Online Supplementary Material: Taxonomy of Integrated Assessment Models

There are three general categories of integrated assessment models: reduced-form, detailed-structure, and agent-based integrated assessment models (NAS, 2017). Reduced-form integrated assessment models represent the climate, the economy, and their interaction at a highly aggregate scale. As their original purpose was to identify the socially optimal emissions and carbon price paths as well as measure the external damage of an additional unit of carbon dioxide on the Business-As-Usual (BAU) emissions path (i.e., the social cost of carbon) to include in benefit-cost analysis, these models include a climate damage function that captures the impact of temperature on GDP (John Weyant, 2017; NAS, 2017). There are several types of reduced-form IAMs: social-cost IAMs (DICE, FUND, and PAGE); computable general equilibrium IAMs (ENVISAGE, ICES, and ENV-Linkages); stochastic dynamic IAMs (DSIC); and analytic IAMs (DSGE).

Detailed-structure IAMs consist of detailed representations of climate systems, the economy (regional and sectoral), climate impacts and adaptation, and energy and technology (including costs of mitigation and adaptation). Traditionally, these models were developed to estimate socioeconomic and emissions trajectories accounting for technologies and policies, though more recently they are also used to study climate impacts, risk, and adaptation, including regional and sectoral interactions, analyze detailed real-world policy proposals, and conduct cost-effective analyses to meet various emission targets (NAS, 2017; Weyant, 2017). Some commonly applied detailed-structure IAMs include AIM, IMAGE, GCAM, MESSAGE, and REMIND (IWG, 2010; Weyant, 2017; IPCC, 2018).

There are also hybrid IAMs that combine a top-down macroeconomic growth model from reduced-form IAMs and a bottom-up technology model from detailed-structure IAMs (Valentina Bosetti et al., 2006; Alan Manne & Richard Richels, 2005; Marcucci & Turton, 2012; Kenneth Gillingham et al., 2018). These models are sometimes classified as reduced-form IAMs (Gustav Engström & Johan Gars, 2015) when the option of including a climate-damage function is exercised, such that the social cost of carbon can be calculated (Gillingham et al., 2018), and other times as detailed-structure IAMs (IPCC, 2018; Allen Fawcett et al., 2009) when these models are used to develop socioeconomic emission scenarios (IPCC, 2018; Fawcett et al., 2009). The two main hybrid IAMs are World Induced Technical Change Hybrid Model (WITCH) and Model for Evaluating Regional and Global Effects of GHG Reduction Policies (MERGE) (Bosetti et al., 2006; Manne & Richels, 2005).

Agent-based integrated assessment models (AB-IAMs) model behavior at the microeconomic scale and then predict macroeconomic phenomena. Specifically, AB-IAMS are based on models of heterogenous individual actors (individual households and firms) and their decisions within a hierarchical structure (neighborhoods and industrial sectors) (Li An et al., 2012, 2014; Francesco Lamperti et al., 2019). Agent-based IAMs are aimed at capturing fuller and more realistic economic behavior (as reflected in ecological macroeconomics), including connections and market failures, to study the sustainability of the climate-economy system and the impact of policies on the stability of the system, estimate climate damages, and identify emergent behavior. Dystopian Schumpeter meeting Keynes (DSK) is the first agent-based IAM (Lamperti et al., 2018).

There are several types of reduced-form IAMs that can be grouped by how they treat uncertainty. There are deterministic (also known as conventional) IAMs in which uncertainty is addressed using Monte Carlo simulation (i.e., solving multiple deterministic models after drawing parameter values from their underlying distributions). Deterministic IAMs can be further subdivided into social-cost (SC) IAMs and computable general equilibrium (CGE) IAMs. SC-IAMs have aggregate structures particularly designed to calculate the social cost of carbon and the socially optimal carbon tax (NAS, 2017). These models include Dynamic Integrated model of Climate and the Economy (DICE); the Framework for Uncertainty, Negotiation and Distribution (FUND) model; and the Policy Analysis of the Greenhouse Effect (PAGE) model (William Nordhaus, 2017; Stephanie Waldhoff et al., 2014; Chris Hope, 2013). Following the development of SC-IAMs, several modelers built computable general equilibrium (CGE) integrated assessment models; these include the Environmental Impact and Sustainability Applied General Equilibrium Model (ENVISAGE), the Intertemporal Computable Equilibrium System (ICES) model, and the ENV-Linkages model (Roberto Roson & Dominique van der Mensbrugghe, 2012; Francesco Bosello et al., 2012; Rob Dellink et al., 2019). Like detailed-structure IAMs, CGE models represent the sectoral and regional breakdown of the economy and the interactions between them, though at a relatively aggregate scale, as well as formally represent feedbacks between the climate and the economy at this sector-regional scale as well as inter-sector and inter-regional relationships within the global economy (Dellink et al., 2019). Unlike SC-IAMs, CGE-IAMs' damage functions affect economic activity through shocks to productivity, input availability, and consumer demand (Roson & van der Mensbrugghe, 2010; Bosello et al., 2012; Dellink et al., 2019). As the primary goal of CGE IAMs is to estimate climate damages to capture indirect economic effects through their computer-generated equilibrium structure, CGE-IAMs do not represent non-market impacts and do not generally focus on estimating the social cost of carbon.

More recently, several teams of economists developed stochastic dynamic IAMs, also known as recursive or stochastic IAMs, to represent optimal decision making under uncertainty. In traditional deterministic SC-IAMs, analysts address uncertainty using Monte Carlo simulations where the deterministic model is run a series of times after randomly drawing parameter values for each run from the underlying parameter distributions and then calculating the average social cost of carbon; this implies a highly stylized representation of uncertainty whereby the true values of uncertain parameters are unknown to the representative agent in the present period, though they will perfectly learn their true values in the near term (Frank Ackerman et al., 2010; Benjamin Crost & Christian Traeger, 2013). Unlike SC-IAMs, stochastic-dynamic IAMs assume persistent uncertainty and that the agent is aware of this uncertainty and ongoing future learning about the climate-economy when making their decisions. While stochastic dynamic IAMs more realistically model decision-making uncertainty, they are limited by their need to simplify the state space due to the curse of dimensionality (though, numerical methods are improving to overcome this issue) (Traeger, 2014; Derek Lemoine & Ivan Rudik, 2017) and their inability to represent non-optimal emissions paths in general. For these reasons and due to the relative transparency of SC-IAMs via simplicity, SC-IAMs remain more policy-relevant than stochastic dynamic IAMs (Crost & Traeger, 2013). Most stochastic dynamic IAMs are stochastic extensions of existing social-cost IAMs, like DICE (Yongyang Cai et al., 2016; Lemoine & Traeger, 2016; Lemoine & Rudik, 2017), including the dynamic stochastic integration of climate and economy (DSICE) framework (Cai et al., 2016).

A subset of stochastic dynamic IAMs are analytic IAMs, which are simplified models that allow for closed-form solutions to the optimal carbon tax or, in some limited cases, the social cost of carbon. However, beyond the simplifications made by stochastic dynamic IAMs in general, these models require stylized and highly simplifying assumptions to maintain tractability (OECD, 2018; Lemoine, 2021). In other words, this literature overcomes the transparency problem of numerical stochastic dynamic models, and to some extent SC-IAMs, at the expense of imposing bold (and potentially incorrect) assumptions.[1] While new analytic IAMs relax these analytic assumptions over time to improve their approximation of numerical estimates (Lemoine & Rudik, 2017; Traeger, 2021), their primary advantage is still their ability to aid policymaker understanding via their relative simplicity (J. Doyne Farmer et al., 2015; OECD, 2018). Like stochastic dynamic IAMs more generally, analytic IAMs have not been embraced by policymakers, potentially because SC-IAMs and other reduced-form IAMs are already relatively simple and easy to understand.

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[1] For example, Mikhail Golosov et al. (2014)'s Dynamic Stochastic General Equilibrium (DSGE) model, the first prominent analytic IAM, makes many simplifying assumptions to linearize the climate-economic problem (Lemoine & Rudik, 2017): logarithmic utility; the representation of the entire climate system using the atmospheric carbon concentration as a linearization of current and past emissions; a constant savings rate; a damage function (measured as a % of GDP) with a constant elasticity relationship to emissions; a full depreciation of capital in each period; and others.

The set of reduced-form IAMs that can calculate the social cost of carbon and other greenhouse gases are social cost of greenhouse gases (SCG) IAMs. Currently, three types of IAMs can calculate the social cost of greenhouse gases: social-cost IAMs, hybrid IAMs, and a limited set of analytic IAMs. The social cost of carbon (SCC) used in cost-benefit analyses of major federal regulations in the United States relies on SC-IAMs. Thus, we focus our attention on the three social-cost IAMs due to their prominence in research and U.S. policy (Bosetti, 2021). In comparison, the hybrid IAMs add additional (potentially unhelpful) complexity and analytic IAMs are not well suited for including feedback effects due to tractability requirements (IWG, 2010; NAS, 2017). Instead, we attempt to integrate reduced-form approximations of climate-society feedback effects into the existing aggregate structures of SC-IAMs to maintain the simplicity that has made them so valuable to policymakers thus far.

Additional References

Ackerman, Frank, Elizabeth A. Stanton, and Ramón Bueno. "Fat tails, exponents, extreme uncertainty: Simulating catastrophe in DICE." *Ecological Economics* 69, no. 8 (2010): 1657-1665.