked together to understand the chain from ecological changes to societal impact and management options. Furthermore, we illustrate how expert opinion can be used in a case of high uncertainty to give management input.

In this report we have regarded direct impacts of ocean acidification on cold water corals, impacts on their ecosystem functions and the services they provide, as well as some management options. We showed that the highest level of certainty is related to negative impact on dead cold water coral structures, and that adaptation measures to reduce the total stress on the corals, and thereby increase their resilience, were rated with the highest confidence.

Among management options, artificial reefs were rated highly, while the experts had very little confidence in geo-engineering techniques to remove CO_2. Mitigation in the form of reduction of CO_2 emissions to the atmosphere can possibly be considered the preferred measure to deal with ocean acidification, but we also describe mitigating and adaptation measures targeted at different levels, from for example protection of the habitat services of corals to protection of their existence value.

Finally, we point to important knowledge gaps that need to be addressed to better evaluate the socio-economic impact of ocean acidification on cold water corals. These include distribution and biology of cold water corals, their response to ocean acidification and their importance as habitat for fish, in particular commercially important species.

While the methodology needs to be refined, we have illustrated that using experts to assess impacts in high uncertainty cases is valuable for identifying key knowledge gaps and to provide inputs to management. That some of the experts in the elicitation exercise expressed that it made them better see the relevance of their basic research for management, is likely also valuable for future research design and priorities.

7 APPENDIX:

7.1 PARTICIPANTS AT EXPERT OPINION ELICITATION AT FRAM OCEAN ACIDIFICATION FLAGSHIP MEETING, TROMSØ, 21 OCTOBER 2013

Name	Institution
Anne Britt Storeng	Miljødirektoratet, Trondheim
Cecilie Hansen	IMR, Bergen
Claudia Halsband	APN, Tromsø
Agneta Fransson	NPI, Tromsø
Melissa Chierici	IMR, Tromsø
Eirik Mikkelsen	Norut, Tromsø
Claire Armstrong	NFH, UiT
Jannike Falk-Petersen	NFH, UiT
Wenting Chen	NIVA, Oslo
Maria Fossheim	IMR, Tromsø
Peter Thor	NPI, Tromsø
Allison Bailey	NPI, Tromsø
Padmini Dalpadado	IMR, Bergen
Evgeniy Yakushev	NIVA. Oslo
Jo Aarseth	Fram Centre, Tromsø
Haakon Hop	NPI, Tromsø
Piotr Kuklinski	Institute of Oceanology, Poland
Mats Granskog	NPI, Tromsø
Johanna Järnegren	NINA, Trondheim

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