ECONOMIC EFFECTS OF OCEAN ACIDIFICATION: PUBLICATION PATTERNS AND DIRECTIONS FOR FUTURE RESEARCH

Abstract

Human societies derive economic benefit from marine systems, yet these benefits may be modified as humans drive environmental change. Here, we conducted the first systematic review of literature on the potential economic effects of ocean acidification. We identified that while there is a growing literature discussing this topic, assessments of the direction and magnitude of anticipated economic change remain limited. The few assessments which have been conducted indicate largely negative economic effects of ocean acidification. Insights are, however, limited as the scope of the studies remains restricted. We propose understanding of this topic will benefit from using standard approaches (e.g. timescales, emissions scenarios) to consider an increasing range of species/habitats and ecosystem services over a range of spatial scales. The resulting understanding could inform decisions such that we maintain, or enhance, economic services obtained from future marine environments.

Keywords: carbon dioxide, climate change, socio-economic

1. Introduction

The relationship between human societies and natural systems is complex. Humans depend on ecosystems for important and valuable services (Costanza et al. 1997, Heal 2000), yet exploitation can directly and indirectly alter the systems which provide them (Liu et al. 2007, Costanza et al. 2014). For example, extraction and burning of fossil fuels by humans is resulting in the emission of carbon dioxide to the atmosphere at a rate unprecedented in the past 66 million years (Zeebe et al. 2016). Marine waters took up an estimated 26% of carbon dioxide emitted in the decade from 2005-2014 driving their acidification, reducing pH, and altering carbonate chemistry (Caldeira & Wickett 2003, Feely et al. 2004, Le Quéré et al. 2015). While the rate of oceanic carbon dioxide uptake may be modified into the future, this process of acidification is virtually certain to be ongoing (IPCC 2014). Such changes to the chemical environment can then affect the biota and habitats that exist within oceanic waters, potentially feeding back to modify the provision of ecosystem services to human societies and impacting human welfare (Doney et al. 2009, Armstrong et al. 2012, Brander et al. 2014).

Marine taxa, and the habitats they form, are anticipated to respond to forecasted ocean acidification. There is a growing body of scientific literature regarding the potential biological and ecological effects of ocean acidification in which experimental manipulations have been used to assess anticipated future changes (see, for example, Dupont et al. 2008, Falkenberg et al. 2013b, Fitzer et al. 2014). A range of organisms have been considered, and while focus was initially largely placed on those with calcified structures (e.g. corals, molluscs, echinoderms) and fish (Przeslawski et al. 2008), attention has broadened to include fleshy algae and diatoms (e.g. Shi et al. 2010, Hepburn et al. 2011, Falkenberg et al. 2013a). Syntheses of experimental results have typically revealed that diverse marine taxa will be affected differentially by ocean acidification with calcifying organisms anticipated to exhibit larger negative responses than non-calcifying organisms which, in contrast, may be negligibly affected or even benefit (Kroeker et al. 2010, Harvey et al. 2013, Kroeker et al. 2013, Nagelkerken & Connell 2015).

Human societies are dependent on a range of ecosystem services, and alteration to their availability may have impacts for welfare and societal structure (e.g. Liu et al. 2007, Cooley & Doney 2009). These human welfare impacts can occur via a pathway whereby chemical changes in marine ecosystems, such as those outlined earlier, modify the occurrence of biota and provision of ecosystem services (Armstrong et al. 2012, Brander et al. 2014). Potential social consequences of forecasted ocean acidification have been foreshadowed by an example from the US west coast where, in 2006, upwelling of carbon dioxide-enriched waters drove production failures in oysters and affected the associated industry. Adaptive procedures are now in place to avoid negative effects of such cyclical upwelling events (as summarised in Branch et al. 2013). This event has, subsequently, been referred to as a ‘canary in a coal mine’ for the potential economic effects of ocean acidification and societal response (Mabardy et al. 2015). In the context of future, longer-term ocean acidification, developing forecasts regarding the potential effects will enable more informed decision making when it comes to pre-emptive actions which could include local mitigation (e.g. reducing local biogeochemical impacts) or adaptation (e.g. moving to alternative ways to obtain currently important ecosystem services, removing other environmental pressures, maintaining key species interactions, or altering use patterns of certain resources) (Brander et al. 2014, Falkenberg et al. 2014, Lam et al. 2014, Punt et al. 2014, Ekstrom et al. 2015). Selection of the specific approach used will be dependent upon what is contextually and regionally appropriate (Ekstrom et al. 2015).

An emerging literature reflects a growing awareness of the potential economic effects of ocean acidification and the need for human response. This diverse literature has, however, not yet been comprehensively synthesised, which we address here by conducting a systematic quantitative review. Specifically, we were interested in identifying key features of the: 1) approaches used – whether the economic effects of ocean acidification have been implied, discussed, or assessed, 2) publication patterns – when and where papers have been published, 3) distribution of studies – which locations, taxa/habitats and ecosystem services have been considered, and, 4) details of assessments conducted – spatial and temporal scales, emission scenarios, methods used and identified economic effects. In addition to reporting on existing literature, we also use this review to identify key gaps in research conducted to date and suggest future directions to inform management strategies and policy development. The summary provided by this review could, therefore, be used to both improve understanding regarding research that has been done to this point, as well as guiding future efforts in this field.

2. Methods

A systematic quantitative literature review was performed using an established framework (as outlined in Pickering & Byrne 2014). Scholarly electronic databases were searched to identify papers published in English language journals related to the economic impacts of ocean acidification. Given we only included papers published in English, we consider this review broadly illustrative but by no means complete. The databases searched included Scopus, Science Direct, Web of Knowledge/Science, EconLit and Google Scholar. Databases were searched between October and December 2015. Keywords used for the search included: ("ocean acidification" OR "marine acidification" OR "seawater acidification") AND (econom* OR valu*). No constraints on the year of publication were imposed. Additional papers were identified from the reference list of those research papers found through the database search. In our search we considered original research and review papers, but not conference proceedings or other, non-peer reviewed reports. Papers identified as potentially relevant were then screened to determine their eligibility.

From each paper that addressed the potential economic impacts of ocean acidification (in isolation from climate change), key items of information were recorded in a database. Items related to the paper details were: 1) author(s), 2) paper title, 3) publication details (year, volume, page numbers, digital object identifier [DOI]), 4) journal name, and 5) journal discipline/branch. In terms of article content we recorded 6) the approach used, that is, if the link each study made between economic effect and ocean acidification was implied (those papers which considered both ocean acidification and economics, but did not clearly state how one may influence the other), discussed (those which discussed the potential link between ocean acidification and its economic effects), or assessed (those which explicitly conducted analysis regarding the potential identified direction and a monetary value of the forecasted economic effect of ocean acidification). For all articles, we also recorded the 7) geographical location of study (we recorded all countries considered within each paper which were then grouped by continent, we also noted those papers which were not specific to any particular country or countries), 8) species or habitat of study (where multiple species/habitats were considered in a single paper all were included in the database, species were then classified into the broader taxonomic groups reported, we also recorded if papers were not specific to a particular species or habitat), 9) ecosystem services considered (each time a good/service included in the CICES, Common International Classification of Ecosystem Services V4.3 [CICES, 2016] framework was mentioned in terms of potential response to ocean acidification it was recorded in the database). Finally, for papers which assessed potential economic effect(s) we also recorded: 10) timescale, 11) emission scenario, 12) spatial scale (i.e. global, regional, national, sub-national, local) 13) how the biological effects were estimated (response variable considered and source from which response to ocean acidification was extrapolated), 14) response variable in which forecasted economic effects were reported, and, 15) forecasted direction of economic impact (as concluded by the author(s)).

3. Results

3.1 Approach used

A total of 105 papers on the economic effects of ocean acidification were identified in English language journals by the end of 2015 (full list in Table S1). Of the papers included in this review, the majority (*n* = 64) implied there was a link between ocean acidification and the economy but did not provide direct discussion or assessment of this relationship. There were a number of studies which did discuss the potential economic effects of ocean acidification (*n* = 33). Relatively few studies directly assessed the link between ocean acidification in isolation from other environmental change and quantified an anticipated effect in monetary terms (*n* = 8).

3.2 Publication patterns

The earliest research paper included in our review was published in 2007 (Gazeau et al. 2007), with the first assessment conducted in 2009 (Cooley and Doney, 2009). Since then, literature regarding the economic effects of ocean acidification has increased, with the majority of papers discussing this topic published in 2014 and 2015 (in both years there were *n* = 19 papers), yet there were still relatively few papers in which the link was explicitly assessed (in 2014 $n = 3$ and in 2015 $n = 2$ papers).

Reflecting the multi-faceted nature of this issue, papers were included in journals covering a range of disciplines (and branches), including earth and environmental sciences (e.g. aquatic environment, earth science, global change, oceanography), life sciences (e.g. biology, ecology, fisheries, toxicology, zoology) and social sciences (e.g. economics, management/policy) (Table 1).

3.3 Distribution of papers – geography, taxa and habitats, ecosystem services

The country mentioned most often in this literature was the United States of America ($n = 30$ papers, including $n = 5$ assessments). The country with the next greatest number of papers was Australia ($n = 9$, including $n = 5$ assessments). There was also a body of literature focussing on both Europe ($n = 19$ countries) and Asia ($n = 9$ countries) (Table 2). There were few papers regarding the effects in Africa, and none on South American countries (Table 2).

The papers identified here typically considered either the response of individual species or the habitats they combine to form. In terms of studies considering and assessing the responses of individual species, the most represented taxonomic group was molluscs. There were fewer studies on fish, echinoderms and crustaceans, which were all similarly represented. Papers on all other taxa were limited, with those that were at least somewhat represented, albeit not the focus of assessments, including calcifying algae, fleshy algae, corals, coccolithophores, polychaetes, and birds (Figure 1; Table 3). In terms of the habitats considered, the majority of the papers addressed coral reefs (assessed in *n* = 1 study), with fewer studies considering macroalgal forests, seagrass meadows (assessed in *n* = 1 study), and biofouling assemblages (Figure 1; Table 3).

The economic significance of the marine taxa and habitat considered was most often linked to the ecosystem services associated with provisioning, with this section mentioned and assessed more often than the regulating and maintenance, and cultural sections combined (Table 4). This dominance of provisioning was driven by a focus on nutrition, both from wild sources and aquaculture (*n* = 86 mentions, *n* = 8 direct assessments). Other products mentioned included fibres, bioactive compounds, jewellery, buttons, and building materials. Mentioned far more infrequently were less tangible ecosystem services such as genetic resources (Table 4). Services provided in regulation and maintenance were also recognised, particularly in terms of the role habitats such as seagrasses play in stabilising sediments, enhancing coastal stability and climate regulation (Table 3). Cultural contributions of marine systems were also recognised, particularly in terms of physical and experiential interaction values, such as diving and fishing (Table 3).

3.4 Methods used in assessments

3.4.1 Timescale

Several assessments were conducted for discrete time points in the future, including the years 2050, 2060 and 2100. The reminder of assessments included continual forecasts through to 2100 (Table 3).

3.4.2 Emission scenarios

Most assessments based forecasted ocean chemistry values on scenarios detailed in the IPCC reports. These include IS92, SRES and RCP. Some assessments did, however, use values reported in other studies which were not identified as based on any of these standard scenarios (Table 3).

3.4.3 Spatial scale

Assessments considered global, regional, national, sub-national and local scales of effects (Table 3). Half of the assessments considered a single spatial scale, with the others considering two or more (Table 3).

3.4.4 Biological impact

In most studies the biological change incorporated in economic forecasts was the response of a single organism feature, or ecological parameter. Some studies did, however, consider more than one parameter (Table 3). In all assessments, the magnitude of effect of forecasted ocean acidification on the parameter of interest was extrapolated from experimental studies, or meta-analyses (Table 3).

3.4.5 Forecasted economic effect

For those studies which assessed the potential economic effects of ocean acidification, an array of response variables were used to express the potential economic effects of ocean acidification, including net present value, revenue flow and consumer welfare values (Table 3). The forecasted direction of change was most often negative with the direction of effect consistent across studies that assessed the same (or similar) taxa/habitats and ecosystem services. That is, negative responses to ocean acidification were found where the services of fisheries, recreation, tourism and coastal protection provided by molluscs, crustaceans, fish or coral reefs were considered. In contrast, a potentially positive effect of ocean acidification was found in the single study that assessed carbon sequestration by seagrass meadows (Table 3).

4. Discussion

There is increasing recognition forecasted ocean acidification has the capacity to affect environmental systems from which human societies derive the socio-economic resources that contribute to our welfare. Here, we report findings from the first systematic review of literature considering the potential economic effects of ocean acidification. We identify that while this is a growing field of research, relatively few assessments have been conducted to date, with those that have been done highly focused in scope. This review therefore highlights the current state of knowledge, key gaps in understanding, and promising methods and approaches that may be used in future research.

Anticipating the potential economic effects of acidification is a relatively new field of research which our systematic review reveals is expanding yet remains relatively superficial with few detailed assessments reported. This topic was first recognized in published academic literature in 2007. By the end of 2015, the body of work had come to include 105 papers. In most of these papers, the link between ocean acidification and economic effects was implied or discussed. The first assessment was published in 2009, with a total of 8 assessments published by the end of 2015. The relatively small number of assessments likely reflects the significant challenges associated with undertaking this type of research.

A key challenge when assessing the economic effects of ocean acidification is the involvement of numerous disciplines. The complex nature of this issue is reflected in the publication pattern of studies reviewed here; relevant papers were published in 60 different journals spanning earth and environmental sciences, life sciences and social sciences. It is the connection between disciplines, specifically biology (physiological effects) and economics, that is suggested to be the weakest component of assessments (Moore 2015). To date, assessments have typically bridged this gap by simplifying the forecasts of biotic responses to change in key physiological parameters shown in few experimental studies, or meta-analyses (Table 3). In addition, the economic analyses are simplified and partial, not taking into account issues like the potential for one species to be used in the place of another (Armstrong et al. 2012). While a good first step, it has been proposed future assessments need to incorporate additional complexity in biological and economic features (e.g. that associated with variability, heterogeneity, non-linearity, threshold effects and irreversibility) (Armstrong et al. 2012, Brander et al. 2014). These more complex representations will require either that a single academic has a good understanding of the various disciplines involved, or there are effective collaborations in teams with expertise from mixed disciplines (Wam 2010). Establishing and maintaining these collaborations requires significant investments of time to ensure interpersonal relationships are built and effective communication patterns established such that the different perspectives, cultures and methodologies are effectively synthesized (Campbell 2005, Marzano et al. 2006, Roy et al. 2013).

Where links have been made between disciplines, assessments of the potential economic effects of ocean acidification indicate significant change may manifest in the future, yet more detailed conclusions are difficult to draw. In most studies, the forecasted effect of ocean acidification is negative, with only one assessment in our review identifying positive economic effects of ocean acidification (Table 3). These negative effects are likely observed as most studies focus on calcifying taxa and the habitats they form (e.g. molluscs, crabs, other invertebrates, corals) which are anticipated to respond negatively to ocean acidification rather than non-calcifying organisms that may respond positively (e.g. seagrasses, algae). Future studies should, therefore, ensure assessments consider a broader range of species for which biological understanding already exists. While we can easily compare the direction of anticipated economic effects of acidification scenarios, more detailed analysis to determine which group is the most sensitive is complicated by differences in the methods used, most notably temporal scales and emission scenarios. Standardizing these aspects will enable future assessments to be comparable to the greatest number already conducted. Assessments attempting to align with published studies should consider the time point of 2100 and established emission scenarios (such as those included in the IPCC reports, as proposed in Riebesell et al. 2010).

Marine species and habitats provide a range of ecosystem services to human societies and while our review identified that many of these services may be impacted by ocean acidification, to date few direct assessments exist. The majority of assessments have considered the ecosystem services of wild animals and their outputs provided by molluscs, crustaceans, fish or coral reefs (Table 3). These species, habitats and services do, however, reflect only a proportion of those included in marine systems whose responses to ocean acidification have been considered, and are typically those for which a market value is easily obtained (Armstrong et al. 2012, Brander et al. 2014, Chen et al. 2015). This focus should be broadened in the future. In studies considering economic effects of climate change more broadly similar issues of narrow focus have been recognized and attempts made to account for them. For example, in an assessment of coral reef change, while the focus was primarily on experiential and physical use (tourism effects), it was noted that this was only a component of the value of this habitat and a crude calculation of the remaining effects added to try and reflect the change more holistically (Chen et al. 2015). A similar approach could be used in future assessments of possible ocean acidification effects.

Ocean acidification may have economic effects at a range of geographical scales, which is reflected in the assessments conducted that have considered global, national, sub-national and local scales. Together, assessments conducted at these different scales contribute to a more holistic understanding. Global-scale assessment allows identification of large changes and can inform general predictions, while the smaller scale assessments provide more specific information that can be then used to inform management strategies developed at this scale (e.g. updating fisheries management plans to include ocean acidification; Cooley & Doney 2009). We propose, therefore, that both global and smaller-scale assessments continue to be conducted within individual studies (as has been done by Cooley & Doney 2009, Narita et al. 2012, Garrard & Beaumont 2014, Lam et al. 2014). Where relevant, future studies could even conduct increasingly fine-scale analyses at the level of, for example, county, human community, port or household (Ekstrom et al. 2015).

While the economic effects of ocean acidification will be a globally-experienced issue, the literature is not yet global in scope. Papers published that recognize this issue are relatively strongly focused on a specific country, the United States of America. A dominance of publications from the United States of America has, however, also been identified in other similar systematic reviews, even though they considered contrasting topics (i.e. community gardens Guitart et al. 2012, urban trees Roy et al. 2012, trail infrastructure Ballantyne & Pickering 2015). Limited geographical distribution of studies has been attributed to general factors including: 1) the database search was limited to English language journals, 2) there may be greater interest in studying the topic in the United States of America than elsewhere, 3) there are comparatively more researchers in the United States of America working on these issues than elsewhere. As suggested in previous reviews, the first and third explanations appear to be the most parsimonious, particularly given the broad range of topics covered in the general academic literature for which such a pattern has been observed. Given this bias, an obvious focus for future research is to increase the geographical scope to include areas where little or no information regarding the potential economic effects of ocean acidification currently exists, particularly where their economic significance is increasing (e.g. southern Chile, Vila et al. 2015). It will be necessary for future research to consider poorly-represented areas given spatial variation may manifest in terms of chemistry (Blackford & Gilbert 2007), biological responses (Parker et al. 2011, Falkenberg et al. in review) and economic features (Roy et al. 2012) to make some areas more likely to experience stronger impacts of forecasted change (Sumaila et al. 2011, Lam et al. 2014, Voss et al. 2015).

Further complicating forecasts of the potential economic effects of ocean acidification is the expectation that other features of the marine environment will be modified concomitantly (IPCC 2014). For example, human activities are also driving increased temperatures in many regions. Promisingly, some assessments of the potential economic effect of combined ocean acidification and modified temperatures have been conducted (Lane et al. 2013, Norman-López et al. 2013, Cooley et al. 2015) As with assessments of ocean acidification, these evaluations of climate change more generally have focussed on provisioning services. Broadening this focus may reveal important impacts not yet recognised. In the context of regulation and maintenance services, for example, the role of marine organisms and habitats in coastal protection may become increasingly important and valuable in the future as human-driven climate change is also anticipated to lead to an increase in storm and wave conditions which could cause socio-economic damage via destruction of coastal infrastructure (Adger et al. 2005). If habitats are maintained, they may be able to reduce wave energy such that the economic costs associated with damage are avoided (e.g. kelp can reduce wave heights by as much as 60 %, Mork 1996; IPCC, 2014). Maintaining such habitats will require management of localised human impacts, such as those which result due to the inputs of nutrients or removal of key species (Russell et al. 2009, Brown et al. 2014). In addition, ecosystems, the services they provide and human societies that derive benefit from them vary at local scales, the effect of which needs to be considered (Armstrong et al. 2012, Brander et al. 2014). Incorporating such cross-scale factors into assessments will be an important part of future research.

5. Conclusion

There is an increasing recognition that ocean acidification is occurring and affecting the biological and ecological systems from which human societies derive socio-economic benefits. Our systematic review reveals that this is reflected by an expanding academic literature, yet there have been relatively few assessments conducted, with the results of those that have been published difficult to compare. We highlight how some of these issues can be resolved by developing stronger inter-disciplinary collaborations and using standardised approaches to select timescales and emissions scenarios. As these issues are resolved, assessments should be targeted to broaden the scope of current research from its relatively limited focus on particular geographic areas, and species/habitats and ecosystem services. Clearly, researchers have only touched upon a small fraction of the potential scope of research into the economic effects of ocean acidification. As more assessments are conducted, they will likely highlight the variability of the economic effect of ocean acidification. Recognising such variability will assist the development of management and policy strategies such that the potentially negative economic effects of ocean acidification are minimised, or even averted, while the potentially positive effects are enhanced.

Supplementary Material

Table S1. Details of papers considering the economic effects of ocean acidification included in this review.

123456

References

Adger WN, Hughes TP, Folke C, Carpenter SR, Rockström J (2005) Social-ecological resilience to coastal disasters. Science 309:1036-1039

Armstrong CW, Holen S, Navrud S, Seifert I (2012) The economics of ocean acidification – a scoping study. Fram Centre

Ballantyne M, Pickering CM (2015) The impacts of trail infrastructure on vegetation and soils: current literature and future directions. Journal of Environmental Management 164:53-64

Blackford J, Gilbert F (2007) pH variability and CO_2 induced acidification in the North Sea. Journal of Marine Systems 64:229-241

Branch TA, DeJoseph BM, Ray LJ, Wagner CA (2013) Impacts of ocean acidification on marine seafood. Trends in Ecology & Evolution 28:178-186

Brander LM, Narita D, Rehdanz K, Tol RS (2014) The economic impacts of ocean acidification. In: Nunes P, Kumar P, Dedeurwaerdere T (eds) Handbook on the Economics of Ecosystem Services and Biodiversity. Edward Elgar, Cheltenham

Brander LM, Rehdanz K, Tol RS, Van Beukering PJ (2012) The economic impact of ocean acidification on coral reefs. Climate Change Economics 3:1250002

Brown CJ, Saunders MI, Possingham HP, Richardson AJ (2014) Interactions between global and local stressors of ecosystems determine management effectiveness in cumulative impact mapping. Diversity and Distributions 20:538-546

Caldeira K, Wickett ME (2003) Anthropogenic carbon and ocean pH. Nature 425:365-365

Campbell LM (2005) Overcoming obstacles to interdisciplinary research. Conservation Biology 19:574-577

Chen P-Y, Chen C-C, Chu L, McCarl B (2015) Evaluating the economic damage of climate change on global coral reefs. Global Environmental Change 30:12-20

CICES (2016) The Common International Classification of Ecosystem Services, CICES Version 4.3. Accessed 28/10/2016. http://cices.eu/

Cooley SR, Doney SC (2009) Anticipating ocean acidification's economic consequences for commercial fisheries. Environmental Research Letters 4:024007

Cooley SR, Rheuban JE, Hart DR, Luu V, Glover DM, Hare JA, Doney SC (2015) An integrated assessment model for helping the United States sea scallop (*Placopecten magellanicus*) fishery plan ahead for ocean acidification and warming. PloS One 10:e0124145

Costanza R, d'Arge R, de Groot R, Faber S, Grasso M, Hannon B, Limburg K, Naeem S, O'Neill R, Paruelo J, Raskin R, Sutton P, van den Belt M (1997) The value of the world's ecosystem services and natural capital. Nature 387:253-260

Costanza R, de Groot R, Sutton P, van der Ploeg S, Anderson SJ, Kubiszewski I, Farber S, Turner RK (2014) Changes in the global value of ecosystem services. Global Environmental Change 26:152-158

Doney SC, Fabry VJ, Feely RA, Kleypas JA (2009) Ocean acidification: the other CO_2 problem. Marine Science 1:169-192

Dupont S, Havenhand J, Thorndyke W, Peck LS, Thorndyke M (2008) Near-future level of CO_2-driven ocean acidification radically affects larval survival and development in the brittlestar *Ophiothrix fragilis*. Marine Ecology Progress Series 373:285-294

Ekstrom JA, Suatoni L, Cooley SR, Pendleton LH, Waldbusser GG, Cinner JE, Ritter J, Langdon C, Van Hooidonk R, Gledhill D (2015) Vulnerability and adaptation of US shellfisheries to ocean acidification. Nature Climate Change 5:207-214

Falkenberg LJ, Connell SD, Russell BD (2013a) Disrupting the effects of synergies between stressors: improved water quality dampens the effects of future CO2 on a marine habitat. Journal of Applied Ecology 50:51-58

Falkenberg LJ, Connell SD, Russell BD (2014) Herbivory mediates the expansion of an algal habitat under nutrient and CO2 enrichment. Marine Ecology Progress Series 497:87-92

Falkenberg LJ, Russell BD, Connell SD (2013b) Future herbivory: the indirect effects of enriched CO_2 may rival its direct effects. Marine Ecology Progress Series 492:85-95

Falkenberg LJ, Styan CA, Havenhand J (in review) Future sperm motility: potential variability in oyster response to forecasted ocean acidification and freshening.

Feely RA, Sabine CL, Lee K, Berelson W, Kleypas J, Fabry VJ, Millero FJ (2004) Impact of anthropogenic CO_2 on the $CaCO_3$ system in the oceans. Science 305:362-366

Fitzer SC, Phoenix VR, Cusack M, Kamenos NA (2014) Ocean acidification impacts mussel control on biomineralisation. Scientific reports 4:6218

Frommel AY, Maneja R, Lowe D, Malzahn AM, Geffen AJ, Folkvord A, Piatkowski U, Reusch TB, Clemmesen C (2012) Severe tissue damage in Atlantic cod larvae under increasing ocean acidification. Nature Climate Change 2:42-46

Garrard SL, Beaumont NJ (2014) The effect of ocean acidification on carbon storage and sequestration in seagrass beds; a global and UK context. Marine Pollution Bulletin 86:138-146

Gazeau F, Quiblier C, Jansen JM, Gattuso JP, Middelburg JJ, Heip CH (2007) Impact of elevated CO_2 on shellfish calcification. Geophysical Research Letters 34:L07603

Guitart D, Pickering C, Byrne J (2012) Past results and future directions in urban community gardens research. Urban Forestry & Urban Greening 11:364-373

Hall-Spencer JM, Rodolfo-Metalpa R, Martin S, Ransome E, Fine M, Turner SM, Rowley SJ, Tedesco D, Buia M-C (2008) Volcanic carbon dioxide vents show ecosystem effects of ocean acidification. Nature 454:96-99

Harvey BP, Gwynn-Jones D, Moore PJ (2013) Meta-analysis reveals complex marine biological responses to the interactive effects of ocean acidification and warming. Ecology and Evolution 3:1016-1030

Heal G (2000) Valuing ecosystem services. Ecosystems 3:24-30

Hepburn C, Pritchard D, Cornwall C, McLeod R, Beardall J, Raven J, Hurd C (2011) Diversity of carbon use strategies in a kelp forest community: implications for a high CO_2 ocean. Global Change Biology 17:2488-2497

IPCC (2014) Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. IPCC, Geneva, Switzerland

Kroeker KJ, Kordas RL, Crim R, Hendriks IE, Ramajo L, Singh GS, Duarte CM, Gattuso JP (2013) Impacts of ocean acidification on marine organisms: quantifying sensitivities and interaction with warming. Global Change Biology 19:1884-1896

Kroeker KJ, Kordas RL, Crim RN, Singh GG (2010) Meta-analysis reveals negative yet variable effects of ocean acidification on marine organisms. Ecology Letters 13:1419-1434

Lam VW, Cheung WW, Sumaila UR (2014) Marine capture fisheries in the Arctic: winners or losers under climate change and ocean acidification? Fish and Fisheries

Lane DR, Ready RC, Buddemeier RW, Martinich JA, Shouse KC, Wobus CW (2013) Quantifying and valuing potential climate change impacts on coral reefs in the United States: Comparison of two scenarios. PloS One 8:e82579

Le Quéré C, Moriarty R, Andrew RM, Canadell JG, Sitch S, Korsbakken JI, Friedlingstein P, Peters GP, Andres RJ, Boden T (2015) Global carbon budget 2015. Earth System Science Data 7:349-396

Liu J, Dietz T, Carpenter SR, Alberti M, Folke C, Moran E, Pell AN, Deadman P, Kratz T, Lubchenco J (2007) Complexity of coupled human and natural systems. Science 317:1513-1516

Mabardy RA, Waldbusser GG, Conway F, Olsen CS (2015) Perception and response of the US west coast shellfish industry to ocean acidification: the voice of the canaries in the coal mine. Journal of Shellfish Research 34:565-572

Marzano M, Carss DN, Bell S (2006) Working to make interdisciplinarity work: Investing in communication and interpersonal relationships. Journal of Agricultural Economics 57:185-197

Moore C (2015) Welfare estimates of avoided ocean acidification in the US mollusk market. Journal of Agricultural and Resource Economics 40:50-62

Mork M (1996) Wave attenuation due to bottom vegetation. In: Grue J, Gjevik B, Weber JE (eds) Waves and Nonlinear Processes in Hydrodynamics. Kluwer Academic Publishing, Springer, Oslo

Nagelkerken I, Connell SD (2015) Global alteration of ocean ecosystem functioning due to increasing human CO_2 emissions. Proceedings of the National Academy of Sciences 112:13272-13277

Narita D, Rehdanz K, Tol RS (2012) Economic costs of ocean acidification: a look into the impacts on global shellfish production. Climatic Change 113:1049-1063

Norman-López A, Plagányi É, Skewes T, Poloczanska E, Dennis D, Gibbs M, Bayliss P (2013) Linking physiological, population and socio-economic assessments of climate-change impacts on fisheries. Fisheries Research 148:18-26

Parker L, Ross PM, O'Connor WA (2011) Populations of the Sydney rock oyster, *Saccostrea glomerata*, vary in response to ocean acidification. Marine Biology 158:689-697

Pickering C, Byrne J (2014) The benefits of publishing systematic quantitative literature reviews for PhD candidates and other early-career researchers. Higher Education Research & Development 33:534-548

Przeslawski R, Ahyong S, Byrne M, Woerheide G, Hutchings P (2008) Beyond corals and fish: the effects of climate change on noncoral benthic invertebrates of tropical reefs. Global Change Biology 14:2773-2795

Punt AE, Poljak D, Dalton MG, Foy RJ (2014) Evaluating the impact of ocean acidification on fishery yields and profits: the example of red king crab in Bristol Bay. Ecological Modelling 285:39-53

Riebesell U, Fabry VJ, Hansson L, Gattuso J-P (2010) Guide to best practices for ocean acidification research and data reporting, Vol 260. Publications Office of the European Union Luxembourg

Roy ED, Morzillo AT, Seijo F, Reddy SM, Rhemtulla JM, Milder JC, Kuemmerle T, Martin SL (2013) The elusive pursuit of interdisciplinarity at the human-environment interface. BioScience 63:745-753

Roy S, Byrne J, Pickering C (2012) A systematic quantitative review of urban tree benefits, costs, and assessment methods across cities in different climatic zones. Urban Forestry & Urban Greening 11:351-363

Russell BD, Thompson JAI, Falkenberg LJ, Connell SD (2009) Synergistic effects of climate change and local stressors: CO_2 and nutrient-driven change in subtidal rocky habitats. Global Change Biology 15:2153-2162

Shi D, Xu Y, Hopkinson BM, Morel FM (2010) Effect of ocean acidification on iron availability to marine phytoplankton. Science 327:676-679

Sumaila UR, Cheung WW, Lam VW, Pauly D, Herrick S (2011) Climate change impacts on the biophysics and economics of world fisheries. Nature Climate Change 1:449-456

Vila AR, Falabella V, Gálvez M, Farías A, Droguett D, Saavedra B (2015) Identifying high-value areas to strengthen marine conservation in the channels and fjords of the southern Chile ecoregion. Oryx:1-9

Voss R, Quaas MF, Schmidt JO, Kapaun U (2015) Ocean acidification may aggravate social-ecological trade-offs in coastal fisheries. PloS One 10:e0120376

Wam HK (2010) Economists, time to team up with the ecologists! Ecological Economics 69:675-679

Zeebe RE, Ridgwell A, Zachos JC (2016) Anthropogenic carbon release rate unprecedented during the past 66 million years. Nature Geoscience 9:325-329

Tables

Table 1. Distribution of papers addressing potential economic effects of ocean acidification across academic disciplines and branches. The number in brackets indicates the number of studies which conducted assessments.

Discipline			Branch		
Name	**Number of journals**	**Number of papers**	**Name**	**Number of journals**	**Number of papers**
Earth and environmental sciences	16 (3)	22 (3)	Aquatic environments	6	6
			Earth and environmental science	4 (1)	4 (1)
			Global change	4 (2)	8 (2)
			Oceanography	2	4
Life sciences	32 (4)	65 (4)	Biology	10	29
			Ecology	4 (1)	6 (1)
			Fisheries, aquaculture, agriculture	7 (1)	11 (1)
			General	4 (1)	10 (1)
			Toxicology and pollution	4 (1)	6 (1)
			Zoology	3	3
Social sciences	12 (2)	17 (2)	Economics	4 (2)	4 (2)
			Management, policy, conservation	8	13

Table 2. Geographic scope for which potential economic effects of ocean acidification has been considered as indicated by the number of papers specific to a particular country. The number in brackets indicates the number of studies which conducted assessments.

Continent	Country	Papers
Africa	Madagascar	1
	South Africa	1 (1)
Australasia and Oceania	Australia	9 (1)
	New Zealand	1 (1)
Asia	China	4 (1)
	Hong Kong	2
	Israel	2 (1)
	Japan	2 (1)
	Philippines	1
	Russia	1 (1)
	South Korea	1 (1)
	Turkey	1 (1)
	Vietnam	1 (1)
Europe	Austria	1 (1)
	Belgium	1 (1)
	Denmark	2 (2)
	Finland	2 (2)
	France	2 (1)
	Germany	1 (1)
	Greece	1 (1)
	Iceland	2 (2)
	Ireland	2 (1)
	Italy	2 (1)
	Luxembourg	2 (1)
	Malta	2 (1)
	Netherlands	3 (1)
	Norway	3 (3)
	Portugal	3 (1)
	Spain	4 (1)
	Sweden	5 (2)
	Switzerland	1 (1)
	United Kingdom	5 (2)
North America	Canada	4 (2)
	Greenland	1 (1)

	Mexico	1 (1)
	Panama	1
	United States	30 (5)
South America	-	

Table 3. Details of the assessments of economic effects of ocean acidification

Study	Timescale	Emission scenario	Spatial scale	Species/habitat	Biological response included in analysis	Biological response extrapolated from	Ecosystem service(s)'	Response variable forecasted economic effect reported in terms of	Direction of forecasted economic effect
Cooley & Doney 2009	2060	SRES A1	National and Sub-national	Molluscs	Calcification	Experimental study (*n* = 1)	Wild animals and their outputs	Net present value, economic revenue losses	Negative
Brander et al. 2012	Through 2100	SRES A2, A1, B2, B1	Global	Coral reefs	Area	Experimental studies (*n* = > 1)	Experiential use, physical use, wild animal and their outputs, mass stabilisation and control of erosion rates, maintaining nursery populations and habitats, bequest	Net present value, annual economic damage	Negative
Narita et al. 2012	2100	IS92a	Global and Regional/National	Molluscs	Calcification and survival	Meta-analysis (*n* = 1)	Wild animals and their outputs and animals from in-situ aquaculture	Total economic cost, consumer and producer surplus	Negative
Garrard & Beaumont 2014	2100	IS92a	Global and National	Seagrass beds	Biomass	Experimental studies (*n* = > 1)	Global climate regulation by reduction of greenhouse gases	Net present value, carbon sequestration	Positive
Lam et al. 2014	2050	SRES A2	Regional and National and Sub-national	Fish and invertebrates	Metablic rate, larval mortality, adult mortality	Meta-analyses (*n* = > 1)	Wild animals and their outputs	Total revenue, fishers' incomes, total fishing cost, economic rets, economic impacts, income impacts, landed value	Negative
Punt et al. 2014	Through 2100	-^	Local	Red king crab (*Paralithodes camtschaticus*)	Juvenile survival	Experimental study (*n* = 1)	Wild animals and their outputs	Maximum economic yield and profit	Negative
Moore 2015	Through 2100	RCP 8.5, 6, 4.5	National	Molluscs `	Growth rate	Experimental study (*n* = 1)	Wild animals and their outputs	Net present value, compensative surplus and equivalent surplus from avoided ocean acidification	Negative
Voss et al. 2015	2100*	-*	Local	Norwegian coastal cod (*Gadus morhua*)	Larval mortality	Experimental study (*n* = 1)	Wild animals and their outputs	Total profits	Negative

^ a calculated approximation based on Hall-Spencer et al. 2008; Calderia & Wickett 2003 (Caldeira & Wickett 2003)
* levels Frommel et al. 2012 and references therein forecast to be experienced

5

Table 4. Ecosystem services recognised by papers addressing potential economic effects of ocean acidification. The number in brackets indicates the number of studies which conducted assessments. (Note: the value may be higher than the number of papers as some considered multiple services.)

Section	Division	Group	Class	Number of studies
Provisioning	Nutrition	Biomass	Wild plants, algae and their outputs	8
			Wild animals and their outputs	51 (7)
			Plants and algae from in-situ aquaculture	4
			Animals from in-situ aquaculture	23 (1)
	Materials	Biomass	Fibres and other materials from plants, algae and animals for direct use or processing	9
			Genetic materials from all biota	1
		Water	Surface water for non-drinking purposes	1
	Energy	Biomass-based energy sources	Plant-based resources	6
		Mechanical energy	Animal-based energy	1
Regulation & Maintenance	Mediation of waste, toxics and other nuisances	Mediation by biota	Bio-remediation by micro-organisms, algae, plants, and animals	4
			Filtration/sequestration/storage/accumulation by micro-organisms, algae, plants, and animals	2
		Mediation by ecosystems	Filtration/sequestration/storage/accumulation by ecosystems	2
	Mediation of flows	Mass flows	Mass stabilisation and control of erosion rates	14 (1)
		Liquid flows	Hydrological cycle and water flow maintenance	1
	Maintenance of physical, chemical, biological conditions	Lifecycle maintenance, habitat and gene pool protection	Pollination and seed dispersal	2
			Maintaining nursery populations and habitats	8 (1)
		Pest and disease control	Pest control	1
			Disease control	1
		Soil formation and composition	Weathering processes	2
			Decomposition and fixing processes	2
		Water conditions	Chemical condition of salt waters	1
		Atmospheric composition and climate regulation	Global climate regulation by reduction of greenhouse gas concentrations	7 (1)

Cultural	Physical and intellectual interactions with biota, ecosystems, and land-/seascapes [environmental settings]	Physical and experiential interactions	Experiential use of plants, animals and land-/seascapes in different environmental settings	4 (1)
			Physical use of land-/seascapes in different environmental settings	6 (1)
		Intellectual and representative interactions	Educational	1
			Heritage, cultural	4
			Entertainment	2
			Aesthetic	2
	Spiritual, symbolic and other interactions with biota, ecosystems, and land-/seascapes [environmental settings]	Spiritual and/or emblematic	Symbolic	1
			Sacred and/or religious	3
		Other cultural outputs	Existence	2
			Bequest	2 (1)

Figure legends

Figure 1. The number of papers in which a) species belonging to a particular taxa or b) habitat types were considered in the context of the potential economic effects of ocean acidification.

Figures

Figure 1.