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Surveys

Challenges and innovations in the economic evaluation of the risks of climate change

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ABSTRACT

A large discrepancy exists between the dire impacts that most natural scientists project we could face from climate change and the modest estimates of damages calculated by mainstream economists. Economic assessments of climate change risks are intended to be comprehensive, covering the full range of physical impacts and their associated market and non-market costs, considering the greater vulnerability of poor people and the challenges of adaptation. Available estimates still fall significantly short of this goal, but alternative approaches that have been proposed attempt to address these gaps. This review seeks to provide a common basis for natural scientists, social scientists, and modellers to understand the research challenges involved in evaluating the economic risks of climate change. Focusing on the estimation processes embedded in economic integrated assessment models and the concerns raised in the literature, we summarise the frontiers of research relevant to improving quantitative damage estimates, representing the full complexity of the associated systems, and evaluating the impact of the various economic assumptions used to manage this complexity.

1. Introduction

Climate change is already having economic impacts around the world and will continue to do so for centuries, but our understanding of how it affects societies and economies is much less developed than our understanding of likely changes in the climate system (Stern, 2013; Auffhammer, 2018). Estimating the economic and social impacts of climate change requires challenging collaborative research between natural and social scientists (Irwin et al., 2018; Ciscar et al., 2019; Stainforth and Calel, 2020). Economists provide important contributions, bringing to bear not only knowledge of impacted markets, but also non-market effects, decision-making under uncertainty, dynamic vulnerability, poverty, and economic development (Stern, 2021).

To make sound policy decisions about the management of climate-related risks, including cost-benefit assessments of adaptation and mitigation actions, estimates of the economic costs of climate change impacts under different scenarios are critically important (Diaz and Moore, 2017). For this to happen, climate hazards, such as shifts in the frequency and intensity of extreme events, need to be translated into climate damages, to estimate the total loss (or gain) in social welfare associated with climate change. Economic assessments of climate change are intended to be comprehensive, capturing: (1) both market (e.g., agricultural production losses) and non-market (e.g., loss of biodiversity or costs of mortality and morbidity) damages (Rogers et al., 2019); (2) impacts of climate change evolving over centuries, including concomitant year-to-year disasters (DeFries et al., 2019); (3) the inequality of impacts; and (4) the challenges of adaptation (Rao et al., 2017). Estimates of the economic risks of climate change have also been developed from bottom-up impact assessments for the United States (Hsiang et al., 2017), the EU (Ciscar Martinez et al., 2014), and globally (Takakura et al., 2019).

There is a notable disconnect between some aggregate economic damage estimates that describe relatively minor impacts compared to the more dire projections coming from non-traditional economics and the climate sciences (Stoerk et al., 2018; Woillez et al., 2020). At present, economic estimates of the impacts of future climate change are widely acknowledged to omit some of the biggest risks (DeFries et al., 2019; Carleton and Greenstone, 2021; Kikstra et al., 2021; Stern and Stiglitz, 2022). As a result, policymakers can be misled about the magnitude and urgency of the challenge the world faces from climate change, and the benefits of investments in adaptation and mitigation (Pindyck, 2017).

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A class of models, called integrated assessment models (IAMs)[1] are designed to combine models of climate change, estimates of environmental changes with economic, social, and technological development, and climate impacts (see Fig. 1). Although many appear in the academic literature, three have been especially influential: DICE (Nordhaus, 2018), PAGE (Yumashev et al., 2019) and FUND (Anthoff and Tol, 2014) (van den Bergh and Botzen, 2014; Ackerman and Munitz, 2016). These models have several limitations, arising from both our incomplete understanding of climate impacts and the more fundamental limitations of traditional economic thinking, as well as uncertainty about the future more generally (Pindyck, 2013; Stern, 2013; Stoerk et al., 2018; Stern and Stiglitz, 2022). Nonetheless, models have an important role to play by providing an opportunity to bring together opposing views and multiple disciplines (Metcalf and Stock, 2017; Weyant, 2017). New research is paving the way to address many of these problems but estimates of impacts that are credible to all relevant parties remain out of reach.

The purpose of this review is to summarise the frontiers of research on areas that could improve the estimation of the social and economic risks of future climate change. This document is not intended to be a comprehensive review of all the relevant research, but instead focuses on literature that has reshaped the frontiers since the publication of the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC). Our discussion is not isolated to IAMs, although this literature is heavily represented below, and we therefore aim to highlight key opportunities for future development across all economic assessments of climate risk.

We further limit our discussion to the evaluation of the risks of climate change impacts and economic damages. An extensive literature uses IAMs and other approaches to study improved mitigation policies and the influence of uncertainty, technological change, and capital investment in these decisions (see e.g., Tavoni et al., 2015; van Vuuren and Kok, 2015; Geels et al., 2016; Gambhir, 2019). A different class of integrated assessment models (process-based IAMs) offers extensive detail on the mitigation process, and mitigation policy evaluation, which we do not discuss here (Clarke et al., 2014; Cointe et al., 2019; Wilson et al., 2021).

We begin in the following section by identifying current challenges to estimating economic impacts. Areas where future research could contribute to the improvement of damage functions are identified on the right of Fig. 1. We expand on some of these open research questions in Section 3 of the paper. Fig. 1 also identifies fundamental economic assumptions that underpin the economic growth model embedded in IAMs. Challenging these assumptions will be an important part of future research to improve the estimation of the social and economic risks of future climate change. Some of these issues are discussed in Section 4.1 of the paper and modelling approaches that provide a framework for examining the economic impacts of climate change under alternative assumptions are introduced in Section 4.2. Section 5 concludes.

2. Challenges of estimating economic damages

2.1. Scientific understanding and model calibration

Economic damages depend upon accurate estimates of climate hazards, models of biophysical impacts, and translations of these impacts into welfare losses. Each of these steps multiplies the level of uncertainty, unknown interactions, and calibration demands. Because of their greater level of abstraction, IAMs are particularly vulnerable to calibration problems. Parameter values are often selected such that, for a narrow range of warming levels, such as 1–3 °C (Diaz and Moore, 2017), estimated damages are consistent with outcomes expected according to common wisdom (Pindyck, 2013). More recent assessments of temperature variability imply that such expected outcomes are underestimations (Calel et al., 2020). Estimates of damages have been shown to be potentially very sensitive to uncertainties about the heaviness of tails of the distribution of expected temperature changes associated with rises in atmospheric concentrations of greenhouse gases, the specification of the damages function, cut-off bounds, the relative risk aversion of society, discounting and rates of pure time preference, and economic growth rates (Weitzman, 2012). Further, it has been argued that catastrophic damages are plausible at higher temperatures, and this necessitates modelling highly non-linear changes in impacts and much greater potential losses at the high end of the temperature distribution (Weitzman, 2010; Kopp and Mignone, 2012; Dietz and Stern, 2015).

The calibration of the damage functions used in cost-benefit IAMs does not reflect the frontier of knowledge in the impact research community. Table 1 provides a summary of recent progress quantifying the impacts of climate change, and SI Fig. 1 compares recent progress with the research represented in the major IAMs. Cost-benefit estimates of current IAMs tend to draw either directly or indirectly on climate impacts literature dating back to the 1990s (Diaz and Moore, 2017; Rose et al., 2017), relying on sectoral studies performed at a time when the understanding of and ability to model climate impacts was significantly less advanced (Kopp et al., 2012). Added to this is the problem that climate change is potentially altering our underlying physical and economic systems, thereby reducing the validity of historic data (Daron and Stainforth, 2015). The sophistication and resolution of estimates of socioeconomically-relevant hazards has also improved, drawing upon impact models (Byers et al., 2018; Lange et al., 2020), although the connection of this work to economic risks is still incomplete.

Multiple lines of evidence are available to improve calibrations. Sector-specific ("bottom-up") damage estimates are available from both econometric models (e.g., mortality, labor productivity, agriculture, crime, and energy demand) and biophysical process models (e.g., agriculture, energy demand, infrastructure, flooding, droughts, and ecosystem losses) (Ciscar et al., 2019). Econometric approaches to aggregate impacts of temperature on economic output ("top-down" estimates) have recently provided an alternative to traditional damage functions, although considerable disagreement remains about the appropriate estimation of these effects (Dell et al., 2014; Burke et al., 2015a). These different approaches also produce different estimates because of the different processes captured (econometric vs. biophysical), different coverage (bottom-up vs. top-down), and handling of non-market damages (economic output estimates vs. welfare losses) (Piontek et al., 2021).

Progress has been made to lower the remaining barriers to including new knowledge into IAM damage functions. Econometric and biophysical models often require high-resolution spatiotemporal weather and socioeconomic data, making them incompatible with aggregate IAMs (Rose et al., 2017). Sarofim et al. (2021) provide a process for translating results into climatology-based damage functions, and Hsiang et al. (2017) develop a flexible architecture for computing damages that is capable of continuously integrating new empirical findings and new climate model projections. However, progress on this issue often requires collaboration between climate, impacts, and CGE modellers, and an institutional base capable of facilitating these collaborations does not yet exist.

2.2. Impact category coverage

Bottom-up estimates of economic damages are incomplete because of the many processes that are understudied. For estimates to be used, they need to have credible methods, empirical validation, and ease of access. Some types of impacts, such as correlated and cascading risks, and climate and social thresholds and tipping points, are particularly

[1] In this document, we focus on cost-benefit IAMs. Another kind of model also called an IAM is a process-based energy model, but these typically do not have climate damage representations (Weyant, 2017).

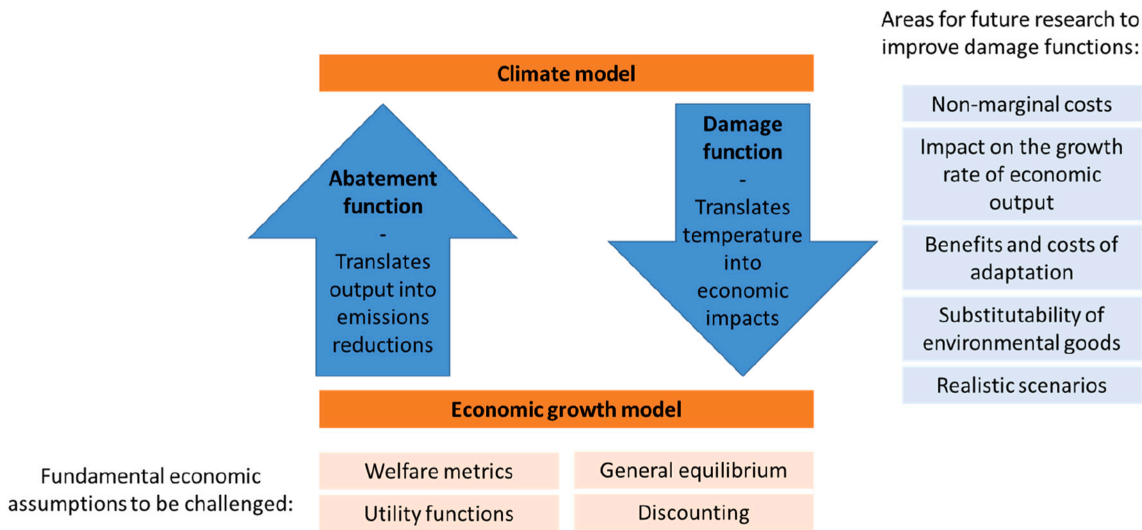

Fig. 1. Features of integrated assessment models explored in this article. The challenges and research frontiers covered in this review reflect a focus on the damage function and economic growth model components of cost-benefit IAMs. Fundamental economic assumptions to be challenged and areas for future research to improve are suggested based on our review of this literature.

Table 1
Progress in impact estimates. Review articles of recent progress in the climate impacts literature, across a range of impact sectors. Discussions of adaptation and areas in need of further research are included in these articles, but we also include rows for reviews of non-impact-specific adaptation and unquantified damages.

Sector	Recent Review articles
Conflict	Burke et al. (2015b), Adams et al. (2018)
Ecosystems	Pecl et al. (2017), IPBES (2019), Olsson et al. (2019) Ch. 4, Mbow et al. (2019) Ch. 5.
Energy supply and demand	Carleton and Hsiang (2016), Cronin et al. (2018), Hoegh-Guldberg et al. (2018) 3.4.9.2
Mortality and morbidity	Carleton and Hsiang (2016), Orimoloye et al. (2019), Son et al. (2019), Hoegh-Guldberg et al. (2018) 3.4.7
Water resources	Kour et al. (2016), Hoegh-Guldberg et al. (2018) 3.4.2
Combined adaptation	Klöck and Nunn (2019), Chapagain et al. (2020)
Unquantified damages	Howard (2014), DeFries et al. (2019)

challenging to estimate.

Much progress has been made in quantifying and monetising effects of climate change. Impacts on agriculture and forestry, water resources, coastal zones, energy consumption, air quality, tropical and extra-tropical storms, human health and mortality, physical performance, cognitive performance, crime, and social unrest have been widely studied and are, at least partially, quantified (Dell et al., 2012; Tol, 2012; Neumann and Strzepek, 2014; Carleton and Hsiang, 2016). However, the impacts across many other sectors remain unclear, particularly non-market impacts and socially contingent impacts - those associated with large-scale dynamics related to human values and equity, such as conflict, famine, and poverty (Watkiss, 2011). There are also physical processes that are not well understood, in terms of both occurrence and impact (Howard, 2014; Revesz et al., 2014; van den Bergh and Botzen, 2014; DeFries et al., 2019). Mora et al.'s (2018) systematic literature search found traceable evidence for 467 pathways by which human health, water, food, economy, infrastructure, and security have been recently impacted by climate hazards such as warming, heatwaves, precipitation, drought, floods, fires, storms, sea-level rise and changes in natural land cover and ocean chemistry.

In-depth explorations of omitted climate-impact channels emphasise the importance of addressing knowledge gaps, but also explicitly recognise barriers to progress, which include a lack of adequate data; uncertainty in forecasts of future climate scenarios; difficulties associated with identifying and disentangling indirect effects; and trade-offs associated with the spatial resolution of data (Hurd and Rouhi-Rad, 2013; Marten et al., 2013; McLeman, 2013; Howard, 2014).

Impacts can also interact through the supply chains, resulting in inter-regional (e.g., crop losses in one area producing food insecurity in an importing country) and inter-sectoral (e.g., food insecurity leading to health impacts) connections. Since the IPCC Fifth Assessment Report, new evidence has emerged on a range of non-trivial interaction effects (Baldos and Hertel, 2014; Zaveri et al., 2016). Computational general equilibrium (CGE) models offer one approach to understanding sectoral impact cascades through supply chains and import/export relationships (Kopp and Mignone, 2012; Ciscar et al., 2019).

2.3. Representations of uncertainty

Extreme risks can be more important than modal outcomes for many issues and actors, and many impact risk distributions have heavy tails (Smith and Stern, 2011). Economic impacts compound multiple sources of uncertainty: uncertainty about the physical nature of future climate change, about the physical impacts of those changes, and about the economic damages that result from those impacts (Dietz, 2012). Although considerable progress has been made to incorporate uncertainty into all major IAMs (Gillingham et al., 2018), and explore long tails (e.g., Ackerman et al., 2010) and risk aversion (e.g., Anthoff et al., 2009a, 2009b), challenges remain.

IAMs most commonly deal with uncertainty through Monte Carlo simulation of a selection of model parameters. Although it is common to take independent draws of parameter uncertainty, physical constraints in the climate system mean they should be jointly sampled, reflecting, for example, the relationship between climate sensitivity and the rate of ocean heat uptake (Roe and Bauman, 2013). Monte Carlo simulations can also be used to capture climate variability and the effects of extreme events (e.g., Kikstra et al., 2021), although this is not common. The simplicity of the damage functions used in IAMs are important for allowing the large numbers of Monte Carlo draws, but new emulation approaches are bridging the gap between these and complex biophysical models (Takakura et al., 2021; Sarofim et al., 2021).

When identifying optimal policies, the Monte Carlo approach assumes perfect knowledge within each deterministic Monte Carlo simulation. In fact, policymakers operate in an environment where decisions are made repeatedly over time as long-term uncertainty is reduced

(Kann and Weyant, 2000; Burke et al., 2016). An alternative modelling approach, stochastic optimisation, captures this dynamic, and results in hedging strategies and other effects of varying risk aversion. Such techniques have been applied in IAMs to investigate policy responses to parameter uncertainty relating to multiple tipping points and the possibility of breaching climate thresholds (Keller et al., 2004; Lemoine and Traeger, 2014; Lontzek et al., 2015; Diaz and Keller, 2016; Lemoine and Traeger, 2016; Lontzek et al., 2016). Further, in the face of significant uncertainty, traditional cost-benefit analysis can fail to represent key decision-making criteria, and alternatives such as minimax regret approaches can be useful (van den Bergh, 2004).

Deep uncertainty describes situations in which conceptual models, probability distributions, and/or the value of various outcomes are unknown or cannot be agreed on (Chen et al., 2021). The existence of deep uncertainty in impacts provides a strong motivation for precautionary policy, as insurance against those disasters (Ackerman et al., 2009). It may be necessary to look to decision-making frameworks that extend beyond the conventional utility-maximizing approach, such as the tolerable windows approach, the safe landing approach, robust decision-making, decision-scaling, the smooth ambiguity model, info-gap decision theory or cost-effectiveness analysis, and ambiguity aversion (Millner et al., 2013; Heal and Millner, 2014; Diaz and Keller, 2016; Simpson et al., 2016; Berger et al., 2017; Stern and Stiglitz, 2022).

2.4. System dynamics and thresholds

Much of the uncertainty inherent in modelling complex interactions between the climate and the economy reflects the lack of complete knowledge and understanding of these systems (Weyant, 2017). An additional source of uncertainty is inherent in the complex dynamics of each system which allows for the possibility of large-scale, nonlinear shifts in the Earth system (Oppenheimer et al., 2014), and the ensuing economic consequences (Wagner and Weitzman, 2015). Included in this list are a range of "tipping points" that have the potential to accelerate climate impacts or make them effectively irreversible.

Lenton et al. (2008) identified nine policy-relevant sources of climate vulnerability to tipping elements from a long list of candidates: Arctic summer sea-ice, Greenland ice sheet, West Antarctic ice sheet, Atlantic thermohaline circulation, El Niño-Southern oscillation, Indian summer monsoon, Sahara/Sahel and West African monsoon, Amazon rainforest, and Boreal forests (see SI Fig. 2). Such nonlinear dynamics do not operate in isolation, and one tipping element can potentially increase the likelihood of other tipping points (Rocha et al., 2018). A global cascade of state shifts represents, arguably, an existential threat to civilization (Lenton et al., 2019) and there is evidence to suggest that real-world examples are already being observed (Caesar et al., 2018; Collins et al., 2019). The timescales and dynamics associated with breaching such critical thresholds in the earth system remain extremely uncertain (Schuur et al., 2015; McKinley et al., 2017).

Similar thresholds and nonlinear effects have been suggested for human systems (Burke et al., 2015b) and biological systems (Thomas et al., 2004), with the potential for cascading impacts, such as mass migrations of people or mass extinctions of species. Kopp et al. (2016) identify four potential social tipping elements that are relevant to integrated assessment of the costs of climate change: public opinion and policy change; technology and behaviour adoption for adaptation or mitigation; migration; and civil conflict. Such amplification mechanisms are also not necessarily negative, with positive tipping elements likely to exist in socioeconomic, technological, and political systems that might deliver, for example, accelerated climate change mitigation (Farmer et al., 2019; Otto et al., 2020; Lenton, 2020), such as learning-by-doing feedbacks in clean technologies.

The leading IAMs have generally failed to reflect the full understanding of most of these negative and positive tipping elements (Lontzek et al., 2015; Farmer et al., 2019). Several studies have attempted to incorporate climate and social tipping points into economic models (Whiteman et al., 2013; Lontzek et al., 2015; Anthoff et al., 2016; Diaz and Keller, 2016; Hope and Schaefer, 2016; Kessler, 2017; Grubler et al., 2018; Nordhaus, 2019; Yumashev et al., 2019). Dietz et al. (2021) perform a model-based meta-analysis combining effects from all IAM studies that include geophysically-based tipping point representations and provide an aggregate "tipping point damage function" which can be used to adjust models that do not include these. However, little is known about the socioeconomic consequences of environmental tipping points, and Dietz et al. only consider outcomes driven by changes in temperature and sea-level rise. Some studies have employed techniques from the field of optimal control under uncertainty to model stochastic tipping elements (Gjerde et al., 1999, Castelnuovo et al., 2003, Lemoine and Traeger, 2016). For example, Cai et al. (2016) incorporate five interacting climate tipping points into a stochastic-dynamic IAM, resulting in nearly an eightfold increase in the social cost of carbon in their results.

2.5. Inequality and spatial heterogeneity

Risk is the interaction of hazard, exposure, and vulnerability, and with respect to climate change, poor communities generally have higher levels of all these factors (Harrington et al., 2018). Climate hazards are expected to increase in many parts of the world, but particularly in the populous tropical, mostly developing, countries (Burke et al., 2015a; Arnell et al., 2019). Developing countries also tend to be highly vulnerable to extreme events as a result of poverty, weak state institutions, insufficient planning, and poor physical infrastructure (Edmonds et al., 2020), as well as having more limited economic and technological capacity to adapt to climatic change (Mertz et al., 2009). Given the centrality of distributional questions to many of the Sustainable Development Goals (SDGs), better modelling of inequality is required with respect to both the impacts and mitigation of climate change (Piontek et al., 2021; Soergel et al., 2021).

A number of barriers exist to incorporating these effects in economic assessments. Models do not currently agree on the relative differences in impacts between developing countries (Watkiss, 2011). Empirical foundations are poor, since estimates of global damages are often based on extrapolations from studies that focus on a small number of richer regions (van den Bergh and Botzen, 2014; Diaz and Moore, 2017). The large regions used in IAMs also mask intra-regional inequality. Dennig et al. (2015) and Budolfson et al. (2017) have shown intra-region inequality can have a greater impact on the social cost of climate change than discounting and catastrophic damages, respectively.

When studying optimal planning, IAMs often exclude the effect of inequality, to separate the climate policy problem from the wealth redistribution problem (Kunreuther et al., 2014; Farmer et al., 2015; Diaz and Moore, 2017). As a result, welfare changes in rich regions and poor regions are implicitly assumed to be equal, despite the greater risks that poor regions face from any level of consumption losses (Stanton, 2011).

Equity-weights have also been employed to correct climate damage estimates. Fankhauser et al. (1997), and more recently Anthoff et al. (2009a, 2009b) and Schumacher (2018), demonstrated how equity weighting can lead to significantly higher global damages from climate change than those reported by unmodified cost-benefit IAMs. As climate damages tend to fall disproportionately on poorer regions, weighting monetary damages by their importance for welfare will tend to increase estimates of global damages (Diaz and Moore, 2017).

3. Some open research questions

3.1. Adaptation

Despite its potential to drastically reduce climate damages, adaptation is one of the least studied areas of climate economics (Burke et al., 2016). The complexity of the adaptation process represents a huge modelling challenge: humans will respond to both the realization and the anticipation of climate change, in ways which will ameliorate hypothetical impacts in some cases, aggravate them in others, and displace the impacts in yet others (Oppenheimer, 2013). Best-responses will be part of a continuous, flexible process, involving learning and adjustment, and plans that incorporate limits to and costs of adaptation.

One barrier which has slowed the incorporation of adaptation decisions into economic assessments has been the lack of data on the aggregated costs and benefits of adaptation (Diaz and Moore, 2017). Assessments of the current state of knowledge on adaptation costs are complicated by gaps in the inclusion of key impact categories. Firstly, a better understanding of the limits to adaptation options and adaptation capacity is required (Trnka et al., 2015; Le, 2020), as well as the impacts of different cost methodologies across climate scenarios and time frames (Sussman et al., 2014; Chapagain et al., 2020). Adaptation practices are also very sector-, impact-, and scale-specific, and a proper evaluation requires a careful bottom-up approach. Recent methodological innovations allow for both the benefits and costs of adaptation to be empirically inferred from observed changes in weather sensitivity for individual sectors, through a revealed preference methodology (Carleton et al., 2020).

There is also limited understanding of how best to incorporate adaptation explicitly into damage estimates and most IAMs fail to do so (de Bruin et al., 2009; Burke et al., 2016). Where adaptation is included in existing damage functions, it tends to be implicit, in the sense that, by assumption, the transition to equilibrium in a new climate state is smooth and instantaneous, ignoring adjustment costs (Diaz and Moore, 2017). Notable exceptions of explicitly modelling adaptation are AD-DICE/RICE (de Bruin et al., 2009), AD-MERGE (Bahn et al., 2019), and AD-WITCH (Bosello et al., 2010). These models show that joint implementation of mitigation and adaptation is welfare improving.

3.2. Changes to economic growth

The use of a damage function itself may be misleading, since it describes damages relative to an exogenous economic trajectory, which is itself unaffected by climate change (Stern, 2013; Dell et al., 2014). It has been argued that the potential disruptions we face at higher temperatures - from large-scale destruction of capital and infrastructure, mass migration and conflict, destruction of ecosystems, adaptation demands that shift resources away from R&D and capital investment - do not characterise an environment suitable for stable and exogenously-growing production (Pindyck, 2013; Stern, 2013). If damages from weather shocks persist, rather than only reducing output within each year, then damages will accumulate over time and the long-term costs of climate change may be orders of magnitude higher than traditional estimates (Pretis et al., 2018), requiring ever more complex and difficult-to-implement policy solutions (Piontek et al., 2019).

There is also empirical evidence of a reduced-form relationship between temperature shocks and gross domestic product (GDP) growth (Moore and Diaz, 2015), but considerable disagreement exists over the details, with considerable variance in estimates (Pretis et al., 2018). A negative impact of higher temperatures on the growth rate is observed in poor countries (Dell et al., 2012; Henseler and Schumacher, 2019; Letta and Tol, 2019). Several studies have shown that the risk to national growth rates is greater for hotter countries (Burke et al., 2015a; Burke and Tanutama, 2019; Kumar and Khanna, 2019; Kalkuhl and Wenz, 2020). A key question is the potential for adaptation to reduce these growth effects, where growth impacts may be mitigated by higher income (Kumar and Khanna, 2019), persistent temperatures (Kahn et al., 2019), and season-specific activities (Colacito et al., 2019). Few studies measure the economic effects of natural disasters over the longer term (Botzen et al., 2019), but Krichene et al. (2021) study the persistence of impacts from tropical cyclones, finding robust evidence that national incomes decline, relative to their pre-disaster trend, and do not recover within 15 years.

3.3. Environmental goods

Ecosystem services provide enormous, but poorly quantified, benefits to society (IPBES, 2019). Initiatives such as BES-SIM and Fish-MIP, have helped to advance understanding of climate-ecology relationships (Bryndum-Buchholz et al., 2019; Rosa et al., 2020). But this is not matched by a comprehensive understanding of the economic implications of climate-related biodiversity and ecosystem service impacts, even though economists have developed a toolbox of techniques for valuing ecosystem services (Sukhdev et al., 2014).

The importance of environmental goods and limitations on the substitutability of these goods with human-produced goods has been long acknowledged (Neumayer, 1999), but ways to translate this issue into economic assessments have lagged. The Dasgupta Review on the Economics of Biodiversity calls for changes to measures of economic success so that Nature, conceptualised as an asset that our economies, livelihoods and well-being all depend on, enters economic and financial decision-making in the same way that human-produced goods do (Dasgupta, 2021). Brooks and Newbold (2014) develop new biodiversity loss and non-use value functions that could be used in cost-benefit IAMs, but this approach excludes use-values associated with tangible ecosystem services. Further work is needed to incorporate the immense risks that climate change poses for biodiversity and ecosystems into economic assessments.

Models often fail to accommodate non-market environmental goods and services, or at most assume that a reduction in environmental services or natural capital can be substituted for by greater economic productivity or increased financial and/or physical capital (Sterner and Persson, 2008, Weitzman, 2009, Barbier and Markandya, 2013). Correctly incorporating in models such environmental costs, and risks of irreversibility justify more ambitious climate change mitigation pathways (i.e., higher social costs of carbon estimates) on economic grounds, without requiring the lower discount rates so hotly debated following the *Stern Review* (Sterner and Persson, 2008). One example is the spectre of complex interconnected and potentially cascading climate risks, such as the impacts of extreme events on energy and water availability which can in turn generate food scarcity and mass migration (de Amorim et al., 2018).

4. Issues involving fundamental economic assumptions

4.1. Utility function preference parameters

The social welfare function translates from individual and instantaneous damages to global losses with an attempt to account for uncertainty, inequality, and time preferences. By collapsing damages to a single metric, the social welfare function allows cost-benefit trade-offs to be evaluated. However, the social cost of climate change, and thereby the benefits of mitigation, necessarily depend upon the ability of the function's parameters to adequately capture different risk preferences, inequality, and discounting (Beck and Krueger, 2016).

In most IAMs, the curvature of the social welfare function, or the elasticity of marginal utility of consumption, simultaneously represents aversion to risk, heterogeneity over regions, and intertemporal substitution (see Fig. 2). This curvature parameter is crucial for translating financial shocks into welfare loss, by effectively weighing the risk of larger shocks, shocks on poorer people, and shocks nearer in time more heavily. Although captured by one value, there is evidence to suggest that these are empirically distinct (Sælen et al., 2009). Possible alternatives are utility functions that separate risk from intertemporal substitution (Epstein and Zin, 1989), risk from current inequality levels (Kreps and Porteus, 1978), or inequality over space and time (Anthoff and Emmerling, 2019). Such alternatives have been implemented in DICE, resulting in a significantly increased social cost of carbon (Crost and Traeger, 2014; Jensen and Traeger, 2014).

Similarly, recognizing the inherent misrepresentation of income

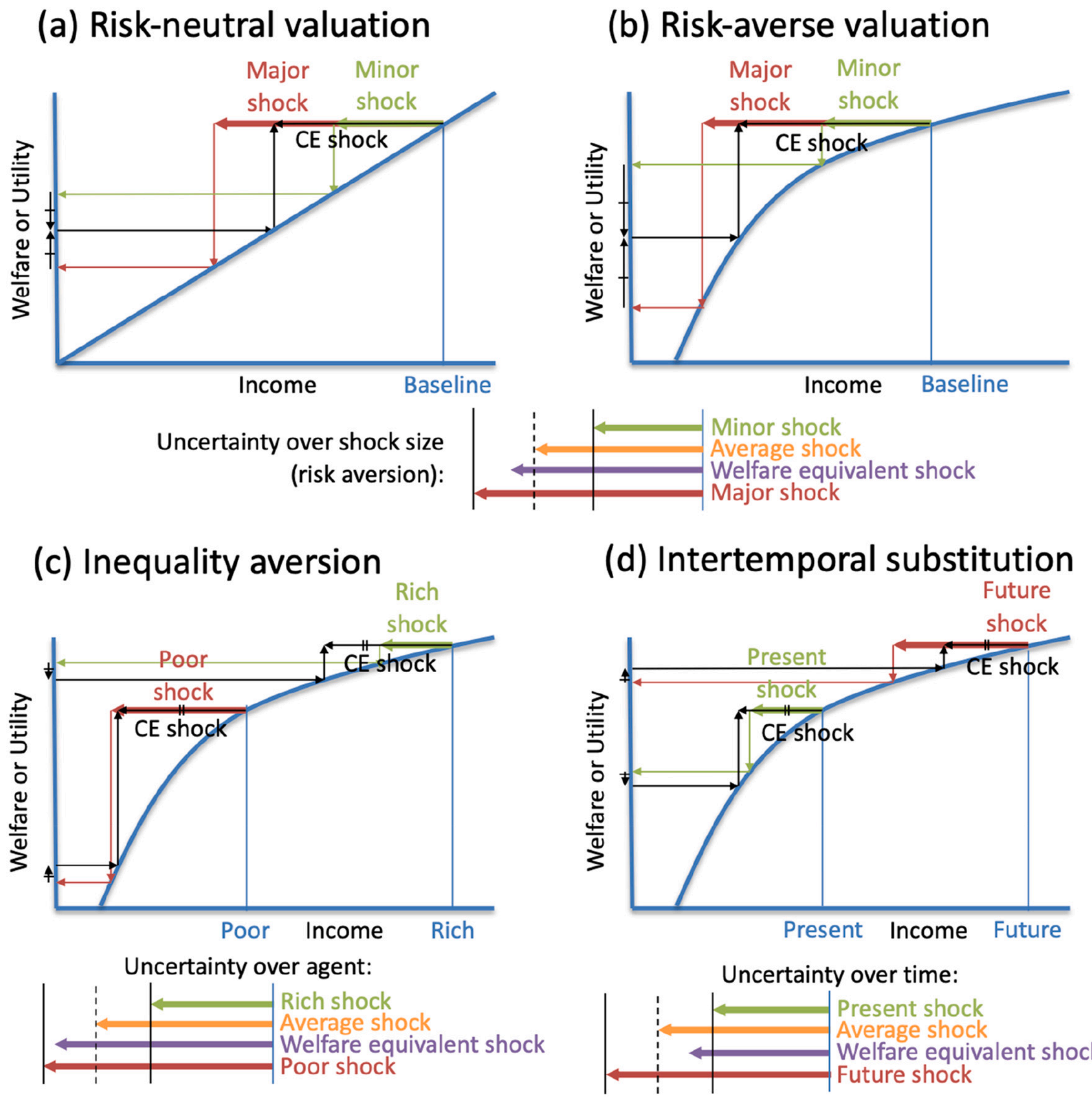

Fig. 2. Consequences of income elasticity over risk, heterogeneity, and time. Each graph shows a utility (for a single agent) or welfare (for a population of agents) function, where concavity represents diminishing marginal welfare benefits from higher incomes. In each case, the derivation of an example certainty-equivalent shock (CE shock) is graphically shown producing the same welfare loss as a pair of shocks arrayed across some dimension of uncertainty or heterogeneity. A certainty-equivalent shock is defined as a single, deterministic reduction in consumption that would produce a welfare loss equal to a given uncertain reduction in consumption, where the uncertainty could be across the size, location, or timing of the shock. Below the derivation graphs, arrows summarise the main consequence of concavity, which effectively weights one shock greater than the other in determining welfare losses, as compared to equally-weighted income losses. (a) A risk-neutral agent is indifferent between an uncertain shock and the mean certain shock. (b) Across uncertainty in the size of shocks, a risk-averse agent loses more welfare for major shocks, resulting in a CE shock closer to the major shock loss than to a minor shock loss. (c) Climate impacts tend to harm poor populations more, such that under a curved welfare function the certainty-equivalent shock is nearly as great as that of the shock experienced by the poor. (d) Future generations are often assumed to be wealthier, and in this case, their greater losses demand little intertemporal substitution, and the CE shock is dominated by the present shock. If future generations are poorer, the effect is reversed, and investment now is incentivised to avoid losses later.

equality in the aggregation of social welfare evaluations has been shown to increase aggregate (global) damage estimates (Fankhauser et al., 1997). This is a similar notion to "prioritarianism" which as an ethical standpoint requires greater weight to be given to well-being changes affecting individuals at lower well-being levels (Adler and Treich, 2015).

Another key social parameter is the pure rate of time preference (PRTP), a measure of the risk associated with not being able to enjoy future consumption (e.g., dying) and impatience, which quantifies the loss of welfare simply because consumption occurs in the future rather than today (Nordhaus, 2007; Stern, 2007). Some have argued for a broadening of such a narrow debate around discount rates to better incorporate issues of inequality and risk (Fleurbaey et al., 2019), and population ethics (Scovronick et al., 2017).

In terms of consensus, a survey of over 200 experts found that, although there is substantial disagreement among experts on their chosen value for the PRTP, the modal value was 0 and 38% of responses were in the range 0–0.1 (Drupp et al., 2018). Hänsel et al. (2020) show that the preference parameters in DICE are not representative of these experts and adjusting them in DICE brings the results more in line with the UN Paris climate goals.

Nevertheless, low values of the PRTP have been criticized because they do not match behaviour observed in market variables, such as interest or savings rates (Nordhaus, 2007; Hampicke, 2011). This disconnect has been explained as a manifestation of the problem of aggregating from individual, subjective preferences to a social welfare determined by an 'outside evaluator' (Kaplow et al., 2010), or due to the application of a *finance-equivalent* discount rate more suited to evaluating Pareto efficiency, versus a *social-welfare-equivalent* discount rate more suited to improving aggregate social welfare (Goulder and Williams, 2012).

One approach to resolving these differences is through Epstein-Zin (EZ) preferences that disentangle risk and time preferences, which both better describe investor behaviour and result in lower PRTP than specified in DICE (Crost and Traeger, 2014). Newell et al. (2021) also provide a framework for harmonizing prescriptive discounting assumptions with projected income growth to inform elasticity and PRTP parameters.

Another approach is to replace the assumption of an infinitely-lived agent, which does not allow for life-cycle saving to be modelled explicitly. An alternative approach uses an overlapping generations model (OLG), which captures intergenerational redistribution and naturally separate private and social discounting (Schneider et al., 2012; Karp and Rezai, 2014). Ergodicity economics offers a related approach, providing a theoretical basis for distinguishing between discounting under certainty and under uncertainty (Peters, 2019).

4.2. Alternative modelling approaches

For some, the assumptions in IAMs are fundamentally flawed because of their grounding in cost-benefit analysis, their simple handling of uncertainty, or their high level of aggregation, and fundamentally different approaches are advocated (Ackerman and Stanton, 2014; Pezzey, 2019). A new wave of literature has emerged that attempts to develop an alternative basis for modelling the consequences of climate change (Farmer et al., 2015; Stern and Stiglitz, 2022), of which four branches are particularly notable.

4.2.1. Alternative ethical and economic assumptions

Several papers have developed economic analyses that relax some of the traditional assumptions of welfare economics. These include limited substitution of environmental goods (Sterner and Persson, 2008), different perceptions of climate risks (van der Ploeg and Rezai, 2019), non-utilitarian ethics (Tol, 2013; Adler et al., 2017), and strong uncertainty (Anthoff and Tol, 2014). In many cases, these adjustments can be done within existing IAMs. Generally, this research provides justification for higher social costs of carbon when we include either non-market environmental goods and services, or fat-tail risks to welfare, or the possibility that future generations might experience lower utility. More broadly, most economic assessments report welfare loss in GDP terms, embedding an assumption that higher rates of GDP per capita are beneficial, and applying alternative measures of wellbeing could shift the narrative considerably (Stiglitz et al., 2010; van den Bergh, 2010).

4.2.2. Process-driven IAMs

Much of this review has been focused on cost-benefit IAMs rather than the alternative process-driven IAMs, such as those used for policy evaluation by the IPCC. Although generally more detailed, most do not model the impact of climate damages on the economy but rather focus on climate change mitigation options. However, some of the important weaknesses of the cost-benefit IAMs pertain to their simple representation of the global economy. The concept of market equilibrium processes is foundational to a class of detailed process IAMs known as Computable General Equilibrium (CGE) IAMs, which are built on assumptions of representative agents, utility/profit maximization and market clearing. Evidence for the prediction accuracy of general equilibrium assumptions is limited but they do provide an approximation of how market forces can distribute economic shocks between sectors and regions (Babatunde et al., 2017). Recent developments incorporating climate damage functions into such process-driven CGE-based IAMs have suggested that including countries' potential climate damages in policy evaluation would facilitate greater action on climate damages by individual countries as a self-preservation strategy (Wei et al., 2020; Piontek et al., 2021). Using an approach that combines a climate damage function with a process-driven IAM, Schultes et al. (2021) show that accounting for climate impacts already occurring below 2 °C substantially raises optimal near-term mitigation efforts.

4.2.3. Analytic IAMs

The complex numeric architecture of computational IAMs means that they are often perceived as black boxes at the user end. The emerging class of analytic IAMs (AIAM) can be helpful tools in facilitating communication between stakeholders and the research community. This work was instigated by the development of an analytically tractable IAM (Golosov et al., 2014), which combines an energy sector model with a linear impulse response of economic production to carbon emissions. Progress in this field has included applications to multi-regional settings (Hassler and Krusell, 2012; Hassler et al., 2019), non-constant discounting (Gerlagh and Liski, 2018b; Iverson and Karp, 2021), intergenerational games (Karp, 2017), regime shifts (Gerlagh and Liski, 2018a), a decentralized market economy (Rezai and Van der Ploeg, 2016), and uncertainty (Traeger, 2021). Such models generated novel insights into the role played by key model assumptions around the substitutability of energy sources; the costs of inaction; the value of committed long-term policies; and attitudes towards intergenerational equity.

4.2.4. Agent-based IAMs

Balint et al. (2017) survey the agent-based literature on the economics of climate change and identify four areas where introducing heterogenous agents can be particularly important in overcoming some of the limitations of cost-benefit IAMs. These include incorporating (i) coalition formation and climate negotiations, (ii) macroeconomic impacts of climate-related events, (iii) the dynamics of energy markets, and (iv) diffusion of climate-friendly technologies. A new class of IAMs use agent-based modelling to allow micro-level interactions between agents representing households and firms with heterogeneous preferences, imperfect knowledge, and localised climate and economic shocks (Lamperti et al., 2018; Czupryna et al., 2020). Although such models face challenges in modelling both the benefits of mitigation (agent-level damage relationships are nascent) and the costs of mitigation (emissions estimates require a more fine-grained representation of the energy and land use systems), they represent an encouraging prospect for future research (Lamperti et al., 2019).

5. Conclusion

Despite the criticisms levelled at IAMs and the uncertainties underlying their results, IAMs have been instrumental in highlighting the role of discounting and economic growth, welfare damages, and uncertainty in evaluating alternative policies (Nordhaus, 2014; Weyant, 2017). Although we have described a myriad of current challenges with IAMs, the field is making progress in the economic evaluation of climate impacts. A summary of some of the key dimensions of the research frontier is shown in Table 2.[2] This is not an exhaustive list of this broad field of research but provides an overview of the direction of future research. Cost-benefit IAMs exist as tools employed within this field of research but by necessity are simplifications of the wider research, and so do not necessarily cover every aspect. All IAMs appear to be heading towards greater sophistication, however they are likely to progress behind the wider research frontiers and may never incorporate some developments given the inherent complexity of these problems (e.g., conflict and

[2] This table was inspired by Watkiss (2005) and developed based on an interpretation of the research frontiers by the authors following a 2020 workshop on "Strengthening Understanding of the Economic Impacts of Climate Change" hosted by Grantham Institute (LSE), Oxford University, and UK Department of Department for Business, Energy & Industrial Strategy.

Table 2
A summary of key dimensions on the research frontier in the economic evaluation of climate risks. Traditional approaches (column 1) are still reflected in many estimates of economic risk (e.g., the SCC), but there is established research that offers an expanded perspective (column 2). The research frontier in each dimension offers many new opportunities (column 3), while there remain significant undeveloped areas of enquiry (column 4). The items listed under Specific climate impacts are a subset of relevant impact types which are under-represented in IAMs, and these rows describe the progress in underlying biophysical impact, however economic valuation of these (e.g., morbidity, SLR adaptation costs, ecosystem service loss) are notably incomplete.

	Traditional	Established	Frontier	Undeveloped
Data inputs for estimating impacts				
Climate-related data	Global resolution	High resolution downscaled	Extreme events, tipping points	Deep uncertainty associated with a changing physical system
Data for evaluating impacts	Marketable goods, infrastructure	Physical inputs (e.g., water, crop yields, labour)	Spatially disaggregated GDP impacts, developing country data	Non-market valuation, ecosystem services and biodiversity loss indicator
Methodologies for producing damage functions				
Econometric methods	Cross-sectional statistics	Econometric models	Econometrics w/ heterogeneity	Empirically calibrated adaptation
Process-based methods	Point-calibrated models (e.g., individual, field)	Coupled models (e.g., water-energy-food)	Gridded and global models, adaptation	Improved representations of uncertainty
Top-down economic impacts	Expert elicitation	Econometric relationships	Non-linearity and persistence	Drivers of long-term adaptation
Features of cost-benefit IAMs				
Regional heterogeneity	Global	Continental	National/ subnational	Local/municipality
Tipping points	ECS feedbacks[a]; economic catastrophe risk	Analytical decision-making	Multiple tipping points, endogenous technological change	Socioeconomic tipping points; socially-contingent outcomes
Equity	Social-welfare function using observed savings and interest rates	Social-welfare function using ethics-based pure time preferences	Separation of intra- and inter-generational equity	Heterogeneous agents with risk preferences vulnerability
Features of non-IAM economic assessments				
Response-times studied	Static changes	Immediate responses	Short-term resilience	Long-run adaptation
Agent-level decision-making	Ignored	Technology adoption studies	Sector-specific adaptation	Agent-based modelling
Specific climate impacts				
Health and disease	Climatic temperature responses	Weather shock responses	Accounting for adaptation; Vector-borne diseases	Multi-disease vulnerability
Sea-level rise	High-tide inundation	Storm surge damage	Cost reduction under optimal protection	Political economy of protection decisions
Ecosystems and biodiversity	Species environmental suitability	Managed ecosystems (e.g., fisheries, forests)	Multispecies interaction	Changing and mosaic environments
Cascading impacts	Qualitative assessment	Summed independent impacts	CGE[b]-mediated equilibria across static risks	Empirically grounded microfoundation models, simultaneous and cascading impacts

[a] ECS- equilibrium climate sensitivity- is the long-term global temperature rise that is expected to result from an increase in atmospheric CO2 concentration. The use of a constant ECS does not produce any tipping point dynamics, but it captures the average outcomes of any tipping points that are included in its calibration.
[b] CGE- Computational general equilibrium models used in traditional economic representations of market dynamics.

migration).

New evidence on the economic risks of climate change is emerging rapidly from both the econometric and process-based research communities. Updated damage estimates have been integrated into IAMs for economic growth (Moore and Diaz, 2015) and agricultural productivity (Moore et al., 2017) resulting in large increases in SCC estimates. New methodological approaches are developing the evidence base for the costs of adaptation, the existence and persistence of growth impacts, and the economic risk to non-market goods. Simultaneously, science from the biophysical process modelling community has begun to converge through the work of model intercomparison projects, as these models continue to improve in resolution and the handling of adaptation (Warszawski et al., 2014).

The US National Academy of Sciences has produced suggestions on needed improvements (National Academies of Sciences, Engineering, and Medicine, 2016, 2017), and Resources For the Future is engaged in a multi-pronged project to implement these changes. This work is partly built upon the recent open-sourcing of RICE, PAGE, and FUND under a common modelling framework (Moore et al., 2018).

Thus, it appears that, with regards to improving the science behind economic assessments, much progress has been made but there are many opportunities for continued advancement. There is, simultaneously, a diversification of models specialising in different features and insights, and both improvements in existing models, along with a generation of new models based on alternative principles. However, difficulties in communication between natural scientists, economists, and modellers remain, slowing the scientific process (Ciscar et al., 2019). Interdisciplinary groups remain rare. Bridging the climate-economic-model cultures and improving models will require the repeated, collaboration-focused convening of researchers engaged in all aspects of the problem.

Important progress in this area may come from outside economics including health, politics, psychology, and anthropology. For modellers to be able to address the shortcomings of the economic models, they will require increased collaboration, and a consistency of assumptions from both climate scientists and economists. Modellers need guidance on other metrics that are relevant to policymakers and other researchers.

Welfare is largely calculated from consumption levels using simple relationships, which could be better informed by behavioural economics and a better understanding of social heterogeneity, and which could take a wider range of inputs and produce a more comprehensive set of output metrics. Further strategic communication and engagement is needed with stakeholders, who are the ultimate users and beneficiaries of climate impact assessments.

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J.R. and R.W. conceived the review. C.T. lead the literature review. J. R., R.W., C.T., and M.I. contributed equally to the writing of the text.

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Declaration of Competing Interest

The authors declare no conflicts of interest.

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Appendix A. Supplementary data

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