An acidic future for Norwegian fisheries?

Assessing the socio-economic vulnerability of the Norwegian fishery sector to the threat of ocean acidification

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Master Thesis Series in Environmental Studies and Sustainability Science,
No 2015:009

A thesis submitted in partial fulfillment of the requirements of Lund University International Master's Programme in Environmental Studies and Sustainability Science (30hp/credits)

LUCSUS
Lund University Centre for Sustainability Studies

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Submitted May 13, 2015

Supervisor: Dr. Torsten Krause, LUCSUS, Lund University

Abstract:

Ocean acidification, caused by the increased uptake of anthropogenic CO_2, describes a change in the ocean's carbonate chemistry. While its chemical processes are well understood, less is known about its biological and subsequently socio-economic consequences. However, there is evidence that marine organisms will be adversely affected by a decrease in pH and carbonate saturation levels. Fishery is a traditionally important economic sector in Norway but stock sizes and consequently also catch could be significantly threatened by ocean acidification. To improve the understanding of potential socio-economic consequences, I conducted a risk assessment among the 19 Norwegian counties following Mathis et al.'s (2014) application of the IPCC's SREX risk assessment framework. The SREX framework combines information regarding hazard, exposure, sensitivity and adaptive capacity. The results show that the northernmost counties are most at risk as high-latitude oceans are considered to be more threatened compared to lower-latitude regions. The second part of the analysis shows that particularly the southernmost counties, which engage in the harvest of crustaceans are more economically exposed due to the fact that these species are more susceptible to ocean acidification and generate a higher catch value. The results of the sensitivity related calculations show that the share of income generated from fisheries is very low compared to the total income. However, direct county comparisons highlight that the northern counties reveal a higher level of sensitivity, as the share of fishermen is substantially higher there than in most other counties. Adaptive capacity is considerably lower in the northern counties than in the other counties. Overall, the final risk assessment points out that 13 out of 19 counties face moderate to high risk from ocean acidification. My research shows that the SREX risk framework is applicable for evaluating the impacts of ocean acidification. In the case of Norway however, substantial improvements can be achieved by increasing the availability of detailed data, such as long-term monitoring of oceanic conditions, better information regarding the biological impact of species, and more detailed employment and income statistics. Overall, my thesis shows that, although still in its infancy, integrated risk assessments are an important prerequisite for any form of interdisciplinary ocean acidification research and the development of successful response strategies. In future studies this quantitative research could be complemented by qualitative methods such as assessing awareness among fishermen through interviews or a participatory approach for incorporating local knowledge into adaptation efforts.

Keywords: Ocean acidification, fishery, risk assessment, vulnerability, Norway, SREX

Word count: 13,177

Acknowledgements

First and foremost, I would like to thank my supervisor, Dr. Torsten Krause, for being open to my ideas and my choice of topic. His valuable comments helped me to structure my thoughts and to stay focused during the entire writing process. Furthermore, I would like to express my gratitude to Lorena Arellano Gosdenovich, Pascale Magin and Diana Noreña Ramirez for their patience and the constructive criticism they provided during our endless thesis meetings. In addition to this, I would like to thank the International Atomic Energy Agency for offering me the opportunity to intern at the Ocean Acidification – International Coordination Centre in Monaco and inspiring me to write my thesis about the socio-economic impacts of ocean acidification. In connection to this, I would like to thank Dr. Sarah Cooley, one of the co-authors of the article by Mathis et al. (2014), for patiently answering my questions regarding the exact application of their methodology. Furthermore, I would like to express my gratitude to the German Academic Exchange Service (DAAD) for funding my stay in Sweden. Last but not least, I would like to thank my father, Dr. Hartmut Heinrich, for helping me make sense of my ideas and for coming up with a catchy title.

Table of Contents

1 Introduction 1

1.2 Thesis rationale 2

1.2.1 Vulnerability assessments 2

1.2.2 Contribution to sustainability science 3

1.2.3 Norway 4

1.3 Research questions 5

2 Background 7

2.1 The ocean acidification process 7

2.2 Biological impacts 8

2.3 Socio-economic impacts 9

3 Methodology 13

3.1 The concept of vulnerability and vulnerability assessments 13

3.2 Ontology and epistemology 14

3.3 Application of the IPCC SREX risk assessment framework following Mathis et al. (2014) 15

3.3.1 Hazard 16

3.3.2 Exposure 16

3.3.3 Vulnerability 17

3.3.4 Risk index 20

4 Results....21

4.1 Hazard....21

4.1.1 Ocean acidification near Norway....22

4.1.2 Allocation of counties and ranking....23

4.2 Exposure....24

4.3 Vulnerability....30

4.4 Risk index....44

5 Discussion....41

5.1 Interpretation of results....41

5.2 Ocean acidification in relation to other marine ecosystem stressors....45

5.3 Mitigation of and adaptation to ocean acidification....46

5.4 Limitations and room for improvement....48

6 Conclusion....51

7 References....53

1 Introduction

Ocean acidification is one of the direct global consequences of anthropogenic climate change and is listed among Rockström et al.'s (2009) nine planetary boundaries. It is however, often regarded as 'the other CO_2 problem' or 'global warming's evil twin' for it is often concealed by the better-known problem of global temperature rise (Doney et al., 2009). Ocean acidification describes a change in the ocean's carbon chemistry. While its chemical processes are largely understood, there is a considerable research gap with regard to its biological and subsequently socio-economic consequences (Brandner et al., 2014). The ocean takes up atmospheric CO_2, which leads to a decrease in seawater pH and carbonate saturation (Sabine et al., 2004). Research shows that this can have adverse consequences for calcifying marine organisms which depend on specific levels of available carbonate minerals to develop their shells. Although adult fish seem to be less sensitive, some species may be adversely affected during early development stages or indirectly through the disappearance of key species in their respective food webs (Ishimatsu et al., 2008). By modifying or even destroying entire marine ecosystems, ocean acidification can also limit the availability of ecosystem services such as fishery, coastal protection or tourism with potentially detrimental consequences for human communities who depend on them (Moberg & Folke, 1999).

Norway is one of the biggest fishing nations worldwide, due to its long coastline and traditionally strong and economically important fishery sector (FAO, 2013). Ocean acidification, however, could negatively influence fish stocks, and thus threaten dependent communities. The Norwegian government is generally interested in improving the sustainability of the fishery sector. Although ocean acidification is recognized as a potential threat in climate change reports, specific response strategies have yet to be developed (Miljøverndepartement, 2013). To assist this process and in an attempt to contribute to the limited availability of interdisciplinary ocean acidification research, I decided to conduct a risk assessment with the aim of ranking the 19 Norwegian counties according to their vulnerability to ocean acidification's socio-economic implications following the example of Mathis et al. (2014). I will attempt to answer questions such as, "To what extend are the Norwegian counties affected if fisheries are threatened by ocean acidification?" and, "Is the level of information sufficient for properly estimating the socio-economic consequences?"

1.2 Thesis rationale

1.2.1 Vulnerability assessments

Although many experts have attempted to define 'vulnerability' there is no uniform definition of the concept. A few decades ago Timmerman (1981) pointed out that the term only provided the broad information that a problem area is of particular concern. Roughly ten years later, Liverman (1990) revealed that 'vulnerability' is often used in relation to topics like susceptibility, adaptability, resilience and risk. In more current times, Adger (2006) describes the concept as a "powerful analytical tool for describing states of susceptibility to harm, powerlessness, […] of both physical and social systems and for guiding normative analysis of actions to enhance well-being through reduction of risk" (p. 286). Reducing the adverse effects of an event prior to its occurrence requires a thorough understanding of the hazard itself, affected natural and social systems, as well as underlying drivers (Füssel and Klein, 2007).

According to Næss et al. (2006), "vulnerability assessments […] are a widely used instrument, comprising a broad group of tools with varying characteristics and goals" (p. 221). Over time, these goals have changed from "mapping potential climate change impacts to an increased focus on strategies facilitating adaptation" (p. 221). Through identifying the people, places and sectors most affected by climate change, vulnerability assessments can greatly contribute to policy and decision-making (Hammill et al., 2013). More specifically, vulnerability assessments can answer questions regarding the adaptive capacity of socio-ecological systems, draw attention to cause and effect relationships and address pressing challenges.

On a less applied level, vulnerability assessments can assist in developing and modifying corresponding theoretical approaches and improve the methodology of analyzing and evaluating vulnerability (Hammill et al., 2013). Despite the possibility to question the effectiveness of vulnerability assessments, for example, by highlighting the difficulty for stakeholders to interpret and apply the provided information or the difficulty of identifying user groups and their respective data requirements (e.g., Cash et al., 2003), I decided to conduct a vulnerability assessment for several reasons. Firstly, the issue of ocean acidification has not yet received sufficient attention to be translated into specific response strategies, which may largely be related to the absence of data regarding ocean acidification's socio-economic consequences (Miljøverndepartement, 2013). To move the topic further up in the agenda it therefore seems to be essential to learn more about the vulnerability of potentially affected people, places or sectors – in this case fishery sectors and inhabitants of the Norwegian counties. Secondly, an improved understanding of vulnerability to ocean acidification may contribute to raising awareness among politicians, fishermen and other relevant stakeholders. I decided to focus on the sub-national level as a scale in order to account for differences within the country. To date, the majority of research evaluates the potential impacts of socio-economic ocean acidification impacts on a national level, which involves a significant degree of generalization. Because of its strong economic performance and the level of education, Norway as a whole would probably not appear to be highly vulnerable. Due to expected local variability with regard to both natural and socio-economic differences a nation-level assessment would not be sufficiently informative for advising Norway's national climate change adaptation policy (O'Brien et al., 2004).

1.2.2 Contribution to sustainability science

According to Hay and Mimura (2006), "sustainability is achieved only when there is full reconciliation between: (1) economic development; (2) meeting, on an equitable basis, growing and changing human needs and aspirations; and (3) conserving the limited natural resources and the capacity of the environment to absorb the multiple stresses that are a consequence of human activities" (p. 23). Sustainability science aims for a holistic approach of understanding human-environment systems in order to account for the complex interactions within and among these systems (Clark and Dickson, 2003). As such, one of the disciplines core objectives is the "goal of creating and applying knowledge in support of decision-making for sustainable development," preferably by means of combining academia and practice (Clark and Dickson, 2003). Understanding the vulnerability of coupled human-environment systems is crucial for improving appropriate policy and decision-making (Turner et al., 2003). According to the International Standards Organization risk assessments are defined as a "process to comprehend the nature of risk and to determine the level of risk" (ISO, 2009). As such vulnerability and risk are concerned with the detection of different aspects of these components. This is done by means of collecting and classifying information with the objective to determine different degrees of susceptibility of, for example, coupled socio-ecological systems (IPCC, 2012). The Hyogo framework for Action highlights that risk assessments can be considered a "starting point for reducing disaster risk and for promoting a culture of disaster resilience [as the basis for this] lies in the knowledge of the hazards and the physical, social, economic and environmental vulnerabilities […], followed by action taken on the basis of that knowledge" (UN, 2005, p. 9). Moreover, the SREX[1] claims "vulnerability and risk assessments are key strategic activities that inform both disaster risk management and climate change adaptation" (IPCC, 2012, p. 91). In addition to this, risk and vulnerability assessments can contribute to developing and refining relevant methodology with the objective to improve the estimation and quantification of these two components (IPCC, 2012, p. 91). As such my thesis serves as a starting point in the investigation of the extent to which ocean acidification can be a socio-economic threat to counties where fishery is an important sector. Information about methodology and the resulting assessment can be used to further research this topic and develop corresponding response strategies.

1.2.3 Norway

I chose Norway to be the focus of my research for several reasons. Firstly, Norway is located in a region particularly vulnerable to ocean acidification. High-latitude oceans, such as the North Pacific Ocean, the Nordic Seas and the Arctic Ocean appear to be most at risk (Fabry et al., 2009). Secondly, interdisciplinary ocean acidification research so far has mainly focused on North America for reasons related to the economic importance of shellfisheries and on less developed low-latitude countries for their dependence on ecosystem services provided by intact coral reef ecosystems (Brandner et al., 2014). To date, there is only one scoping study available focusing on Norway, which offers a broad overview of ocean acidification impacts on various ecosystem services but provides no information on the vulnerability of affected social systems (Armstrong, 2012). Thirdly, with a shoreline of over 25,000 kilometers, Norway has the longest coastline in Europe, and some of the world's richest fishing grounds. The oceans surrounding Norway yield several commercially valuable fish and crustacean species, such as herring, capelin, cod and shrimp. In Norway, fisheries not only play a key role in economic development but also contribute substantially to the national economy (FAO, 2013). Moreover, fishery production is of great importance for trade and makes Norway the world's second largest exporter of fish and fish products with markets in many different parts of the world. Lastly, the Norwegian government appears to be generally interested in the topic of climate change and has included ocean acidification in several policy reports focusing on climate change mitigation and adaptation.

[1] Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation (SREX)

1.3 Research questions

Based on the natural and socio-economic data available my thesis investigates possible consequences of an increasing ocean acidification (OA) on the (local) fishery and related economies of all Norwegian counties. The study aims on starting a discussion on a relevant socio-economic problem for Nordic Countries that might arise if ocean acidification reaches values posing a severe threat to the ecology of the Nordic Seas.

Main research question:
How are the Norwegian counties affected by ocean acidification with respect to the three risk components 'hazard', 'exposure' and 'vulnerability'?

Furthermore, I attempt to answer the following questions:

1. How far is the SREX framework applicable to the Norwegian fishery sector?
2. What other stressors could amplify the impact of ocean acidification in Norway?
3. What mitigation or adaptation strategies exist and how is the threat of ocean acidification accounted for on an institutional level?

2 Background

2.1 The ocean acidification process

The absorption of CO_2 by the ocean is an important mechanism that throughout time has kept global temperatures at a level suitable for the survival of life on Earth (Feely et al., 2009). Since the Industrial Revolution, the ocean has taken up approximately 25% of the anthropogenic CO_2 emissions (Sabine and Feely, 2007). However, the absorption of CO_2 initiates a number of chemical reactions, which ultimately reduce seawater pH[2], as well as the saturation state of carbonate minerals (Steinacher et al., 2009). This process is commonly referred to as ocean acidification (Caldeira and Wickett, 2003). Atmospheric CO_2 dissolves in seawater, usually leading to a proportional increase of seawater and atmospheric CO_2 levels (Feely, 2009). Then, through the subsequent hydration of water carbonic acid is formed, which immediately disintegrates into bicarbonate ions (HCO_3^-) and carbonate ions (CO_3^{2-}) (Feely et al., 2009). Following this, carbonic acid (H_2CO_3) dissociates into H^+ and HCO_3^- ions. The H protons react with carbonate to form further carbonate ions. This implies that the dissolution of CO_2 ultimately leads to a decrease of seawater pH and carbonate concentrations (Feely, 2009). The reduction of relevant carbonate minerals has an adverse affect on various marine organisms that require calcites or aragonite for the development of their exoskeletons (Fabry et al., 2008; Hoegh-Gulberg and Fine, 2005). The saturation level (Ω=1) of the more soluble aragonite is approximately 50% lower than that of calcite (Steinacher et al., 2009). For this reason, aragonite saturation is considered a "key variable for assessing biological impacts of ocean acidification" (Steinacher et al., 2009, p. 516) and also suitable for measuring the hazard component of risk assessments (Mathis et al., 2014). The carbonate compensation depth (Ω=1) marks the water depth below which carbonate shells are subject to dissolution. Supersaturation occurs at levels above 1 (Ω>1) and undersaturation (Ω<1) at values below 1 (Feely et al., 2009).

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[2] pH levels are indicated on a logarithmic scale ranging from 0 to 14. Values below a pH of 7 are considered acidic. The current pH of seawater is approximately 8.1, while pure water has a pH of 7 (WHOI, 2012).

2.2 Biological impacts

Early experiments studying the impact of ocean acidification on marine organisms mainly focused on calcifying organisms, as the chemical processes driving ocean acidification directly interferes with the ability of these organisms to develop their skeletons and shells (Gattuso et al., 1998). Mollusks and corals have received particular attention due to their relevance for the economic performance and food security of dependent countries (Brandener et al., 2014). Cooley et al. (2012) mention that the responses of mollusks to changes in seawater chemistry vary among species but that the effect on the majority of species tested in their study was either neutral or negative. In experiments with Eastern Oysters (*Crassostrea virginica*), Gazeau et al. (2013) found that a significant decrease of seawater pH modifies calcification rates, which causes a thinning of the oyster's shells. Talmage and Gobler (2009) showed that ocean acidification slows down larvae development and raises death rates of several North American mollusk species such as the Atlantic bay scallop (*Argopecten irradians*). Many studies focus on corals as they provide ecosystems services required for the existence of dependent communities (Hoegh-Gulberg and Fine, 2005). Corals consist on aragonite that forms their skeletons. When pH decreases too much and carbonate is significantly less available, calcification and growth rates are significantly reduced (Kleypas and Langdon, 2006). The fate of fish species in terms of potential ocean acidification responses is considerably less well studied and data is only available for a small number of commercially valuable species (Ishimatsu et al., 2008). The same is true for crustacean species, for which research is mainly available for culturally or commercially valuable species such as the American Lobster (*Homarus americanus*) (Keppel et al., 2012). For the impact of ocean acidification on Norwegian crustacean and finfish species, please see section 4.2.1).

2.3 Socio-economic impacts

With most research only published after 2008, the study of the socio-economic impacts of ocean acidification is very young and research findings remain limited (Brandner et al., 2014). Hilmi et al. (2013) and Brandner et al. (2014) provide an overview of currently available research and conclude that there are considerable knowledge gaps that need to be filled in the near future. Cooley and Doney (2009), Cooley et al. (2012) and Mathis et al. (2014) among others highlight the importance and urgency of this kind of research by pointing out that seafood industries worldwide are already experiencing the adverse impacts ocean acidification, or will likely see in the near future. Similar to studies about biological responses, the study of socio-economic impacts also focuses largely on mollusks for reasons related to economic performance and food security (Brandner et al., 2014). Moreover, their physical responses are fairly well understood, which facilitates the modeling of subsequent socio-economic consequences (Cooley et al., 2012). In addition to this, there are a few studies about the socio-economic consequences focusing on coral reefs (e.g., Kite-Powell, 2009; Brandner et al., 2012). Due to the still limited understanding of complex interactions of marine ecosystems and the biological responses of many fish species, it is challenging to make accurate and detailed predictions (Cooley et al., 2012). Brandner et al. (2014) add to this that available research often differs in terms of methodology, which complicates the comparison of research findings. While some evaluate economic loss in terms of gross revenue (e.g., Cooley and Doney, 2009; Armstrong et al., 2012), others apply methods such as compensating variation (Moore, 2011) or a comparison of consumer and producer surpluses (Narita et al., 2012), others assess vulnerability without any kind of monetary estimations (e.g., Finnoff, 2010; Sumaila et al., 2011). In the following I will provide an overview of available research in the field.

Brandner et al. (2012) developed an integrated assessment model combining the IPCC's SREX and FUND[3] to assist with the quantification of potential economic loss associated with the ocean acidification impact on coral reefs. Results show that the exact economic value depends on the rates assumed for CO_2 emissions, ocean acidification and associated loss of coral cover, as well as population growth and income. Brandner et al. (2012) conclude that the economic loss resulting from the impact of ocean acidification on shellfish is relatively small compared to total income, but that it is likely to increase rapidly in the coming centuries.

[3] Climate Framework for Uncertainty, Negotiation and Distribution

Using experimental data about the biological responses of mollusks to changes in seawater chemistry as well as fishery harvest and price data, Cooley and Doney (2009) estimate the loss for the US economy to account for approximately US$ 2.6 billion by the year 2060, assuming constant catch rates, price and revenues, as well as a unchanged ecological and economic conditions.

Taking a slightly different approach to predict the potential economic loss to the US mollusk market[4], Moore (2011) uses an integrate model incorporating biogeochemical and economic aspects of ocean acidification. Contrary to the aforementioned studies, he applies the compensating variation method, which is defined as the “amount one would have to deduct from a person’s income to make him just as well off after a change in prices and income as he had been in the initial situation” (Chipman and Moore, 1980). Using a Cobb-Douglas function adjusted for application to environmental issues, he finds the decreased welfare to amount to approximately US$ 735 million by the end of the century (Moore, 2011).

Narita et al. (2012) who investigate the implications of ocean acidification for the global mollusk industry use a partial-equilibrium analysis to calculate consumer and producer surpluses in order to determine changes in welfare. They estimate annual global cost under a business-as-usual scenario to account for roughly US$ 100 billion by 2100.

Harrould-Kolieb et al. (2009) attempt to rank countries according to their degree of vulnerability to ocean acidification, which they base on criteria such as fishery catch, seafood consumption, extent of coral reefs and projected level of ocean acidification in near-shore waters.

Cooley et al. (2012) develop a framework aimed at evaluating individual countries susceptibility to ocean acidification with a special focus on the role that mollusks play in terms of economic importance and food security. Based on the individual countries’ score in categories such as the share of GDP and protein intake from mollusks, as well as their adaptive capacity to the consequences associated with decreasing seawater pH, they calculate so-called transition decades. These periods describe when the respective country will reach a state, where seawater chemistry has been altered to the extent that it becomes impossible for mollusks to develop in the same way as they do under today’s conditions (Cooley et al., 2012).

Mathis et al. (2014) developed a risk and vulnerability framework in order to assess the consequences of ocean acidification for Alaska and to rank the state’s individual regions

[4] Including oysters, scallops, clams, and mussels

based on their level of resilience to the issue. Please see 3.3 for a more detailed description of Mathis et al.'s (2014) methodology.

Focusing on the United States on a sub-national level, Ekstrom et al. (2015) evaluate the vulnerability and adaptive capacity of US shellfisheries to ocean acidification. Ekstrom et al. (2015) apply the same SREX risk assessment framework. They do, however, incorporate different indicators such as the impact of local influential factors amplifying the environmental impact of ocean acidification and the proximity to research facilities involved in corresponding research.

Armstrong et al. (2012) provide the only available study focusing on the implications for the Norwegian economy. Based on meta-studies by Hendriks et al. (2010) and Kroeker et al. (2010), they calculate revenue losses including monetary and non-monetary ecosystem services, including direct and indirect, as well as, positive and negative impacts. Particularly the latter makes this assessment unique, as the majority of research does not incorporate any potentially positive implications (Armstrong et al., 2012). By comparing the potential impacts of ocean acidification on provisioning (e.g., fishery) and regulating ecosystem services (e.g., carbon uptake), Armstrong et al. (2012) conclude that the impact on regulating services may be much higher and thus much more dramatic than that on provisioning ecosystem services. In the North Atlantic region ocean acidification is likely to only significantly impact particularly fishery-dependent countries like Greenland and Iceland (Haraldson et al., 2012). Armstrong et al. (2012) highlight however, that although fisheries do not play a big role with regard to the national economy of many countries, they can be extremely relevant on the local to regional level both with regard to commercial and recreational aquaculture and fishing.

3 Methodology

3.1 The concept of vulnerability and vulnerability assessments

There are several conceptualizations of vulnerability available, depending on the specific area of application. Füssel and Klein (2007), for example, identify three main schools of thought: the risk-hazard framework, the social-constructivist framework, and a framework developed and used by the Intergovernmental Panel on Climate Change (IPCC). Building their methodology on dose-response relationships, the risk hazard framework is probably the most technical conceptualization of vulnerability and mainly used in the context of disaster and risk management (e.g., UNDHA, 1993, Dilley and Boudreau, 2001). The social-constructivist framework is often applied in the fields of political economy and human geography as it takes a social scientific approach. Assuming causal relationships with respect to a community's coping capacity, it understands vulnerability as a deduced condition of a community that is strongly influenced by socio-economic and political factors (Dow, 1992; Adger and Kelly, 1999). The recent IPCC assessment reports and the Special Report on managing the risks of Extreme Events and Disasters to Advance Climate Change Adaptation (SREX) define vulnerability as "the degree to which a system is susceptible to, or unable to cope with adverse effects of climate change, including climate variability and extreme events" (IPCC, 2012, p. 33). As such, vulnerability is generally regarded as "a function of the character, magnitude, and rate of climate variation to which a system is exposed, its sensitivity and its adaptive capacity (IPCC, 2012, p. 33).

For the purpose of this thesis I decided to follow the example of Mathis et al. (2014) and Ekstrom et al. (2015) and apply the IPCC's conceptualization of risk and vulnerability, as it appears to be a promising methodology for analyzing this case. In addition to this, the application of the framework facilitates the comparison of my results with those published in similar studies (Mathis et al., 2014). In the SREX report, disaster risk is defined as "the likelihood over a specified time period of severe alterations in the normal functioning of a community or a society due to hazardous physical events interacting with vulnerable social conditions, leading to widespread adverse human, material, economic, or environmental effects that require immediate emergency response to satisfy critical human needs and that may require external support for recovery" (IPCC, 2012, p. 32). It is worth highlighting that disaster risk is considered to be a constantly evolving path that, if unmanaged, will threaten the well-being of a system. Disasters are considered to be outbreaks along this path (Cardona et al., 2010). Although climate impacts are not necessarily single-events but gradual changes, the SREX includes them in their definition of disaster risk if they either “impact livelihoods negatively by seriously affecting ecosystem services and the natural resource base of communities”, “have consequences for food security” or “have impacts on human health” (IPCC, 2012, p. 32). Ocean acidification meets the first two requirements and thus qualifies for this particular conceptualization of risk.

Regarding risk as a combination of hazard, exposure and vulnerability, subdivided into sensitivity and adaptation, is characteristic for the IPCC reports. Separating exposure from the hazard component is a recent modification, based on the assumption that risk is not only determined by the hazard itself, but also by the exposure and vulnerability to these hazards (IPCC, 2012).

3.2 Ontology and epistemology

In my thesis I conduct a risk assessment based on a combination of natural and social sciences. In terms of ontology, my methodology can be allocated to the realm of objectivism. My quantification of risk is solely based on objective measurements and statistical data that describe environmental and social conditions independent of the perceptions and interpretations of individuals or society as a whole. This is in line with Bryman (2012) who mentions that social phenomena are external to individuals and can neither be controlled nor influenced by them, thus describing an objective reality. With regard to epistemology my thesis can be considered positivist for several reasons. Firstly, I assume that in this early stage of research (see section 1.2) and not involving qualitative methods, it makes sense to treat social and natural sciences in the same way. This assumption is shared with (empirical) realism and in accordance with Bryman (2012) who highlights that positivist social science research is neither influenced by normative values but instead is based on observations that are free of the influence of pre-existing theories. Secondly, I assume that my thesis is reproducible, which according to Kannel and McGee (1987) is a pre-requisite for any research to be accepted by the scientific community. Lastly, Hayes (1992) claims that positivism is “the hegemonic conception underlying analyses of ‘risk’”, which supports my line of reasoning (p. 405).

3.3 Application of the IPCC SREX risk assessment framework following Mathis et al. (2014)

For evaluating the socio-economic implications of ocean acidification on the Norwegian fishery sector, I decided to apply the methodology of Mathis et al. (2014) in an attempt to facilitate the comparison of research results as suggested by Brandner et al. (2014). Mathis et al. (2014) applied a slightly modified version of the previously mentioned risk assessment framework developed by the IPCC and presented in the SREX. In their research, Mathis et al. (2014) rank census areas in Alaska based on scores they achieved in the categories hazard, exposure and sensitivity and adaptive capacity. Mathis et al. (2014) use seawater pH and aragonite saturation levels to quantify hazard. They use the NCAR CESM1-BGC model to determine past, present and future trends of ocean acidification near Alaska. The exposure score is based on catch revenue data from three groups of shellfish and finfish species that are weighted according to their expected potential vulnerability to the impacts of ocean acidification. In Mathis et al.'s (2014) application of the SREX risk assessment framework the sensitivity component is largely based on labor force and income statistics of inhabitants involved in the harvesting and processing of fish and fish products. The adaptive capacity score is based on seven variables: personal income, PFD[5] dependence, unemployment, poverty, education, job diversity and food prices. All individual scores combined then result in a final score showing the risk that individual census areas are facing. Due to differences with regard to applicable variables and available data, I applied a slightly modified version of the risk assessment framework based on the applicability and availability of data (figure 1). The following sections provide detailed information of my methodology, including the divergences from the original study.

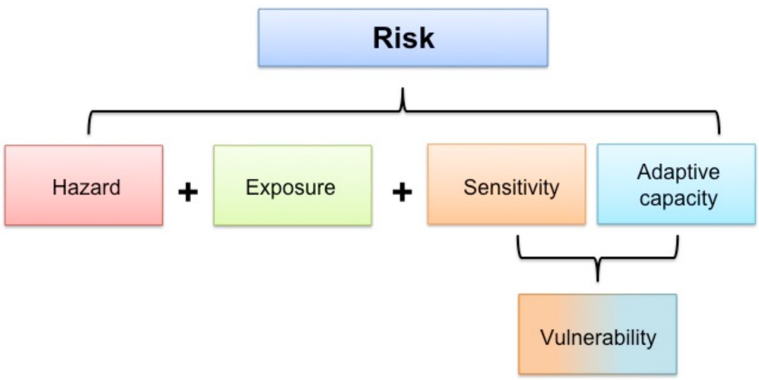

Figure 1. IPCC SREX risk assessment framework adapted from Mathis et al. (2014)

[5] PFD is a financial allowance paid to all Alaska residents

3.3.1 Hazard

In the SREX report 'hazard' refers to "the possible future occurrence of natural or human-induced physical events that may have adverse effects on vulnerable and exposed elements" (IPCC, 2012, p.69). Moreover, the SREX report highlights that hazards are components of risk but not the risk itself (IPCC, 2012). In the case of ocean acidification, 'hazard' can be measured or calculated based on factors like carbonate saturation or seawater pH. While Mathis et al. (2014) based their estimation of the hazard component on data from modeling future changes in aragonite saturation, I was limited to data about past (Skjelvan et al., 2014) and present values (Chierici et al., 2014) as no models exist for the ocean regions surrounding Norway. Following Mathis et al.'s (2014) example I divided the ocean regions and ranked them from 1 (most threatened) to 4 (not threatened). Assuming that the majority of fishing vessels harvest fish in the ocean regions adjacent to the counties they are registered in, I assigned the values '1' to '3' to the coastal counties and reserved the value '4' for the landlocked counties, assuming that they are not at risk as there are no fishing vessels registered in these counties.

3.3.2 Exposure

In many risk assessment frameworks, exposure is incorporated into the vulnerability component (Mathis et al., 2014). In the SREX framework however, it is considered separately, which makes this approach slightly different from previous IPCC reports (IPCC, 2012). According to Lavell et al. (2012), this distinction not only highlights the component's importance but also makes it possible to quantify exposure based on socio-economic factors. The SREX defines exposure as the "inventory of elements in an area in which hazard events may occur" (IPCC, 2012, p. 69). This definition assumes that risk only occurs where either human populations or human-valued resourced are located (IPCC, 2012). Moreover, they highlight that exposure is a "necessary, but not sufficient, determinant of risk" and that exposure is required for being vulnerable but not vice versa (IPCC, 2012, p. 69).

Following the example of Mathis et al. (2014), I decided to use socio-economic values to determine the exposure of the Norwegian fishery sector to ocean acidification. Mathis et al. (2014) argue that exposure typically focuses on where valuable species are located but that it can also be measured in terms of their relative importance to humans in certain areas. While Mathis et al. (2014) based their estimations on catch revenue and subsistence data (economic and nutritional exposure), I was limited to using catch value data as neither revenue nor subsistence data were available for the Norwegian fishery sector. Like Mathis et al. (2014), I subdivided the harvested species into three categories according to the degree to which they are potentially affected by ocean acidification, although my grouping of species is slightly different. While Mathis et al. (2014) roughly distinguished between shellfish, salmon and other finfish (weighted by factors 2, 1, and 0, respectively) I decided to differentiate between crustaceans (no other shellfish in 'wild' fisheries), potentially affected finfish according to literature and either not affected or not yet studied finfish species according to literature. The groups were then weighted in the same way, mirroring their expected affectedness.

Economic exposure was then computed as

$$E_E = 2C_{Cat1} + C_{Cat2},$$

Where E_E stands for the economic exposure, C_{Cat1} for the percentage of total catch value of category 1 species (crustaceans), and C_{Cat2} for the percentage of total catch value from category 2 species (potentially affected finfish). Catch value statistics were obtained from the Norwegian Directorate of Fisheries and represent catch data by counties where the fishing vessels are registered in. The resulting values are then normalized to values between 0 and 1 and ranked so that the highest values receive a score of 1 and the lowest values a score of 4.

3.3.3 Vulnerability

Sensitivity

The SREX risk assessment framework considers vulnerability to be a combination of sensitivity and adaptive capacity. The IPCC report defines sensitivity as the "degree to which a system is affected by or responsive to climate stimuli" (p. 894). Mathis et al. (2014) highlight that the concept of sensitivity differs from 'exposure' as it additionally "includes scaling factors related to people's varying degree of reliance on the species" (p. 7). I was limited to studying economic sensitivity while Mathis investigated both economic and nutritional sensitivity. Mathis et al. (2014) quantified economic sensitivity by comparing gross earnings of fishermen and people involved in the processing of fish products. Due to a significant lack of data, I decided to estimate sensitivity as the share of total income in a county generated from fishery compared to the total income in the same area. As there are no statistics regarding per capita income or average fishery income in the Norwegian counties, I had to modify existing statistics to serve the purpose of my calculations. In the absence of income data specifically from fisheries, I calculated the total income from fisheries by multiplying the number of registered full-time fishermen by the average income of self-employed persons in primary industries, although this may be inaccurate as there may be significant differences between individual primary industry divisions. The calculation of the total income of the population required several steps based on data obtained from Statistics Norway. As income statistics are only available as per household income, I first calculated the average amount of employed persons in a household, assuming that only those have an income directly generated from work as compared to children, unemployed persons and pensioners. Having calculated the average income of employed persons I multiplied this with the total number of employed persons in each county. Sensitivity was then calculated as

$$\mathbf{S} = \frac{\text{Average personal income from primary industry * Number of employed fishermen per county}}{\text{Average personal income per employed person * total number of employed inhabitants per county}}$$

The resulting values are then normalized to values between 0 and 1 and ranked so that the highest values receive a score of 1 and the lowest values a score of 4.

Adaptive capacity

The second component of vulnerability is adaptive capacity, which in the SREX framework is defined as the “ability of an individual, family, community, or other social group to adjust to changes in the environment guaranteeing survival and sustainability” (IPCC, 2012, p. 73). Brooks et al. (2005) provide another definition of sensitivity, which they describe as the ability of a system to change itself in order to increase its coping range according to climate variability and potential future conditions.

The term ‘adaptive capacity’ is often used interchangeably with the term ‘coping capacity’ although many claim that the two terms are fundamentally different (IPCC, 2012). While ‘adaptive capacity’ is predominantly used in relation to ex-ante conditions, ‘coping capacity’ usually describes ex-post situations and the “ability of people, organizations, and systems, using available skills and resources, to face and manage adverse conditions, emergencies and disasters” (IPCC, 2012, p. 51). While the concept of ‘adaptive capacity’ has been applied to climate change impacts on fisheries (e.g., Allison et al., 2009) its use in relation to the threat of ocean acidification has been limited. Mathis et al. (2014) combine seven variables (personal income, poverty, unemployment, PFD[6], education, job diversity and food prices) in order to assess the census area’s adaptive capacity in cases of a crisis in fishery. Due to reasons related to inapplicability of variables and lack of data, I had to modify these calculations and base my estimation of the adaptive capacity of the Norwegian counties on the variables ‘personal income’, ‘unemployment’, ‘poverty’ and ‘education’.

Personal income. Mathis et al. (2014) consider personal income, poverty and unemployment to be suitable variables for evaluating economic stability. I calculated personal income as explained in section 3.3.3. In order to avoid the incorporation of children, unemployed persons, and pensioners, I divided the resulting value by the average number of employed persons per household. The results were then normalized to values between 0 and 1. Household income data and population were obtained from Statistics Norway.

Poverty. Poverty is defined as the percentage of the population that has an income below the annual poverty line, which according to the European Union includes any household that has an “income per consumption unit lower than 60% of the median income of the population” (Statistics Norway, 2013, p.5). The results were then normalized to fall between 0 and 1.

Unemployment. I calculated unemployment based on unemployment and population statistics obtained from Statistics Norway for the year 2014. For this, I calculated the number of inhabitants between 15 and 74 and divided this by the number of inhabitants registered unemployed in that county. The values were then normalized to values between 0 and 1.

Education. Mathis et al. (2014) determine education based on the number of people aged 25 years in beyond, who have completed high school. They assume that it will be easier for these people to find a new occupation in the case of a decline of fisheries. I calculated education as the share of inhabitants of a county that have at least completed upper secondary school. As these statistics were not readily available I calculated them by combining the shares of people with upper secondary, short tertiary and long tertiary education. The values were then normalized to a value between 0 and 1.

Combining variables. In order to combine the variables I followed the example of Mathis et al. (2014) – slightly adjusted to my four instead of seven variables.

$$V = \sum_{n=1}^{4} I_n \alpha_n$$

Vulnerability (V) is calculated as the sum of the variables (I_1=average personal income, I_2=unemployment, I_3=poverty, I_4= level of education) with each of them weighted by a factor of 100 or 33 (α_1=100, α_2=33, α_3=33, α_4=100), assuming that the impact of some variable is approximately three times more significant than the one of the others (Mathis et al., 2014). The resulting values were than divided into quartiles and scored from one to four so that low adaptive capacity indicated by a low V value received a score of 4 and high adaptive capacity indicated by a high V value received a score of 1. This is in line with the calculations Mathis et al. (2014) applied in their study.

3.3.4 Risk index

The final risk index as applied by Mathis et al. (2014) combines the rankings of all previously calculated components using the following formula

I= 0.33*H'+0.33*E'+ 0.33*(0.5*S'+0.5*A'),

where H' refers to the hazard score, E' to the exposure score, S' to the sensitivity score and A' to the overall adaptive capacity score. I then subdivided the resulting values into high, moderate and low risk categories.

4 Results

4.1 Hazard

Norway is bordering the Barents Sea in the north, the Norwegian Sea along its west coast and the North Sea in the south (figure 2). Overall, 17 out of 19 counties border these three ocean regions. The remaining two counties are landlocked, one of them bordering Sweden in the east. Feely et al. (2009) provide an overview of average values for of ocean acidification related parameters in the regions (table 1).

Table 1. Average concentrations of relevant parameters for surface regions based on the global ocean data analysis projected data set (adapted from Feely et al., 2009)

Ocean	Salinity	Temperature	pH (seawater scale)	Aragonite (Ω_{Ar})
Arctic Ocean (North of 65°N)	34.639 ± 0.53	4.35 ± 3.0	8.231 ± 0.006	2.41 ± 0.3
North Atlantic (60°W to 0° 0° to 64.5°N)	35.643 ± 1.37	19.56 ± 7.3	8.125 ± 0.006	3.47 ± 0.6

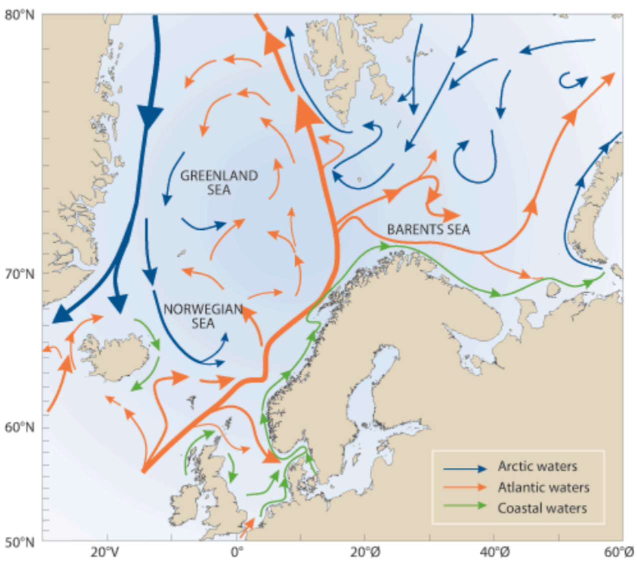

Figure 2. Maps of the North East Atlantic and respective ocean currents (orange= Atlantic waters, blue= Arctic/ Polar waters, green= coastal waters) (Skjelvan et al., 2014)

4.1.1 Ocean acidification near Norway

Barents Sea. The Barents Sea is a highly dynamic region due to the influence of the inflowing Atlantic and Arctic water, as well as the melting sea ice cover. Measurements show that the lowest Ω_{Ar} is found in the deep waters around Bjørnøya and in the northeastern Barents Sea. The measurements indicate that less saline waters tend to be more susceptible to further decreases in $CaCO_3$ saturation (Chierici et al., 2014). The pH values in the Barents Sea region vary between 8.04 and 8.15 due to varying influences of warm and salty water from the Atlantic and cold and fresher water from the Arctic (Chierici et al., 2014). Aragonite saturation varies between 1.2 at the northernmost measurement stations and 2.2 at a latitude of 78.5°N (Chierici et al., 2014).

Norwegian Sea. Warm and saline Atlantic water from between the Shetland and Faroe Islands and Iceland flows into the Norwegian Sea and heading northward, taking up atmospheric CO_2 on the way (Chierici et al., 2014). Over the past 30 years, surface Ω_{Ar} and pH have decreased by 0.0041 and 0.0023 units, respectively (Skjelvan et al., 2014). Changes are primarily driven by increases in biological activity, salinity and the increased uptake of anthropogenic CO_2 (Skjelvan et al., 2014).

North Sea. Overall, there is relatively little data available for the North Sea (Skjelvan et al., 2014). Measurements taken across the Skagerrak along the Torungen-Hirtshals show the influence of less saline coastal waters. The lowest Ω_{Ar} value of 1.4 was measured in the deep water in the Oslofjord during winter. Values along the Torungen-Hirtsals transect are 8.04 for pH and 1.8 for Ω_{Ar}, respectively. Seasonal variability across the Skagerrak is primarily driven by pronounced changes in salinity, for example resulting from balancing perturbations from riverine and Baltic sources. Varying pH and Ω_{Ar} can be a result of varying biological activity in the region. There seems to be disagreement regarding the extent to which seasonal variability influences ocean acidification (Skjelvan et al., 2014).

4.1.2 Allocation of counties and ranking

Based on reports by Chierici et al. (2014) and Skjelvan et al. (2014), which are in agreement with other scientific data (e.g. Feely et al., 2009) on the pronounced threat of ocean acidification for high latitude regions, I assumed the Barents Sea to be most at risk compared to the Norwegian Sea and the North Sea. Assuming further that small and medium sized Norwegian fisheries are mainly fishing in their adjacent ocean regions, I allocated the two northernmost counties Finnmark and Troms to the Barents Sea. Consequently, these counties receive a score of 1, which indicates the highest risk.

The ranking of the remaining two ocean regions is less clear. Due to the absence of explicit information regarding the current and projected development of the region with regard to pH and Ω_{Ar} values, which makes it impossible for me to assign a clear score, I decided to develop two scenarios in order to account for the possibility that either ocean region is more at risk than the other. For this reason, the counties bordering the Norwegian Sea receive a score of 3 in the first and a score of 2 in the second scenario. I allocated the counties of Nordland, Nord-Trøndelag, Sør-Trøndelag, and Møre og Romsdal to the Norwegian Sea.

The countries bordering the North Sea will receive a score of 2 in the first and score of 3 in the second scenario. I allocated the counties of Sogn og Fjordane, Hordaland, Rogaland, Vest-Agder, Aust-Agder, Vestfold, Oslo, Østfold and Akershus to the North Sea, as they all share a border with this sea region.

The two remaining counties, Hedmark and Oppland, are landlocked and therefore not considered to be at direct risk. They receive a score of 4, which indicates very low risk. Figure 3 shows the county ranking for the first and figure 4 for the second scenario.

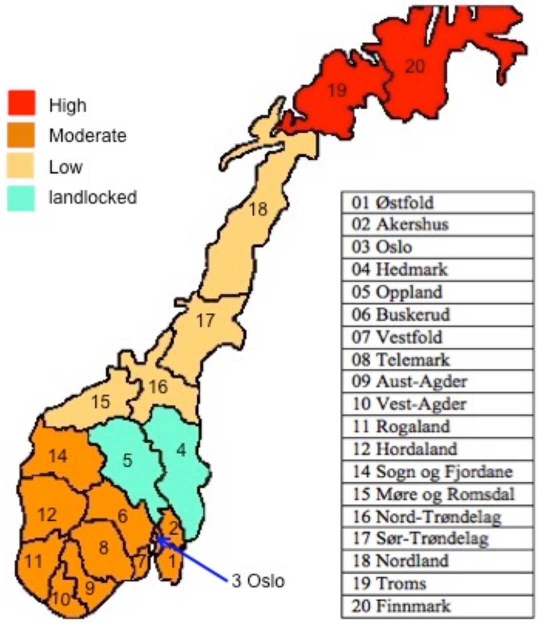

Figure 3. Hazard ranking for scenario 1

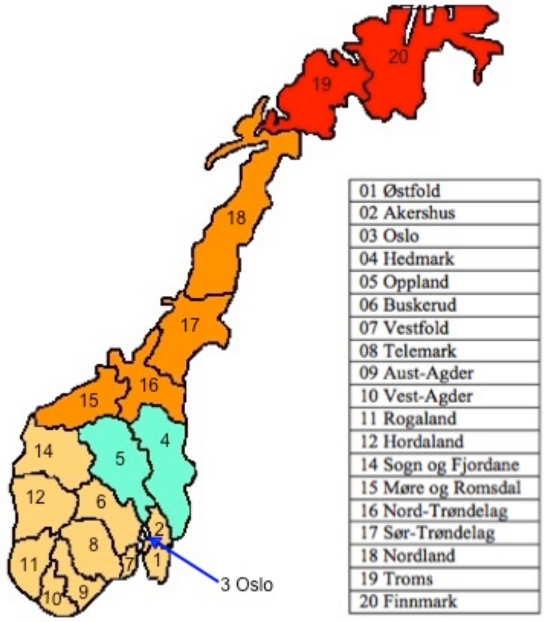

Figure 4: Hazard ranking for scenario 2

4.2 Exposure

For the estimation of economic exposure I followed the example of Mathis et al. (2014) and grouped the species harvested by Norwegian fishing vessels as described in section 3.3.2. The degree to which species are, or will be affected by ocean acidification varies considerably among species. There is information available for 14 out of the approximately 45 harvested crustacean and fish species. In the following, I will give a brief overview of the biological impact of ocean acidification on a selection of species relevant for the Norwegian fishery sector (table 2).

I decided against including aquaculture, mainly because impact of ocean acidification on farmed species is less clear than on wild fisheries and because I don't know to what extent Norwegian aquaculture facilities can and do control the chemistry of the water used for growing fish.

Table 2. The grouping of species and potential biological impact according to literature[7]

Category	Species name (English)	Species name (Latin)	Potential OA impact	References (selection)
1	Edible crab	*Cancer pagurus*	• Sensitive to ocean acidification induced hypercapnia, which lowers the organisms heat tolerance by 5°C	Metzger et al. (2007)
1	Red king crab	*Paralithodes camtschaticus*	• Shortening of hatch duration by approximately 1 third. • Embryos and larvae tend to become longer and develop larger eyes and smaller yolks • Reduced survival with decreased pH, reaching	Long et al. (2013)
1	Shrimp	*Pandalus borealis*	• Significant delay in development time	Bechmann et al. (2011)
1	Norwegian lobster	*Nephrops norvegicus*	• Suppression of central immune functions under OA	Hernroth et al. (2012)
2	Atlantic herring	*Clupea harengus L.*	• Negative linear relationship between elevated pCO_2 levels and the DNA/RNA ratio, potentially leading to problems with biosynthesis and consequently embryo development	Franke and Clemmesen (2011)
2	Cod	*Gadus morrhua*	• OA likely to damage the organisms inner organs proportionally to increased pH levels • Potential adverse effect on juvenile organisms	Frommel et al. (2012) Moran et al. (2011)
2	Atlantic Halibut	*Hippoglossus hippoglossus*	• Adverse effect on growth rates of juvenile organism	Gräns et al. (2014)
2	Turbot	*Psetta maxima*	• "Declining size at age and poor recruitment in fish stocks"	Warren (2009, p.21)
2	Wolffish	*Anarhichas minor*	• Significant energy tradeoff due to reduced plasma Cl^-	Ishimatsu et al. (2008)
2	Wild salmon	*Salmo salar*	• Reduction of ability to fertilize • Considerable reduction in population size already	Daye and Glebe (1984) Sandøy and Langåker (2001)

[7] Category 3 species (non-threatened, no available literature) are not included as they are weighted by a factor of 0 and thus left out of the calculations.

I calculated and ranked the economic exposure following Mathis et al.'s (2014) methodology based on 2014 catch value data obtained from the Norwegian Directorate of Fisheries (Directorate of Fisheries Norway, 2015). Figure 5 shows an overview of the shares of catch value obtained from category 1, 2 and 3 species based on where fishing vessels are registered.

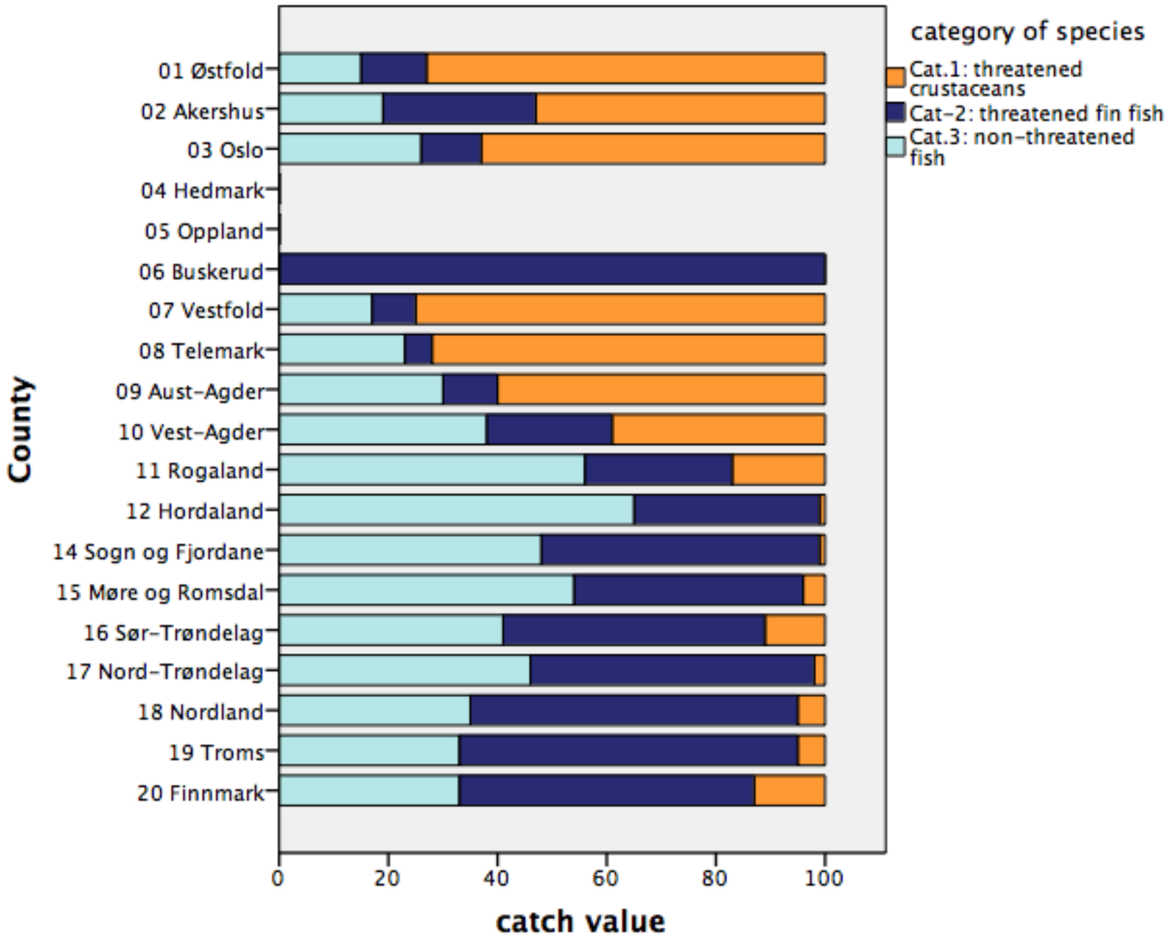

Figure 5. Shares of catch value obtained from category 1, 2, and 3 species based on where fishing vessels are registered. Catch value data from 2014 was obtained from the Directorate of Fisheries Norway (2015)

Figure 6 provides an overview of the economic exposure ranking. Due to large harvest quantities and high catch values of category 1 species, the southeastern counties Østfold, Akershus, Oslo, Vestfold and Telemark seem be at highest risk (rank 1). Particularly high shares of catch value obtained from category 1 species characterize these counties. The share of category 1 species ranges between 53% in Akersus and 75% in Vestfold. Category 2 species in these counties account for 5% to 28% of total catch value. Although the share of catch value from category 1 species in Aust-Agder (59%) is higher than in Akershus (53%), the calculations only result in a economic exposure level of 2, as the share of catch value obtained from category 2 species is considerably lower in Aust-Agder (10%) than in Akershus (28%). Particularly high shares of catch values obtained from category 1 species characterize all of the high-exposure counties. Although Vest-Agder shows a similarly high share of category 1 species, the calculations show a score of 2 due to the double weighting of category 1 species, which was previously explained. In addition to Aust-Agder, the southernmost county Vest-Agder also show a score of 2, as well as the two northernmost counties Finnmark and Troms. While the two southern counties Aust-Agder and Vest-Agder are characterized by high shares in category 1 and moderate to low shares in category 2, this is reversed for the two northern counties Finnmark and Troms. The county of Buskerud also express a score of 2 but seems to be an exception compared to the other counties.

Although landlocked, at least one fishing vessel is registered in Buskerud, which harvests exactly one category 2 species. This results in a share of 100% of catch value obtained from a moderately threatened species. Assuming that this implies the disruption of the entire fishery sector in the county this should theoretically indicate very high risk. Due to the weighting of the individual categories, however, other counties seem to be more at risk. Based on the calculations, the counties bordering the Norwegian Sea south of Troms (Nordland, Nord-Trøndelag, Sør-Trøndelag) and Rogaland in the southwest receive a score of 3. These counties are characterized by moderate shares of catch value obtained from category 2 species between 27% (Rogaland) and 59% (Nordland). In comparison to this, the share of catch value obtained from category 1 species is relatively low and ranges from 2% in Nord-Trøndelag to 17% in Rogaland. The least exposed counties include those bordering the Norwegian Sea south of Sør-Trøndelag, which are all characterized by high shares in the not threatened category 3 species. In addition to this, the landlocked counties Hedmark and Oppland are included in the low risk category as no fishing vessels are registered in either county. Figure 5 shows an exact overview of catch values, normalized economic exposure values and the final economic exposure ranking.

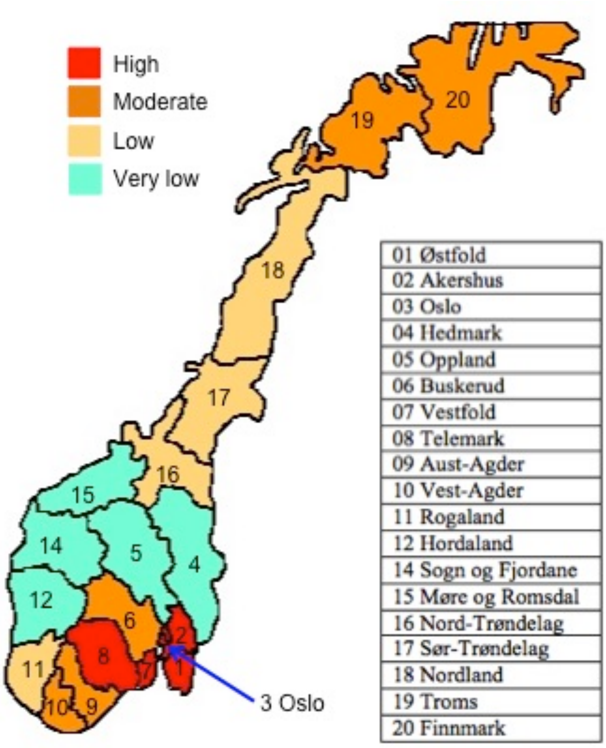

Figure 6. Ranking of counties based on level of economic exposure. The scores are based on weighted catch value (explained in section 3.3.2) and registering location of vessels.

Using statistical data based on the locations where fish is landed, as opposed to where fishing vessels are registered, shows a slightly different situation both with regard to the distribution of catch value (figure 7) and the overall economic exposure ranking (figure 8). As there is no catch landed in Akershus, this county is no longer economically exposed to ocean acidification. Aust-Agder is economically highly exposed when using location of fish landing as the basis for calculation. While the two northernmost and southernmost counties were second most at risk, this group of counties now includes those between Sør-Trøndelag and Finnmark (i.e., the five northern counties). The western counties previously characterized by the least economic exposure are now facing an increased level of economic exposure, while Rogaland shows a decrease in economic exposure compared to the previous version, as does Vest-Agder. Buskerud adds to the other two landlocked counties and receives now a score of 4, as no fish harvest is landed in these counties.

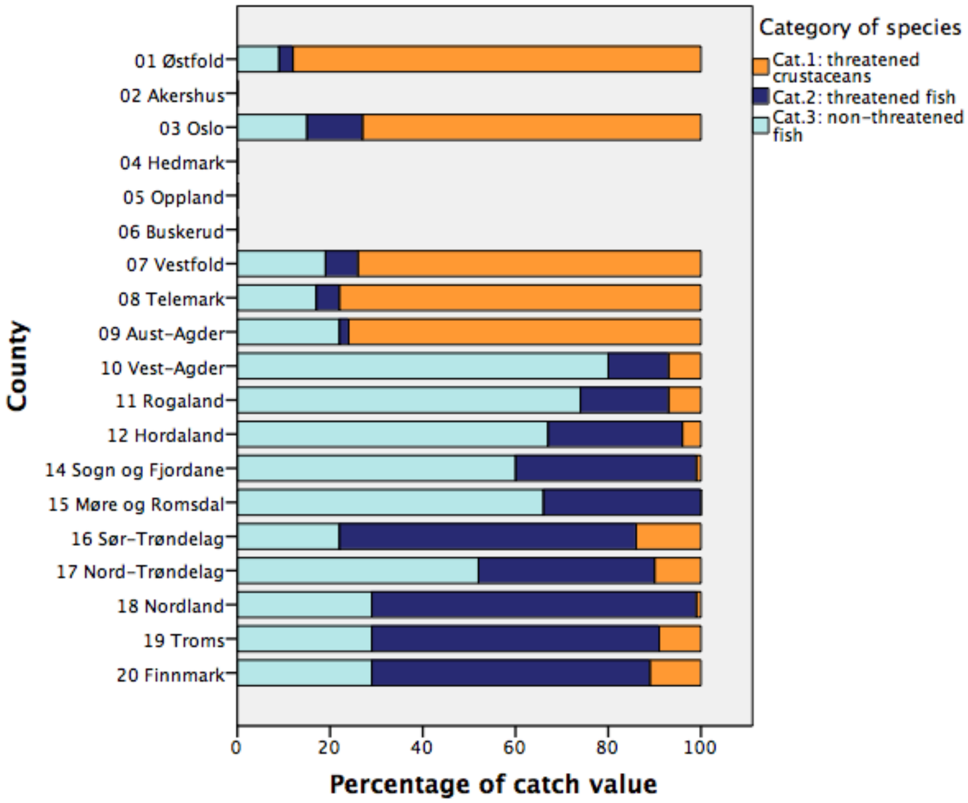

Figure 7: Shares of catch value obtained from category 1, 2, and 3 species based on landing location. Catch value data from 2014 was obtained from the Directorate of Fisheries Norway (2015)

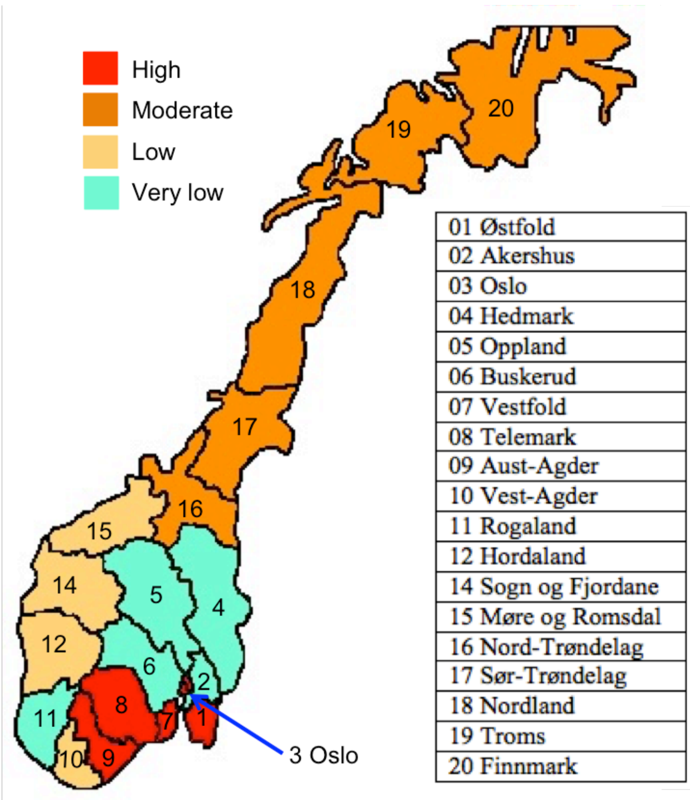

Figure 8. Ranking of counties based on level of economic exposure. The scores are based on weighted catch value (explained in section 3.3.2) and landing location of vessels.

4.3 Vulnerability

4.3.1 Sensitivity

I calculated sensitivity based on the explanation in section 3.3.3. The three northernmost counties Finnmark, Troms and Nordland, as well as the two western counties Sogn og Fjordane and Møre og Romsal show the highest scores. In the three northern counties this coincides with an above average income from self-employed inhabitants in primary industry and significantly larger numbers of part-and full-time fishermen in the counties. In Møre og Romsdal the income from self-employed inhabitants in primary industry is very similar to the average income in the county. Moreover, the number of fishermen is the second highest among the Norwegian counties, which explains the high sensitivity rank of 1. The moderately sensitive counties do not show a clear regional pattern. Hedmark and Oppland are in the opposite situation. Although landlocked, a small number of fishermen are registered in these counties. The same applies for the neighboring counties Buskerud, Akershus and the capital city Oslo. Although the number of fishermen registered in Oslo is higher than in the other very low sensitivity counties, it is outweighed by the second highest average personal income among the Norwegian counties, which is considerably higher compared to the average income from self-employed inhabitants in primary industries. The remaining moderate and low risk counties do not show a clear regional pattern and income and fishery numbers are very similar in these categories.

Table 3. Sensitivity score and sensitivity ranking, based on population and income statistics (2014) obtained from Statistics Norway.

County	Average personal income (all industry in 2010 USD)	Employed inhabitants	Average personal income from primary industry (2010 USD)	Number of fishermen	Normalized score	Ranking
Østfold	47,293.16	133,670	49,245.25	134	0.0261	3
Akershus	59,317.70	289,552	49,245.25	46	0.0011	4
Oslo	59,222.22	330,918	49,245.25	42	0.0004	4
Hedmark	44.680.32	93,855	49,245.25	22	0.0046	4
Oppland	44,769.90	95,313	49,245.25	13	0.0016	4
Buskerud	50,933.76	136,962	49,245.25	13	0	4
Vestfold	49,359.82	116,346	49,245.25	72	0.0144	3
Telemark	46,868.67	83,298	49,245.25	57	0.0172	3
Aust-Agder	48,546.32	54,738	49,245.25	113	0.0548	2
Vest-Agder	49,095.30	87,171	49,245.25	314	0.0964	2
Rogaland	58,373.99	238,570	49,245.25	498	0.0457	3
Hordaland	53,544.26	256,886	49,245.25	965	0.0921	2
Sogn og Fjordane	46,602.65	57,378	49,245.25	646	0.3233	1
Møre og Romsdal	49,097.64	133,870	49,245.25	2,218	0.4526	1
Sør-Trøndelag	54,133.80	155,628	49,245.25	400	0.0615	2
Nord-Trøndelag	44,403.26	66,730	49,245.25	274	0.1222	2
Nordland	46,174.60	119,790	49,245.25	2,767	0.6722	1
Troms	48,837.42	82,125	49,245.25	1,405	0.47	1
Finnmark	46,449.14	38,146	49,245.25	1,317	1	1

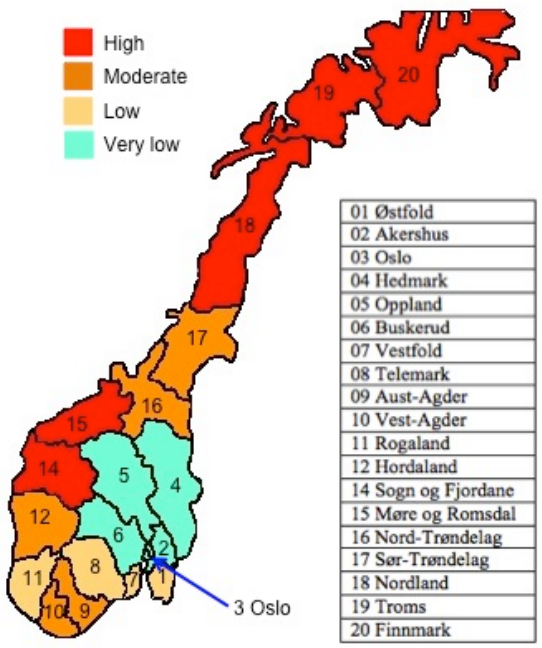

Figure 9. Sensitivity ranking based on population and income statistics (2014) obtained from statistics Norway.

4.3.2 Adaptive capacity

Following the explanation of the methodology in section 3.3.3, adaptive capacity is calculated based on the four variables personal income, poverty, unemployment and education assuming that all four of these factors influence the extent to which the counties can respond to the consequences of ocean acidification.

Personal Income. Personal income was calculated based on the average number of employed persons per household and per county. By far the highest personal income is found in Akershus, which lies adjacent to the capital city, and Oslo itself. Together with the counties of Rogaland, Hordaland and Sogn of Fjordane, these counties receive very high scores with regard to this adaptive capacity variable. The landlocked counties Hedmark and Oppland, as well as Nord-Trøndelag, Finnmark and Nordland received the lowest scores, as the average personal income levels were the lowest in these counties.

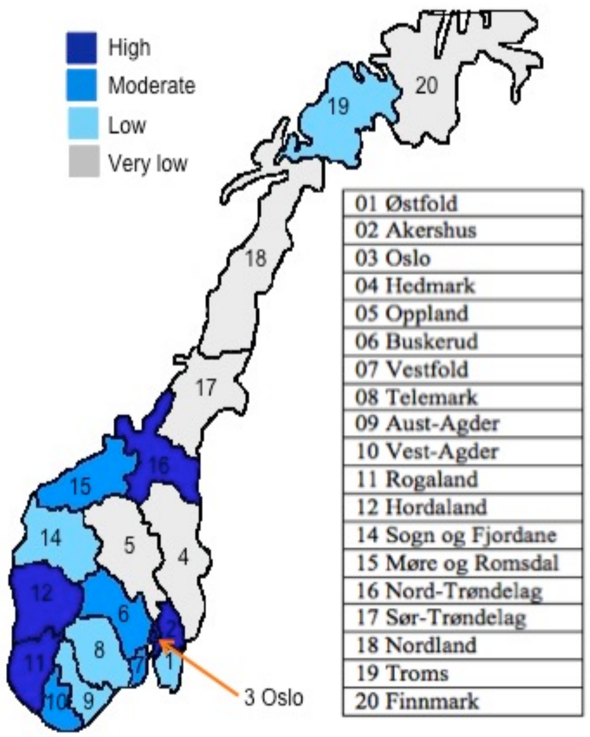

Figure 10. Compared personal income level among counties based on 2014 data obtained from Statistics Norway.

Unemployment. The share of unemployed persons is highest in the capital city Oslo (2.59%) and Østfold (2.47) in the southeast, and Finnmark (2.45) in the far north. These counties thus receive high scores. The lowest shares of unemployment are found in Sogn and Fjordane (1.4), Oppland (1.54) and Troms (1.59), which consequently receive very low scores for this variable. The two northernmost counties Troms and Finnmark have fundamentally different values with regard to unemployment.

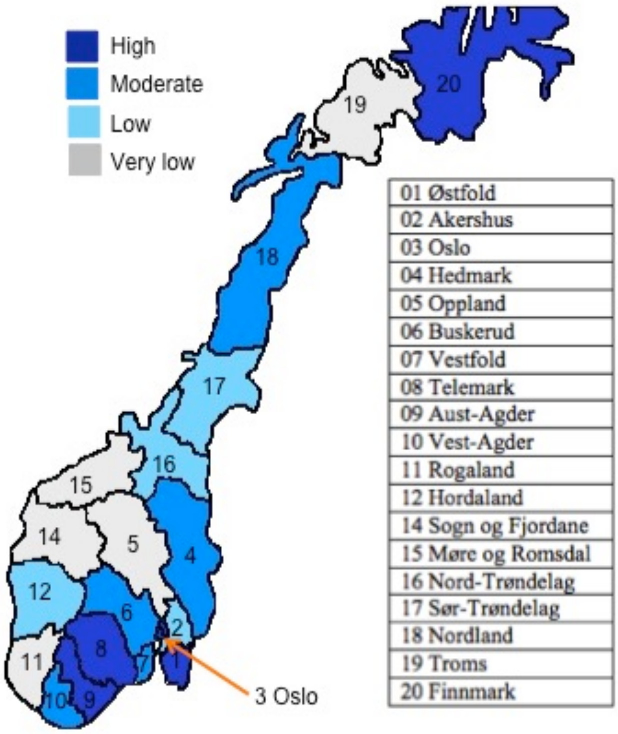

Figure 11. Compared level of unemployment among counties based on 2014 statistical data obtained from Statistics Norway

Poverty. Based on 2014 statistics, by far the highest share of inhabitants living below the poverty line appears to be in Oslo (13.7%). This is followed by Østfold (9.9%), Hedmark (9.5%) and Telemark (9.5%). In contrast to this, the lowest shares of poverty are found in the counties of Rogaland (6.1%), Akershus (6.4%), Sogn of Fjordane (6.9%) and Møre og Romsdal (6.9%).

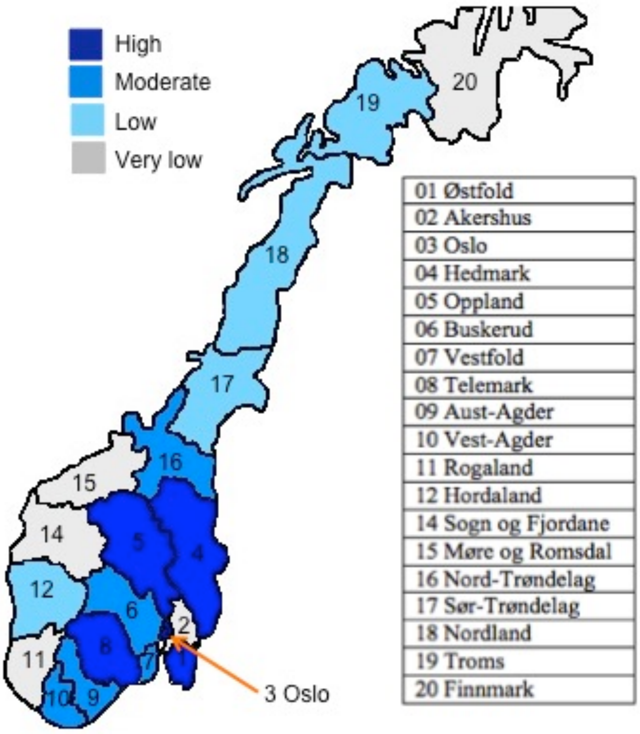

Figure 12. Compared share of inhabitants living in poverty based on 2014 data obtained from Statistics Norway

Education. Overall, the share of persons who have at least completed upper secondary education is generally very high in Norway as a whole. The highest percentage of people with this level of education is found in the capital city Oslo (78.8%), followed by Akershus (74.8%), and Sør Trondelag (74%). The lowest share of inhabitants with at least an upper secondary school degree are found in Finnmark (63.4%), Nordland (66.1%), Hedmark (65.8%) and Østfold (66.5%).

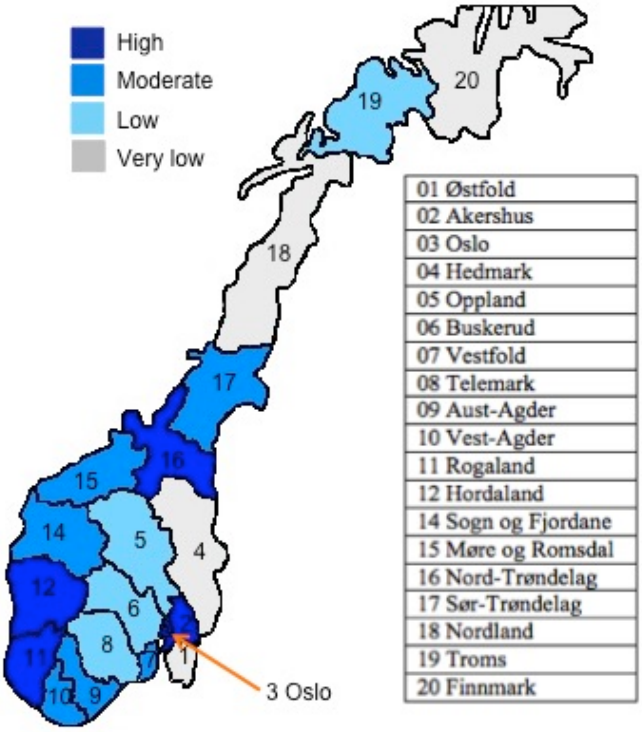

Figure 13. Compared shares of inhabitants who have at least completed upper secondary education based on 2014 data obtained from Statistics Norway

Final adaptive capacity score. Combining all of the above mentioned factors shows that the highest level of adaptive capacity can be found in Akershus, Oslo, Rogaland, Hordaland, and Sør-Trøndelag, which all receive an overall score of 1. This is followed by Buskerud, Vestfold, Aust-Agder, and Vest-Agder, which receive a score of 2. Østfold, Telemark, Sogn og Fjordane, Møre og Romsdal, and Troms receive a score of 3, while Hedmark, Oppland, Nord-Trøndelag, Nordland and Finnmark receive an overall score of 4, which makes them the counties with the lowest degree of adaptive capacity.

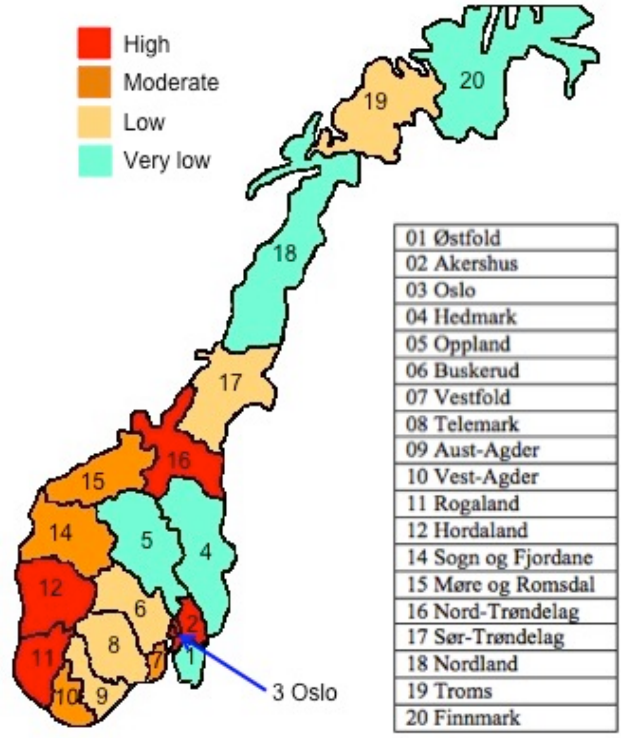

Figure 14. Combined adaptive capacity ranking

4.4 Risk index

The final risk index combines the scores from the four categories hazard, exposure, sensitivity and adaptive capacity. The resulting values were then subdivided into three equal groups accounting for the three risk categories 'high risk', 'moderate risk' and 'low risk'. Due to the absence of universal guidelines on how to assign values to the individual risk index, I decided to use three equal value ranges. This implies, that the resulting index values are to be understood as relative to the remaining counties.

The first version of the risk index is based on the assumption that the counties bordering the Barents Sea are most at risk, followed by the North Sea and ultimately the Norwegian Sea. The landlocked counties receive the lowest hazard rank. Figure 15 clearly shows that the northernmost counties, Finnmark and Troms, face the highest overall risk. Moreover, the southeastern counties Østfold, Vestfold and Telemark bordering the Oslofjord and the North Sea are also facing high risk in a direct comparison of counties. The counties bordering the Norwegian Sea face moderate to low risk with regard to ocean acidification when compared to the other counties. In this version of the risk index, 13 out of 19 counties face moderate to high risk. The coastal counties Sør-Trøndelag, Møre og Romsdal, Rogaland and Hordaland are likely to face low risk. The same is, not surprisingly, true for he two landlocked counties Hedmark and Oppland.

The second version of the risk index is based on changes of the hazard component (figure 16). This scenario assumes that while the counties that border the Barents Sea remain highly at risk, the Norwegian Sea now receives a score of 2, while the North Sea is considered the sea region least at risk, and receives a score of 3. Like before, the landlocked counties receive a score of 4 for the hazard component as they are considered not to be facing any risk. The final risk index reveals that while the overall number of counties facing high or moderate risk remains similar, the distribution of counties within the individual risk categories slightly changed. In this scenario, Nordland and Akershus in addition to Finnmark, Troms and Østfold face high risk, while the southern counties Telemark and Vestfold only encounter moderate risk. Other changes include that Sør-Trøndelag and Møre and Romsdal, which belonged to the low-risk counties in the first scenario now face moderate risk. In contrast to this, Sogn and Fjordane is now likely to face low risk instead of moderate risk.

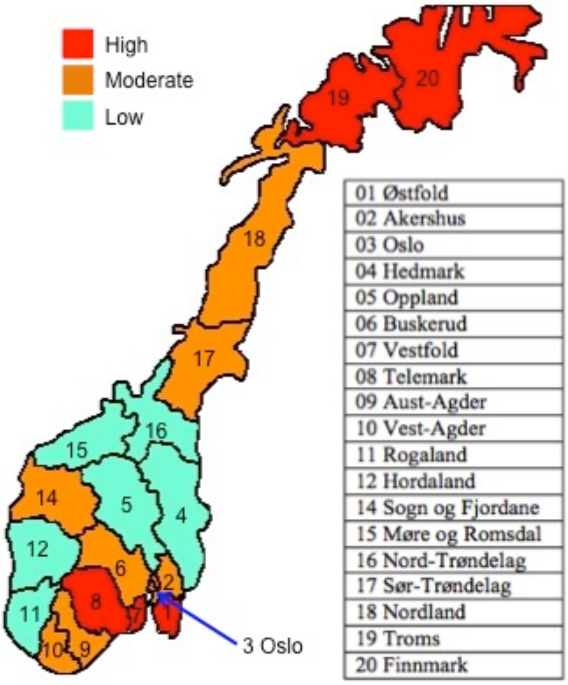

Figure 15. Risk index for scenario 1

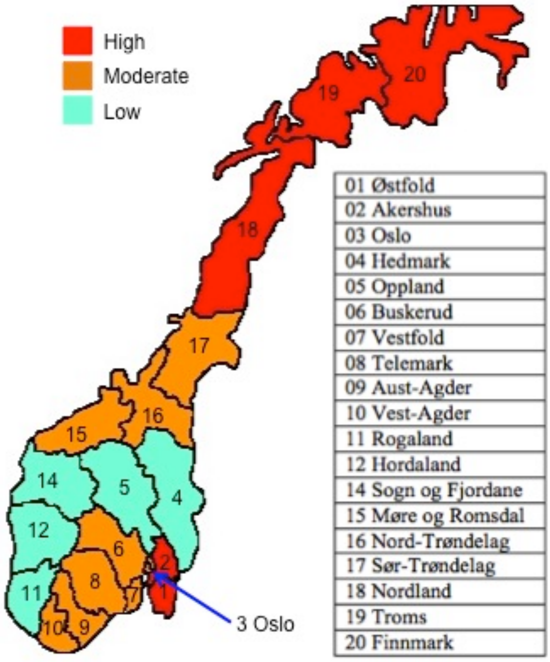

Figure 16. Risk index for scenario 2

Table 4. Overview of final risk ranking (H= hazard, E= exposure, S= sensitivity, A= adaptive capacity, sce= scenario, high risk: 0-2.035, moderate risk: 2.036-2.75, low risk: 2.75-3.465, ranking: 1= high risk, 4= very low risk)

County	H sce 1	H sce 2	E	S	A	Risk index sce. 1	Risk cat. sce. 1	Risk index sce. 2	Risk cat. sce. 2
01 Østfold	2	3	1	3	1	1.65	high	1.98	high
02 Akershus	2	3	1	4	4	2.31	moderate	2.64	high
03 Oslo	2	3	1	4	4	2.31	moderate	2.64	moderate
04 Hedmark	4	4	4	4	1	3.465	low	3.465	low
05 Oppland	4	4	4	4	1	3.465	low	3.465	low
06 Buskerud	2	3	2	4	2	2.31	moderate	2.64	moderate
07 Vestfold	2	3	1	3	3	1.98	high	2.31	moderate
08 Telemark	2	3	1	3	2	1.815	high	2.145	moderate
09 Aust-Agder	2	3	2	3	2	2.145	moderate	2.475	moderate
10 Vest-Agder	2	3	2	2	3	2.145	moderate	2.475	moderate
11 Rogaland	2	3	3	3	4	2.805	low	3.135	low
12 Hordaland	2	3	4	2	4	2.97	low	3.3	low
14 Sogn og Fjordane	2	3	4	1	3	2.64	moderate	2.97	low
15 Møre og Romsdal	3	2	4	1	3	2.97	low	2.64	moderate
16 Sør-Trøndelag	3	2	3	2	4	2.97	low	2.64	moderate
17 Nord-Trøndelag	3	2	3	2	2	2.64	moderate	2.31	moderate
18 Nordland	3	2	3	1	1	2.31	moderate	1.98	high
19 Troms	1	1	2	1	3	1.65	high	1.65	high
20 Finnmark	1	1	2	1	1	1.32	high	1.32	high

5 Discussion

5.1 Interpretation of results

Hazard. My thesis largely relies on the data available about Norway and the surrounding ocean regions. Data collection has been carried out for the past few years but is not yet comprehensive enough for the deduction of accurate trends or for projections of the future, as well as for the influence of local factors such as the level of primary productivity, upwelling and river inflow (Skjelvan et al., 2014). Mathis et al. (2014) account for this by complementing their basic oceanographic model with a biogeochemistry component.

I subdivided the ocean regions into the three broad categories North Sea, Norwegian Sea, and Barents Sea. The actual impacts of ocean acidification could, however, vary significantly within these regions for the aforementioned reasons. Moreover, I assumed that the Norwegian fishery is rather local to the extent that large parts of the fishing fleets would remain within their adjacent sea regions. This allocation of the counties to the sea regions may perhaps bias the results to a certain extent. In the absence of detailed information regarding the exact fishing locations of the individual fishing vessels it was necessary to generalize. Overall, the aforementioned factors could potentially have an impact on the overall outcome of the risk assessment although the comparison of the two scenarios shows that while the distribution of the risk may vary among counties, the overall number of counties facing high or moderate risk remains roughly the same.

Exposure. The results clearly show that counties characterized by a high share of catch value obtained from category 1 species (crustaceans) are generally more economically exposed to ocean acidification than those with a large share of the supposedly not affected category 3 species. It is possible to argue that this development is the logical consequence of the uneven weighting of the individual categories, which based on Mathis et al. (2014) was supposed to emphasize the stronger impact of ocean acidification on crustaceans. In line with Mathis et al. (2014) I conducted the same calculations without weighting the first and the second category. Based on the pronounced lack of data for most of the category 3 species I did, however, leave them out of the calculation.

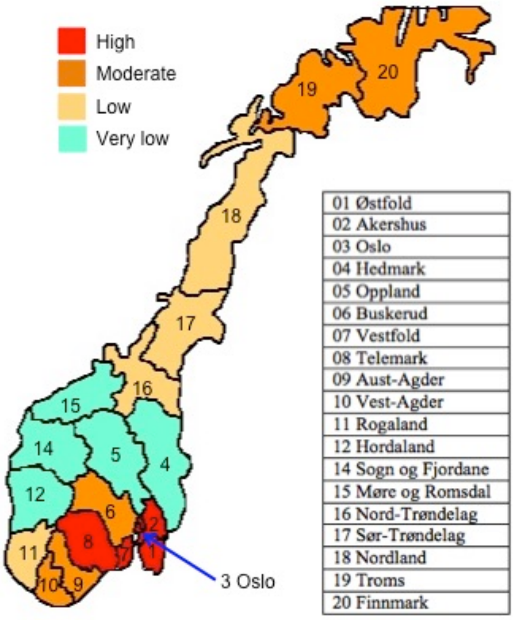

Figure 17. Economic exposure based on weighted categories as shown in section 4.2.1

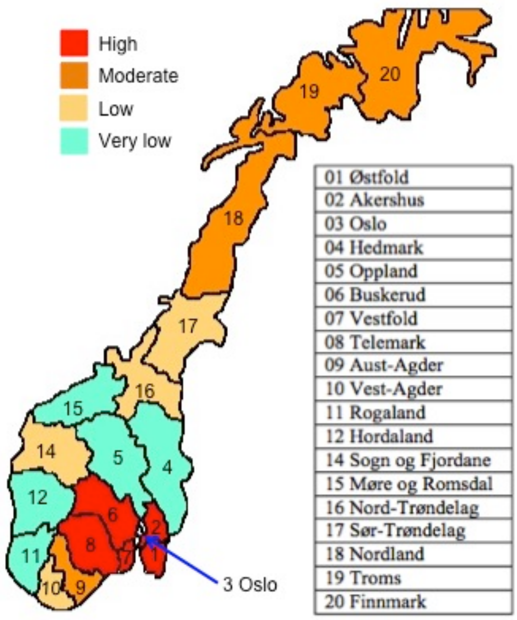

Figure 18. Economic exposure based on evenly weighted categories for comparison

The comparison of the weighted and non-weighted scores of economic exposure shows that the number of counties per category has not changed. Instead, four out of the 19 counties show a change in the degree of economic exposure. While Nordland and Sogn og Fjordane would have higher level of exposure the two southwestern counties Rogaland and Vest-Agder would be less economically exposed to ocean acidification (see section 3.3.2). This implies that weighting may have an influence on the risk faced by the individual counties but not the overall level of Norway's economic exposure. Overall, my evaluation of the degree of economic exposure is based on the current level of knowledge. This implies that the results could change once more and improved data on the biological impact of ocean acidification on marine organisms is available. This could, for example, make the incorporation of additional species necessary and lead to higher economy exposure scores in the individual counties.

Sensitivity. The analysis of the sensitivity component shows that both the proportion of inhabitants employed in fisheries and the total income generated from fishing compared to the total income from all industry is very low in all counties. The amount of fishermen registered by county of residence shows that the numbers vary considerably among counties. While Møre og Romsdal, which is one of the counties most involved in fishing activities, employed more than 2200 full-time and part-time fishermen, the surrounding counties Sogn og Fjordane and Sør-Trøndelag only employ a few hundred. Comparatively high numbers of fishermen between approximately 1300 and 2760 fishermen can explain the high sensitivity of the Northern counties. The sensitivity of certain counties could be higher than expected when including inhabitants involved in the processing of fish and fish products. Statistical data obtained from Statistics Norway shows that this affects, in total, almost 9070 additional inhabitants. Data is, however, only available for nine other counties and 'other counties', which does not allow for a clear allocation of employees in fish processing to the individual counties and makes it thus difficult to account for.

Similar to the exposure component the incorporation of aquaculture would probably increase the number of inhabitants involved in fisheries even further. Statistics obtained from Statistics Norway show that approximately 1535 licenses have been awarded to the farming fish including salmon, rainbow trout and other species (2013), which gives an indication about the amount of people involved in fish farming (Directorate of Fisheries Norway, 2015).

Adaptive capacity. Looking at the adaptive capacity scores of the different variables separately shows interesting, yet expected outcomes. In ten out of 19 cases high unemployment and poverty, indicating low adaptive capacity, occur jointly with high personal income and education and vice versa. The majority of the remaining cases show similar values for all four variables. Oslo seems to be an extreme case as it exhibits high scores for all four variables, which is potentially related to Oslo being the capital city. As such it is not only the economic center and thus attracts both well educated citizens and those with a high income, but also those who are less educated or in search for employment. Finnmark and Troms are examples of the opposite extreme providing relatively bad scores for all four categories, with the exception that Finnmark additionally shows a very high share of unemployment among its inhabitants. Overall, Statistics Norway lists an average unemployment rate of 4.1% (2015), which indicates that unemployment is in fact higher than the values calculated here. This can be explained by the fact that I included all inhabitants registered as unemployed and not only those that are considered job seeking. In the original application of the risk assessment framework, the four variables were weighed differently with unemployment and poverty being multiplied by a factor of 33 while personal income and employment were multiplied by a factor of hundred to account for the difference in level of influence. In order to assess the impact of the weighting, I conducted the same calculations without weighting. The results show that eleven out of 19 counties kept the same combined adaptive capacity score while five counties increased their overall score of adaptive capacity by one level while the remaining decreased their score by one level. Overall, this shows that weighting the individual variables decreases the adaptive capacity score of the counties.

Risk Index. The final versions of the risk index clearly show that the majority of Norwegian counties are either facing high or moderate risk from ocean acidification, independent of whether the North Sea or the Norwegian Sea is comparatively more at risk. Considering the overall high living standard in Norway, the results, although showing moderate to high risk in direct comparison, probably express a much lower degree of risk in an international comparison, including, for example coral- and shellfish dependent developing countries. Nevertheless, my results show that the Norwegian fishery sector will be at risk, once aragonite saturation and pH values drop beyond a certain level. In order to prevent negative effects on the economy and the Norwegian population, immediate action is necessary in order to prepare adequately for ocean acidification.

5.2 Ocean acidification in relation to other marine ecosystem stressors

Ocean acidification is only one of many human-induced problems marine ecosystems face. Although marine ecosystems are less well studied than terrestrial ones, there is overwhelming proof that anthropogenic activities drive significant changes in the oceans, which affect fish stocks (Hoegh-Guldberg and Bruno, 2010). Apart from ocean acidification, these stressors include nutrient input, pollution, warming, deoxygenation, habitat degradation, changes in net primary production, invasive species and overfishing (Halpern et al., 2008; Bopp et al., 2013). While some species (e.g., jellyfish) may benefit from change because of a greater availability of nutrients, reduced competition or warmer temperatures, others may be adversely affected by alterations of their immediate environment, leading to physiological changes, as well as decreased reproduction and survival.

Warming is one of the most prominent consequences of climate change (Doney et al., 2012). According to Cheung et al. (2013), direct impacts of temperature on marine organisms include “changes in distribution and abundance, phenology, […], alteration of community structure and trophic interactions, an ultimately affecting fisheries” (p. 365). Pelagic organisms may be able to actively escape unfavorable conditions by migrating to places offering more suitable environmental conditions (Cheung et al., 2013).

Ocean acidification can also influence biochemical processes within organisms. Moreover, it can decrease the thermal tolerance window of marine organisms, which has been studied in experiments with edible crab (*Cancer pagurus*). Metzger et al. (2007) emphasize that “interactions of […] temperature and anthropogenic increases in […] CO_2 will need to be considered during future investigations of the effects of climate change on ecosystems” (p. 144).

In addition to this, broad-scale warming, as well as fresh water input in high-latitude regions from rivers and melting sea ice, can lead to the vertical stratification of the water column causing an alteration of currents, mixing and ventilation patterns (Doney et al., 2012). Warming decreases the uptake of dissolved oxygen and stratification reduces the mixing of surrounding water bodies (Gilbert et al, 2010). In coastal regions, the excess input of nutrients causing eutrophication has similar effects on the availability of oxygen (Cai et al., 2011). While organisms can tolerate deoxygenation to a certain extent, hypoxia leads to severe physiological stress and can even cause the organisms’ deaths (Bopp et al., 2013). Moreover, eutrophication could “increase the susceptibility of coastal waters to ocean acidification” as fertilizers, as well as sulfur and nitrogen oxide are weak acids directly decreasing the pH level near shore (Crain et al., 2008; p. 766). Ekstrom et al. (2015) support this, calling eutrophication a key amplifier of ocean acidification.

Apart from climate change related stressors, more human activities have a substantial impact on marine ecosystems, for example through overfishing, which causes a decrease in stock sizes and even the extinction of entire species (Jackson et al., 2001). In addition to these direct impacts, overfishing can also lead to the removal of species that are particularly important as food sources for other larger species and may thus interrupt important food chains (Oliver and Metzner, 2005).

Investigating the combined effect of ocean stressors, Crain et al. (2008) find that 26% are cumulative, 36% synergistic and 38% antagonistic, dependent on the actual stressor pair and the influence of additional stressors. This shows that ocean acidification should be considered not individually but as one of many ocean stressors that influence fisheries now, and will do so even more in the near future. Hence, the impact on fisheries can be considerably more severe than previously outlined in this thesis. The understanding of the effect of combined stressors needs to be improved in order to improve the potential risk fisheries will be facing in the future (Kelleher, 2012).

5.3 Mitigation of and adaptation to ocean acidification

Billé et al. (2013) distinguish three major possibilities to mitigate ocean acidification. The most prominent strategy agreed upon in the literature is the reduction of atmospheric CO_2, preferably by reducing global greenhouse gas emissions. As ocean acidification is solely caused by the increased uptake of CO_2 this measure seems to be the most promising (Billé et al., 2013). Coastal pollution and the release of methane hydrates resulting from the thawing of permafrost or oceanic methane hydrates could however, limit the success of reducing atmospheric CO_2. Reducing coastal pollutants is another means to reduce the level of ocean acidification together with the prevention of ocean warming, which could otherwise enhance the risk of releasing methane hydrates (Billé et al., 2013).

A decrease of anthropogenic CO2 emissions requires international cooperation and substantial changes of governance systems (Billé et al., 2013), which raises questions regarding the distribution of responsibility among intergovernmental institutions for approaching this topic. To date, international and intergovernmental bodies that have added ocean acidification to their agenda include the Convention on Biological Diversity (CBD), the

United Nations Environment Programme (UNEP), the Intergovernmental Oceanographic Commission (IOC), and the Intergovernmental Panel on Climate Change (IPCC).

On the national level, already existing jurisdiction such as Clean Water or Clean Air Acts could contribute to the mitigation of the problem by preventing coastal and atmospheric pollution, which could enhance respective changes in seawater chemistry (Kelly et al., 2011).

Adaptation can take place on several institutional levels. Response actions can be subdivided into physical adaptation strategies and the development of respective management plans. To date, there are very few examples of fisheries that have installed technology to avoid the impact of changes in seawater chemistry to their hatcheries (Billé et al., 2013). In the Pacific Northwest, a few hatcheries and oyster farms have installed a monitoring system for relevant changes, which warns up to two days prior to the expected occurrence of low aragonite or pH levels (Billé et al., 2013). Another hatchery has relocated their facilities to a region that is considered unaffected by ocean acidification (Billé et al., 2013). Financial constraints and the absence of high-resolution monitoring are among the most common obstacles to adaptation (Billé et al., 2013). Another local adaptation measure includes the increase of local pH levels through increasing weathering by adding alkaline rocks into the water. This process, which is commonly referred to as 'liming', although potentially successful, is usually not considered economically feasible. In any case adaptation efforts can only be a complementary strategy to mitigation efforts (Köhler et al., 2010).

Besides direct adaptation efforts, appropriate management strategies can reduce the negative impact of ocean acidification. Cooley and Doney (2009) recommend the adoption of the precautionary principle in order to ensure the productivity of fisheries, which could lead to short-term reductions in revenue but likely improves the long-term success of the fishery sector. In fact, larger fish stocks and increased revenues could be a positive consequence of an adjusted management strategy. They do, however, point out that focusing on a long-term time scale is challenging in the face of more pressing issues (Cooley and Doney, 2009). Moreover, the delayed response of seawater chemistry to reductions in global CO2 emissions is likely to obscure the positive feedback of a management change (Andrews et al., 2008). Independent of the actual measure it is important to understand that adaptation measures can only be complementary to mitigation efforts, as the reduction of CO2 emissions is the most crucial strategy for tackling ocean acidification (Cooley and Doney, 2009).

5.4 Limitations and room for improvement

To date, the situation with respect to data availability is not optimal. There is a need for more relevant oceanic physico-chemical parameters in space and time such as pH values and carbonate saturation levels of the sea areas discussed in this study. Furthermore, better knowledge of the biological effects of acidification on all parts of the food web and on the whole life cycle of fish and shellfish species is necessary. Extended modeling activity that improves projections of future trends in acidification is another prerequisite for better estimating the socio-economic consequences of ocean acidification. Based on the present status of oceanic information, the deduction of accurate trends for projections of the future must be treated with care (Skjelvan et al., 2014).

I chose Norway to be the focus of this study because fishery is an important and thus relevant factor for economy and employment. Initially, I assumed that sufficient data was available to apply the modification of the SREX risk assessment framework of Mathis et al. (2014) to a European country, which previously had never been done. Early in the research process I realized that there is a substantial lack of data, which inhibited the exact replication of Mathis et al.'s (2014) study. While I managed to overcome some of the data gaps, the absence of certain variables prevented me from producing entirely comparable results.

- An improvement of the hazard components requires detailed monitoring data and accurate projections.
- The quantification of economic exposure may be improved by a better understanding of the species' biological responses to ocean acidification. In addition to this, data on subsistence fisheries and the nutritional value of seafood to Norwegians would be helpful.
- Improving the sensitivity component requires detailed knowledge about the companies in the fishery sector, as well as information about average income of fishermen and those involved in the processing of fish and fish products. Information regarding the importance of the fisheries with respect to tourism and culture would allow a more detailed analysis of the counties' sensitivity to ocean acidification.
- Adding social variables such as social capital and community cohesion could complement the variables used for the estimation of adaptive capacity.

The lack of data observed in this study seems to be a common conclusion of research publications in all fields involved in ocean acidification research (e.g., Brandner et al. 2012; Mathis et al., 2014; Ekstrom et al., 2015). The lack or resolution of data and information appears to be a main cause of generalizations and simplifications (IPCC, 2012). This could ultimately result in unfavorable characteristics of results such as limited accuracy and completeness, as well as scientific and technical mistakes (IPCC, 2012).

6 Conclusion

My thesis provides one of the first risk assessments ever conducted on the socio-economic impacts of ocean acidification to a European fishery sector on a sub-national level. I applied the IPCC's SREX risk assessment framework, which Mathis et al. (2014) had previously applied to the Alaskan fishery sector. The SREX method allows the incorporation of environmental, economic and social components. By combining natural and social sciences I compared the Norwegian counties with respect to the hazard, exposure, sensitivity, and adaptive capacity. The results point out that the northernmost counties are most at risk, as high-latitude oceans are considered more threatened compared to lower-latitude seas. The second part of the analysis highlights that particularly the southernmost counties, which engage in the harvest of crustaceans are more economically exposed, due to the fact that these species are more susceptible to ocean acidification and have a higher catch value. The results of the sensitivity related calculations show that the share of income generated from fisheries are very low compared to the total income. However, direct county comparisons show that the northern counties show a higher level of sensitivity, as the share of fishermen is substantially higher than in most other counties. Moreover, adaptive capacity seems to be considerably lower in the northern counties as compared to the rest. Overall, the final risk assessment shows that 13 of the 19 counties face moderate to high risk from ocean acidification.

My research shows that the SREX risk framework is applicable for evaluating the impacts of ocean acidification on fishery sectors. In the case of Norway, however, substantial improvements can be achieved by increasing the availability of detailed data, such as long-term measurements of oceanic conditions, better information regarding the biological impact of species, as well as more detailed employment and income statistics. Due to the restricted availability of data, my thesis focuses almost entirely on the economic impact of ocean acidification. My thesis is based on the current level of knowledge but the results could change once more and improved data is available. In future studies, my work could be complemented by incorporating information regarding subsistence fisheries, the nutritional importance of fish to Norwegians and the contribution of social factors, such as social capital and community cohesion to adaptive capacity. The quantitative risk assessment could then be followed by a qualitative or even participatory approach, assessing the awareness and perception of ocean acidification, as well as the development of effective and efficient mitigation and adaptation strategies. Overall, my thesis shows that, although still in its infancy, integrated risk assessments are an important prerequisite for any form of interdisciplinary ocean acidification research and the development of successful response strategies.

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