UK Ocean Acidification Research Programme

UK Ocean Acidification programme synopsis

Fisheries, food-webs and ecosystem services

www.oceanacidification.org.uk

How ocean acidification might affect fisheries and ecosystems - and ourselves

Seafood is the most tangible marine 'ecosystem service', providing important economic and societal benefits at the national and global scale, through both aquaculture and capture fisheries. The sustainable management of these resources requires understanding of species-specific factors for a wide range of finfish and shellfish, as well as factors affecting the health and productivity of the marine ecosystem as a whole – on which fisheries necessarily depend.

Ocean acidification is an environmental stressor that is intensifying, and of increasing concern. Many studies over the past decade have shown adverse impacts on marine organisms, particularly shellfish and corals. For finfish the evidence is less clear: the UKOA programme therefore supported new studies on the effects of ocean acidification on selected species of commercial importance. The focus has been on early life-stages, since these are generally more susceptible to changes in environmental conditions.

The effects of temperature increase were also investigated, since increasing amounts of atmospheric CO_2 will result in ocean warming as well as ocean acidification. Additional, closely-linked research considered potential impacts of ocean acidification on key aspects of marine food-webs and a range of marine ecosystem services, with a preliminary assessment of their socio-economic implications.

This synopsis provides a summary of work carried out by the UKOA consortium project **"Improved understanding of population, community and ecosystem impacts of ocean acidification for commercially important species"** that included research on their associated ecosystems and socio-economics. Studies were led by Kevin Flynn, Swansea University, with formal partners at the universities of Exeter and Strathclyde, and Plymouth Marine Laboratory. Components included experiments on the impacts of increased seawater acidity and temperature on the survival and growth of juvenile stages of selected finfish and shellfish species; studies on the phytoplankton and zooplankton on which fish feed; mathematical modelling of ocean acidification impacts on plankton and fisheries; and consideration of the socio-economic implications of ocean acidification (and other aspects of climate change) for UK fisheries and for other, less direct, services provided by marine ecosystems.

Specific aims of the consortium study were:

- To examine the physiological and behavioural responses of commercial fish and shellfish to ocean acidification and their capacity to resist and acclimate
- To 'scale up' from laboratory studies to population and stock level responses to ocean acidification including an analysis of possible consequences for planktonic and benthic food-webs, and impacts on the production and yields of commercial fish and shellfish stocks
- To investigate the possible socio-economic consequences relating to ocean acidification at an ecosystem level.

Key findings:

- Ocean acidification (with warming) is expected to alter competitive interactions between species at the base of the marine food chain, with knock-on effects for other marine organisms, including fish.
- Studies on copepods (key food for fish) showed that CO_2 impacts are highly dependent on life stage, and that parental exposure to future CO_2 levels affects reproductive success; the sensitivity of this group to ocean acidification is likely to have been under-estimated.
- Young stages of European sea bass and Atlantic herring seemed resilient to acidification treatments. Abundant, high quality food may have countered associated stresses, whilst other factors also complicate interpretation of these results.
- Fitness and survival of commercially-important shellfish may be at risk from ocean acidification, including species-specific impacts on their immune systems and energy trade-offs.
- The changes in marine ecosystems brought about by continued ocean acidification and warming are expected to be complex and significant. Although seagrasses may benefit, net effects are likely to be damaging. Scenario-based models of future impacts on fisheries and society have been developed, but overall consequences are extremely difficult to predict.

Outputs include:

Campbell AL, Mangan S, Ellis RP & Lewis C (2014). Ocean acidification increases copper toxicity to the early life history stages of the polychaete Arenicola marina in artificial seawater. Environmental Science & Technology 48, 9745-9753.

Cripps G, Lindeque P & Flynn KJ (2014) Have we been underestimating the effects of ocean acidification in zooplankton? Global Change Biology 20, 3377-3385

Ellis RP, Widdicombe S, Parry H et al. (2015) Pathogenic challenge reveals immune trade-off in mussels exposed to recycled seawater pH and increased temperature. Journal of Experimental Marine Biology & Ecology 462, 83-89

Fernandes JA, Cheung WWL, Jennings S et al. (2013) Modelling the effects of climate change on the distribution and production of marine fishes: accounting for trophic interactions in a dynamic bioclimate envelope model. Global Change Biology 19, 2596-2607

Flynn KJ, Blackford JC, Baird JC et al. (2012) Changes in the pH at the exterior surface of plankton with ocean acidification. Nature Climate Change 2, 510-513

Flynn KJ, Clark DR, Mitra A et al. (2015) Ocean acidification with (de)eutrophication will alter future phytoplankton growth and succession. Proceedings of the Royal Society B 282, 20142604

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.

Hopkins F, Ellis R, Pope E & Papathanasopoulou E (2013) Ocean acidification and shellfish: effects on UK aquaculture? Shellfish News 35, 39-42

Morris DJ, Speirs DC, Cameron AI & Heath MR (2014) Global sensitivity analysis of an end-to end marine ecosystem of the North Sea: Factors affecting the biomass of fish and benthos. Ecological Modelling 273, 251-263.

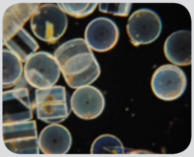
Pope EC, Ellis RP, Scolamacchia M et al. (2014) European sea bass, Dicentrarchus labrax, in a changing ocean. Biogeosciences 11, 2519-2530

For full list of publications arising from this component of the UKOA programme, see separate hard-copy document or online at www.oceanacidification.org.uk

Effects on food-webs and ecosystems

Ocean acidification and eutrophication

The marine food-web is supported by phytoplankton (microscopic plants). Their photosynthesis decreases the amount of CO_2 dissolved in seawater, naturally driving a seasonal cycle for pH in the upper ocean particularly in coastal waters. Local year-to-year changes in phytoplankton growth, e.g. due to changes in nutrient availability, may therefore reinforce or counteract the global trend of increasing ocean acidification. Feedback processes can also occur if different groups of phytoplankton react differently to these changes, thereby influencing other parts of the food web. The growth of three contrasting phytoplankton species was studied experimentally under different pH and nutrient conditions, and mathematical models used to characterise the effects of these factors. Different pH scenarios were shown to modify competitive interactions between the species, thereby altering phytoplankton succession. This finding indicates that ocean acidification impacts in shelf seas will depend on whether nutrient loads are increasing (eutrophication; mostly caused by agricultural fertiliser and river inputs) or decreasing (de-eutrophication, a consequence of pollution control), with implications for trophic dynamics throughout the food web, including fisheries.



Additional information on ocean acidification effects on phytoplankton is given in Ocean acidification effects in the upper ocean (UKOA Synopsis 4).

Importance of studying all life stages

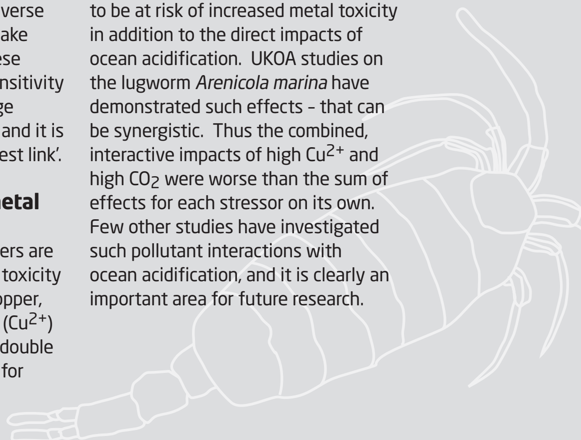
Copepods are small crustacea that frequently dominate the zooplankton biomass and feature strongly in fish diets. Previous studies focusing on adult females indicated that copepods are relatively insensitive to ocean acidification. However, UKOA research suggests otherwise: using a range of life stages of both sexes of *Acartia tonsa*, it was found that egg production and hatching were poor indicators of full life-cycle survival under high CO_2, with nauplii being the most sensitive stage (with up to threefold increase in mortality at 1000 μatm CO_2). Prior exposure to increased CO_2 by adults, including males, could also affect reproductive success.

In the experiments, the copepods were kept well-fed, whereas under natural conditions food shortages or adverse changes in food quality could make these impacts more severe. These studies confirm that species' sensitivity to ocean acidification can change markedly during their life cycle, and it is necessary to identify the 'weakest link'.

Ocean acidification and metal toxicity

Many estuaries and coastal waters are contaminated by metals whose toxicity varies with seawater pH. For copper, the toxic free ion concentration (Cu^{2+}) increases as pH falls, and could double under CO_2 conditions projected for 2100.

Marine organisms living in or near affected sediments are therefore likely to be at risk of increased metal toxicity in addition to the direct impacts of ocean acidification. UKOA studies on the lugworm *Arenicola marina* have demonstrated such effects – that can be synergistic. Thus the combined, interactive impacts of high Cu^{2+} and high CO_2 were worse than the sum of effects for each stressor on its own. Few other studies have investigated such pollutant interactions with ocean acidification, and it is clearly an important area for future research.



Shellfish aquaculture

The economic value of UK shellfish farming was estimated to be £33.2m in 2012, around 5% of the total UK aquaculture industry. Whilst many studies have documented adverse effects of ocean acidification on shellfish, such effects are complex and may vary between species.

Oyster breeding and breathing

The Pacific oyster *Crassostrea gigas* is farmed in the UK. In the US west coast, where seawater pH is naturally lower, large-scale hatchery failures for this species have been linked to ocean acidification and costly water treatment measures have been introduced. UKOA research investigated the effects of high CO_2 and increased temperature on *C. gigas* reproduction (sperm motility and consequent fertilisation success). They found that temperature had the greatest effect, decreasing the percentage of motile sperm and their swimming speed, whilst raising fertilisation success. Studies on the larvae of this species confirmed that a good, varied diet was essential for mitigating against stress.


Oysters

The native European oyster, *Ostrea edulis*, broods its eggs within the shell, and it has been suggested that this might protect them against changing CO_2 levels. Experiments simulating ocean acidification conditions for this species showed that the ability to control pH inside their shells was limited, but the treatment animals had a higher oxygen content – indicating that they were opening their shells more often (to breathe or feed) under high CO_2/low pH conditions. This could have implications for fitness and survival, since open oysters are more open to attack from predators, parasites and infection.


Scallops

Immune-system responses in mussels

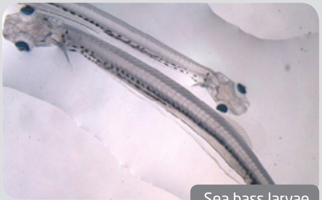
There are other, more direct, mechanisms for ocean acidification to increase the risk of disease – potentially of serious concern for aquaculture. Under high CO_2 conditions, more metabolic energy is needed for pH regulation, decreasing the amount available for the (energetically-expensive) maintenance of the immune system. Such effects have been shown for several species of molluscs and crustaceans. For the mussel *Mytilus edulis*, UKOA studies have shown that decreased antibacterial activity under ocean acidification conditions is reversible, since the immune response was restored when the treated animals were exposed to a pathogen.

Some fish may be resilient

The most recent assessment of climate change impacts by the Intergovernmental Panel on Climate Change considered that finfish were 'vulnerable' to ocean acidification, based on 51 studies of 40 species. However, the confidence of that assessment was low, since species' responses differed markedly: whilst around 75% of studies showed negative impacts at mean ocean surface values projected by 2100 with continued high emissions (up to 850 µatm CO_2), the other studies showed either no significant impacts or positive effects. UKOA experiments on early life-cycle stages of sea bass and herring would seem to add to the latter category, but their interpretation is not straightforward - as discussed below.

Sea bass studies

Around 12000 larvae of the European sea bass *Dicentrarchus labrax* were reared from egg-hatch under a matrix of two temperatures (17 and 19 °C) and seawater CO_2 levels (ambient and 1000 µatm). Increases in temperature and CO_2 were both associated with a lower daily mortality, and resulted in significantly heavier juveniles at the end of the ~10 week study. However, the increased CO_2 also raised resting metabolic rate and reduced maximum metabolic rate, suggesting functional impairment with need for increased food intake.



Sea bass larvae

Measuring Herring

Caution is needed in applying these results to natural conditions, since the parent fish used in the study came from an aquaculture facility, with unknown water chemistry. At a different sea bass culturing facility, CO_2 levels greater than 1000 µatm are known to occur, and caustic soda is used to control pH; that treatment also greatly raised alkalinity to levels rarely seen in nature. It is not clear whether farmed fish might have adapted to high CO_2 conditions over several generations, nor whether similar adaptation might also be possible in the wild, when faced with competitors and the likelihood of food limitation.

Herring studies

Two experiments were carried out on Atlantic herring *Clupea harengus*, raising them for 26 days from egg-hatch under conditions of 14.5°C and 16.5°C, and at 380 µatm (control) and 750 µatm CO_2. In the first experiment, larval growth and survival appeared to be enhanced under higher CO_2, but the poor survival of the control gave cause for concern. In the second experiment, a different method of stocking was used; that gave the opposite result, with impaired growth and survival at higher CO_2. The eggs for these studies were wild-sourced, and it is possible that differences in pre-exposure or prior nutritional history may have contributed to this variability in response.

For both these studies, and consistent with shellfish work, the abundance of high quality food appears of critical importance to support any additional metabolic costs associated with acidification-related stress.

Multi-stressor impacts on ecosystem services

A wide range of experimental studies have shown that individual species at all trophic levels in the marine food web can be affected by (and some may adapt to) both ocean acidification and warming. However, combining all this information to forecast what may happen on decadal time-scales in the real world, under different climate change scenarios and other human-driven pressures, is extremely complicated and uncertain. Although direct, short-term effects on the physiology of a single species may be relatively clear, indirect, longterm effects that involve inter-species interactions within food webs are not.

As an example of a beneficial single-species impact, enhanced photosynthesis by seagrasses is likely to increase their above- and below-ground biomass in a future high CO_2 world. This should be good for carbon sequestration, with an estimated total economic value as an 'ecosystem service' of several £ billion per year by 2100. Other physico-chemical ocean processes may counteract that effect, decreasing net CO_2 uptake; nevertheless, such potential benefits justify active conservation of existing seagrass beds in the UK and globally, not least because they also represent important ecosystems and breeding/nursery grounds for fish.

Indirect effects of ocean acidification and warming on marine food webs are likely to arise through changes to the food supply of fish and other predators, with changes in predation pressure then affecting the abundance of their prey. Such bottom-up and top-down effects would cascade through the food web in a subtle way, with potential to significantly affect the productivity of higher trophic levels.

UKOA research has developed food web models which explicitly represent the balance between bottom-up and top-down cascading effects, and how these affect fish abundances. Results of these models are very dependent on what assumptions are made regarding species' responses to ocean acidification and warming (including scope for multi-generational adaptation), and also on future fishery management strategies.

Nevertheless, the future productivity of demersal fish and other carnivorous benthic fauna seems likely to decline for UK waters, whilst the productivity of pelagic fish could increase (due to the indirect effect of decreased predation from demersal fish). The socio-economic consequences of those changes can also be estimated, but should be considered as illustrative values rather than definitive predictions at this stage.

UK Ocean Acidification Research Programme

What is ocean acidification?

The global ocean currently absorbs more than a quarter of the CO_2 produced by burning fossil fuel and other human activities, slowing the rate of climate change. Global warming would therefore be far worse if it were not for the ocean. However, there is a cost: when CO_2 dissolves in seawater it forms carbonic acid, decreasing the pH and causing other chemical changes. These processes are known as ocean acidification.

The acidity (H+ concentration) of the surface ocean has already increased by nearly 30% due to these events, mostly in the past 50 years. If future CO_2 releases continue to follow current global trends, by 2100 ocean acidity will increase by as much as 150%, at a rate of change 10 times faster than at any time in at least the last 65 million years. Such a major alteration in ocean chemistry will have (and is already having) wide implications for marine life.

Ocean acidification is a relatively new field of research, with the overwhelming majority of studies carried out over the last decade. While the topic is attracting increasing attention among policy makers, international leaders and the media, there is still much to be understood about the fundamental biogeochemical, physiological and ecological processes; interactions with other stressors (notably temperature change) and the consequences of ocean acidification for society. UK scientists are at the forefront of these research areas, working in partnership with many international colleagues.

What is the UK Ocean Acidification research programme?

Widespread concern about ocean acidification emerged after the Royal Society report Ocean acidification due to increasing atmospheric carbon dioxide in 2005. A range of research initiatives were subsequently developed at both the national and international level.

The £12m, five year UK Ocean Acidification research programme (UKOA) was the UK's response, starting in 2010 and jointly funded by the Natural Environment Research Council (NERC), the Department for Environment, Food and Rural Affairs (Defra) and the Department of Energy and Climate Change (DECC).

The overall aims of UKOA were to increase understanding of processes, reduce uncertainties in predicting impacts and improve policy advice. Scientific studies have included observations and surveys; impacts on upper-ocean biogeochemistry; responses by seafloor organisms; effects on exploited species, food-webs and human society; ocean acidification in the geological past; and regional and global modelling. In addition to national policy liaison, UKOA has made significant contributions to the work of the Intergovernmental Panel on Climate Change (IPCC), the UN Framework Convention on Climate Change (UNFCCC), the UN Convention on Biological Diversity (CBD), the UN Sustainable Development Goals (SDGs) and many other governmental and non-governmental initiatives and activities.

NERC Science of the Environment

Department for Environment Food & Rural Affairs

Department of Energy & Climate Change

Living With Environmental Change

Boot KJ, Flynn KJ, Heath M, Speirs D, Turley C, Williamson P (2015)
UK Ocean Acidification research programme synopsis: Fisheries, food-webs and ecosystem services. UKOA/PML