recovery in four of the six selected species might have been due to factors unrelated to the drought event (for example, an early recovery could have been superimposed on an unrelated trend in the opposite direction). Just the same, these results have high potential relevance for other drought sensitive taxa and it is frightening how great a shift in land use and CO_2 emissions may be required to aid drought-sensitive species.

The large-scale analysis performed by Oliver *et al.*[3] reinforces the opportunities created by the production of large-scale and long-term datasets, which can frequently only be created with the help of the general public through citizen science approaches. As for birds, monitoring schemes and distribution analyses for butterflies are well established and increasingly deliver data that are used in the study of climate change impacts. For example, one of the most highly cited papers in *Nature Climate Change* dealing with terrestrial biodiversity is entirely based on citizen science data from species distribution and monitoring-based trends of birds and butterflies[6]. Furthermore, "if we are to achieve genuinely informed and effective engagement on climate change issues"[7], having citizens involved as direct contributors to research is surely helpful. For natural scientists, collaborating with the public should be encouraged[8] and is often a step out of their comfort zones that may well contribute to changing our intellectual climate[7]. ❐

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CLIMATE TARGETS

Values and uncertainty

Policymakers know that the risks associated with climate change mean they need to cut greenhouse-gas emissions. But uncertainty surrounding the likelihood of different scenarios makes choosing specific policies difficult.

Robert J. Lempert

Climate change presents a risk management challenge. But covering oneself against this risk is significantly more complex than buying insurance for your car or house. In those cases, accurate actuarial tables exist that define the risk, and one can compare the known costs of premiums with known replacement costs. In contrast, managing climate risks involves judging poorly understood outcomes and likelihoods while engaging people with many different views regarding, for instance, how much to value the present versus the future. Writing in *Nature Climate Change*, Laurent Drouet and colleagues[1] offer an intriguing new take on this challenge, which combines several interesting innovations.

First, they conduct a meta-analysis, extracting a wide range of estimates of future climate change, impacts and mitigation costs from the data generated by the three working groups of the IPCC Fifth Assessment Report[2–4], and extrapolate outcomes over a wide range of futures.

Second, they include deep uncertainty by projecting impacts and future climate using different types of model and considering separately bottom-up versus top-down estimates of mitigation costs.

Third, they consider alternative ethical stances towards risk by using three different decision criteria: expected utility, which weighs all outcomes according to their estimated likelihood; a 'maxmin' criteria that focuses entirely on the worst-case outcomes; and a maxmin expected utility, which considers outcomes from only the worst-case models, but weighs these outcomes by their estimated likelihood.

Fourth, they use an exploratory analysis[5,6], the purpose of which is not to generate a normative policy recommendation, but rather to examine the implications of a wide range of futures and values. In particular, Drouet and colleagues seek to identify self-consistent sets of values, expectations and policies that can inform processes of deliberation and social choice.

Using this analytic machinery, they ask at what level global cumulative carbon budgets should be set, according to each of the alternative decision criteria. They find that with low cumulative emissions targets, uncertainty regarding the cost of mitigation has the biggest impact on the overall cost. With high targets, uncertainty regarding climate impacts has the biggest effect on the costs.

As uncertainty regarding future impacts is larger, the worst-case criterion gives a low cumulative emissions target (one consistent with the internationally agreed goal of keeping warming below 2 °C). The expected utility criterion pays more attention to the best estimates for impacts and mitigation costs, so gives a higher target for any but the lowest discount rate, where the long-term damages begin to dominate the balance of benefits and costs. Interestingly, uncertainty about the climate system weighs least heavily.

Commentators often claim that climate science implies a need for the 2 °C target, but Drouet and colleagues make it clear that our choice depends most strongly on our expectations about the behaviour of future biological and socio-economic systems — that is, the impacts of climate change and the cost of mitigation — and our values, such as preferences towards the future and how much attention we pay to worst cases.

How might the answer have turned out differently if additional futures or criteria were included in the study? Drouet *et al.* extrapolate well beyond the historical data. We have no direct evidence regarding the impacts of a world beyond 4 °C of warming, or one in which a large economy runs without net greenhouse-gas emissions. As people are known to do a poor job of considering worst cases, it is likely that the IPCC estimates are conservative in that regard. Expanding the worst cases considered might significantly affect the distance between the cumulative emissions targets implied by Drouet and colleagues' expected utility and maxmin criteria.

The conditions that favour a 2 °C target might also expand if such an analysis considered a broader range of decision frameworks. For instance, Drouet *et al.* employ only a utilitarian social welfare function that weights all individuals equally. If the analysis added a so-called prioritarian social welfare function[7] that judged policies more by their impact on the poor than on the rich, the conditions that favour low climate targets would include a focus on not only worst cases or low discount rates, but also the amount of attention paid to the poorest among us.

Drouet and colleagues also shed light on the difficult challenge of iterative climate risk management. Combined with uncertainty about outcomes, differing values lead to different global climate targets. But to the extent that policy learning will rely on direct observations of actual system behaviour, we all might prefer to reduce uncertainty by directly exploring the tails of the mitigation cost distribution rather than the tails of impacts distribution, if only because experiments towards the former can be made more localized and reversible.

As such, this analysis suggests that robust climate policy — consistent across many values and uncertainties — might prioritize aggressive efforts aimed towards encouraging and rewarding technological, institutional and social innovations that could forge a path to a zero-emissions economy. ❐

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CLIMATE CHANGE ECOLOGY

Salmon behaving badly

Projected future CO_2 levels reduce the growth of juvenile salmon and alter their behaviour, with implications for the productivity of coastal ecosystems unless populations can adapt.

Philip L. Munday

Pink salmon (*Oncorhynchus gorbuscha*) are anadromous fish that start life in fresh water but spend the majority of their juvenile and adult lives out at sea. Writing in *Nature Climate Change*, Ou *et al.*[1] report that CO_2-induced acidification of aquatic habitats could dramatically affect the performance of young pink salmon during the transition from a freshwater to marine lifestyle.

Pink salmon are remarkable fish — they hatch from eggs buried in the gravel of rivers and streams, emerging into a freshwater environment. The tiny hatchlings, with a yolk sac still attached to their belly, remain close to their birth place for a few months. Once the yolk sac is consumed they migrate downstream to the ocean, where they transition to a saltwater lifestyle. The juvenile salmon grow rapidly in the ocean and in less than two years they return as adults to their natal streams where they spawn and complete their lifecycle[2]. All of the complex physiological changes that enable juvenile salmon to survive in saltwater, after starting life in fresh water, occur while they are just a few centimetres long and weigh less than a quarter of a gram. This is a time of rapid change in the salmon's life and they are also at high risk of predation from larger fishes and other predators.

Ou *et al.*[1] observed reductions in growth, yolk conversion efficiency and maximal capacity for oxygen uptake in juvenile salmon reared at projected future CO_2 levels. Furthermore the juvenile salmon exhibited significant alterations in olfactory preferences and anti-predator behaviour. Salmon have enormous cultural significance in the northern Pacific, they support commercial and recreational fisheries, and they are fundamental to the function and productivity of coastal ecosystems[3]. Consequently, any effects of elevated CO_2 on the growth and survival of juvenile salmon could have far-reaching ecological, economic and social consequences.

When research into the biological effects of ocean acidification started in earnest, a little over ten years ago, fishes were assumed to be largely immune to rising CO_2 and declining pH in the ocean because they have well-developed physiological mechanisms to defend against CO_2-induced acidosis of their blood and tissues. However, carefully designed experiments have since shown that even relatively small increases in ambient CO_2, consistent with climate change projections, can affect the growth, development and survival of some marine fishes, especially during their larval and juvenile stages[4,5]. Even more surprising was the discovery that near-future CO_2 levels can impair sensory functions and alter the behaviour of juvenile fishes[6,7]. A wide range of behaviours are now known to be affected by permanent exposure to elevated CO_2 in marine fishes[5]. A major knowledge gap, however, is the potential effects of rising CO_2 levels on freshwater fishes[8] and those species that start life in fresh water before moving to the sea, such as salmon. Do these species suffer the same impacts of CO_2-induced acidification as marine fishes?

Ou *et al.* set out to answer this question for juvenile pink salmon, the most abundant salmon species in the northern Pacific. Salmon eggs were placed in fresh