Vestlandsforskingsnotat nr. 2/2015

Havforsuring og sjømatnæringen på Vestlandet: Kunnskapsstatus og handlingsrom

Rapport fra et forprosjekt

Carlo Aall (Vestlandsforsking), Abdirahman Omar (UNI Research), Knut Yngve Børsheim (Havforskningsinstituttet), Debora Davies (Vestlandsforsking)

Vestlandsforsking, Pb 163, 6851 Sogndal • Tlf.: 906 33 600 • Faks: 947 63 727

Vestlandsforsking notat

Tittel Havforsuring og sjømatnæringen på Vestlandet: Kunnskapsstatus og handlingsrom. Rapport fra et forprosjekt	**Notatnummer** 2/2015 **Dato** 12.05.2015 **Gradering** Open
Prosjekttittel Havforsuring og sjømatnæringen på Vestlandet: Kunnskapsstatus og handlingsrom (SUR-VEST)	**Tal sider** 40 **Prosjektnr** 6346
Forskarar Abdirahman Omar (UNI Research), Knut Yngve Børsheim (Havforskningsinstituttet), Debora Davies (Vestlandsforsking), Carlo Aall (Vestlandsforsking)	**Prosjektansvarleg** Carlo Aall
Oppdragsgivar Regionalt Forskningsfond Vestlandet	**Emneord** Klimaendringer, havforsuring, klimatilpassing, sjømatnæringen
ISSN: 0804-8835	**Pris:** 50 kroner

Forord

Dette er en forprosjektrapport finansiert av Regionalt forskningsfond Vestlandet fra at samarbeidsprosjekt mellom Vestlandsforsking (prosjektleder), Havforskningsinstituttet og UNI Research AS avdeling Uni Klima. Rapporten sammenstiller tilgjengelig kunnskap for når det gjelder havforsuring og muligheter tilpassing til havforsuring for sjømatnæringen på Vestlandet. Rapporten er videre ment å gi et kunnskapsgrunnlag for utarbeiding av et hovedprosjekt på dette temaet.

Arbeidet har vært organisert ved først å fordele arbeidet med kunnskapsinnhenting som følger:

• Hvilke mekanismer påvirker surheten av havet? • Hva er omfanget av havforsuring som følge av økt konsentrasjon av CO_2 i atmosfæren?	UNI Research
• Hva er effekter av havforsuring på vekstvilkår for organismer i havet? • Hva er de mulige konsekvensene av havforsuring for sjømatnæringen generelt? • Hvordan kan disse konsekvensene slå ut for sjømatnæringen på Vestlandet?	Havforskningsinstituttet
• Hva er aktuelle tiltak for å tilpasse samfunnet til mulige konsekvenser av havforsuring for sjømatnæringen generelt? • Hvilke av disse tiltakene er aktuelle på Vestlandet?	Vestlandsforsking

Materialet har så blitt presentert på et arbeidsseminar i Bergen torsdag 16. oktober 2014, for så å ha blitt bearbeidet til tre delkapitler. Disse har så blitt satt sammen og bearbeidet av Vestlandsforsking ved Carlo Aall.

Følgende har deltatt i skrivingen av delkapitlene:

- Innledning: Carlo Aall
- Kapittel 1: Abdirahman Omar (UNI Research)
- Kapittel 2: Knut Yngve Børsheim (Havforskningsinstituttet)
- Kapittel 3: Debora Davies (Vestlandsforsking)

Sogndal, 12 mai 2015

Professor Carlo Aall

prosjektleder

Innhold

Sammendrag

Bakgrunn

Den foreliggende rapporten er fra et forprosjekt om havforsuring og klimaendringer. Formålet med forprosjektet er å oppsummere kunnskapsstatus og derigjennom å legge grunnlaget for en hovedprosjektsøknad. Mer spesifikt har forprosjektet hatt som mål å oppsummere kunnskapsstatus på følgende tre områder: (1) Mekanismene bak og omfanget av havforsuring som følge av økt konsentrasjon av CO_2 i atmosfæren; (2) effekter av havforsuring på vekstvilkår for organismer i havet og mulige konsekvenser av havforsuring for sjømatnæringen generelt og spesifikt på Vestlandet; og (3) aktuelle tiltak for å tilpasse samfunnet til mulige konsekvenser av havforsuring for sjømatnæringen generelt og spesifikt på Vestlandet.

Mekanismene bak og omfanget av havforsuring som følge av økt konsentrasjon av CO_2 i atmosfæren

En fortsettelse i de globale utslippene av CO_2 - og en eventuell økning av disse - er av global bekymring, ikke bare fordi de er de viktigste driverne av menneskeskapt global oppvarming, men også fordi de forårsaker uheldige endringer i havets kjemi. Økningen i atmosfærisk CO_2-innhold fører til en tilsvarende økning i overflatehavet som tar opp mer CO_2 fra atmosfæren. Gjennom denne prosessen har havet så langt absorbert om lag *halvparten* av all menneskeskapt CO_2 fra fossile brensler og sementproduksjon siden begynnelsen av den industrielle revolusjonen. Dette opptaket av menneskeskapt CO_2 i havet har ført til lavere pH (forsuring), lavere konsentrasjon av karbonat ion (CO_3^{2-}) og dermed lavere metning av kalsiumkarbonat (Ω) i sjøvannet - en prosess som kalles *havforsuring*.

Studier basert på rekonstruksjoner og modelleringsstudier tyder på at opptak av menneskeskapte CO_2 har senket den gjennomsnittlige pH-verdi i overflatehavet med ca. 0,1 enheter til nåværende gjennomsnittlig verdi på 8.1, som er antatt å være den laveste i løpet av de siste 20 millioner år – om lag 17,5 millioner før menneskeslekten (Homo) oppsto i Afrika.

Nyere observasjoner fra tidsseriestasjoner i forskjellige havområder viser også gjennomgående endringer i overflatehavets kjemi som følge av havforsuring drevet av opptaket av menneskeskapt CO_2. Disse inkluderer langsiktige negative trender mellom -0,0013 og -0,0026 per år og -0,0018 og -0,0115 per år for henholdsvis pH og Ωa (metningstilstand for aragonitt). Simuleringer med regionale og globale Earth System modeller (ESM) viser havforsuringstrender som er i tråd med observasjonene fra åpent hav-stasjoner. For kystområdene derimot, er observerte trender i pH-endringene helt annerledes enn de forventet fra oseanisk CO_2-opptak alene skulle tilsi. Andre biogeokjemiske prosesser, muligens relatert til endringer i tilførsel av næringssalter fra land, kan spille en viktig rolle i å påvirke havforsuring i kystfarvann. Åpent havområder på høye breddegrader (som de Nordiske hav) er også spesielt utsatt for havforsuring fordi kaldere vann som fins her inneholder naturlig høy konsentrasjon av CO_2, noe som gjør at konsentrasjonen av karbonat ion er naturlig lavere sammenlignet med havområder ved lavere breddegrader. Simuleringer gjort med ESM tyder på at de observerte trendene når det gjelder endringer i havforsuring, havsirkulasjon, biogeokjemi og økologi, vil fortsette eller akselerere i 21. århundre.

Effekter av havforsuring på vekstvilkår for organismer i havet og mulige konsekvenser av havforsuring for sjømatnæringen generelt og spesifikt på Vestlandet.

De globale utslippene av karbondioksid til atmosfæren kommer til å fortsette å senke pH i alt sjøvann inklusive norske kystnære farvann i overskuelig fremtid. Det er klart påvist at de forventede forandringene i havets karbonkjemi vil påvirke en rekke marine arter, men så langt man kan forutsi er de samlede effektene på økosystemet ikke entydige. Noen arter vil få problemer, men andre arter vil øke konkurranseevnen. Det som er best dokumentert, er at arter som er avhengig av kalkskall vil få dårligere levevilkår dersom utslipp av CO2 til atmosfæren fortsetter i nåværende tempo. Det betyr at kommersielt interessante arter som blåskjell og østers er i faresonen, sammen med andre ikoniske innslag i fjæresonen som rur og strandsnegl.

Vannets surhetsgrad påvirker alle livsprosesser, og effekter av havforsuring er påvist i en rekke arter. Spesielt tidlige livsstadier hos den marine faunaen kan være sårbare. Voksne individer har muligheter for å regulere kroppskjemi, men egg og larver er i direkte likevekt med sjøvannet.

Oppdrettsnæringen kan komme til å møte flere utfordringer i forbindelser med fremtidens klima. Sannsynligvis vil teknologi kunne håndtere mange av disse utfordringene, så som økt frekvens av uvær, men forandringer i økosystemet som for eksempel økte forekomster av plagsomme alger eller for eksempel maneter er vanskeligere å håndtere. Når det gjelder fiskeoppdrett vurderes havforsuring i seg selv som en mindre utfordring i forhold til andre miljømessige forandringer knyttet til predikterte klimaforandringer.

Aktuelle tiltak for å tilpasse samfunnet til mulige konsekvenser av havforsuring for sjømatnæringen generelt og spesifikt på Vestlandet

Stadige forandringer er en vedvarende situasjon i kysten og marine miljøer. Dette forholdet har preget havbruks- og fiskerisektoren, noe som har ført til i en sterk tradisjon for tilpasning. Denne tradisjonen har fulgt to ulike spor. På den ene siden har forvaltere lagt stor vekt på ressursbevaring og effektivisering i næringen. Dette er gjort først og fremst gjennom begrensinger på høsting av ressursene og å utvikle alternative inntektskilder i de tilfeller der slike begrensninger har fått store negative økonomiske konsekvenser for næringen. På den andre siden har næringen tilpasset seg gjennom endringer i teknologi, driftsopplegg og økonomiske forhold. Spørsmålet er hvorvidt og i hvilken grad disse to tradisjonene for tilpassing i tilstrekkelig grad kan svare på utfordringer forårsaket av havforsuring, og om det eventuelt trengs nye tiltak og metoder for å øke robustheten i havbruks- og fiskerisektoren.

Virkningene av havforsuring er fortsatt mangelfullt beskrevet og kvantifisert og vanskelig å isolere fra andre stressfaktorer. Forskningen på dette feltet er fortsatt i en oppstartfase. Det som likevel er kjent, er at havforsuring vil påvirke kystsamfunn og økosystemer i varierende grad og langs ulike tidsskalaer.

Viktige tilpasningstiltak som omtales i internasjonal litteratur er blant annet: Evaluere hvordan eksisterende politikker, ikke bare innen fiskeri og havbruk, kan styrkes eller utvidet i den hensikt å hindre havforsuring, styrke robusthet i kyst- og havøkosystemene, tilpasse menneskelige aktiviteter og reparere skader. Fremme tverrfaglige tilnærminger til det å forstå bedre effekter av havforsuring på samfunnet. Redusere andre stressfaktorer på kyst- og havøkosystemene - som den diffuse avrenningen - gjennom integrert kystsoneforvaltning og etablering av marine verneområder. Øke tilpasningsevnen ved å styrke opplæring og veiledning av næringsaktører, berørte lokalsamfunn og lokale og regionale myndigheter som er involvert i kystsoneplanlegging. En analyse av barrierer for omstilling av lokalsamfunn som er særlig sårbar for storskala endringer i havbruks- og fiskerinæringen.

Det finnes en rekke aktuelle strategier og tiltak å tilpasse næringen og samfunnet til konsekvensene av havforsuring. Et overordnet råd er å legge til grunn en «no regret» tilnærming i valg av strategier og tiltak; altså å velge de som framstår som fornuftige uavhengig av nivå på klimaframskrivningene og (dermed) grad av havforsuring.

Innledning

Det har etter hvert kommet fram mye kunnskap om mulige effekter i Norge av klimaendringer, hvordan dette igjen kan ramme samfunnet og hva samfunnet kan gjennomføre av tiltak for å tilpasse seg forventede klimaendringer (Aaheim mfl, 2009; Alfsen m.fl., 2013). Norge har også blant de fremste fagmiljøene nasjonalt og internasjonalt på flere kunnskapsområder som er avgjørende i denne sammenhengen, og flere av disse fagmiljøene finner vi på Vestlandet – som Uni Research avdeling Uni Klima (studier av klimaendringer og havmiljø), Havforskningsinstituttet (effekter av klimaendringer på havmiljøet) og Vestlandsforsking (lokal klimatilpasning). I dette prosjektet har vi ønsket å kombinere kunnskapen fra disse tre forskningsmiljøene for å belyse et tema som så langt har vært overraskende lite fremme i klimaforskningen og klimapolitikken, nemlig temaet klimaendringer og havforsuring og spørsmålet om hvordan tilpasse seg problemene som et surere hav kan medføre.

Sjømatnæringen, det vil si fangst-, oppdretts-, fiskeforedlings- og grossistleddet, er rimeligvis sterkt påvirket av de fysiske og biologiske egenskapene i havet. Det har vært gjennomført en rekke forskningsprosjekter - bl.a. innen det nylig avsluttede forskningsprogrammet NORKLIMA - om hvordan endringer av temperatur kan påvirke disse forholdene og hvilke konsekvenser dette kan ha for sjømatnæringen, bl.a. følgende prosjekter (oversikt hentet fra Aaheim et al, 2009):

- ECOBE - Effects of Atlantic Climate Variability on the Barents Sea Ecosystem
- MACESIZ - Marine Climate and Ecosystems in the Seasonal Ice Zone
- CLIMAR – Climate And Production Of Marine Resources
- NESSAS - Norwegian Component of the Ecosystem Studies of Sub-Arctic Seas
- NESSAR - Ecosystem Studies of Subarctic and Arctic Regions
- FishExChange - Expected Change in Fisheries in the Barents Sea

I noe mindre grad er det gjennomført studier som spesifikt ser på konsekvenser for oppdrettsnæringen (se bl.a. Berg m.fl, 2007). I sammenligning er det forsket lite på mekanismene bak og omfanget av havforsuring som følge av økt konsentrasjon av CO_2 i atmosfæren og hvordan et surere hav kan påvirke sjømatnæringen (Børsheim og Golmen 2010). Videre har det gjennom det siste tiåret blitt forsket på betingelser for og handlingsrom for lokal klimatilpasning (se Aall et al, 2012; 2015 for en oversikt), men lite av den genererte kunnskapen gjelder de spesifikke klimautfordringene innen sjømatnæringen (Hovelsrud og West, 2008; Keskitalo og Kulyasova, 2009).

Sjømatnæringen er viktig for Vestlandet. Næringen skapte i 2010 ca 13.300 årsverk nasjonal - hvorav ca. 9.800 årsverk innen Vestlandet – og sto for en samlet verdiskaping på i underkant av 14 milliarder kroner. Sjømatnæringen har vært en av de store vekstnæringene i norsk økonomi de siste ti årene målt i verdiskaping. I perioden 2000-2009 var den årlige økningen i verdiskapingen for fiskeri og havbruk 5,5 prosent, mens hele landets verdiskaping i form av BNP økte med 1,9 prosent og industriens verdiskaping med 1,5 prosent. I en rekke kommuner på Vestlandet står sjømatnæringen for 5-15 % av den lokale sysselsettingen (Fiskeri- og kystdepartementet, 2013). Det er store forventninger til at verdiskaping fra sjømatnæringene på Vestlandet kan øke i årene fremover, men det er knyttet usikkerhet til hvordan dette kan påvirkes av klimaendringer. Usikkerheten er særlig stor rundt spørsmålet om hvilke følger havforsuring kan få. Det er derfor svært viktig å få avklart hvordan økt havforsuring kan påvirke produksjonsvilkårene for sjømatnæringen på Vestlandet, og samtidig få avklart behov for forskning og hva som er det aktuelle handlingsrommet for tilpasning gitt dagens kunnskapsstatus.

I det videre gjøres en kunnskapsoppsummering på følgende områder:

(1) Mekanismene bak og omfanget av havforsuring som følge av økt konsentrasjon av CO_2 i atmosfæren
(2) Effekter av havforsuring på vekstvilkår for organismer i havet og mulige konsekvenser av havforsuring for sjømatnæringen generelt og spesifikt på Vestlandet.
(3) Aktuelle tiltak for å tilpasse samfunnet til mulige konsekvenser av havforsuring for sjømatnæringen generelt og spesifikt på Vestlandet

De etterfølgende kapitlene er skrevet på engelsk med tanke på å gå videre med tekstene i en søknad om et hovedprosjekt.

Ocean acidification as a result of increased atmospheric concentration of CO_2

Definition, cause, and chemical reactions

The global carbon dioxide (CO_2) annual emissions due to fossil fuel burning and cement production are currently estimated to be at 9.7 gigatonnes carbon (Gt C=10^{15} gC) (Peters et al, 2013), which is a record high since pre-industrial era. The continuation and acceleration of these emissions is of global concern, not only because they are the main drivers of anthropogenic global warming (IPCC, WGI 2013), but also because they derive adverse change in the chemistry of the ocean. The concentration of CO_2 in the ocean follows Henry's law which states that an increase in the atmospheric CO_2 concentration leads to an increase in the surface ocean through absorbing more CO_2 from the atmosphere. Therefore, the ocean absorbed about 50% of the CO_2 that was emitted from fossil fuels and cement production (Ref) since the industrial revolution began around the 1800s. This uptake of anthropogenic CO_2 in the ocean leads to lower pH (acidification), lower concentration of carbonate ion (CO_3^{2-}) and, thus, lower saturation of calcium carbonate (Ω) in seawater – a process known as ocean acidification (OA).

CO_2 is an un-reactive gas in the atmosphere, but when it is dissolved into the ocean (Eq. 1), and that is by the exchange between the atmosphere and the ocean due to the difference in partial pressure, it becomes reactive and takes part in several chemical, physical, biological, and geological reactions

$$CO_{2(atmosphere)} \leftrightarrow CO_{2(dissolved)} \quad (1)$$

The second set of reactions involves the hydration of water to form carbonic acid (H_2CO_3)

$$CO_{2(dissolved)} + H_2O \rightarrow H_2CO_3 \quad (2)$$

H_2CO_3 dissociates and releases hydrogen ions into the water

$$H_2CO_3 \rightarrow HCO_3^- + H^+ \quad (3)$$

The ionization of the bi-carbonate (HCO_3^-) releases the carbonate ion (CO_3^{2-})

$$HCO_3^- \leftrightarrow H^+ + CO_3^{2-} \quad (4)$$

These reactions (Eq. 2, 3, 4) are very rapid, on time scales of tens of seconds for CO_2 hydration and microseconds for subsequent acid-base reactions (Zeebe and Wolf-Gladrow, 2001; Dickson et al., 2007).

Three variables that are commonly used to quantify ocean acidification are:

1) pH which is a measure of the acidity or basicity of the seawater and is defined as

$$pH = -\log(H^+) \quad (5)$$

2) Degree of saturation for carbonate ions

$$\Omega = \frac{[Ca^{2+}][CO_3^{2-}]}{K_{sp}} \approx \frac{[CO_3^{2-}]}{[CO_3^{2-}]_{sat}} \qquad (6)$$

3) The Revelle factor which is a measure of the surface ocean resistance to absorb atmospheric carbon dioxide posed by bicarbonate chemistry

$$\mathrm{Re} = \frac{DIC}{pCO_2}\frac{\partial pCO_2}{\partial DIC} = \frac{\partial \ln pCO_2}{\partial \ln DIC} \qquad (7)$$

Overview of observational evidence and modelling results

Evidence from reconstructions and modelling studies suggest that from 1800 to 2009 dissolution of anthropogenic CO_2 has lowered the average pH of the surface ocean approximately by 0.1 units (Caldeira & Wickett 2003) to the current average value of 8.1 which is believed to be lower than experienced during the last 20 million years (Pearson and Palmer, 2000).

Accurate techniques for the measuring the marine carbonate system parameters have been available only in the last few decades and these have been utilized in time series stations in different oceanic regions. Currently, data obtained at these stations provide some of the best information we have about the trend of ocean acidification, and thus provide in depth understanding of the response of the ocean carbon cycle to natural variability and anthropogenic perturbation. Bates et al. (2014) combined data collected at seven independent CO_2 time series stations for periods from 15 to 30 years (Table 1). They found highly consistent changes in surface ocean chemistry that result from ocean acidification driven by the uptake of anthropogenic CO_2. Long-term negative trends ranging between -0.0013 and -0.0026 yr^{-1} and -0.0018 and -0.0115 y^{-1} were found for pH and Ωa (saturation state for aragonite), respectively. Additionally, consistent increases in the Revelle factor (cf. eguation 6) ranging from +0.011 yr^{-1} to +0.019 yr^{-1} were found, indicating that the capacity of these ocean regions to absorb anthropogenic CO_2 decreased. Furthermore, given the strong non-linearity of the seawater carbonate system, the reduced uptake capacity implies accelerating ocean acidification.

Table 1 *Data collected at seven independent CO_2 time series stations for periods from 15 to 30 years (Bates et al., 2014).*

Time-Series Site	Revelle Factor	pH	$\Omega_{aragonite}$
Iceland Sea	0.019 ± 0.001	−0.0014 ± 0.0005	−0.0018 ± 0.0027
Irminger Sea	0.030 ± 0.012	−0.0026 ± 0.0006	−0.0080 ± 0.0040
Bermuda Atlantic Time-series Study (BATS),	0.014 ± 0.001	−0.0017 ± 0.0001	−0.0095 ± 0.0007
European Station for Time series in the Ocean at the Canary Islands (ESTOC)	0.019 ± 0.002	−0.0018 ± 0.0002	−0.0115 ± 0.0023
Hawaii Ocean Time-series (HOT)	0.014 ± 0.001	−0.0016 ± 0.0001	−0.0084 ± 0.0011
CArbon Retention In A Colored Ocean (CARIACO)	0.011 ± 0.003	−0.0025 ± 0.0004	−0.0066 ± 0.0028
Munida	0.028 ± 0.008	−0.0013 ± 0.0003	−0.0085 ± 0.0026

Recently, Lauvset and Gruber (2014) combined available cruise data and empirical relationships to estimate the long-term pH trend in the North Atlantic (north of 45N) over the period 1981 to 2007. Their finding, −0.0022 ± 0.0004 yr^{-1}, was in good agreement with the above time series station data. They reported that long-term trend in pH was nearly entirely driven by the long-term trend in surface ocean CO_2, which have been shown to correlate well with the atmospheric CO_2 (e.g. Omar and Olsen 2006).

In the Nordic Seas, time series data from OceanWeather Station Mike (OWSM) (66 N, 2E) revealed an annual increase of in inorganic carbon pH change of −0.001 pH-units year^{-1} in surface water between 2001 and 2005 (Skjelvan et al., 2008). Furthermore, a recent report by the Bjerknes Centre (Skjelvan et al., 2013) showed that surface waters in the Norwegian Sea in addition to the Fram Strait has strongest decline in pH over the past 30 years ; with a magnitude (0.11 - 0.07 pH units) similar to that seen globally since the start of the industrial revolution. Additionally, the study showed an acidification trend throughout the water column even in the deepest waters in several thousand meters. This is the consequence of deep convection in these high latitude areas and it shows that, although the absorption of anthropogenic CO_2 takes place in the surface ocean, physical and biogeochemical processes are at work to transfer the acidification signal to deeper waters.

High latitude waters like the Nordic Seas are particularly vulnerable to ocean acidification because here the colder water contain naturally high concentration of CO_2, and consequently the concentration of carbonate ion is naturally lower compared to lower latitude ocean. Low carbonate concentration means lower ability to counteract ocean acidification compared to water, for example, the tropics. This implies that global CO_2 increase will result in a higher rate of acidification in the Nordic Seas. In fact, model simulations indicate that polar surface waters in the Arctic will become under-saturated for aragonite in the near future (atmospheric carbon dioxide of 400–450 ppm) (Orr et al., 2005).

Comprehensive process understanding of OA requires sound combination of observational data and modelling. The above mentioned observed changes in oceanic carbonate parameters do not occur in isolation, but show up in combination with changes (natural/anthropogenic) in other relevant oceanic processes such as biological activity, air-sea exchange of heat, stratification, etc. The changes have been documented for the global ocean as rising sea surface temperatures, upper-ocean warming, sea level rise, altered precipitation patterns and river runoff rates, and sea ice retreat and thinning in the Arctic and West Antarctic Peninsula (Bindoff et al., 2007). Due to the complexity involved, modeling is the only way to achieve description of main relevant processes as well as the resultant impact on the marine carbon cycle. Models are also necessary in order to project/hindcast future/past OA. This is especially true since they enable us teasing apart the effects of anthropogenic forcing from those of natural (internal and external) factors. However, model simulations are trustworthy when they are calibrated and validated against accurate observational data.

Simulations with Earth System Models (ESM), which are the most comprehensive models in terms of processes, show that the observed trends of changing ocean circulation, biogeochemistry, and ecology, will continue or even accelerate over 21st century. Increasing atmospheric CO_2 will continue to drive global warming. The ocean will warm up in the surface and become vertically stratified with reduced primary productivity. Ocean uptake of atmospheric CO_2 will probably continue in a reduced rate, but this will not reduce OA significantly (Doney et al., 2014).

ESMs have relatively coarse spatial resolution and their results are more representative for open ocean basins. Therefore, regional models have been used for OA studies that focus on certain regions, like shelf and/or coastal seas. For the Nordic Seas and Norwegian shelf seas (Barents Sea and North Sea), simulation results from regional models are qualitatively similar to those obtained with ESMs.

Skogen et al. (2014) has investigated the effects of rising atmospheric CO_2 and climate change on the acid–base state in the Nordic and Barents Seas. They used scenario with medium low CO_2 emission (IPCCs A1B scenario) and found a pH change of −0.19 from 2000 to 2065 in the surface water. The authors also pointed out some caveats in their model including misrepresentation of coastal currents and salinity fronts closer to the coast than about 100 km, and the lack of an annual cycle in the river runoff forcing. Nevertheless, it is interesting to note that the magnitude of the above pH change, obtained this area using medium low CO_2 emission scenario, equals that obtained for the global ocean using the highest CO_2 emission scenario of AR5 i.e. RCP 8.5 (Doney et al., 2014).

In the southern North Sea, Blackford et al. (2006) used a coupled carbonate system–marine ecosystem–hydrodynamic model to simulate the temporal and spatial variability in pH. For a scenario with an atmospheric CO_2 of 500 ppm in 2050, the calculated an average pH decrease of 0.1 pH units from today's mean pH levels in the southern North Sea, 8.0-8.6. While this is somewhat in line with the expectation of continued uptake of CO_2 in the surface ocean as well as with the ESM simulation results, observational data from the Dutch coast show that this does not need to be the case. Provoost et al (2010) analyzed these data which have been collected by the Dutch monitoring authorities in different coastal systems (North Sea, Wadden Sea, Ems-Dollard, Eastern Scheldt and Scheldt estuary) in 1975 – 2004. Their results show that pH increased in 1975-1987 and then decreased afterwards, with rates of 0.01 to 0.025 pH yr^{-1} and - 0.02 to -0.03 pH yr^{-1}, respectively. These observed rates of pH change are completely different than those expected from oceanic CO_2 uptake alone, and Provoost et al. (2010) suggested that other biogeochemical processes, possibly related to changes in nutrient loading, can play a dominant role in ocean acidification in the coast.

Wootton et al. (2008) reported a decreasing pH rate which is an order of magnitude higher than the projected CO_2-based global average rate of change (Orr et al., 2005) and observed open ocean pH decrease (Dore et al., 2009; Lauvset and Gruber, 2014; Santana- Casiano et al., 2007). They used 8 years of high resolution pH dataset acquired at the Tatoosh Island in the coastal water on the Washington Shelf and found a substantial variation in pH values across multiple time scales. The diurnal and seasonal pH changes were 0.25 and up to 1.0 units, respectively. Over the entire study period pH changed by 1.5 unit with a significant decreasing trend of 0.045 (0.039 to 0.054) unit per year, and the rate of pH decline appeared to be accelerating.

The high, observation-based pH trends reported by Wootton et al (2008) and Provoost et al (2010) suggest that for *coastal* systems: **(i)** OA may be *more* pressing issue, **(ii)** pH trends are driven by changes in biogeochemical processes *in addition to* oceanic uptake of atmospheric CO_2, and **(iii)** mechanistic understanding of pH trends requires *long-term, multi-time-scale and multi-parameter* observations. This is especially true in order to be able to separate the changes that are imported from the open ocean (or even from land) from those operating at the local scale. For instance, the distribution of surface water pH and CO_2 in the

North Sea has been shown to be influenced by the North Atlantic Oscillation (NAO), through seawater import from the North Atlantic and Baltic Sea, as well as local processes (Salt et al., 2014). Regarding the need of long-term data, Omar et al (2010) have pointed out that high inter-annual variability observed in surface seawater fugacity (fCO_2) in the North Sea could conceal the trend resulting from the equilibration with the increasing atmospheric CO_2 even over a 20 years period.

In acknowledging the above points, Riche et al (2014, p. 36), who reviewed time series for the Strait of Georgia noted: “the timing of geochemical cycles in the Strait of Georgia is delicately poised, with, for example, deep-water oxygen reaching a hypoxic tolerance threshold in the spring, just before deep-water renewal replenishes the oxygen from outside. […] Timing is particularly important for monitoring. Relatively long records for basic water properties like temperature and salinity are accompanied by much shorter records for biogeochemical properties like dissolved O_2, pH, nutrients and vertical flux, making it difficult to assemble a clear picture of the sorts of changes that may be occurring in the latter. A confident assessment of the ecological resilience of the Strait of Georgia will requires longer time series of biological and geochemical properties that are collected with consideration for the strong seasonal variability.”

Effects of ocean acidification on marine life

Introduction

For all life processes pH is an essential variable, and advanced multicellular organisms have made their existence possible by being able to control the pH of their body fluids extremely carefully. Single celled and small multicellular organisms are directly exposed to external pH, and have to be adapted to cope with the variation and range of pH offered by the environment. Therefore, when pH of the environment systematically changes, it is reasonable to expect changes in the ecosystem producing effects cascading from the smallest and most vulnerable, potentially transcending throughout the food web.

It is possible to predict the development of changes in the carbon chemistry of seawater when CO_2 is added, but the biological consequences of the changes need to be investigated using experiments. The challenge of predicting consequences of ocean acidification has resulted in an impressive research effort since the first early warnings of adverse effects on marine life forms from the predicted future ocean carbon chemistry (Caldeira & Wickett 2003; Orr et al. 2005). The output in the field measured as number of publications has doubled every 1.44 year since 2005, and in 2013 there were published 663 papers on the topic.

Recent reviews show that the interpretation of the literature on biological effects of ocean acidification is far from straightforward (Harvey et al. 2013; deVries et al. 2013). What is agreed so far is that the literature indicates ocean acidification as a *major influence* in future changes of ecosystem variables such as growth rate and viability of individual species (Harvey et al., 2013; Kroeker et al., 2013). Some species will meet with reduced rate of success in the predicted future ocean (Fabry et al., 2008), but notably other species will have increased rate of success (Koch et al., 2013). It is currently only possible to conclude that ocean acidification in concert with other drivers such as temperature and oxygen will cause changes in future marine ecosystems (Kroeker et al., 2013; Waldbusser and Salisbury, 2014). Calcification is the process most obviously vulnerable to acidification, but the impact varies widely among species (Kroeker et al. 2010).

Fisheries and aquaculture

Ocean acidification is one out of a number of other factors that may present threats or challenges to the performance of commercial fisheries and aquaculture, and reviewers note that predictive power suffers from serious knowledge gaps (Sumaila et al. 2011, Callaway et al. 2012, Cheung et al. 2012). One of the more robust predictions foresees increased species richness at altitudes above 40˚N, a development already documented for the last decades in the North Sea (Cheung et al. 2009). These changes may represent an asset for Norwegian fisheries because new species may become available for trade and consumption.

Aquaculture may face challenges from global warming, changes in water runoff and storm frequency, but presumable technological modification can keep pace with such changes (Callaway et al. 2012). Aquaculture will have the options of moving offshore as well as onshore, and they may turn to alternative species with better adaption to altered climate variables. However, it is also clear that present changes favour the introduction of species new to high latitude; spread of non-native nuisance clearly may happen (Callaway et al. 2012). Warmer water may favor the spread of decease, but also general nuisance phenomena such as toxic algal blooms or jellyfish. Any prediction of the quantitative changes in frequency or severity of such blooms is *completely outside the reach of present analyses*. Climate change and changes in human use of the near shore sea landscape has recently been identifies as drivers of establishment of highly problematic recruitment for such blooms in Chinese near shore environments (Qui 2014). It seems wise to keep high awareness of possible consequences when we establish new practices in confined environments such as fjords. Increased abundance of jellyfish has previously been causing problems in aquaculture both due to cage net interference and due to direct biological damage such as gill poisoning by jellyfish tentacles (Callaway et al. 2012). Biological invasions such as toxic algae and jellyfish may be harder to tackle than increased storm frequency and water level rise because the latter can be met with technological adaption. Among the foreseen future challenges, ocean acidification is presently evaluated as a minor problem to the aquaculture of finfish.

Prospects for Norwegian shellfish industry

Some organisms are dependent on body armor produced from varieties of calcium carbonate and they will be vulnerable to the state of solubility of their armor - which increases during ocean acidification. Species important in the shellfish industry are in this category and they are potentially threatened by ocean acidification (Ries et al., 2011). Gazeau et al. (2007) demonstrated that the calcification rates of the edible mussel (*Mytilus edulis*) and Pacific oyster (*Crassostrea gigas*) declined linearly with increasing pCO_2. They predicted that mussel and oyster calcification may decrease by 25 % and 10 %, respectively, by the end of the century, following the IPCC IS92a scenario (740 ppmv in 2100). Further studies indicated that although the effects of acidification on adult life stages are significant and disturbing, the effects on larvae are more disturbing and such effects have been demonstrated in a wide range of species (Talmage & Gobler 2009; Gazeau et al. 2011; Gazeau et al. 2013). Norwegian researchers have demonstrated deformity effects in scallop larvae (Andersen et al. 2013), and early life stages of lobster (Agnalt et al. 2013). Adverse effects could be clearly linked to the increase in CO_2 input to seawater (Miller et al. 2009), but ocean warming can conceivably contribute considerable to reductions in calcite formation in a warmer and less alkaline future ocean (Macenzie et al. 2014a). Moreover, not only calcification is at risk, ocean acidification combined with warming may alter immune response and disease status in the blue mussel (Macenzie et al. 2014b), and such effects awaits further study in other species.

Interestingly, species show different responses to the combined stress of acidification and warming (Zhang et al. 2014). For the Mediterranean mussel (*Mytilus galloprovenciales*), warming counteracts some adverse effects of acidification (Kroeker et al. 2014). In a study that observed responses for a quarter of a year, the Mediterranean mussel (*Mytilus galloprovenciales*) was compared to the striped Venus clam (*Chamelia gallina*), and it was clearly demonstrated that the clam was more susceptible than the mussel as measured by mortality, dry weight and shell damage, and that the clam was affected the most both by acidification and warming (Bressan et al. 2014).

For shellfish industry it may be worthwhile to consider screening for species, strains or varieties with adapted abilities already developed to thrive in the predicted future ocean carbon chemistry. Breeding programs such as been well established in agriculture may have a potential in shellfish aquaculture to prepare for the future challenges. The economic cost globally towards year 2100 of business-as-usual for shellfish production in the predicted future ocean is estimated at above 100 billion USD (Narita et al. 2012).

Knowledge gap relating to the Norwegian fjords

The Norwegian Shellfish industry is located in the fjord landscape and produces mostly blue mussel, and a marginal amount of oysters. However, the potential for increased production has been noticed since long.

Clearly, the global ocean acidification will affect the growth conditions in Norwegian Fjords just like anywhere else on the planet, and there exist prognosis for the development of carbon chemistry in offshore waters of Norway (Skogen et al. 2014). However, presently it is impossible to present precise prognoses for fjord waters. Although the physics and chemistry of most Norwegian fjords and coastal regions has been well described (Inall & Gillibrand 2010), the carbon chemistry is not yet determined. The brackish water is a mixture of marine waters and terrestrial runoff, the resultant chemistry is complicated, and detailed measurements are needed to map the present state of the carbon system (Waldbusser and Salisbury 2014; Reum et al. 2014). This has not been done except for at a few locations at the very outlet of the fjords, and more systematic surveys are needed, as well as efforts to implement such measurements in models suited to predict future development of fjord water carbon chemistry. Initiatives from marine researchers are presently under review by funding agencies, and hopefully the data can be collected in near future expeditions. Without a proper set of data for the present state, the only prediction that can be made is the same as for the global shellfish industry. The conditions for shellfish breeding will worsen due to ocean acidification, but we cannot predict how fast.

Adapting to ocean acidification

Introduction

As a part of the pre-project SUR-VEST, the Western Norway Research Institute has set out to summarize the scientific literature on adaption options for the sea food sector in the face of ocean acidification (OA), both in general and more specifically in relation to Western Norway.

Table 2 *Breakdown of key articles drawn from the literature search for scientific articles*

Area of research	Key papers pulled from the search
Biodiversity conservation: (0 of 23)	Purely natural science-based work on effects of climate change/ocean acidification.
Engineering environmental: (1 of 5)	Detecting and Coping with Disruptive Shocks in Arctic Marine Systems: A Resilience Approach to Place and People Carmack et al. 2012
Environmental studies: (4 of 11)	Ecosystem-Based Adaptation to Climate Change in Caribbean Small Island Developing States: Integrating Local and External Knowledge Mercer et al. 2012 Wicked Challenges at Land's End: Managing Coastal Vulnerability Under Climate Change Moser et al. 2012 Ocean Governance for the 21st century: Making marine zoning climate change adapt-able Craig, 2012 Adaptation now Adger et al. 2009
Fisheries: (2 of 17)	Mainly impact studies of ocean ecosystems, a few mention adaptation strategies. Impact of climate change in Mediterranean aquaculture Rosa et al. 2012 Local solutions to manage the effects of global climate change on a marine ecosystem: a process guide for marine resource managers Higgason & Brown, 2009
Food science technology: (1 of 2)	Climate change and food safety: A review Tirado et al. 2010
Law: (1 of 2)	Ocean Governance for the 21st century: Making marine zoning climate change adapt-able Craig, 2012 This article also appears under Environmental studies (above).
Multidisciplinary sciences: (1 of 39)	Mainly contributions from natural sciences on effects on marine organisms. Articles that contain the search word "adapt*" focus on how species adapt to changes in environmental conditions (environmental adaptation). The role of interactions in a world implementing adaptation and mitigation solutions to climate change Warren, 2011
Public administration: (1 of 1)	The ocean and climate change policy Galland et al. 2012
Veterinary sciences: (0 of 1)	An article on the climate vulnerability of mussel farming in the Adriatic Sea.

Owing to the limited results derived from the initial scientific literature search, a broader search was conducted to included synthesis reports and policy documents. As ocean acidification has come to the attention of national and international organisations there has been an ensuing number of synthesis reports and policy documents some of which highlight and recommend adaptation measures. The ISI web of knowledge database was used initially. An asterisk (*) was employed after the first part of a word in the search, in order to include various forms of the word. For example, a search for adapt* included both ”adapt”, ”adapting”, ”adaptation”, ”adaptive” etc. ”Citation” refers to the number of registered citations of the publication in ISI Web of Knowledge. This is not necessarily in accordance with information from other databases, but provides a certain indication of the publication’s impact (few citations may be a result of the publication being quite new). A similar search was conducted on the AGRIS database, where results were dominated by acid rain effects. This was followed up with an extend search of grey literature for policy and synthesis documents produced by OA organizations and focus groups. The first search on ISI produced a high number of articles on coral bleaching. By excluding “coral” from the search, the list was reduced from 524 to 430 articles. ISI provides the option of limiting and refining the search to 100 areas of research or categories each listed together with a number of hits in each category. After selection we were left with *98 publications* in the research fields listed below. The publications are grouped according to the scientific profile of the journals, with the number of references in a parenthesis following the category name.

General overview

The majority of the articles resulting from the initial search of scientific publications were not directly relevant to the question of how the seafood sector may adapt to ocean acidification (OA). With regard to adaptation this initial search highlighted that the primary focus to date has been on *ecological adaptation*. When the search was expanded to include socio-economic impacts and policy responses to OA and climate change in general, current adaptation measures and potential future options, though not always labelled as such, became more apparent.

Overall the existing body of relevant literature is both nascent and sparse. This is not on the whole surprising; the field of natural resource management, goods and services provided by marine and coastal ecosystems have generally received far less attention, particularly in the economic valuation literature, than those provided by terrestrial ecosystems (Brander et al. 2012).

Though there is limited data and limited studies of adaptation measures to OA, the direct harm to ecosystems and industries dependent upon them is estimated to get worse as the oceans become more acidic. As economic harms increase, efforts to mitigate these harms will likely increase proportionately. Conversely, the benefits of combating OA will become both clearer and nearer in time as the cost of inaction grows. Most of these effects of OA are largely judged as negative as illustrated by the IPCC AR5 briefing report on Climate Change: Implications for Fisheries & Aquaculture released in May 2014. It’s five key findings were summarised as follows:

- Climate change and acidification are altering ocean ecosystems in profound ways, with consequent impacts on fisheries and aquaculture. Drivers include rising water temperature, rising levels of carbon dioxide (CO_2) uptake from the atmosphere and hypoxia (inadequate oxygen).
- Projected impacts on fisheries and aquaculture are negative on a global scale; severely so in many regions. Major impacts include displacement of stocks and, for aquaculture, mortality of shellfish from acidic water. However, in some regions, fish stocks are projected to increase.
- Impacts of climate change and ocean acidification are generally exacerbated by other factors such as overfishing, habitat loss and pollution. This is contributing to an increase in the number of ‘dead zones’ in the ocean, as well as to an increase in harmful algal blooms.
- Coral reef ecosystems are declining rapidly, with the risk of potential collapse of some coastal fisheries. Incidences of coral bleaching are likely to increase. Aquaculture may be affected through reduced catches of feed-fish and increasing severity of tropical storms and flooding. Fishers can adapt to some climate impacts.
- Measures available include reducing nonclimate stressors such as pollution; changing fishing pressure, gear or target species; increasing aquaculture; and moving to dynamic management policies. However, the scope for adaptation to some factors (such as ocean acidification) is very limited. Political con- flicts over fishing may increase as stocks migrate.

The literature supports the premise that reducing CO_2 emissions is a key to reducing ocean acidification (Kelly and Caldwell, 2013; Bille et al. 2013). Until a legislative solution for the atmospheric CO_2 problems has been found, bottom-up adaptation strategies offer a way forward (Kelly and Caldwell, 2013).

Change is a constant in coastal and marine environments and harvesters and fisheries-dependent communities have a long history of adaptation. The question amongst fisheries is whether climate change warrants a different adaptive response to that already employed for more transitory phenomena. Here we will look at the background of adaptation in fisheries and thus set the stage for considering responses to OA. For the purpose of this report fisheries will be used to refer to both capture and culture activities, while fishers will refer to workers in both sectors.

There are historically *two* divergent viewpoints within fishery adaptation. On the *one* hand fishery managers focus on fishery biology and ecology, and there is a recurring theme in the literature of preserving the viability of fish stocks through resource conservation measures, such a harvest restrictions, stock translocation, pollution reduction, and habitat protection. Managers also consider efficiency measures that take fishers out of the fisheries in-order-to reduce pressure on stocks and to promote transition to alternative sources of income. On the *other* hand fishers think of adaptation interims of changes in technology, operations, and finances that allow them to survive and prosper in the face of environmental upheaval.

So we find within fisheries a range of existing tools for adaptation including policy and governance actions, specific technical support, and community capacity building activities that address multiple sectors. These existing adaptation activities can address short or long term impacts. They can be autonomous and involve changing the timing or locations of fishing as species arrive earlier/later or shift to new areas. They can be planned, driven in part by research funding and or undesirable ecological as in the case with aquaculture. However, with regard to climate changes there is the concern that long-term trends are masked by short-term variations, and these in turn are shaping fishers perceptions of the need for and their own capacity for adaptation.

This report will now consider the range of existing and potential adaptation strategies and actions open to fisheries and aquaculture within a global and Norwegian context. The adaptation options that follow have been grouped under following headings, broadly based on the IPCC recommendations for adaption within fisheries and aquaculture.

1. Modify and strengthen fisheries management policies and institutions
2. Support innovation and research.
3. Integrated management and conservation of fisheries with other coastal zones uses
4. Fisheries adaptation
5. Diversification within coastal communities

Adaptation options

Modify and strengthen fisheries management policies and institutions

Adaptation within fisheries can include a variety of policy and governance actions. To date most planned, top-down, public sector driven adaptation programs within fisheries management have primarily been concerned with resource depletion and have focused on promoting biological resilience, stock rebuilding, and reducing overcapacity in the fishing fleets. Examples of this include:

- Permit or vessel buybacks, subsidy reductions, and other means of reducing overcapacity.
- IFQ—individual quota management schemes.
- Marine reserves and other schemes for improving fish stock resilience and rebuilding.
- National and regional strategies to prevent habitat destruction
- Ecosystem approach to fisheries (EAF) management, which encompasses the marine environment and target commercial fish stocks; adaptive fishery management.
- Programs to promote diversification through tourism and aquaculture development

At a regional level climate change impacts including OA could give-rise-to spatial displacement of both aquatic resources and people. Policies that are flexible and support easier entry and exit into new fisheries and out of those that are declining can ease both socio-economic impacts from changing fisheries and also prevent overfishing of the edges of stocks as they move away. At the national level, policies that discourage economically unviable fisheries can lead to economic diversification and increased economic resilience, but are only possible if there is advanced knowledge of which populations will prove more resilient and economically viable in the future.

Mainstreaming the issue by integrating fisheries and aquaculture sectors fully into climate change adaptation and food security policies at the national level could be a key step forward in increasing knowledge exchange and adaptation capacity.

In their review of management and policy options Bille et al. (2013), identify nine types of management responses, grouped under these four headings: preventing ocean acidification; strengthening ecosystem resilience; adapting human activities; and repairing damages. This potential to buy time, e.g. by relieving the pressure of other stressors, and help marine life face unavoidable acidification is a reoccurring theme in fisheries management, but as the authors highlight, the policy challenges are significant and will involve succeeding in areas of environmental management where many efforts have thus far failed (Bille et. al; 2013).

However, in their USA based study Kelly and Caldwell (2013) propose ten ways states can combat ocean acidification through existing policy mechanisms. These include changing water quality criteria for marine pH, enhanced water treatment and more stringent standards through to direct action to enforce public nuisance and criminal statutes and putting more informed smart growth and smart land use changes into practice. Their study highlighted the potential for existing mechanisms to tackle the range of stressors and control smaller-scale agents of OA directly affecting local fisheries, while research into the socio-economic impacts of OA is ongoing.

Key measures

- Greater support for OA research, monitoring, and forecasting and make use of emerging predictive information related to natural climate variability to support fishery management and planning.
- Greater support to national and international fishery management institutions to manage the expected changes.
- Design and implement national and international fishery management institutions that recognize shifting species ranges, accessibility, and abundances and balance species conservation with local needs for economic efficiency and stability.
- Include ocean acidification in global climate change policy discussions along with increasing temperatures, sea level rise, point and non-point pollution, living resources overexploitation and introduction of alien invasive species.

- Develop mechanisms to maintain marine biodiversity because loss of species impacted by ocean acidification will disrupt the food web.
- Support communication and information sharing on climate change and OA impacts and fisheries adaptation to improve collaboration.
- Develop pilot projects intended to foster resource protection and fisheries adaptation.
- Mainstream the issue by integrating fisheries and aquaculture sectors fully into climate change adaptation and food security policies.
- Incorporate stakeholders by engaging the private sector in ocean acidification actions.
- Develop consensus and commitment mechanisms across public and private sectors to build resilient marine ecosystems.
- Consider how existing policies, not only within fisheries, can be strengthened or extended for the purpose preventing ocean acidification; strengthening ecosystem resilience; adapting human activities; and repairing damages

Support innovation and research

The fundamental issue for OA decision support – and therefore informed adaptation – is the quality and timing of relevant information (AMAP 2013). While research on various aspects of climate change has generated a large number of studies, ocean acidification has only recently been recognised as a serious threat for the environment that will have economic consequences. There has been a growth in studies on the ecological impacts of OA. However, estimates of economic impacts are still sparse, despite their considerable importance for policy decisions and adaptation within fisheries (Brander et al., 2012).

Within the OSPAR Maritime Area, namely the North-East Atlantic, member states including Norway, are investing resources in monitoring the ocean carbon system and in establishing an ocean acidification baseline. Typically, these OA monitoring activities take advantage of other ongoing monitoring or platforms (e.g. hydrographic, fisheries surveys) by adding additional carbonate system measurements. This ensures cost-effective and valuable data collection. Better coordination of efforts would reduce geographical overlaps in the areas sampled. There are two major monitoring programs in place in Norway, focusing on Arctic waters; 1) Climate and Pollution Agency (KLIF) "Monitoring OA in Norwegian waters;" and 2) Ocean Acidification Flagship at the Fram Centre, funded by Ministry of Environment (MD) and Ministry of Fisheries and Coastal Affairs (FKD). The funding for much of the current monitoring activities is often short term (finite-life projects) and few resources are currently committed to securing consistent long-term monitoring.

As previously mentioned, the field of OA adaptation is characterised by a lack of available information. Only a partial set of potential impacted ecosystem services have been assessed – namely mollusks and coral reef recreation – with focus on direct use values that can be more easily addressed (Brander et al., 2012). A simple economic comparison with losses from harmful algal blooms (HABs) has been attempted in the US, under the basic assumption that damage to lower trophic levels and cascading economic consequences resemble those that could occur due to ocean acidification (Hoagland et al., 2002). Other ecosystem services with direct use values (e.g. fin fish) have not yet been considered. Likewise, other value categories including indirect use values (e.g. regulating services) and non-use values (e.g. existence and bequest values for marine biodiversity) have not been addressed (Brander et al., 2012).

Because fisheries represent a primary industry change in catch, potential may also indirectly affect other dependent sectors, from boat building to international transport. Thus, it is crucial to take indirect economic activities into account when assessing the full economic impact of ocean acidification on fisheries and the need and potential for adaptation. It should be noted, however, that this type of analysis is yet to be done. Although there is still no detailed study on the economic impact of ocean acidification on global fisheries one approach to estimating the impacts is through ‘Economic Valuation’ based on changes in ex-vessel prices, fishing costs and projected catch under different ocean acidification scenarios (Hilmi et al., 2013).

Ocean acidification is a highly interdisciplinary and growing field. Addressing challenges in marine social-ecological systems requires an in depth understanding of both ecological and social processes, as well as how they interact. It requires an understanding of the dynamics of marine social-ecological dynamics at multiple scales and in diverse setting and thus needs to attract a new breed of interdisciplinary graduate students, postdoctoral investigators, and principal investigators (NOAA, 2010, p 25 -26). Within the USA, NOAA advocates new training opportunities be establish to help scientists transition to this new field, and thus engage researchers in fields related to management and decision support. Consideration should also be given to ways recruitment into OA research is and will be conducted in the future in Norway in-order-to accelerate progress in OA research and how these then feeds back into the fisheries sector to support adaptation.

In a policy briefing note on the impacts of OA by the European Science Foundation (ESF), a breakdown of dissemination, outreach and capacity building actions was included. The ESF highlighted the need for more effective communication between researchers, funding bodies and the wider scientific community (2009). While research funding organisations may already be aware of ocean acidification and are funding research in this area, they are not necessarily aware of the full spectrum of European activities or gaps in the research (ESF, 2009). The ESF report also advocated stronger links with the international research community to stimulate research, share resources, and avoid needless redundancy. As well as improving communication within the scientific community measures are also needed to foster communication between researchers and stakeholders. Local knowledge and perspectives are increasingly considered essential inputs to studies of human-environment interactions (West & Hovelsrud 2009, e.g., Berkes et al., 2002). The complexity and uncertainty characterising coupled social and ecological change supports the argument for pursuing interdisciplinary research that incorporates both scientific and lay expertise (Tyler et al., 2007; Smit et al., 2008).

There are a number of programmes that are looking at means to integrate scientific and local knowledge with in fisheries management in Norway. Two such projects are EcoFishMan and GAP II. Both are ongoing EU–projects in which Norway is participating and which look, in part, to challenge established knowledge regimes by developing new models for integration of different knowledge sources and the utilisation of expert advice in new ways. Though not directly concerned with OA, they do highlight means and methods for transforming stakeholder engagement within fisheries, and promote cooperation between scientists and fishers to manage sustainable fisheries. This has included fishers self-sampling fisheries across the Baltic, North Sea and Mediterranean and contributing data directly to local research. In the case of Norway, the focus has been on the management of cod-fisheries and how to put greater emphasis on fishers’ knowledge, as opposed to scientific knowledge, during the participatory process (Gap II, 2014)

Key measures

- Additional data from the marine and life sciences is needed or economists and social scientists to achieve comprehensive assessments of the societal impacts of OA.
- There is a need to establish coastal monitoring networks for standardised measurement of ocean acidification with coherent monitoring and data exchange to reduce overlaps, duplications and facilitate efficient use of resources.
- Promote interdisciplinary approaches to foster build better linkages between socio-economists and life scientists to enable future understanding of the impacts of ocean acidification on society.
- These research results, syntheses, and assessments need to provide content in a format of value to managers, policy makers, and the general public.
- Impacts of ocean acidification should be included in any future national or regional climate change assessments.
- The certainty associated with ocean acidification, due to the simplicity of the chemical reaction of CO_2 and water, provides a powerful supplementary reason adding to the certainty of climate change

Integrated management and conservation of fisheries with other coastal zones uses

Coastal zones are vulnerable because their biodiversity and range of ecosystem services make them popular settlement areas, tourist destinations, important business zones and transit points. Identifying specific management measures to stem the impacts of OA is made all the more challenging because it is occurring in combination with other indirect drivers such as terrestrial nutrient runoff, changes in freshwater input and upwelling (Kelly and Caldwell, 2013). On top of this there are also additional anthropogenic stressors such as pollution, overfishing, habitat destruction, marine traffic congestion, which combine to produce patchwork affect along coastlines.

Ultimately there are a multitude of overlapping and often conflicting forms of resource utilisation along any given coastline. Sectoral approaches can lead to disconnected decisions that undermine each other, and result in inefficient use of resources and missed opportunities for more sustainable coastal development. Integrated Coastal Zone Management (ICZM) is widely seen as the right way to provide cross-sectoral and integrated planning and management of the coastal zone. It is touted as the best means for realising and implementing an ecosystem approach to fishery and aquaculture (Kreuger, 2012), and if employed effectively would facilitate climate and OA driven adaptation measures.

A national ICZM policy does not exist in Norway (Kreuger, 2012). Instead it employs decentralised spatial planning, enabling local communities and counties to extend their planning into marine waters through the planning and building act (PBA). PBA has a high focus of participation from inhabitants, NGO's, governmental offices and agencies and administrative levels for implementation: municipal, county and central government (Kreuger, 2012). Still, the national government can overrule local authorities, either in the capacity of handling complains on local land-use plans (e.g. from nature conservation interests) or in the case of making land-use plans when national interests are at stake (e.g. when implementing major infrastructure constructions such as state harbours and state road bridges).

Though ICZM as such has no legal basis in Norway it is feasible for an integrated planning approach be employed but is dependent upon the commitment and motivations of the municipalities (Kreuger, 2012). Within Norwegian waters Marine Spatial Planning (MSPs) is implemented along the coast rather than ICZM. While fisheries have large stakes in Norway, relative to other users such as the oil or shipping industry, they are a small player within Marine Spatial Planning. This could have direct implications for the adaptive capacity of fisheries as spatial ordering and zoning do not necessarily offer the flexibility needed for fishers to remain mobile in light of shifting resources.

A significant tool used within ICZM is Marine Protected Areas (MPAs) - also referred to as closed areas, marine reserves, no-take areas or marine sanctuaries. Closed areas in fisheries are not new, having been part of traditional management measures in artisanal fisheries around the world. MPAs are a more recent concept that contributes to both conservation and fisheries management by way of an ecosystems approach. MPA's have been shown to increase resilience of marine habitats and support fish and shellfish populations for sustainable marine harvests. As such, their expansion could increase fisheries resilience to the impacts of OA. While being a useful tool for helping to achieve multiple objectives from different sectors, they are not an end in themselves and need to be designed carefully in order to be successful (Flaaten and Mjølhus, 2010).

In the Honolulu Declaration on Ocean Acidification and Reef Management (McLeod et al., 2008, p 7 - 10) the following policy and management recommendations were identified incorporating the best of ICZM and MPAs. While the report itself does focus on reefs, the measures proposed do have implications and wider applications for fisheries management along the Norwegian coastline.

- Incorporate reefs of low vulnerability or susceptibility to ocean acidification into MPA zoning plans during development or routine review.
- Incorporate into MPA management plans specific adaptation strategies and actions to address climate-change threats (ocean acidification and warming and sea-level rise), including monitoring of their effectiveness.
- Regularly review coral reef management plans to incorporate the latest research and scientific findings into a proactive and adaptive approach to address ocean acidification impacts.
- Develop, test, and, where appropriate, apply interventions to reduce the effects of ocean acidification on high-priority areas and species, for example by reducing impacts from local disturbances.
- Develop, test, and implement innovative interventions to reduce damage to reefs weakened by ocean acidification, and to promote the replenishment of reef communities impoverished by loss of coral species to the combined impacts of climate change, including elevated seawater temperatures and sea-level rise.
- Integrate coral reef management with land-use and coastal zone planning and practices to reduce pollutant inputs (notably, ammonium compounds, nitrogen and sulphur oxides) that increase the acidity of local waters.

Key measures

- Combinations of stressors on marine systems tend to harm the ecosystem to a greater extent than the sum of the individual stressors would (Crain et al., 2008), reducing individual stressors — such as non-point source runoff — through effective use of ICZM and MPAs, increases the ability of the system to withstand OA, thus contributing to the overall resilience of coastal ecosystems (Kelly and Caldwell, 2013).
- Key to the success of ICZM is effective and purposeful stakeholder engagement. For greater understanding of the "human dimensions" of OA it is important to identify which user groups will be affected, and consider this an iterative process in itself.

- In the case of Western Norway, municipalities and local administrative departments play a key coordinating role in managing the coastal areas. Guidance on climate change and OA impacts and how to adapt to them needs to be explored.
- Through integrated management approach cooperation with forestry, water, and other resource managers could be facilitated. The adequacy of management practices in all sectors affecting fisheries (e.g., water resources, coastal management) needs to be examined to ensure that proper responses are made as the climate and pH levels of coastal waters change.
- With regards increasing resilience and managing integrated approaches, case study examples in Western Norway and other high latitude fisheries, should be explored to illustrate strengths and weakness of the current coastal planning and management systems.

Fisheries adaptation

According to the World review of Fisheries and Aquaculture (2008) employment in fisheries and aquaculture has grown substantially in the last three decades, with an average rate of increase of 3.6 percent per year since 1980. It is estimated that, for each person employed in capture fisheries and aquaculture production, about three jobs are produced in secondary activities, including post-harvest the primary and secondary sectors support the livelihoods of a total of about 540 million people, or 8.0 percent of the world population.

In Norway the farming of salmon and rainbow trout is taking place in close to 160 municipalities along the Norwegian coast with approximately 5,900 people are directly employed in aquaculture production. In addition, jobs are created in transportation, the supply industry, as well as in commerce. Including spin-off effects, an estimated 21,000 people are employed in aquaculture related activities in the country. Employment in fishing is decreasing in capital-intensive economies, in particular in most European countries, North America and Japan. This is the result of several factors, including decreased catches, programmes to reduce fishing capacity and increased productivity through technical progress (O'Brien, 2010).

Norway’s fisheries are characterised by their ready access to information, capital, technology, and managerial expertise. Sophisticated fishery management systems are tasked to manage for biological sustainability and government programs support the industry through technology transfer, financing, and other forms of assistance. Norway’s first generation of fisheries management looked to restrict access, set catch limits and impose technical restrictions on when, where and how fisheries could take place. The second generation takes a precautionary approach that considers the interaction between fisheries and climate, and the integration of different types of knowledge and concerns. From a management perspective Norway has significant capacity to develop and secure adaptation to climate and OA driven changes within fisheries.

However, Norway has subordinated longer-term sustainability to the interests of coastal communities as in the case of the coastal cod fishery (O'Brien, 2010) and does face a range of problems within its fisheries that can impede adaptation. This includes an ageing fishing population, reduced transfer of knowledge and skills, out migration, increased distance to markets, low recruitment and high entry costs. Current exports to distant markets determine acceptable species, product form, quality, timing, and other factors, reducing flexibility to substitute alternative species. For some fishers being located on the limits of abundance for some key species can constrain product substitution. High equipment and operating costs also limit fishermen's ability to experiment with new resources and methodologies. Fishers typically considered themselves be highly adapted to natural climatic and environmental variability and often consider the greatest barrier to adaptation stemming from management and policy mechanisms. There are many examples of this, such as income tax and quota systems restricting multiple incomes and thus reducing flexibility and the capacity to diversify. This is explicit; however, individual perceptions of high resilience can also prove a barrier to adaptation, if fishers do not perceive their own vulnerabilities.

For capture fisheries the adaptations open to them are mainly reactive, bottom-up adaptation measures and include:

- Purchasing larger, more sophisticated vessels with multi-fisheries capabilities to travel farther, migrate to different locations that offer better fishing opportunities, diversify fishing activities, and exploit a wider range of species and stocks.
- Maintaining multiple licenses or permits to allow shifting from one target species to another.
- Development of flexible fish product processing capacity for utilizing emergent resources.
- Diversifying incomes into non-fishing activities, which may include aquaculture and tourism.
- Spreading risk through insurance, cooperatives, and alternative forms of financing.
- Improving operational efficiencies, such as fuel efficiency and improved product handling, storage, and preservation.

For culture fisheries a greater range of adaptations, sustainable development and diversification options are open. The report "Forsuring av havet. Kunnskapsstatus for norske farvann" (Børsheim and Golmen, 2010) discusses possible consequences of ocean acidification for the seafood sector, and touches briefly on adaptive measures. Declining access to fish fodder, if the pelagic fish that is currently used for fish fodder should be negatively affected by ocean acidification, is a possible future scenario. An adaptive measure proposed is to replace today's fodder with fodder from agricultural sources, most likely imported from other countries with a longer growing season (Børsheim and Golmen, 2010, p.77).

Relocation of industries elsewhere is an adaptive measure mentioned by the IPCC in Chapter 5 (IPCC 2014a, p.48). This may be a useful measure given that pH levels are expected to vary across geographical locations, so that finding areas with a suitable pH range is at all possible. If more drastic relocation of aquaculture plants is required, e.g. from one region to another in the context of the Western Norwegian seafood sector, moving further north (where ocean temperatures are generally expected to be lower, in contrast to areas further south, which may experience problematic ocean temperatures in the future) is the most logical scenario. However, the future frequency and magnitude of extreme weather incidents further north may constrain the range of options for relocation. Also, fish farms are dependent on a certain proximity to the homes of employees (Aaheim et al., 2009, p. 27- 28).

The adaptive strategy of avoiding acidified water, has been applied at a commercial shellfish hatchery in Netarts Bay on the northern Oregon coast (Barton et al. 2012). The area is subject to large fluctuations in carbonate chemistry driven mainly by natural mechanisms. Hatchery operators have implemented a strategy to avoid early morning tank-filling operations during strong upwelling conditions and as a result have restored a significant amount of lost production (Barton et al., 2012,). This adaptive strategy could be of use to the seafood sector in Western Norway. However, most fish farms in Norway are sea-based, not land-based. Such adaptation measures would therefore involve drastic changes from the way things are currently working.

The strategy of selecting and cultivating pre-adapted strains is presented in Parker et al. (2012), referring to experiments conducted on oysters in Australia. In Chapter 7, a similar approach - "Shifting to more tolerant strains of molluscs to cope with increased acidification" - is mentioned (Huppert et al., 2009 in IPCC 2014c, p. 32). Whether or not the same strategy might be applicable to fish and other parts of the seafood sector, is not mentioned. Nevertheless, this adaptive strategy may be of relevance to some parts of the seafood sector.

Adaptation to other consequences of climate change, such as higher sea temperature and a higher frequency or magnitude of storms, may also be applicable to ocean acidification. The Norwegian Official Report on adaptation to climate change (Aaheim et al., 2009), refers to a study of climate change adaptation in the coastal community Flora in Western Norway. Some of the measures proposed in the study include higher sea temperature include relocation to sites closer to the ocean, a shift from sea-based to land-based fish farms, or relocation to the ocean. Furthermore, closed tanks in the sea are mentioned, as well as substituting cod and salmon with other species that are able to handle higher sea temperature better (Aaheim et al., 2009, p. 27). These measures could also be relevant to tackle ocean acidification, if low pH levels should become a threat to the sector.

There is one more potential avenue for adaptation with aquaculture fisheries, namely Integrated MultiTrophic Aquaculture (IMTA) systems. IMTA is a different way of thinking about aquatic food production that is based on the concept of recycling. Instead of growing only one species (monoculture) and focusing primarily on the needs of that species, IMTA mimics a natural ecosystem by combining the farming of multiple, complementary species from different levels of the food chain.

Key measures

- Case studies need to be undertaken on the economic and social impact of ocean acidification on local fisheries including cultured species and species important for marine leisure activities in Western Norway.
- Fishers Cooperation and collaboration with such studies are a step in the right direction for stakeholders to assess how ocean acidification may alter local economies and determine where problems or opportunities will arise and increase their communities adaptive capacity.
- As well as collaborating with researchers and policy makers, greater collaboration within fisheries could address how climate change may affect daily operations and long-term viability.
- Implement best practices and adaptive management of fisheries and aquaculture to increase ecological resilience of marine ecosystems.
- Increase the adaptive capacity of fishing communities through education about ocean acidification, and by training and support to diversify livelihoods where needed.
- Improve multi-stakeholder exchange of information and com- munication among parties (coastal communities, businesses, researchers, resource managers, inter- national organizations and policy makers)
- Consideration should be given to ways to spread risk, for example, through insurance and cooperative operation arrangements.
- Promote fisheries conservation and environmental education among fishers
- Access to higher-value markets can increase uptake of adaptive fishing efforts though there is an associated risk of overexploitation.

- Shift to culture-based fisheries – though may be limited by other climate driven impacts including diminishing water quality and access, coastal erosion and increased vulnerability to storm damage.
- Shift aquaculture to non-carnivorous commodities
- Selective breeding for increased resilience
- Moving/planning siting of cage aquaculture facilities
- Change aquaculture feed management: fishmeal and fish oil replacement;
- Improve water-use efficiency and sharing efficacy
- Shift to propagated seed for previously wild-caught seed stocks.
- Closing off seawater intake systems and recirculating hatchery water when available seawater suffers periods of low pH

Diversification within coastal communities

Diversifying livelihoods, markets and products will enable marine harvest coastal communities to become better able to deal with a range of uncertainties that include climate change and OA. This diversification could include the development of IMTA or algae cultivation for biofuels or non-fishery economic activity such as ecotourism.

Realising the potential for diversification in part stems from an understanding of not only the material but also non–material benefits of ecosystem services such as leisure and recreation, cultural heritage, education, training and research. Cultural ecosystem services also contribute to the non–material benefits that people obtain from the environment such as aesthetic information, spiritual experience, and inspiration for culture and art. The degradation of the marine environment due to acidification may result in losses in these specialised ecosystem services or may require increased cost and effort to avoid their loss. For example, the bioremediation of waste, occurs through diverse processes, and may be reduced if OA negatively affects marine bacteria, resulting in reduced water quality and the desirability of a destination for tourism purposes.

The AMAP review of OA impacts in Arctic communities, suggests that tourist and local recreational fishers in the AMAP area appear adaptive when it comes to fishing and target those species available in their areas. While OA will affect some species more than others and may in the future alter the relative composition of recreational catches by tourists and local residents, but it is not likely that people’s overall pleasure and welfare will be affected by such a change (AMAP, 2013). However, this does not consider the full range of effects OA may have on the Norwegian coastline

The prevalence of harmful algal blooms in a more acidic ocean in the future may lead to restrictions on recreational activities due to a reduction in water quality; this may alter the health benefits obtained from marine recreation. In addition, ocean acidification may impact charismatic species an their recreational value (e.g. through ecotourism and wildlife watching activities).

More substantive studies are needed for Western Norway to realise the diversification options and potential barriers to building more diversified local economies. It has been shown though that people are motivated to act based on their emotional connection with place, and that place attachment may offer a better starting point for climate change adaptation than an emphasis on climate change impacts.

Conclusions

There is no easy solution to that of adapting to ocean acidification. However, the rapid timescales, economic and social impacts and potential irreversibility could stimulate more dynamic climate talks in the future (Bille´ et al. 2013).

There are a number of factors that may impede planned adaptation responses to OA. In part these stem from the fact OA impacts are still poorly defined and quantified and they are largely ‘invisible’, underwater, and difficult to isolate from other stressors. Also OA will impact societies and ecosystems unevenly, within different time scales and as a result, the motivation to take action will be uneven as well (Bille´ et al. 2013).

Ultimately for both capture and culture fisheries a “no regrets” approach that relies on building general resilience without a heavy reliance on specific climate impact projections, is recommended. These include strategies emphasising operational flexibility, diversification of products, and new forms of income generation. As a result long established norms of vessels, gear, target species, products, seasonal commitment, and other familiar patterns of the fishing industry lifestyle may have to give way: “business as usual” may be replaced with “whatever it takes.” Ideally though “whatever” should be planned and sustainable.

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