Using the traditional approach, with a pure rate of time preference (the marginal rate of substitution between present and future consumption) of 1.5%, DICE indicates carbon taxes of around 40 US$ per tonne of carbon (tC) at present, rising to around 100 US$ per tC by 2050 and leading to emissions of 8.5 Gt yr^{-1} in 2050 with carbon emissions continuing to rise until 2100. Using the authors' approach, present carbon taxes of around 100US$ per tC rise to over 200 US$ per tC by 2050, resulting in an abatement rate of 45% by 2050 and emissions of 7 Gt yr^{-1} in 2050. Global emissions peak decades earlier (in the 2030s), optimal peak global temperature is reduced by 1 °C (from 3.7 °C to 2.5 °C) and optimal CO_2 concentrations are reduced by 120–160 ppm.

The study by Crost and Traeger follows other recent advances in CBA that incorporate uncertainty analysis. Future optimal policies depend on the realization of damages, considering all possible damage outcomes. Damage uncertainty and risk aversion are considered jointly, as recommended by Kopp and colleagues[5].

In particular, the researchers explore the implications of uncertainty about the characteristics of the damage function. The analysis indicates that uncertainty about the form of the function — explained by the lack of observed climate impacts for a temperature rise exceeding 1°C and the tendency of climate impacts projections to focus on temperature increases of 2–3°C — leads to larger optimal taxes. Previous studies[5–9] have also emphasized the influence of the form of the damage function on the optimal level of taxes.

The uncertain damage function exponent follows a normal distribution centred on a value of 2 with a standard deviation of 0.5. A standard DICE2007 climate modelling approach is used, and thus does not encompass uncertainty in climate sensitivity (the equilibrium temperature response to doubling of atmospheric CO_2 concentration), which is set to 3.08. In fact, the dynamical approach required a simplification of the climate model in DICE2007, but the model still performs as well as the original DICE2007 in projecting climate change responses.

The approach used by Crost and Traeger complements existing work that has shown how the traditional approach to CBA needs to incorporate fat-tailed distributions of the damage function exponent and the climate sensitivity to reflect low probabilities of climate catastrophe[7,8,10,11]. These studies also found that optimal carbon taxes were significantly underestimated in the standard CBA approach, but for different reasons.

Ackerman *et al.*[12] adopted a different approach from the incorporation of Epstein-Zin utility into DICE, and also found that emission abatement was more than doubled by 2075. Both studies illustrate the importance of interdisciplinary research in combining insights from different research communities.

Most existing integrated models used in CBA adopt the same generic treatment of consumer preferences. Although Crost and Traeger based their study on an analysis with DICE2007 only, the implication of their work is that most CBA approaches have hitherto greatly underestimated optimal carbon taxes and hence the optimal level of global temperature rise. Incorporation of fat-tailed distributions for climate sensitivity and climate damages[7,8,10,11] as well as declining discount rates[13] — all recommended by economists[9], but not used in this study — would be expected to further increase optimal carbon taxes and further decrease optimal global temperature rise. ❐

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INTEGRATED ASSESSMENT

Modelling agricultural adaptation

Agriculture-focused integrated assessment models may be overstating the ability of poor countries to adapt to climate change. Empirical research can elucidate limits of adaptation in agricultural systems and help models better represent them.

Ian Sue Wing and Enrica De Cian

Producing enough food to satisfy the future demands of a growing world population is a challenge made all the more momentous by the vulnerability of agriculture to climate change. Projecting future crop yields and production at global scales and characterizing associated climatic risk are critically important. The workhorses of this research are biophysical process-based models, which simulate the growth and development of different crops at discrete locations, and integrated assessment models (IAMs), which simulate interactions between the climate and the economy using stylized representations of both systems. However, the resulting projections are only as good as the models themselves, especially when it comes to adaptation. In a forthcoming paper in *Energy Economics*, Thomas Hertel and David Lobell investigate[1] how well models capture both the numerous pathways through which climate affects agriculture and the subsequent adjustments producers make to soften adverse effects. They find current models of tropical areas are generally wanting.

Effects of climate change on crop production and food systems are already being observed in both tropical and temperate areas, with a preponderance

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of negative impacts on agricultural productivity heightening concerns about future food security and the capacity of producers to adapt[2,3]. The article by Hertel and Lobell — part of a special issue showcasing a recent US National Bureau of Economic Research conference on empirical and IAM approaches to climate impacts research[4] — critically examines the state of integrated assessment modelling of agricultural adaptation to climate change, and outlines possibilities for empirical studies to contribute to this area of research.

The authors first summarize the agricultural impacts described in the literature through the lens of key biophysical channels — how elevated temperature and atmospheric CO_2 can affect the growth of food crops — and then inventory the extent to which these pathways are represented in the different types of model used in integrated assessment research. They argue that the historical development of crop models as decision support tools in field management (for example, cultivar choice, fertilizer application rates, timing of planting, harvesting and irrigation) has resulted in the incorporation of only a subset of impact pathways — ones that management changes have the potential to allay. The resulting gaps are a particular worry for the tropics, where most developing nations are located and where temperatures are already above the optimum for many crops[5]. Moreover, the fact that the most frequently omitted processes are associated with biophysical limits to adaptation in tropical agriculture leads models to understate the magnitude of adverse impacts faced by poor countries.

Hertel and Lobell go on to analyse the types of adaptation mechanism incorporated within models. There is a prevalence of 'autonomous' adaptations — those that occur in response to market forces, involve managerial intensity decisions based on known technology, and can be implemented quickly without requiring substantial investments. In contrast, few models simulate 'planned' adaptations in the form of deliberate, costly investments in infrastructure and information acquisition, and thereby miss important ways in which aspects of the broader social and economic environment might impede adaptation. Evidence of this abounds. Agricultural research and development overwhelmingly occurs outside the tropics, and has often yielded returns only after substantial lags. The adoption of new technology typically involves a mix of autonomous and planned responses, but poor farmers are least capable of bearing the risks that accompany such decisions. Although planned adaptations such as public policies, investments in physical and intangible capital, or increased market integration have been shown to benefit farmers' economic environment, these elements are largely absent from modelling studies.

These gaps suggest that models risk overstating the potential for adaptation to agricultural impacts, especially in poor countries. Here too, the problem is structural: difficulty capturing the richer domain beyond market responses results in IAMs systematically downplaying the institutional constraints and market barriers that limit how fast agricultural systems can feasibly adjust. It is in poor countries that such constraints bind most tightly, and producers are most limited in their ability to adopt new technologies and access the markets, credit, insurance and innovations crucial to successful adjustment with current technologies.

Hertel and Lobell argue that empirical research can help address these issues in two ways. One is generating observationally derived estimates of model parameters that are critical to impacts and adaptation behaviour. Priorities include yield responses to temperature extremes, the timing and magnitude of technology and crop productivity improvements resulting from research and development spending, and the diffusion of such advances to non-innovating countries. Another priority is testing models' structural representations of adaptation by comparing their simulated management adjustments with observations in areas where significant climatic changes are already occurring. To what extent are farmers who face higher temperatures actually switching cultivars or crops, adjusting nutrient levels or investing in irrigation, and how do their responses differ depending on how well integrated they are into the global economy? These questions are ripe for investigation because advances in IAMs enable the incorporation of answers. The increasing capability of IAMs to simulate agricultural production at sub-national scales enables them to capture biophysical heterogeneity. The challenge is finding ways to incorporate economic and institutional heterogeneity — both of which are likely to be as important. Equally consequential is the caveat that models' inability to match current or historical observations doesn't necessarily translate into biased projections of the future. Our own view is that complementary research is needed to show how models might be anticipating structural shifts that facilitate adaptation, and rigorously test their assumptions.

Hertel and Lobell[1] paint a sobering picture: the impacts of climate change on agriculture will be most severe in regions where adaptation potential is biophysically constrained and producers are least equipped to take advantage of existing opportunities to adapt. Improving the capabilities of IAMs to capture these circumstances — by using observational studies to identify how and why they arise, and incorporating the relevant biophysical, economic and institutional processes into models' future projections — is our best hope for overcoming barriers to adaptation in the tropics. ❐

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