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The economic impacts of ocean acidification on shellfish fisheries and aquaculture in the United Kingdom

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ABSTRACT

Ocean acidification may pose a major threat to commercial fisheries, especially those for calcifying shellfish species. This study was undertaken to estimate the potential economic costs resulting from ocean acidification on UK wild capture and aquaculture shellfish production. Applying the net present value (NPV) and partial equilibrium (PE) models, we estimate both direct and economy-wide economic losses of shellfish production by 2100. Estimates using the NPV method show that the direct potential losses due to reduced shellfish production range from 14% to 28% of fishery NPV. This equates to annual economic losses of between ö3 and ö6 billion of the UK's GDP in 2013, for medium and high emission scenarios. Results using the PE model showed the total loss to the UK economy from shellfish production and consumption ranging from ö23–ö88 million. The results from both the direct valuation and predicted estimate for the economic losses on shellfish harvest indicate that there are regional variations due to different patterns of shellfish wild-capture and aquaculture, and the exploitation of species with differing sensitivities to ocean acidification. These results suggest that the potential economic losses vary depending on the chosen valuation method. This analysis is also partial as it did not include a wider group of species in early-life-stages or predator-prey effects. Nevertheless, findings show that the economic losses to the UK and its devolved administrations due to ocean acidification could be substantial. We conclude that addressing ocean acidification with the aim of preserving commercially valuable shellfish resources will require regional, national or international solutions using a combined approach to reduce atmospheric CO_2 emissions and shift in focus to exploit species that are less vulnerable to ocean acidification.

1. Introduction

Ocean acidification occurs as seawater absorbs atmospheric levels of carbon dioxide (CO_2). Atmospheric CO_2 has increased over recent years and is projected to increase further by the end of the century as fossil fuel reserves continue to be exploited (IPCC, 2001; Caldeira and Wickett, 2003; Blackford and Gilbert, 2007; Doney et al., 2009). Observational studies suggest that the absorption of CO_2 has already decreased pH levels in the global ocean by 0.1 pH units since 1750 (Orr et al., 2005) and that the present rate of change is faster than at any time during the last 55 million years (Pearson and Palmer, 2000). In the UK/European shelf seas, results from observations and modelling studies have shown that CO_2 levels in the near-surface seawater can currently vary between 200–450 ppm, contributing to a pH change of as much as 0.1 units. Recent studies have demonstrated an overall decreasing trend in pH of –0.0035 ± 0.0014 per year, indicating rapid acidification for the surface (Williamson et al., 2017). These systems will be subject to variability. In most cases the main effect will be attributable to temperature changes which are extremely variable over spatial and temporal scales in shallow shelf seas. These changes will considerably modify i) CO_2 solubility hence pH, ii) biological processes such as photosynthesis and respiration, which contributes to an up-take and CO_2 release, and iii) riverine inputs from anthropogenic sources, that will contribute to enhanced biological production (Williamson et al., 2013; 2017).

The potential direct biological impacts of ocean acidification occur at both the molecular and cellular level (Kroeker et al., 2013; Le Quesne and Pinnegar, 2012), and will act to diminish the ability of calcifying organisms to construct their shells or skeletons, especially affecting species with a low level of biological control over the calcification process. Ocean acidification and decreasing carbonate ion concentration could therefore directly impact organisms including molluscs and

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Table 1
Responses of molluscs and crustaceans based on selected literature review on the biological experiments conducted between 2005–2015. Total published materials on "ocean acidification" count 89,993 through Science Direct database of which publication title, Marine Pollution Bulletin (275), Marine Chemistry (421), and Climate related (274). Studies used to calculate effect sizes for mollusc and crustaceans are highlighted in bold.

Authors *multi-species experimental design	Category Molluscs & Crustaceans	Species	Life-cycle stages/ experimental duration	Effect level biological processes vs pH, CO2
Fabry et al. (2008); Lannig et al. (2010); Vengatesen and Ko (2012); Dineshram et al. (2012); Ivanina et al. (2013*); Götze et al. (2014*); Gazeau et al (2010); Havenhand and Schlegel (2009); Barros et al. (2013); Omera et al. (2013*)	Oyster Oyster + clam*	Crassostreo gigas Crassostrea angulata Crassostrea virginica, Mercenaria mercenaria	2 hours Veliger larvae, 28 days, embryonic development Juvenile	10% decrease in calcification rate, energy, and primary & nucleotide metabolism, cytoskeleton structure. Decreasing calcification with increasing CO_2 and decreasing pH, salinity, temperature, pH, pH 7.4 in low-salinity larval shell smaller, shell 16%, calcium content 42 in CO_2, no response in shell thickness*, sperm motility. 740 ppm; 1036-2008 ppm; 7.55-8.07; 7.9, 7.6, 7.4; 7.76-8.16; ~395, 800, 1500 pCO2; 800-2000 pCO2.
Fabry et al. (2008); Duarte et al. (2014); Fitzer et al. (2014); **Berge et al. (2006)**; Gazeau et al. (2010); Bressan et al. (2014)*; Wang et al. (2015); Navarro et al. (2013)	Mussel Mussel + clam*	P. purpuratus Mytilus edulis Bivalve	Shell dissolve Juvenile Adult & juvenile 44 days, juveniles,75days	25% decrease in calcification rate, mortality. Shell diss. No effect by temperature but CO_2 level. Not aragonite in juvenile shells, 6month. Shell growth reduced between pHu6.67 and 7.1. 23 days mortality. Different mode between clam and mussel in survival, growth, and shell integrity from OA, temperature, no changes. 7.1/740 ppm; 12-16 °C/390, 700, 1000 ppm; 380, 550, 750, 1000, pCO_2; 6.7-8.1; pH7.4/3 – 6months; ~380, ~750, ~1200 pCO2, 7.67-8.25
Fabry et al. (2008); Clements and Hunt (2014); Range et al. (2011)	Clam	M. mercenario		Reduced thermal tolerance, mortality reduced in acidified treatments. 7.0-7.2, 6.8-7.8.
Klok et al. (2014)	Cockle	Ceratodesma edule	5 days	Reductions on shell length, shell weight, cockle flesh over co2, DEB but difficult to differentiate between assimilation, maintenance and growth 6.7-8.3
Fabry et al (2008); Sanders et al. (2013)	G. Scallop Scallop + prawn	P. magellanicus P. maximus	77days	Decrease in fertilization, development DNA and RNA clearance rates, respiration rates, condition index and cellular turn over. < 8.0; 7.82-8.18, temp 15oc
Hendriks et al. (2010)	Mollusc	Bivalve	Larvae Gametes	Calcification & fertility, fertility & growth, primary production, respiration, survival. 0.86 ± 0.093, 1.02 ± 0.015, 0.91 ± 0.031, 0.99
Van Colen et al. (2012)		Macoma balthica	Egg, larvae, embryos	Effects in fertilization, embryogenesis and reduction of larval development. 7.8-8.5
Hendriks et al. (2010)	Crustacean		Larvae	Fertility growth. 0.89 ± 0.081
Fabry et al. (2008); Long et al. (2013); Small et al. (2010); Walther et al. (2009, 2010, 2011), Haye et al. (2011); Hammer et al. (2012); Schiffer et al. (2014)	Crab	C. pagurus. N.puber, P. camtschaticus, Necora puber	Shell dissolve Juveniles 30 days	Intracellular acid/base disruption, lack of pH regulation, decreased survival, metabolic resistant to low pH. 10000 ppm; 7.98-6.04/0.08-6.04 kPa; pH7.7; 6.0-8.05; low pH 6.8; 7.4, 6.9, 6.6, 6.3.
Styf et al. (2013); Hernroth et al. (2012, 2015)	Nephrop	Nephrops narvergicus Hyas araneus	Eggs, 16 weeks Larvae	Embryonic responses % yolk consumption, mean heart rate, oxygen consumption, oxidative stress, larvae for higher metabolic costs, no survival effect by pCO_2, THCs 35% reduced. 0.4 units, temp 5-18oc; Tem. 5, 10, 12, 14, 16, 18 & low pH.
Kurihara et al. (2008); Donohue et al. (2012); Zheng et al. (2015)	Shrimp	Palaemon pacificus	Egg juvenile, 30, 15 weeks	Decreased survival, growth, egg production.7.6-7.9; pCO_2. 8.2, 7.8, 7.6 pH.
Kurihara et al. (2008), Richards et al. (2015*)	Prawn, Prawn + scallop*	Palamon elegans	30days	10-18oc, 7.84-8.10 (larvae), 14oc 7.95-7.96 (juvenile)
Agnalt et al. (2013)	Lobster	Hommarus gammarus	Larvae/juvenile, 140 days	Growth slows at 10oc after 5 wks no effect in to stage 4. Deformities in larvae and juveniles
Lardies et al. (2014)	Mollusc	C. concholepas juvenile	Juvenile/72 hrs	Metabolic activity, respiration. Increased PCO2 increases a high metabolic rate on the gastropod.
Manríquez et al. (2014)	Mollusc	C. concholepas larvae	Larvae, weeks	Changes in survival and hatching success at elevated CO2 conditions
Vargas et al. (2014)	Mollusc	C. concholepas larvae	Larvae, 6 weeks	High PCO2 levels influenced the larvae ingestion and clearing rates
Vargas et al. (2014)	Mollusc	Perumytilus purpuratus	Larvae, 6 weeks	Negative effect of elevated pCO_2 on the clearance and ingestion rates
Duarte et al. (2014)	Mollusc	Mytilus chilensis	Juvenile, 60 days	Negative effects of the OA were found on growth and net calcification rates of this species over shell deposition, but not by the shell dissolution processes.
Berge et al. (2006)	Mollusc	Mytilus edulis	Adult, 44 days	Results showed induced CO_2 resulted in a reduction of pH affects the growth of M. edulis negatively
Sanders et al. (2013)	Mollusc	Pecten Maximus	Juvenile, 3 months	Results suggests that abundant food helped to counter balance any effects from changes in water chemistry
Talmage and Gobler (2010)	Mollusc	Argopecten irradians	Larvae, 36 days	High CO_2 concentrations resulted in malformation and erosion of shells. Growth was also affected under high CO_2 conditions.
Talmage and Gobler (2010)	Mollusc	Mercenaria mercenaria	Larvae, 36 days	High CO_2 concentrations resulted in malformation and erosion of shells. Growth was also affected under high CO_2 conditions when compared with pre-industrial rates of PCO_2 concentrations.
Heinemann et al. (2012)	Mollusc	Mytilus edulis	Adults, 3 monts	

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