Briefing note on Matt Ridley article "Who's afraid of acid in the ocean? Not me" as published in The Times, 4 November 2010

Response on behalf of UK Ocean Acidification Research Programme (UKOARP)[1]

Summary

Matt Ridley's Opinion article (www.thetimes.co.uk/tto/opinion/columnists/article2793749.ece; paywall applies) is correct in identifying that there are uncertainties and some contradictory evidence regarding biological responses to future ocean acidification (which, chemically, is an inevitable consequence of increasing carbon dioxide levels in the atmosphere). However, for several aspects the article over-simplifies complex issues, or is inaccurate, or is potentially misleading. In particular, small changes in pH do result in large changes in acidity, and negative effects of ocean acidification on calcification are well-documented.

One important and undisputed fact is not mentioned at all. The calcium-based shells and other structures of organisms such as corals and molluscs slowly dissolve in seawater that is under-saturated in calcium carbonate. This effect can occur (and already does) in alkaline water with pH values considerably greater than 7.0, and will be increased by ocean acidification.

Ridley's conclusion that ocean acidification will either be beneficial or have no overall biological effect is a simplistic and invalid interpretation of the evidence. Whilst changes in ocean CO_2, pH and carbonate chemistry will undoubtedly result in winners as well as losers, the calculation of an overall average response is scientifically flawed. That is because positive and negative impacts do not cancel out, but both contribute to ecosystem perturbation. It is also flawed from a human perspective, since an increase in (say) marine algae, bacteria or jellyfish would not provide socio-economic compensation for a decrease in (say) shellfish and corals. Both changes could be 'bad news' from a human perspective. The magnitude of ocean acidification effects on key ecosystem components is, however, still uncertain – which is why the UK has an ocean acidification research programme, co-funded by NERC, Defra and DECC, and why there are also significant research investments by the EU, Germany, the US and others.

Annex 1 gives details of references cited. Annex 2 provides an independently-produced response letter published in The Times on 8 November. A non-technical summary of current knowledge on ocean acidification can be found at www.epoca-project.eu/index.php/what-do-we-do/outreach/rug/oa-questions-answered.html .

Ridley text	Comments
Today in Beijing an alliance of scientists called Oceans United will present the UN with a request for $5 billion a year to be spent on monitoring the oceans. High among their concerns is ocean acidification.	1. There are, of course, many other important aspects of ocean monitoring, not just ocean acidification. The funding request by Oceans United identified 14 topic areas where additional data are required, including the need for a globally-comprehensive tsunami warning system. The total value of marine economic services has been estimated as at least $20 trillion per year (Costanza *et al*, 1997). It is therefore not unreasonable – although it may be politically unrealistic – to seek expenditure of 0.0025% of that amount on assessing the sustainability of such services, and how they may be changing,
As global warming loses traction on the public imagination, environmental pressure groups have been cranking the engine on this "other carbon dioxide problem". "Time is running out", wrote two activists recently in Scientific American, "to limit acidification before it irreperably harms the food chain on which the world's oceans – and people – depend". The fear is that acidification stops shellfish, coral, plankton, lobsters and crabs from building their protective shells.	2. Acidification does not necessarily stop organisms building their shells. Nevertheless, there are well-established negative effects on calcification [see (9) below] and, once built, shells and other calcium carbonate-based exoskeletons will dissolve more easily in a high CO_2 world. The point at which such material becomes unstable is determined not only by acidity levels but also by ocean temperature and pressure, by the crystalline structure of the calcium carbonate, and (for some species) by protective organic coverings. Dissolution already occurs In the deep ocean, at pH greater than 7.0. The area of seafloor affected (and hence largely devoid of calcified organisms, or their remains – that over many millennia may create geological strata such as the white cliffs of Dover) is increasing, with upward movement of the 'saturation horizon' by 50-200 m since 1800. Such saturation horizons are naturally shallower in regions of upwelling (eg. off California) and in polar waters, where more CO_2 dissolves. For surface waters in the Arctic Ocean, winter undersaturation for the aragonite form of calcium carbonate already occurs locally, with year-round undersaturation predicted for 10% of the upper ocean by 2018, around 50% by 2050, and 100% by 2100 (Orr *et al,* 2005; Steinacher *et al* 2009; projections assume 'business as usual' increases in atmospheric CO_2).

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The trouble is, a shoal of new scientific papers points to the conclusion that this scare is based on faulty biochemical reasoning and exaggerated extrapolation.	3. The biochemistry of ocean acidification impacts and calcification processes is complex, and aspects are not well understood. Nevertheless, recent studies have not indicated any faulty reasoning nor exaggerated extrapolation by the research community. See also (9) and (12) below.
We have been here before. In 1984 acid rain was the scare of the day. As science correspondent of The Economist, I wrote: "Forests are beginning to die at a catastrophic rate. One year ago, West Germany estimated that 8 per cent of its trees were in trouble. Now 34 per cent are... that forests are in trouble is now indisputable". Experts told me that all Germany's conifers would be gone by 1990 and the Ministry of the Interior said all forests would be gone by 2002.	4. The effects of acid rain on forests lie outside the expertise of the UKOARP research community. Those with such expertise have, however, provided ample evidence that extensive forest die-back in Europe in the 1970s and 1980s did occur, with pollution from acid rain as a major cause (e.g. Godbold & Hüttermann, 1994; Rodhe *et al*, 1995). Projections made in the early 1980s for German forest cover in 1990 and 2002 may have been over-pessimistic – but were presumably made on the basis that regional sulphur dioxide (SO_2) and nitrogen oxide (NOx) emissions would continue to rise.
Bunk. Acid rain did not kill forests. It did not even damage them. Forests thrived in Germany, Scandinavia and North America during the 1980s and 1990s despite acid rain. I was a gullible idiot not to question the conventional wisdom I was being fed by those with vested interests in the alarm.	5. Acid rain is now much less of a problem in Europe than it was. That is incontrovertibly a consequence of improvements in air quality, driven by emission reduction protocols involving more than 20 countries. Thus energy-related emissions of SO_2 and NOx have declined by around 70% and 45% respectively (European Environment Agency, 2008). The recovery of the health of forests – and of freshwater ecosystems – can be directly linked to the control of these pollutants, that (unlike CO_2) have a short atmospheric lifetime.
Talking of vested interests, the European Project on Ocean Acidification is now a consortium of more than 100 scientists from 27 institutes and 9 countries. This summer it funded 35 scientists to spend six weeks in the Arctic studying the problem, "assisted" by the Greenpeace ship Esperanza. Think how little incentive the scientists would have to say: "Sorry, lads, we realise it is not much of an issue after all."	6. International collaborations have been and will continue to be particularly important for ocean acidification research. For example, by developing standard analytical methods and other research protocols, hence improving the comparability of experiments and the robustness of hypothesis-testing. The use of a Greenpeace ship for the 2010 Arctic study was strictly limited to the transport of hardware (experimental seawater enclosures, known as mesocosms) for a single research group. There was no involvement of Greenpeace in the experiments themselves, nor in subsequent data analyses. Researchers participating in the Arctic study were based at the international station of Ny-Ålesund, and their findings will be subject to rigorous peer review before scientific publication.
Start with a few facts. The oceans are not acid but alkaline, with an average pH of about 8.15 (0-7 being acid, 7-14 being alkaline). But they vary both in space and over time, Arctic seas being less strongly alkaline than tropical, and some bays and reefs being actually acid because of underwater volcanic emissions. The dissolution of carbon dioxide in the oceans may lower the pH slightly to about 7.9 or 7.8 by the end of the century at the worst.	7. It is correct that the oceans are alkaline, containing lower concentrations of hydrogen ions (H^+) than distilled water. Since pH values are the inverse logarithm of H^+ concentrations, one pH unit represents a ten-fold change in H^+. Adding CO_2 increases H^+ levels, making seawater less alkaline and more acidic, lowering pH. The term 'acidification' is therefore appropriate, since acidity is increased. For comparison, an increase from 5°C to 7°C is described as warming, even though (for most of us) both those temperatures are considered cold. It is also correct that there is natural variability in ocean pH. Biological tolerance of pH changes (and other associated changes in water chemistry) can therefore be expected, on either side of an optimal, 'preferred' pH value. The tolerance range and optimal value can be expected to vary between species, and may change through individual acclimation or genetically-driven selective adaptation. Nevertheless, increased frequency of extremes and/or relatively small changes in mean values can be damaging, with stress impacts that may affect health or reproduction. Again comparisons with temperature can be made: whilst humans can survive a very wide range of daily and seasonal temperature changes, a 2°C increase in summer maximum values can significantly affect national mortality rates. Furthermore, an increase of 2°C in the global annual mean temperature would have a major impact on the productivity of many plant crops, with implications for human food supply. The business-as-usual ("at the worst") prediction for global pH values in surface waters is indeed around 7.8 by 2100.
Environmentalists like to call this a 30 per cent increase in acidity, because it sounds more scary than a 0.3 point (out of 14) decrease in	8. If "environmentalists" call a 0.3 decrease in pH a 30% increase in acidity, they are under-estimating rather than over-estimating changes in H^+ concentration. Since the pH scale is logarithmic, as noted above, a 0.3 pH

alkalinity, but no matter. It is still well within the bounds of normal variation.	change represents a doubling (100% increase) in acidity, as defined in terms of H^+ concentration (strictly speaking, pH is an index of H^+ activity; but differences between concentration and activity are unimportant for the range of seawater pH values). A 30% increase in acidity actually occurs when pH changes by 0.11 units. Such a change has already occurred in the surface ocean, as a consequence of atmospheric CO_2 levels increasing from pre-industrial values of 280 ppm to around 390 ppm today. For processes that are directly affected by acidity, the relative change in H^+ concentration matters more than the change in pH value. However, there are also other changes in water chemistry, as discussed under (9) below. Note that logarithmic scales are used elsewhere to cover wide ranges; e.g. the decibel scale (sound energy) and the Richter scale (earthquake strength). A magnitude 8 earthquake is ten times more powerful than a magnitude 7 one, but only one unit on the scale separates them. Note also that the conventional lower and upper limits of the pH scale (0 and 14) are arbitrary. Lower (negative numbers) and higher pH values are also theoretically possible.
Enough numbers. Try chemistry. The scary reasoning rests on the argument that lower pH will mean less dissolved carbonate in the water. But a new paper from North Carolina proves what some scientists have long suspected, namely that corals and other species do not use carbonate as raw material to make their shells, they use bicarbonate. And dissolving carbon dioxide in water actually increases bicarbonate concentrations.	9. Whilst the issues here are complex, the potential for ocean acidification to enhance the calcification of corals and other organisms through increased bicarbonate availability has not been proven by Jury, Whitehead & Szmant (2010) [assuming that to be the "new paper from North Carolina"]. To explain why not, chemistry, numbers and some biology are all needed. Key context is that a tripling of CO_2 compared to pre-industrial levels (from 280 ppm to 840 ppm; a not-unrealistic scenario for the century ahead) will have three main effects: i) increase global surface seawater H^+ concentrations by around 160%, changing pH from 8.2 to 7.8; ii) increase bicarbonate ion (HCO_3^-) concentrations by around 17%, from ~1800 to ~2100 μmol kg^{-1}; and iii) decrease carbonate ion (CO_3^{2-}) concentrations by around 55%, from 225 to 100 μmol kg^{-1} (data from Royal Society, 2005; Table 1). Experiments to investigate ocean acidification effects should therefore focus on similar absolute values and proportional changes. However, it is extremely difficult to separate these three effects in experiments. Jury *et al* used six treatments (including a control) to vary bicarbonate levels nearly 5-fold (from 777 to 3579 μmol kg^{-1}) for the coral *Madracis auretenra.* Results showed a 3-fold change in calcification rates. However, that does not mean that the 10-20% increase in bicarbonate expected to arise from ocean acidification will increase calcification in this species, or others, for the following reasons: • The range of bicarbonate values used was not environmentally realistic (and could even be considered "ludicrous", see scenario range above) • The main effect observed by Jury *et al* was a reduction in calcification at low bicarbonate levels; there was no significant change for the three treatments at mid-range bicarbonate values, from 1820 to 2221 μmol kg^{-1} • The two low-bicarbonate treatments (at 777 and 1088 μmol kg^{-1}) that showed much reduced calcification were also low in carbonate (at 110 and 157 μmol kg^{-1}); interactive effects could therefore apply • Earlier studies that had suggested a bicarbonate-calcification link for corals (Marubini *et al,* 2008; Herfort *et al*, 2008) were also unable to separate bicarbonate/carbonate effects • Other experiments on corals (e.g. Langdon *et al*, 2000; Silverman *et al*, 2007) found that calcification rates were more closely linked to carbonate ion concentrations than bicarbonate levels • The 25 coral studies analysed by Hendricks *et al* (2010) showed a mean decrease in calcification of 29% for treatments equivalent to CO_2 values from 477 to 2000 ppm. The meta-analysis by Kroeker *et al* (2010), based on 22 coral studies, also showed a statistically significant decrease. [Also see (12)]. • There are particular problems in investigating ocean acidification effects on warm-water corals, since these contain symbiotic algae. Thus it is feasible that algal photosynthesis may be enhanced by raised CO_2, thereby indirectly benefitting their animal hosts. For all these reasons, the Jury *et al* results should not be generalised to other organisms. Nevertheless, a fundamental feature of calcification that does universally apply is that the process requires energy, with active H^+ transport

	(out of cells) becoming more difficult under lower pH conditions. Thus a doubling of external H+ concentration can be expected to approximately double the energy required for intracellular pH regulation. Some species do seem able to maintain (or even increase; Wood *et al*, 2008) calcification rates under such conditions. But that response is not a cost-free option. Animals must either obtain more energy by eating more (that will affect food web dynamics) or reduce other physiological processes (such as growth or reproduction). Calcifying plants must photosynthesise more, using nutrients more rapidly. Under competitive environmental conditions, small changes in performance can result in severe outcomes. Indirect ecological implications may, however, not be apparent in relatively short term laboratory experiments where food and nutrients are usually abundant, and competitors and predators absent.
This may explain why study after study keeps finding that, far from depressing growth rates of marine organisms, higher but realistic levels of carbon dioxider eitrher do not affect them or increase their growth rate. By far the most numerous calcifiers in the ocean are called coccolithophores. There is now strong evidence that coccolithophores are growing faster and larger as a result of human carbon dioxide emissions. Stands to reason if they use bicarbonate.	10. A wide range of animal, plant and microbial responses, both positive and negative, to "realistic" ocean acidification has been demonstrated. For some species, different studies have given different results. "Study after study keeps finding..." implies that results all point the same way: that is incorrect. Also see (11) and (12) below. For coccolithophores (micro-algae), the linkages between inorganic carbon uptake, CO_2 usage for photosynthesis, and calcification are not well understood, despite considerable research attention (e.g. Paasche 1964, 2001; Thierstein & Young, 2004). Whilst experiments have sometimes shown larger cell-sizes in CO_2-elevated cultures, their growth has been slower, not faster – and different strains of the same coccolithophore species have shown markedly different responses (e.g. Langer *et al,* 2009). It is difficult to identify the carbon source used by these organisms due to very rapid inter-conversion of carbonate and bicarbonate in seawater, and their short turnover times in cells. This is an active (but technically challenging) research area.
Studies of oyster sperm, cuttlefish eggs, juvenile sea stars, coral polyps and krill all point to the same conclusion: damage only occurs when carbon dioxide reaches ludicrous levels that are not expected for many centuries, if at all.	11. Resilience to ocean acidification has been demonstrated for some animal species, but this is not universal: studies do <u>not</u> all point to the same conclusion. Very many experiments have shown damage at realistic CO_2 levels, including shell degradation, failure of egg-hatching, and sub-lethal effects on metabolic rates and behaviour. The increasing volume of the deep ocean and polar waters in an unsaturated state for calcium carbonate (as either aragonite or calcite) will almost certainly result in such effects occurring on a decadal, not century time-scale.
When I voiced some of these doubts in my latest book, I was accused of cherry-picking studies. So let's look at a "meta-analysis", a summary of relevant published studies. Iris Hendriks and Carlos Duarte, of the Spanish Council for Scientific Research, found that in 372 studies of 44 different marine species "there was no significant mean effect" from lower pH. They concluded that marine life is "more rersistant to ocean acidification than suggested by pessimistic predictions" and that it "may not be the widespread problem conjured into the 21st century".	12. Those wishing to draw attention to ocean acidification as an environ-mental threat should not overstate the case. It is possible that ocean acidification impacts may be less widespread than indicated by "pessimistic predictions". Yet there are still many uncertainties and unknowns. Meta-analyses, such as those by Hendriks *et al* (2010), Kroeker *et al* (2010) and Liu *et al* (2010) have an important role in assembling information on specific groups and on specific processes. Contrary to Ridley's assertion that acidification might benefit calcification, Hendricks *et al* found that "*calcification is most sensitive to ocean acidification*", whilst Kroeker *et al*'s overall conclusion was that *"Our analyses suggest that biological effects of ocean acidification are generally large and negative, but the variation in sensitivity amongst organisms has important implications for ecosystem responses".* Some cautions regarding meta-analyses are, however, necessary. In particular, the wider generalisations of Hendriks *et al* (2010) – who combined all data to conclude that there is overall no significant mean effect – have been subject to considerable criticism and discussion (Dupont *et al*, 2010; Hendriks & Duarte, 2010). Specifically: • Hendriks *et al* did not use standard methods for meta-analyses which standardize studies for precision, account for variation between studies, and test for heterogeneity in effect sizes. • Those authors used multiple responses from the same experiments, hence over-weighting the experiments reporting multiple responses. • Subtle (yet important) features are likely to be lost in meta-analyses, such as varying sensitivities during the life cycle of an organism (eg echinoderms are sensitive as larvae, but resistant as adults) • Whilst positive and negative impacts may (to some degree) cancel out within a single taxon or functional group, the ecological effects of different

	groups responding differently (some winners, some losers) are likely to be cumulative, or even synergistic, with regard to whole-ecosystem response. Kroeker *et al* (2010) used more rigorous criteria for data selection, with their meta-analysis limited to 139 studies where pH manipulations were less than 0.5 units. They also used more sophisticated statistical techniques, including a random effects model, the use of re-sampling to determine significance, and taking much greater account of the heterogeneities in their categorical analyses. Whilst 17 studies were shared by both meta-analyses, results from 56 additional studies were included by Kroeker *et al*. Their overall conclusion, quoted above, is therefore considered robust.
I had assumed the evidence for damage from ocean acidification must be strong because that is what the media keep saying. I am amazed by what I have found. Make no mistake: there are lots of threats to the ecosystems of the ocean, from overfishing to nutrient run-off, but acidification is way down the list. The attention deflects funds and action from greater threats. It is time that scientists had the courage to admit this.	13. There is strong evidence for ocean acidification impacts, even if aspects of this evidence are not always as clear-cut as researchers might wish (or the media might suggest). Increased scientific attention to this topic has shown that the biochemical, physiological and ecological processes are complex. They therefore require additional research to fully understand their ecosystem consequences – and hence to quantify socio-economic implications, and the appropriate scale of policy responses. Until that research has been completed, it would seem premature to either attempt any ranking of relative threat (e.g. compared to over-fishing and nutrient runoff) or to dismiss ocean acidification as unimportant, based on what would seem to be an incomplete and possibly biased assessment of existing information.

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Also: 12 papers on ocean acidification impacts can be found in the Theme Section of *Marine Ecology Progress Series* (2008) "Effects of ocean acidification on marine ecosystems", vol 373, 199-309.

Annex 2: Letter published in The Times on 8 November 2010

Sir,

Matt Ridley (Opinion, Nov 4) should brush up on his basic chemistry and biology before he criticises scientists who worry about ocean acidification.

First, any shift of acidity is still important even if it is (just) within natural ranges; and in the future it will be much larger than that. Second, it has been known for some time that some organisms may make shells starting from bicarbonate ions. But there is abundant evidence that dissolution of their shells is controlled by the carbonate ion concentration, so decreases in carbonate means a problem for retention of shells.

Third, his claim of "no significant mean effect" of predicted future CO_2 levels is only true because that is an average over several processes and many species, among which there will certainly be winners and losers.

Overall, decrease in calcification rate means a change in the ecosystem structure, and probably its function too, with unpredictable consequences. We entirely agree that the jury is out on how damaging acidification will be, but the scientific community is right to be concerned to research this "other CO_2 problem".

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