marginal abatement cost curves can be used to evaluate the probable effects on emissions and the induced total abatement costs. The estimation of costs may be complicated by general equilibrium and trade effects, as well as by co-benefits of induced technological change. I believe, however, that the accounting rules should be simple, and only take into consideration the most immediate of the possible effects. In the presence of significant co-benefits of the policies for the respective country, this may lead to an overestimation of the total costs, but eliminating such effects may render the estimates potentially very complicated and intransparent.

Estimates of abatement costs are already available for many countries. They are often based on specific abatement targets. For example, a recent study evaluates proposals from China and India for their 2020 emissions targets[11]. The results of this study indicate that implementing China's target of reducing the emissions intensity of the economy by 40–45% may require a comparable effort to that implied by the targets announced by the EU and the US. However, to evaluate countries' overall efforts in the area of climate protection, estimates of their total costs that explicitly take into account also their investments into low-carbon technologies will be needed, in addition to their direct mitigation costs.

Let me finally point out that the balanced-efforts approach is also compatible with the adoption of a global carbon tax, which many economists view as the most efficient policy instrument for climate stabilization[1]. While a uniform carbon price can help to implement emissions reductions efficiently, the resulting costs (as percentage of GDP) of such a uniform tax could vary drastically across countries. This could make it hard to reach an international agreement that establishes a uniform carbon tax. To neutralize these cost disparities, a global transfer scheme could be implemented, but this would probably be even harder to agree upon than a global carbon tax, considering the unprecedented amounts of monetary transfers between countries that would be needed. Under a balanced-efforts scheme, such cost disparities can be offset more easily. Countries that suffer less under a uniform carbon tax would simply be asked to contribute more to the other global public good: knowledge in the area of low-carbon technologies. ❐

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COMMENTARY:

Lessons learned from ocean acidification research

Ulf Riebesell and Jean-Pierre Gattuso

Reflection on the rapidly growing field of ocean acidification research highlights priorities for future research on the changing ocean.

Research on ocean acidification has gone through a remarkable surge over the past decade. Known to only a small number of researchers ten years ago, the issue of ocean acidification has developed into one of the fastest growing fields of research in marine sciences, and is among the top three global ocean research priorities[1]. Notably, 50% of the papers have been published in the last three and half years, two-thirds of which deal with biological responses (Fig. 1). The development of this field has greatly benefitted from close collaboration, both within and between national and international projects, from an early community-driven agreement on best practices in ocean acidification research and data reporting[2], from concerted communication spear-headed by a Reference User Group (http://go.nature.com/guz4EE), and from international coordination (www.iaea.org/ocean-acidification). A large number of high-profile reports, targeting the science community and the general public as well as stakeholders and decision makers, have summarized the state of knowledge in this field as concisely and accurately as possible[3,4]. Ocean acidification and its consequences have received growing recognition at intergovernmental levels[5], and more recently also at the governmental level, as reflected by the US State Department's *Our Ocean Conference*, where ocean acidification was one of three topics addressed. In view of its fast and striking development, it is timely to reflect on the successes and deficiencies of ocean acidification research and take a look forward to where the field should be heading.

Where ocean acidification research has clearly made the strongest progress in recent years is at the level of single species or strains with respect to their acclimated (short-term) physiological responses to the single-driver ocean acidification. It is, however, the long-term response of communities, ecosystems and ecosystem services to a multitude of environmental alterations that is of major interest to scientists, citizens, fishermen, ecosystem managers and policymakers. Also of major importance is a better understanding of the potential of marine organisms to adapt to ocean acidification and other co-occurring environmental changes. To fill the knowledge gaps, future ocean acidification research faces three major challenges. It needs to expand (1) from single to multiple drivers, (2) from single species to communities and ecosystems, and (3) from acclimation to adaptation (Fig. 2).

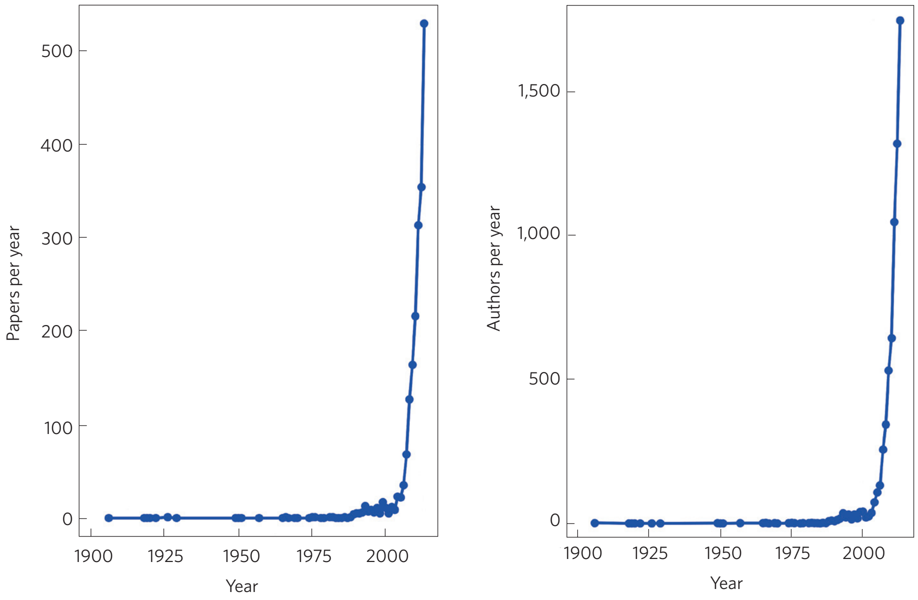

Figure 1 | The number of papers published and number of authors publishing on ocean acidification per year from 1900 to present (data from ref. 15.). The number of papers increased by 35% per year between 2000 and 2013 compared with an increase of 4.8% per year for all scientific fields (Web of Science database).

From single to multiple drivers

Ocean acidification obviously occurs concomitantly with other global environmental alterations, including warming, de-oxygenation, and increased stratification, which in turn alters the availability of nutrients and light. At the regional scale, other factors to consider include eutrophication, overfishing and species invasion and extinction. There is mounting evidence that change in one environmental factor influences an organism's sensitivity to changes in other factors[6]. Owing to interactive effects of two or more drivers, which can be additive, synergistic or antagonistic, it is generally not possible to extrapolate from single- to multiple-driver responses. More recent work has therefore switched to multi-factorial experimental designs (for example, ref. 7); however, these become increasingly challenging when testing for three or more environmental factors. With an increasing number of parameters and processes, comparing studies becomes ever more difficult, as the ranges of values tested are likely to deviate from one study to another. Considering that most biological processes react to environmental changes according to a parabolic function, an organism's response may turn out to be very different depending where the value tested falls on its optimum curve. Different strains of a population are known to have different optima, for example, for temperature[8], and therefore response patterns are expected to be even strain-specific. Thus, an inherent risk in the imperative expansion to multiple drivers is a loss of comparability between data sets and a growing probability of conflicting evidence (challenge 1).

From organisms to ecosystems

Elucidating an organism response to ocean change and understanding the underlying mechanisms is the first step for predicting future changes in ocean biology. But even if the responses of all species to all environmental changes were known, it would not enable the response of communities and ecosystems to be forecast, as that would require additional information on competitive and trophic interactions. Understanding the impacts of ocean acidification at the level of communities and ecosystems, and assessing their consequences for ecosystem services, can therefore only be achieved through a combination of experimental approaches involving natural communities and field studies, taking advantage of natural gradients in key environmental parameters to substitute space for time. While the field studies often suffer from confounding factors that complicate the interpretation of the data, large-scale experimental approaches are usually limited in the number of experimental units, making it difficult to test for multiple drivers (challenge 2). Both approaches generally require large teams of scientists with a long-term commitment and secure funding.

From acclimation to adaptation

It is well established that organisms can adapt to ocean change, either through selection of existing genetic variation or via novel mutations[9]. The adaptive potential is proportional to the population size and generation time, with highest adaptation rates expected for species with large population sizes and short generation times. While these two criteria are met by many taxa in the pelagic and benthic realms, a surprisingly small number of studies have investigated the evolutionary adaptation of marine organisms to ocean acidification or, for that matter, any other environmental driver. The few studies that have been conducted so far indicate that adaptation becomes evident in phytoplankton after only a few hundred generations (about 6 to 12 months) and can compensate, at least partly, the adverse effects of ocean acidification[10,11]. With generation times on the order of days or less for many of the marine microbes, adaptive responses are likely to become substantial on timescales of human-induced global change. Adaptive responses have been found in a few other taxa[12], suggesting its potentially widespread occurrence. The question is not, therefore, whether adaptation can occur but whether it can occur rapidly enough to keep ecosystem functions and services unchanged[9]. Experimental evolutionary studies are typically conducted in culture experiments with isolated strains, eliminating the influence of competitive and trophic interactions. Under these circumstances it is difficult to assess the trade-offs related to the observed adaptive responses, so the

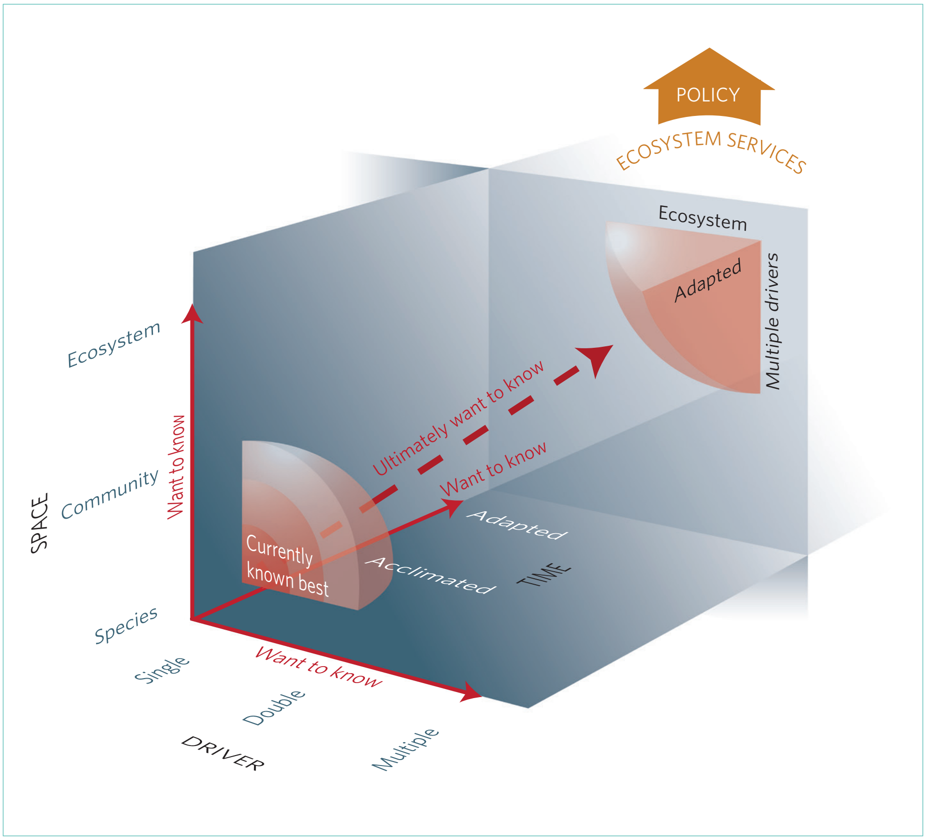

Figure 2 | Present state of knowledge and knowledge needs: most information on the impacts of ocean change currently available is on acclimated single species/strains under the influence of a single driver (lower left corner). Red arrows indicate the direction where we need to expand our understanding. Assessment of impacts on ecosystem services, leading up to science-based policy advice, requires information on adapted responses to multiple drivers at the ecosystem level (upper right corner). Original figure design by Rita Erven.

question remains how representative these findings are for the real world. Owing to the specific requirements of experimental evolutionary studies, including long-term exposure to the variable tested and a high level of replication, these approaches are not easily combined with multiple-driver or community-level approaches (challenge 3).

Future priorities

So how do multiple drivers, species interactions, and adaptation combine to shape the future ocean? The answer is: We won't know until we have tested at the relevant scales! Given the difficulty of conducting well-constrained multiple-driver studies at the community to ecosystem level in long-term perturbations covering adaptive responses, there is a high probability that ocean acidification research, or research on ocean change in general, will split into three major branches addressing the three challenges independently (Fig. 2), which, due to practical constraints, may soon run short of opportunities for joint investigations. Because it will be impossible to examine the sensitivity of every species at all relevant scales, it will be crucial to set priorities. This includes (1) concentrating on reference organisms[13] and keystone species, including ecosystem engineers, (2) identifying commonalities and developing unifying concepts[14], (3) focusing on species, processes and ecosystems considered most vulnerable or most resilient to ocean change, and (4) covering the range of processes from subcellular to ecosystem dynamics and biogeochemical cycling.

Progress will also be contingent on our ability to bridge between the diverging research branches on multiple drivers, competitive and trophic interactions, and adaptation. This requires concerted interdisciplinary efforts, for instance through joint experiments at the community level, long-term, multigenerational studies and a close integration of laboratory, field and modelling studies. Quite crucial in this context will be to establish the funding opportunities for large-scale integrative projects, long-term monitoring, and international collaboration. Because of the urgency of the issue, it is important to pay special attention to aspects that matter most to human societies, that is, those that relate to ecosystem services and may lead to management options and policy advice. The paramount challenge for our research community will therefore be to assimilate the growing knowledge in each of these diverging research branches into an integrated assessment of short- to long-term responses to multiple drivers and their underlying mechanisms at the level of organisms, populations, communities and ecosystems. If this can be achieved successfully, research on ocean acidification and its co-occurring environmental changes is likely to continue its impressive course and may develop into a role model for global change science. ❐

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