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Modelling what matters: How do current models handle environmental limits and social outcomes?

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ABSTRACT

Models that represent the economy, society, and environment are critical macroeconomic policy tools. However, economic output as measured by Gross Domestic Product (GDP) is increasingly being seen as an unreliable and undesirable economic indicator and policy goal. Instead, multiple indicators of environmental impacts and social outcomes are needed to make decisions about sustainable development.

Drawing on the Doughnut of social and planetary boundaries, and the Sustainable Development Goals, we analyse 50 models to assess the state of the art in modelling the environment, society, and economy. We categorise models according to their economic foundation and modelling approach, assess their coverage of 15 environmental and 21 social indicators, and identify feedbacks between different model parts. We further construct a targeted sample of 15 models that represents the diversity in modelling approaches and indicator coverage, and use this sample to investigate how environmental and social indicators are linked to macroeconomic drivers.

For the environment, indicator coverage is best for climate change, energy use, and land conversion. Within current models, environmental impact is largely driven by GDP and agricultural production. For society, coverage is best for jobs, income (wages and inequality), and productivity. Within current models, social outcomes are largely driven by income per capita, government spending, and governance. Models rarely contain feedbacks from the environment and society to the economy, and few include any biophysical limits.

The current focus on monetary flows limits understanding of the interconnections between environmental, social, and economic systems. We argue that modellers should rely less on economic variables as determinants of social and environmental outcomes. Specific provisioning systems could be modelled in more detail to allow models to explore growth-agnostic ways of achieving a good life for all within environmental limits.

1. Introduction

No country in the world meets basic needs for its citizens at a globally sustainable level of resource use (O'Neill et al., 2018). As such, one of the most pressing challenges for the 21st century is how to achieve human wellbeing and equity within planetary boundaries. To address this challenge, we need a better understanding of the interactions between environmental, social, and economic systems (Hafner et al., 2020; Hardt and O'Neill, 2017; Wiebe et al., 2023). Economic discourses that treat these systems in isolation or that rely on a one-dimensional indicator to evaluate performance cannot provide the information that is needed (Brand-Correa et al., 2022). Instead, we need models that integrate multiple environmental, social, and economic systems and that use a variety of indicators. In this article, we analyse the inclusion of environmental and social indicators in existing macroeconomic models.

Mainstream economics has been criticised for treating the economy as operating in isolation from the broader social and environmental systems in which it is embedded (Daly and Farley, 2011; Martinez-Alier and Schlüpmann, 1990; Schneider et al., 2010). The Doughnut of social and planetary boundaries has emerged as a useful framework for envisioning the environmental and socioeconomic challenges of our times (Raworth, 2017a). It defines a set of non-substitutable social thresholds and planetary boundaries, delineating a safe and just space for humanity where basic needs are met for all without overburdening the planet's

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ecosystems.

The Doughnut provides measurable targets, but it does not explicitly address how to achieve them. To explore possible pathways towards a sustainable future, several academic fields have developed models that link the economy with environmental and social systems. We refer to this class of models as Environment–Society–Economy (ESE) models. These models approach policy simulation more holistically, as economic outcomes can be assessed together with environmental and social outcomes. There are various types of ESE models, such as integrated assessment models (IAMs), general and partial equilibrium models, and system dynamics models.

Planetary boundaries and human needs have received increased attention from policymakers, for instance through the adoption of the Sustainable Development Goals (SDGs) by the United Nations, or the implementation of Doughnut Economics Action Labs by local governments (DEAL, 2024). This new policy focus is reflected in ESE models, and some studies discuss the possibility of including SDGs in specific model types such as climate–economy models (van Soest et al., 2019) and IAMs (Koasidis et al., 2023). However, a structured analysis of the inclusion of the Doughnut framework's social and environmental indicators across different model types is lacking in the literature. Furthermore, it is not clear what general approaches are used to model these indicators.

This article addresses these two gaps by assessing the level of adoption of important environmental and social indicators in ESE models, drawing on the Doughnut framework and Sustainable Development Goals. We examine (1) the prevalence of different environmental and social indicators, (2) the approaches used to model these indicators, and (3) the driving variables that affect these indicators. By providing a better understanding of common modelling formulations for a broad set of environmental and social indicators, we aim to help facilitate their inclusion in existing models. Additionally, our analysis highlights which indicators are currently missing, providing directions for improvement.

The remainder of this article is structured as follows. Section 2 discusses the literature on the Doughnut framework, types of ESE models, the distinction between neoclassical and heterodox economics, and the advent of ecological macroeconomics. Section 3 discusses the methods we used to assess the coverage of indicators. In Section 4 we present the main results from our analysis, and in Section 5 we discuss key insights originating from this analysis. Section 6 concludes by arguing that although some environmental and social indicators are well covered, more work is required to ensure a broad inclusion of important indicators in ESE models.

2. Literature review

2.1. The Doughnut of social and planetary boundaries

The concept of planetary boundaries has emerged as a focal point in environmental research, emphasising the critical Earth system processes that have sustained the Earth's climate in the stable Holocene epoch, a period conducive to the flourishing of human societies (Rockström et al., 2009). This framework delineates a "safe operating space" by defining nine planetary boundaries. Exceeding these boundaries increases the risk of destabilising the Earth system. The Sustainable Development Goals include multiple targets that relate to these boundaries (Randers et al., 2019). Recent research highlights the severity of the situation, as six of the nine planetary boundaries have now been transgressed (Richardson et al., 2023) and there are growing concerns about the probability of achieving the SDGs by 2030 (Leal Filho et al., 2023).

The economist Kate Raworth has expanded upon the planetary boundaries framework through her work on the Doughnut of social and planetary boundaries (Raworth, 2017b). Within this framework, the ecological ceiling provided by planetary boundaries is complemented by a social foundation, which establishes minimum social thresholds to avoid critical human deprivation (Fig. 1). Together, these two sets of boundaries determine a "safe and just space", where human prosperity is not at odds with the preservation of a good life for future generations. However, previous research has shown that, currently, no country operates within this safe and just space (O'Neill et al., 2018). Furthermore, historical analysis shows that countries are transgressing planetary boundaries faster than they are achieving social thresholds (Fanning et al., 2022).

The looming threats of ecological and societal breakdown make the question of how to achieve a good life for all within planetary boundaries even more urgent. This question remains the subject of vigorous debate (Grunwald, 2018; Starke et al., 2023). Some argue that economic growth can continue in an environmentally sustainable manner, effectively decoupling economic activity from its impact on the Earth system (Bowen and Hepburn, 2013; Drummond et al., 2021). Proponents of post-growth theories challenge this narrative with empirical evidence to the contrary (Haberl et al., 2020; Parrique et al., 2019; Vogel and Hickel, 2023), emphasising the need to separate wellbeing from material throughput (Jackson and Victor, 2019a) and to transform the provisioning systems that satisfy human needs (Fanning et al., 2020; Vogel et al., 2021).

2.2. Types of Environment–Society–Economy models

Environment–Society–Economy models have proven to be an essential tool to simulate possible transition scenarios and to evaluate policy proposals. To create structure in the diverse modelling landscape, several taxonomies have been proposed. We employ existing model categorisations, building mainly on previous reviews of macroeconomic approaches to modelling environmental and social outcomes by Wiebe et al. (2023) and Hardt & O'Neill (2017). This taxonomy consists of six categories, namely equilibrium models, integrated assessment models, macro-econometric and input–output models, stock–flow consistent models, system dynamics models, and "other" models (to capture those not completely fitting in the previous categories).

It is essential to recognise that these categories are not mutually exclusive and that their boundaries are fuzzy. As such, models may fit into multiple categories when they combine different techniques. For example, input–output and stock–flow consistent approaches can be

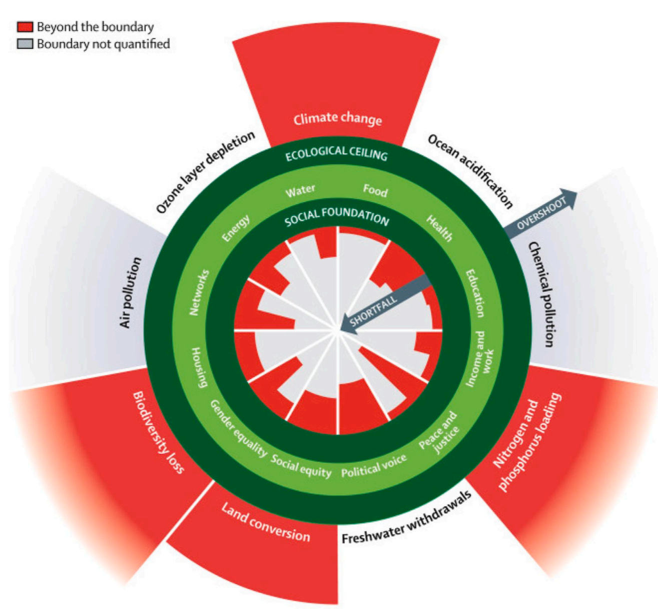

Fig. 1. The Doughnut of social and planetary boundaries. The figure shows substantial shortfall, with respect to meeting human needs, and substantial overshoot, with respect to planetary boundaries, at the global scale. Source: Raworth (2017b) under a Creative Commons 4.0 license.

added to many other approaches and are not necessarily standalone models. Results can be simulated either through optimisation techniques (e.g. general equilibrium) or non-optimisation approaches (e.g. system dynamics). Furthermore, within each category, substantial diversity in theoretical and ideological foundations exists.

Equilibrium models include all optimisation-based models that maximise or minimise a single objective, usually welfare or cost, respectively. These models are typically based on neoclassical assumptions. The main classes are computable general equilibrium (CGE), partial equilibrium, and dynamic stochastic general equilibrium (DSGE) models. Some examples are E-QUEST (Janos et al., 2021) and MAGNET (Shutes et al., 2018).

Integrated assessment models (IAMs) are defined as models that explore interactions between economic activity, society, and the environment (IPCC, 2023). Despite this broad definition, the majority of IAMs focus on the interaction between the climate system and the economy at the global scale (IAMC, 2020a). IAMs have important policy impacts, as their analyses have been used in assessment reports of the Intergovernmental Panel on Climate Change (IPCC). Often a distinction is made between aggregate cost–benefit models such as DICE (Barrage and Nordhaus, 2023) and more detailed process-based models such as REMIND (Aboumahboub et al., 2020) and IMAGE (Stehfest et al., 2014). For a more detailed classification of IAMs, the reader is referred to IPCC (2023). Note that the original definition of IAMs is identical to our definition of ESE models. However, we found that many models from our sample are not considered IAMs, as they are not part of the model list of the IAM Consortium (IAMC, 2020b). Therefore, we chose to retain the term “ESE models” to refer to this broader class of models.

Macro-econometric and input–output models are often combined and calibrated to actual data. Macro-econometric models estimate the behaviour of economic agents based on historical observations, contrary to the optimising behaviour of equilibrium models. Input–output models express the economy as a set of flows between distinct sectors and are used to assess the direct and indirect effects of macroeconomic changes on a sectoral level. When extended with data on biophysical flows, they provide insights into the impact of economic activities on the environment. Some examples are E3ME (Hafner et al., 2021) and GINFORS-E (Lutz et al., 2010).

Stock–flow consistent (SFC) models typically focus on the financial side of the economy. They track monetary stocks and flows between economic actors and money creation by banks. Financial stocks are simultaneously assets for one party and liabilities for another. By accounting for the origin and destination of all transactions, stock–flow consistent models have the advantage of describing an economy without “black holes”. As stock–flow consistency is an accounting framework that tracks monetary flows, it can be applied to various types of models. Furthermore, the method can also be extended to stocks and flows of matter and energy. Some examples of SFC models are LowGrow SFC (Jackson and Victor, 2019b) and DEFINE (Dafermos and Nikolaidi, 2022).

System dynamics provides a methodology that approaches model-building from a different perspective. It originates from systems theory (Forrester, 1971) and focuses on understanding the behaviour of complex systems by including dynamic interactions and nonlinear feedback mechanisms between different elements. This technique is used in a wide range of disciplines and has gained popularity in heterodox macroeconomics. Some examples of system dynamics models are MEDEAS (Capellán-Pérez et al., 2020), WILIAM (Samsó et al., 2023), and Eurogreen (D’Alessandro et al., 2020).

Lastly, we include “other” models with a focus on specific indicators that do not fall into the above categories, such as LUISA for land use (Lavalle et al., 2020), feminist macroeconomic models for unpaid care work (Ilkkaracan et al., 2021; Vasudevan and Raghavendra, 2022), and a theoretical model for natural capital (Dasgupta, 2021). Due to their specific focus, the techniques used do not necessarily match the typical macroeconomic categories.

2.3. Neoclassical vs. heterodox economics

Another way of distinguishing between models is to look at their theoretical foundations. Here we distinguish between neoclassical and heterodox approaches. Colander (2000) characterises the neoclassical school by the tenets of utilitarianism, focus on marginal trade-offs, farsighted rationality, methodological individualism, and a focus on the general equilibrium of the economy. As we found these assumptions in most IAMs and equilibrium models, we will describe these categories as neoclassical. The neoclassical school remains the dominant economic paradigm, which manifests itself in the rankings of economics departments and journals, and curricula taught to students (Colander, 2009). In contrast, heterodox economics is a group of economic theories that have intellectual roots in post-Keynesian, feminist, ecological, and other disciplines (Brand-Correa et al., 2022). These schools focus on concepts such as capital accumulation, intersectional understandings of socioeconomic relationships, care, economic and social reproduction, the environment, and provisioning systems (Lee, 2012). Heterodox schools of thought typically reject a number of neoclassical assumptions and also tend to use a broader range of methods.

A clear dividing line between heterodox and neoclassical economics is their vision of the substitutability between economic inputs like labour, capital, material, or energy. Substitutability implies that a certain input can be replaced by another input to produce the same outcomes. The weak versus strong sustainability debate is directed, in particular, towards the substitutability of different forms of natural capital by built capital (Neumayer, 2013). Weak sustainability argues that these forms of capital can be substituted for each other. Strong sustainability argues that substitution possibilities are limited because natural capital provides different types of functions, and that not all these functions can be substituted by built capital (Neumayer, 2013). The Doughnut of social and planetary boundaries follows the strong sustainability approach, since failure to achieve one environmental or social goal cannot be compensated for by better performance on another (O’Neill et al., 2018).

Human needs theory underpins the social goals of the Doughnut, as it is argued that human beings have a set of non-substitutable basic needs (Doyal and Gough, 1991; Max-Neef et al., 1991). In this regard, human needs theory is different from neoclassical utility theory, which conceptualises human welfare by the one-dimensional concept of utility, and implicitly treats human needs as substitutable by focusing on preference satisfaction (Gough, 2023).

2.4. Ecological macroeconomics

Mainstream ESE models have been criticised for (1) reducing climate mitigation to monetary cost–benefit analysis and underestimating future damages (Ackerman et al., 2009; Drouet et al., 2021; Ludwig et al., 2005), (2) addressing climate change while ignoring overshoots of other planetary boundaries (Gambhir et al., 2019; Hickel et al., 2021), (3) relying on overly optimistic assumptions about the ability of technological solutions to reduce environmental pressures (Hickel and Kallis, 2020; Larkin et al., 2018), and (4) not representing the socio-technical challenges of transition scenarios (Geels et al., 2016, 2017; van Sluisveld et al., 2020).

To address these shortcomings, many scholars have started developing alternative approaches, giving rise to the field of ecological macroeconomics. The seminal *Limits to Growth* report proposed the first ecological macroeconomic model (World3) that embedded human socioeconomic systems within a finite biophysical environment (Meadows et al., 1972), which subsequent analyses have continued to validate (Herrington, 2021; Turner, 2008). At the same time, scholars such as Herman Daly described the macroeconomy as an open subsystem within the finite biophysical ecosystem, urging economists to consider the question of the optimum scale of human activity (Daly, 1991a). Victor and Rosenbluth (2007) subsequently introduced the LOWGROW model, which explored policy options to achieve environmental and social goals

Table 1
List of environmental and social indicators considered in our analysis of Environment–Society–Economy models.

Environmental indicators	
Climate change	Metrics of climate change, e.g. CO_2, all greenhouse gas emissions, and/or simulated climate response to anthropogenic greenhouse gas emissions.
Phosphorus loading	Excessive use of phosphorus as fertiliser.
Nitrogen loading	Excessive use of nitrogen as fertiliser.
Water use	The use of water, either blue (freshwater from lakes, rivers, and reservoirs), green (water in the soil, usually used by plants and soil microorganisms), or tracking of other water sources or uses (e.g. grey).
Land conversion	The conversion of natural lands into land useful for human activity.
Biodiversity loss	The loss of biodiversity, reduction in the number and variety of species.
Ozone layer	Emissions that damage the ozone layer.
Air pollution	The emissions of air pollution, including anthropogenic aerosols, particulate matter (e.g. fine particulate matter PM10 or PM2.5), or other pollution.
Chemical pollution	The release of hazardous chemicals or plastic waste into the environment.
Marine harvesting	Depletion of fish stocks due to fishing activity.
Human appropriation of net primary production (HANPP)	The human appropriation of net primary production or biomass.
Ecological footprint	Society's pressure on ecosystems, measured as the amount of biologically productive land necessary to meet its needs.
Material use	The extraction, conversion, and disposal of biomass, minerals, and fossil fuels.
Energy use	The total energy use by society.
Soil quality	Depletion of soil nutrients or erosion of soil, ability for soil to sustain agriculture (carbon content and nutrient content). Can also include sediment quality or runoff for water basins.
Social indicators	
Energy access	Access to energy or electricity.
Water access	Access to safe drinking water.
Sanitation access	Access to safe sanitation infrastructure.
Housing access	Access to safe and affordable housing.
Education	Access to quality education, or metrics of education (e.g. literacy rates, rate of secondary school completion).
Health	The life expectancy or healthy life expectancy of the population.
Political voice	Governance that responds to democratic will.
Income	Measure of income per capita. In relation to a poverty line this can be used to measure income poverty.
Jobs	Unemployment rates, and other measures of quality of work (e.g. whether jobs are "decent" or "dignified").
Food access	Access to food and decent nutrition, and other metrics of food security.
Internet access	Access to the internet or telecommunications.
Mobility access	Access to affordable transportation, with an emphasis on public transport.
Income equality	Income equality within countries (could also include income equality globally or between countries).
Social support	Access to a support network of family, friends, or community members.
Gender equality	Equality and empowerment for women and girls (e.g. distribution of unpaid care work, pay, labour time, health outcome equity).
Peace	Measure of whether there is peace in a society (e.g. violent crime rates, absence of inter- and intra-national conflict).
Justice	The effectiveness of the rule of law, equal access to justice, absence of corruption.
Life satisfaction	An individual's subjective evaluation about their life. Can also include eudaimonic and hedonic conceptions of wellbeing.
Work–life Balance	The time spent on paid and unpaid work versus the time spent on personal or leisure time.
Economic development	Technological improvements, increases in labour productivity, or other measures of structural change or economic progress.
Resilience	The ability of our societal system to withstand shocks or disturbances (e.g. economic downturns, environmental catastrophes).

without relying on perpetual economic growth.

Since then, more sophisticated ecological macroeconomic models have been developed, including LowGrow SFC (Jackson and Victor, 2019b), Eurogreen (D'Alessandro et al., 2020), and WILIAM (Pastor et al., 2020), with several reviews documenting their contributions (Hafner et al., 2020; Hardt and O'Neill, 2017; Wiebe et al., 2023). Although not the only field that links macroeconomics to environmental and social systems, ecological macroeconomics distinguishes itself by adhering to three key principles. First, the economy is conceptualised as a subsystem of society, which is in turn a subsystem of the biosphere (Daly, 1991b). There is an inextricable connection between these different systems, and they can profoundly affect each other (Fontana and Sawyer, 2016). Second, the discipline allows for the exploration of multiple, non-substitutable goals (O'Neill, 2020), in contrast to traditional aggregate measures like Gross Domestic Product (GDP), which have faced substantial critique (Coscieme et al., 2020; Hoekstra, 2019; Stiglitz et al., 2009). Third, ecological macroeconomic models are frequently used to explore post-growth pathways. More specifically, they are used to understand how positive social outcomes can be achieved or maintained in scenarios of low growth or degrowth (Jackson and Victor, 2020; O'Neill, 2020; Slameršak et al., 2024).

The "provisioning systems" framework has gained attention in ecological economics as a way of understanding the link between biophysical resource use and social outcomes. Fanning et al. (2020, p. 3) define a provisioning system as "a set of related elements that work together in the transformation of resources to satisfy a foreseen human need". Vogel et al. (2021) perform a global analysis of how energy use and needs satisfaction depend on a set of provisioning factors. Their analysis shows that improving provisioning systems can be an important strategy to improve basic needs satisfaction while reducing environmental pressures. Furthermore, studying provisioning systems can help us to understand growth dependencies and how social welfare can be decoupled from economic activity (Corlet Walker et al., 2021). Scholars have started addressing this challenge by analysing specific provisioning systems in more detail, for example for mobility (Dillman et al., 2023; Virág et al., 2022) and housing (zu Ermgassen et al., 2022).

While there exists some literature on the inclusion of social and environmental indicators in IAMs, a broader comparison of indicator coverage between different types of ESE models is missing from the literature. We provide a high-level analysis of ESE models from all approaches, with a focus on the inclusion of social and environmental indicators, and on the different ways in which they are modelled.

3. Methods

To assess the level of adoption of important environmental and social indicators in Environment–Society–Economy models, we carried out four main steps. First, we compiled a list of 15 environmental and 21 social indicators. Second, we constructed a long list of 90 ESE models. Third, we reduced this list to a medium list of 50 models for which we analysed the indicator coverage. Fourth, we created a shortlist of 15 models, which we analysed in detail to understand how they model the environmental and social indicators and what their driving variables are.

In the first step, we compiled a list of important environmental and social indicators (Table 1). The starting point for this list was the Doughnut framework (Raworth, 2017b) and the Sustainable Development Goals (United Nations, 2015), supplemented with inputs from other relevant literature on environmental and social indicators (Hafner et al., 2020; Hardt and O'Neill, 2017; Wiebe et al., 2023). We also added indicators from studies operationalising the Doughnut, specifically from O'Neill et al. (2018) and relevant studies cited by it (i.e. Cole et al., 2014; Dearing et al., 2014).

In the second step, we created a longlist of 90 ESE models. We first aggregated models featured in MIDAS (European Commission, 2017), which is a key database aggregating models used in European policy-making, and literature reviews by Wiebe et al. (2023), Hafner et al. (2020), and Hardt & O'Neill (2017). We also searched online databases (Google Scholar and Scopus) for new literature that cited these reviews using the following search terms: ecological, environmental, climate, health, education, macroeconomic, econometric, model, (public) health, (socioeconomic) determinants, (social) provisioning, (life) satisfaction, and well (-/)being. Parenthesised terms were included in combination with their paired terms. We supplemented these studies with other grey literature and model documentation found by searching using Google and Google Scholar.

Our underlying selection criterion was the capacity of the models to model environmental limits and social thresholds, such as those in the Doughnut or Sustainable Development Goals. We sought models that linked at least two of the three spheres of environment, economy, and society. Furthermore, we applied more specific criteria: (1) suitability for mid- to long-term policy evaluation (a time horizon of at least 5 years), (2) consideration of societies at the national or global scale, (3) inclusion of multiple agents (such as households, firms, and governments), and (4) the ability to disaggregate the economy into different sectors. For our selection, we allowed both theoretical and empirical models.

In the third step, we reduced the longlist to a medium list of 50 models for the analysis of the inclusion of social and environmental indicators. First, we removed models that were redundant or ill-equipped to model relevant indicators. This step required some subjective judgement as to which models (1) were better developed and up to date, (2) included enough relevant indicators, or (3) could be excluded because they were similar to already-included models. We also searched for the latest versions of these models and replaced any outdated versions. The details and sources of models on the medium list are described in Supplementary Materials 2.

For the medium list of models, the documentation and relevant literature were reviewed and searched with key words to evaluate the inclusion of the indicators from Table 1 (see Supplementary Materials 1, Table S1 for more information). To confirm the validity of our results we contacted the authors of the models and asked them to verify our assessment. Overall, we had an author response rate of 72%. This evaluation enabled the creation of a high-level assessment, detailing the extent of coverage for each indicator.

In the last step, we created a shortlist of 15 models for an in-depth

Table 2
Models in the shortlist, including each model's categorisation and a brief description.

Model name	Model category	Model description
GEM-E3	General equilibrium, integrated assessment	Computable general equilibrium macroeconomic model linking economy, environment, and energy systems. Used to assess energy, climate, and air quality policies. Global trade analysis project (GTAP) calibrated.
MAGNET	General equilibrium	Recursive dynamic, multi-region, multi-sector computable general equilibrium model used to analyse policy scenarios on agricultural economics, bioeconomy, food security, climate change, and international trade. GTAP-calibrated.
International Futures scenarios (IFs)	General equilibrium, integrated assessment	Global model combining a general equilibrium-seeking economy and dynamic input–output data with diverse environmental and social impacts, aimed at understanding broad trends. One of the few models to include socio-political changes and geopolitical effects.
REMIND	General equilibrium, integrated assessment	Global energy model that solves for a cost-optimal mix of investments in the economy and the energy sectors of each model region given a set of population, technology, policy, trade, and climate constraints.
E3ME	Macro-econometric and input–output, integrated assessment	Macroeconomic model with two-way linkages between the economy, wider society, and the environment. Designed to address national and global economic and economy–environment policy challenges.
EXIOMOD	General equilibrium, macro-econometric and input–output, integrated assessment	Input–output-based country- and global-level model designed to measure environmental impacts of economic activity with consistent trade linking between countries at the commodity level.
Earth4All (E4A)	System dynamics	Global system dynamics model with a broad coverage of environmental and social systems. Successor to the Limits to Growth models.
iSDG	System dynamics	Country-level system dynamics model with broad coverage of environmental and social indicators. Designed to explore national pathways to achieve the Sustainable Development Goals and other ways of living well within limits. One of the few models to include socio-political changes and geopolitical effects.
MEDEAS	System dynamics, input–output, integrated assessment	National and global system dynamics energy transition model focused on energy constraints with a detailed representation of the energy and industrial systems (with input–output).
LowGrow SFC	System dynamics, stock–flow consistent	National system dynamics macroeconomic model with stock–flow consistent financial accounting, calibrated to Canada.
Eurogreen	System dynamics, input–output, stock–flow consistent	National system dynamics macroeconomic model designed to explore post-growth futures with a detailed representation of the industrial system and socioeconomic classifications (with input–output and stock–flow consistent accounting).
Onaran et al. (2022)	Other	Theoretical model designed to explore gender equality in terms of employment and wages. Analysis limited to changes in GDP, productivity, and employment.
Vasudevan and Raghavendra (2022)	Other	Theoretical two-sector model within the post-Keynesian tradition that addresses the linkages between self-employment, the macroeconomy, and unpaid care work.
Ilkkaracan et al. (2021)	Macro-econometric, other	Theoretical model exploring the effect of public investment in the care sector on gendered income and time poverty.
Dasgupta (2021)	Other	Stylised theoretical model designed to show the economy's dependence on natural capital. The model has orthodox underpinnings (e.g. a Cobb–Douglas production function, substitutability of production factors) but the economy can collapse due to overuse of natural capital.

analysis of modelling approaches. From the medium list, we first selected the models with the broadest indicator coverage. We then revised this selection to ensure diversity in model categories, theoretical foundations, and indicator coverage. The protocol is described in more detail in Supplementary Materials 1.

Each model on the shortlist (Table 2) was subjected to an in-depth analysis, focusing on the modelling of our list of indicators (Table 1). We documented the variables employed as drivers of the environmental and social indicators as well as the functional relations used within each model. As full documentation of all the functional relations was not available for all of the models, we decided to focus on the dependencies between variables instead of on their specific mathematical formulation. We represented these dependencies graphically as networks of variables, with arrows between variables that affect each other. For instance, if the network contains an arrow from variable A to B, the value of B depends on that of A.

These visualisations show the high-level structures and relations that are used to model the environmental and social indicators. For each indicator we compared the networks of influencing variables between the models and identified the variables and dependencies that reoccurred in multiple models. With these common elements, we then constructed "archetypes" for each indicator, which represent the essential structure that is shared among models. If we found significantly different approaches for a given indicator, we created an archetype for each of the approaches. We used these archetypes to quantify which variables most often affect environmental and social indicators. This quantification offers valuable insights into the variables commonly used by modellers, shedding light on their perceived importance and convenience. Finally, we also created a mapping of the 36 indicators onto the 17 Sustainable Development Goals (Supplementary Materials 1).

4. Results

In this section we discuss the results of our analyses regarding the coverage of environmental and social indicators in Environment–Society–Economy models. We first discuss the inclusion of the environmental and social indicators in our model sample (Section 4.1). Second, we report common modelling approaches for some of the environmental and social indicators (Section 4.2). Lastly, we discuss which driving variables are often used to model the indicators in our set (Section 4.3). The analysis in Section 4.1 is based on the medium list of 50 models, while the analyses in Sections 4.2 and 4.3 are based on the shortlist of 15 models.

4.1. Models and their coverage of environmental and social indicators

The environmental indicators that are most covered in our 50-model medium list are climate change, energy use, and land conversion (Fig. 2). This prevalence can be explained by the observation that ESE models are often used by scholars and policymakers to analyse climate mitigation and the related energy transition (Drouet et al., 2021; Gambhir et al., 2019). The prominence of environmental indicators like water, land, and material use is largely explained by their presence in environmental extensions of input–output tables (Kitzes, 2013).

The indicators soil quality, ecological footprint, and human appropriation of net primary production (HANPP) are the least included. HANPP, which measures human impact on ecosystems by quantifying biomass used or altered by humans (O'Neill and Abson, 2009), is now included in the planetary boundaries framework (Richardson et al., 2023), but was only modelled in detail in our sample by iSDG. Soil quality is covered poorly but can be included in a model by using a method based on nutrient balances, such as the approach of Roy et al. (2003). The ecological footprint is not included explicitly in many models, but some models have been used to calculate ecological footprints, such as EXIOMOD 2 (Bulavskaya et al., 2016) and LowGrow SFC (Victor, 2023).

On the social side, the most covered indicators are those that are easily derived from a conventional macroeconomic framework, such as jobs, income, and economic development (Fig. 2). Gender equality is often represented as gendered income inequality because of data availability on wages and employment at this level. Other sources of inequality are still absent in current models (e.g. race, gender/sexual identities, and disability). While many models focus on modelling energy use, fewer contain adequate measures of energy access. With the exception of internet access, the least covered social indicators are those that are intangible and thus difficult to quantify, such as peace, justice, political voice, social support, and resilience.

Generally, system dynamics models and IAMs cover the most indicators while stock–flow consistent models cover the least (Supplementary Materials 1, Fig. S1). This may be the case because system dynamics models and IAMs have been explicitly designed to simulate the interaction of economic, social, and environmental systems. The two models that cover the most environmental and social indicators from our list in Table 1 are iSDG (25 indicators) and IFs (22 indicators). See Supplementary Materials 2 for the results for all models.

Additionally, we mapped the coverage of all 36 indicators from our 50-model sample onto the 17 Sustainable Development Goals (Fig. 3). The most covered goals are Decent Work and Economic Growth, Affordable and Clean Energy, No Poverty, and Climate Action. With the

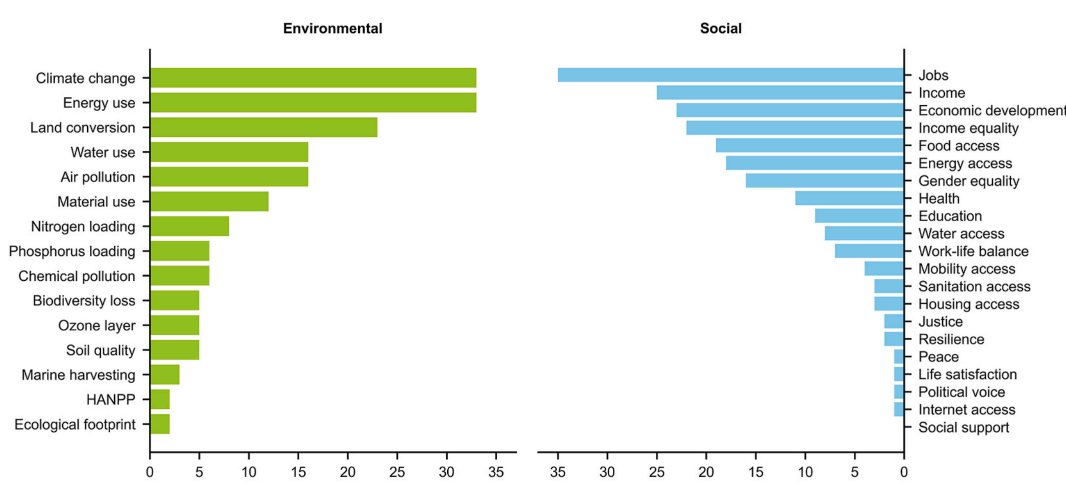

Fig. 2. Coverage of environmental and social indicators across the medium list of 50 models.

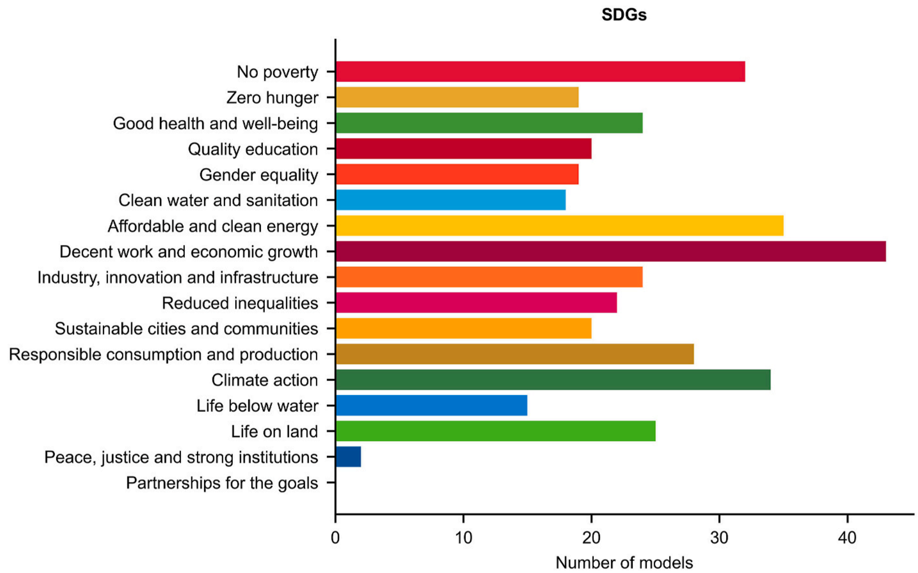

Fig. 3. Coverage of the Sustainable Development Goals (SDGs) across the medium list of 50 models.

exception of the goal on partnerships, the least-covered goal is Peace, Justice, and Strong Institutions. Life Below Water is also not well covered by existing models, especially in comparison to Life on Land.

4.2. Archetypes for modelling environmental and social indicators

To understand how models connect environmental and social indicators to their socioeconomic drivers, we constructed archetypes for all 36 indicators as represented in our 15-model shortlist. Each archetype represents an approach to modelling an indicator that we identified in our analysis of the shortlisted models. Here we present archetypes for the most- and least-modelled indicators, as well as for indicators with particularly unique approaches. The complete set of archetypes for all 36 indicators can be found in Supplementary Materials 1. Note, however, that the primary purpose of these archetypes is to build up our understanding of the main driving variables in existing models (presented in Section 4.3).

4.2.1. Environmental indicators

4.2.1.1. Climate change and energy use. Climate change and energy use are the most-modelled environmental indicators in ESE models. Moreover, the modelling community treats energy use as climate change's most important driver (Fig. 4a). Energy-related emissions are commonly calculated as the product of energy use and emissions intensities per energy unit. Energy use can be determined from the demand side or the supply side.

The demand-driven approach converts the monetary flows from demand from households and industries into energy demand with energy intensity variables. In the supply-driven approach, energy is calculated as an input to total production, and varies with production levels. Most IAMs use a supply-driven approach to decide on energy use. These include REMIND, GEM-E3, and MAGNET. However, heterodox models tend to use a more demand-driven approach. These include Eurogreen and LowGrow SFC.

The emission intensity of energy use depends on the mix of energy sources such as coal, gas, and renewables. In some models, the energy mix is specified as an exogenous trend (e.g. Eurogreen, LowGrow SFC). In other models, the energy sector is modelled explicitly, and the energy mix is driven endogenously through prices (neoclassical models), resource availability, or policy priorities (e.g. MEDEAS).

4.2.1.2. Land conversion. We present land conversion because it is both one of the most frequently modelled and well-developed environmental indicators. The demand for land is driven predominantly by population size and income per capita (Fig. 4b). Typically, models distinguish between the categories of forest, urban, agricultural, and other land. The stock of forest land is converted into agricultural or urban land when the demand for these types increases. The demands for agricultural and urban land are sometimes in competition (e.g. Earth4All). Some models include demand for land for renewable energy generation (e.g. MAGNET, MEDEAS).

Agricultural land may be split between cropland and grazing land, to distinguish between the impacts of plant-based and meat-based diets, where meat demand grows with increasing income per capita. In some models the government can intervene through conservation and reforestation policies to limit forest conversion. In Earth4All, farming practices can also impact the rate of land conversion.

4.2.1.3. Material use. We include an archetype for material use since it provides a clear example of the difference between how heterodox and neoclassical models treat environmental indicators (Fig. 4c). In heterodox models (left-hand side) the material intensities are fixed or follow an exogenous trend. In neoclassical models (right-hand side), the material intensity of economic activity is affected by the price of materials as they can be substituted for other production factors. The material flows can be modelled on the aggregate scale of the whole economy, or they can be disaggregated by sector and material type. Environmentally extended input–output databases typically include extensive information on material use.

4.2.2. Social indicators

4.2.2.1. Jobs. We present jobs (employment) because it is the most-modelled social indicator. Neoclassical and heterodox models differ in how they model labour demand. In the heterodox approach (Fig. 5a) the labour demand depends on the total production or total capital, but is not directly substitutable for capital or energy (e.g. Earth4All; iSDG; Onaran et al., 2022; Vasudevan and Raghavendra, 2022). Some models include variation between sectors in how labour demand is determined. For instance, Onaran et al. (2022) keep labour productivity out of the social reproduction sector to stress that productivity gains there are undesirable. Usually, agricultural land or capital drives the agriculture labour demand, and changes in labour productivity can have long-term

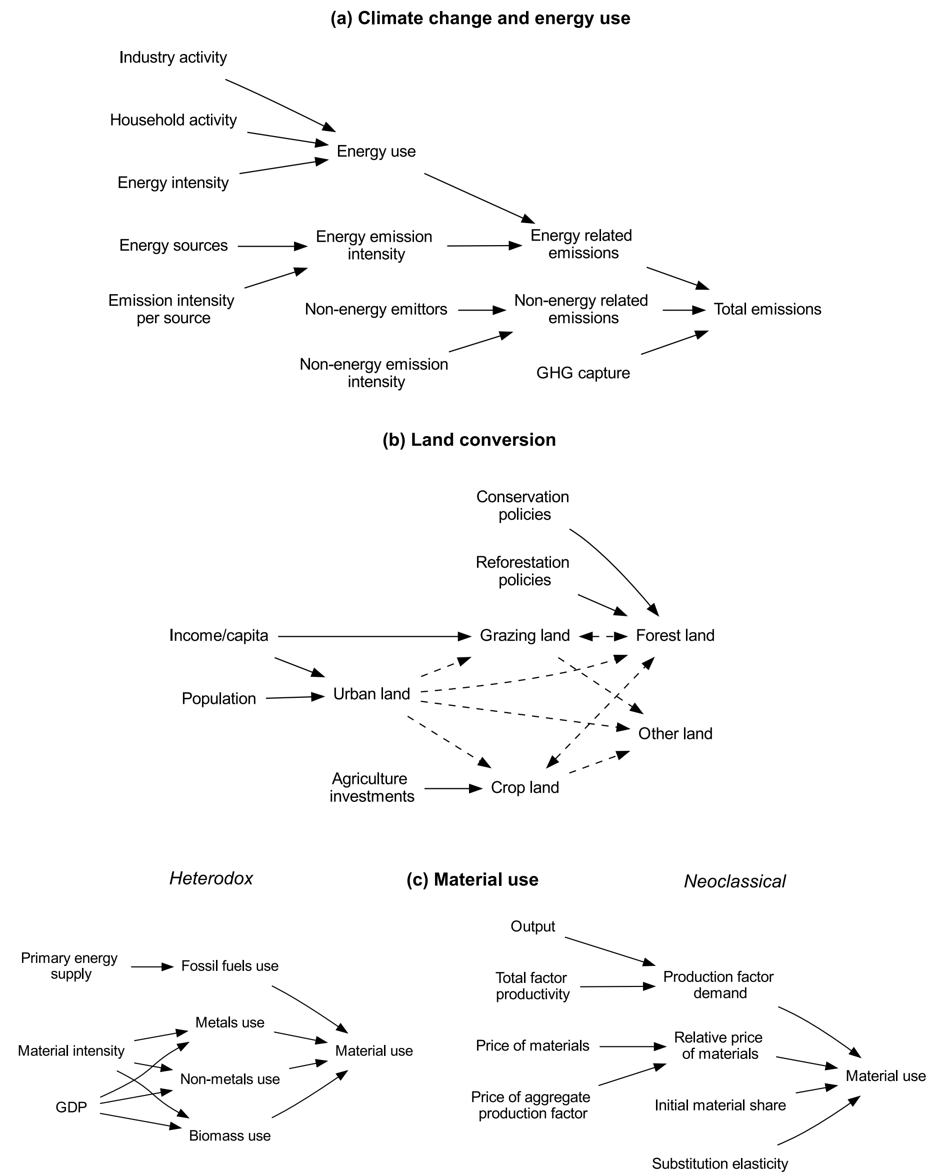

Fig. 4. Archetypes for selected environmental indicators from shortlist of 15 models. The graphs show which variables influence the selected environmental indicators. Causal directions are indicated by arrow direction. **(a)** Climate change and energy use. **(b)** Land conversion. Dashed arrows indicate a flow between stocks in the opposite direction of the arrow (e.g. urban land is taken from grazing land). Bidirectional arrows indicate that the flow between stocks can go both ways (e.g. forest land can be converted into grazing land and vice versa). **(c)** Material use. Both the heterodox (left) and neoclassical (right) approaches are shown.

effects on labour demand.

The neoclassical approach treats labour as an input to the production process, partially substitutable by energy and capital. This approach typically uses a constant elasticity of substitution tree (Shutes et al., 2018). The structure is similar to that of material use (Fig. 4c, right-hand side), so we don't present it again in Fig. 5. The reader is referred to Supplementary Materials 1 (Fig. S29) for the neoclassical archetype. Some models (EXIOMOD 2, GEM-E3) provide a more detailed representation of the labour market and allow for unemployment, while others (REMIND) treat labour mainly as an exogenous variable.

4.2.2.2. Economic development. We present economic development since it is both widely modelled, and it is perhaps the indicator that best reveals the importance of pre-analytic visions of modellers in how indicators are represented. Economic development refers to technological improvements, increases in labour productivity, or other measures of structural change or economic progress. Some models focus on productivity of a specific factor such as labour, while others include the total factor productivity (i.e. the aggregated productivity of all inputs in the economic process). Over all models there is a wide variety of drivers linked to productivity growth (Fig. 5b). The variables that we show represent those included in at least two of our surveyed models.

It seems that the choice of the drivers of productivity included in any particular model is influenced not only by empirical observations, but also by the modeller's pre-analytic vision and ideological considerations. Within a growth paradigm it makes sense to argue that certain social outcomes are important policy targets if they positively influence productivity growth. This approach treats social outcomes as instrumental variables to achieve GDP growth. By contrast, a strong sustainability approach like the Doughnut treats social outcomes as ends in themselves. It challenges the primacy of economic growth as a policy goal, and instead defines social progress in broader terms.

4.2.2.3. Political voice. We present political voice because it is both one of the least-modelled indicators and one of the most intangible and difficult indicators to model. Political voice is only included in two

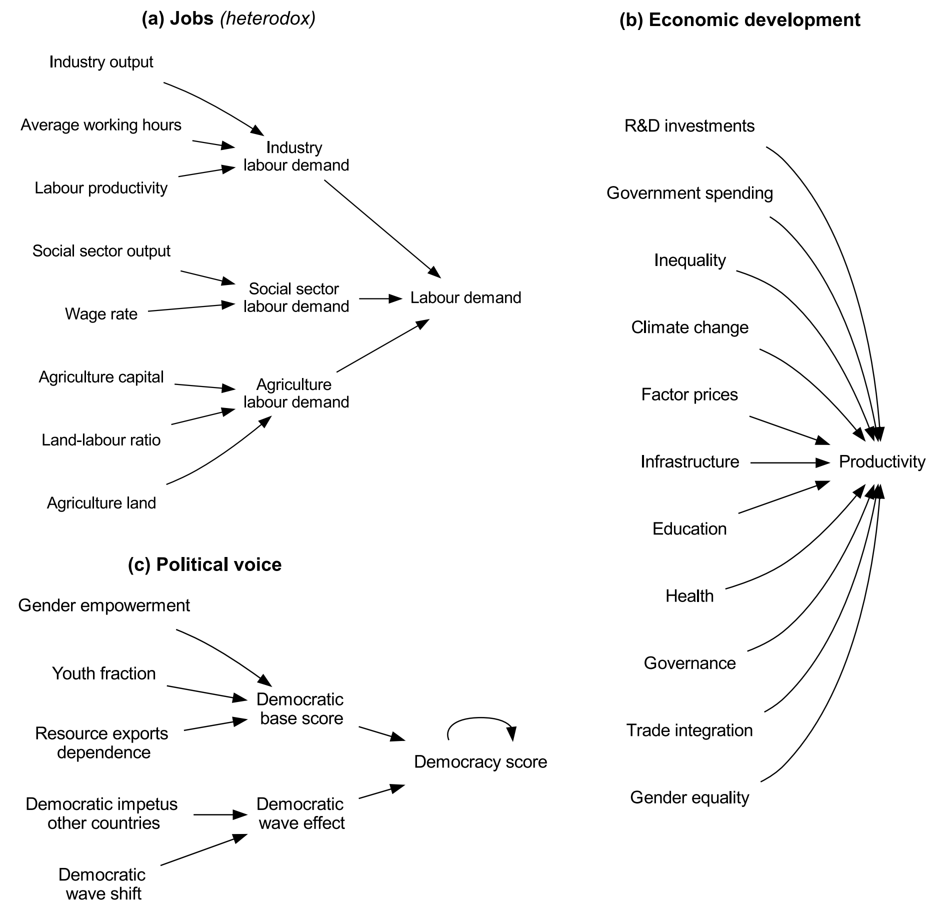

Fig. 5. Archetypes for selected social indicators from shortlist of 15 models. The graphs show which variables influence the selected social indicators. Causal directions (i.e. order of operation) are indicated by arrow direction. **(a)** Jobs, showing the heterodox approach. **(b)** Economic development, as represented by productivity and a set of its theorised drivers. **(c)** Political voice, showing the endogenous approach from IFs.

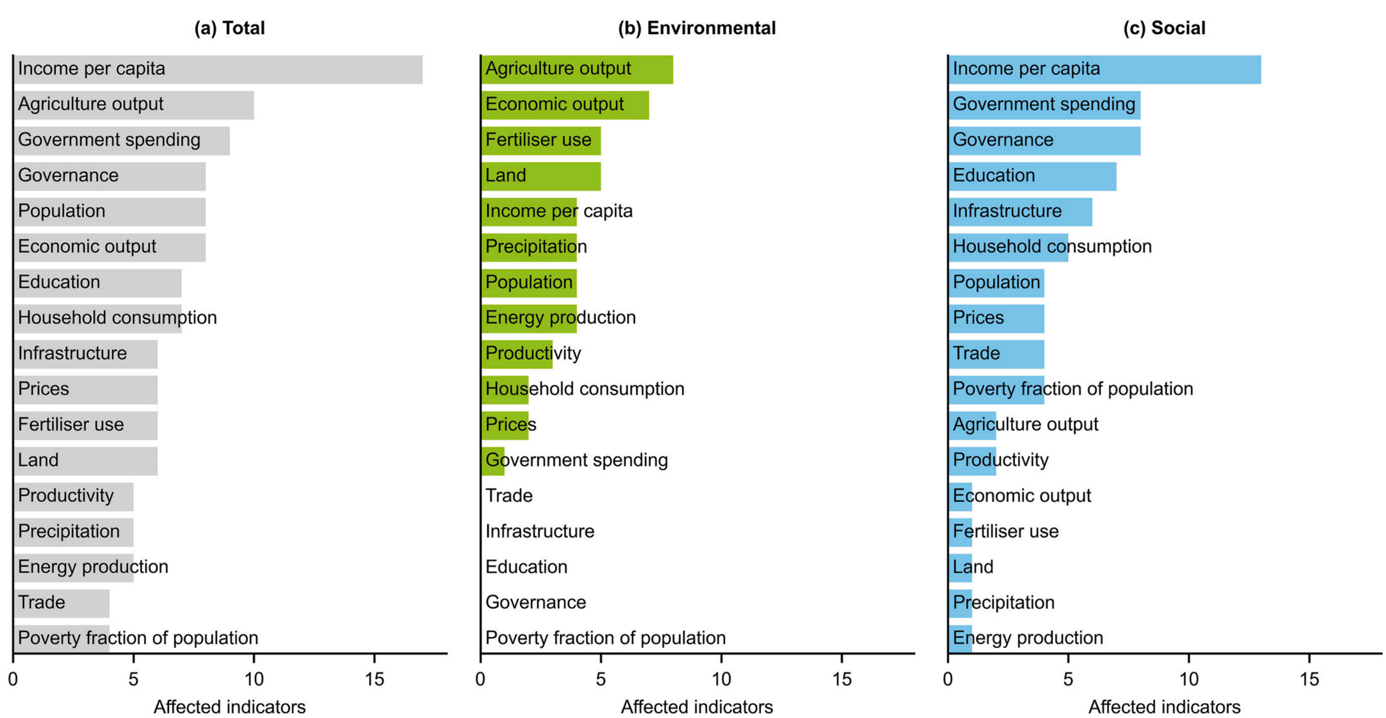

Fig. 6. The most important driving variables in terms of how many environmental and social indicators they affect, based on the archetypes for all indicators.

models in our sample: iSDG includes it exogenously, while IFs endogenises political voice (Fig. 5c) as the democratic score from the Polity IV index for democracy, a widely used measure of a country's level of democracy (Center for Systemic Peace, 2021). IFs includes theoretical contributions from political science, namely the democratic wave effect and the age-structural maturity thesis. Furthermore, it includes path dependency of the democracy score using a moving average.

4.3. Driving variables for the environmental and social indicators

We used the full collection of archetypes (Supplementary Materials 1) to analyse which variables are most often used as drivers of the environmental and social indicators (Fig. 6). Overall (Fig. 6a), income per capita is most widely used as a driving variable, followed by agriculture output, government spending, governance, population, and economic output (i.e. GDP).

On the environmental side (Fig. 6b), the most important drivers are the agriculture sector (i.e. agricultural output and fertiliser use) and economic output (GDP). GDP is a prevalent driver for environmental impacts because it measures aggregate economic activity and can be linked to biophysical flows with intensity variables.

On the social side (Fig. 6c), a strong emphasis is given to income per capita and the role of governments, through the variables for governance and government spending. Governance is only included in two of the models from our shortlist. It is included endogenously in IFs, and exogenously in iSDG. In both models, governance plays a key role in determining water access, education, health, mobility, and productivity. Government spending, while playing a critical role in social provisioning, is a narrow description of the role that the state could play in a post-growth transition (Corlet Walker et al., 2021). Exceptionally, IFs and iSDG make noteworthy attempts at modelling health and education provisioning systems.

5. Discussion

Our results show that a number of important environmental and social indicators, such as those contained in the Doughnut of social and planetary boundaries, are not commonly included in existing Environment–Society–Economy models. Consequently, there may be a gap in understanding how transition pathways towards a sustainable future affect social and environmental objectives. The least-covered environmental indicators are those that are difficult to link to GDP in an aggregate way. On the social side, the most intangible indicators are covered the least, as they are more difficult to quantify and cannot easily be linked to a macroeconomic framework.

Moreover, even if environmental and social indicators are modelled, relevant information for modelling the Doughnut framework may be lacking. For instance, the inclusion of environmental indicators does not imply the inclusion of environmental limits or feedback mechanisms. Similarly, a model that includes social indicators does not necessarily show whether people's basic needs are being met.

Within this section we discuss some of our core findings in more detail. These include how current models link social outcomes and environmental impacts to the economy (Section 5.1), the issue of substitutability between different goals (Section 5.2), how biophysical limits are incorporated (Section 5.3), the drivers of productivity growth (Section 5.4), model documentation standards (Section 5.5), the contributions and implications of this research (Section 5.6), and the limitations of our analysis (Section 5.7).

5.1. Linking the economy to society and the environment

In current models, environmental pressures are mainly calculated as the product of sectoral economic output with intensity variables. Although this approach gives a high-level overview, it obscures which types of production and consumption are the most intensive. For the most-covered indicators, namely climate change and energy use, we generally find a more detailed structure of their determinants. On the social side, most models link social outcomes to household income per capita, GDP per capita, or public spending. Notable exceptions are iSDG and IFs, which provide more detailed representations of, for instance, the education and healthcare systems.

The least-covered social indicators were intangible constructs such as political voice and social support. Although several databases and indicators exist that measure these constructs (Center for Systemic Peace, 2021; Kaufmann and Kraay, 2023), they have been criticised for their conceptualisation, measurement, and aggregation (Munck and Verkuilen, 2002; Slinko et al., 2017; Thomas, 2010). Furthermore, there is mixed empirical evidence on their determinants (Rød et al., 2020). This highlights a key tension around intangible indicators. On the one hand, they are often not included in models because it is difficult to represent them accurately. On the other hand, their omission risks that important goals are not considered by policymakers, entrenching a bias towards quantifiable constructs.

A comprehensive and intersectional representation of inequality presents a special challenge in macroeconomic modelling. We find inequality represented in macroeconomic models along two dimensions: (1) the axes of discrimination (e.g. gender, race, ability) and (2) the forms of inequality (e.g. income, time use). Gender and skill level are the most prevalent axes of discrimination, while the forms of inequality that are included in current models include income, employment, time use, and education level.

There are several potential avenues to improve the representation of social and environmental dimensions in ESE models. First, the provisioning systems literature can provide a deeper understanding of how the provisioning of specific goods and services is related to resource use and social outcomes (Fanning et al., 2020). Second, modelers could take inspiration from feminist macroeconomics to include time-use data. Time-use patterns are known to have an effect on wellbeing (Tomczyk et al., 2021) and would allow the representation of essential unremunerated activities such as care and volunteer work (Dengler and Plank, 2024). Lastly, the representation of inequality could be extended further by including more axes of discrimination and by measuring the inequality of social outcomes such as access to healthcare or mobility.

5.2. Substitutability

The Doughnut framework starts from a vision of strong sustainability, as it does not allow for substitution between its goals. Within this context, neoclassical single-target optimisation is problematic due to its aggregation of multiple goals into a single metric, implying that these goals are substitutable. In theory, optimisation-based models could align with the Doughnut framework by imposing minimum thresholds on social indicators and maximum limits on environmental pressures. Although imposing such constraints may be technically challenging, this approach could provide valuable benchmarks for transition pathways.

On the production side, neoclassical models allow for substitution between production factors such as built capital and energy. The degree of substitutability — and which factors can be substituted — depends on the model, and even on the sectors that are modelled. In contrast, most heterodox models envision production as having non-substitutable inputs. Therefore, ecological impacts can only be reduced through gains in efficiency and productivity.

On the consumption side, neoclassical models allow for substitution between different goods, but some impose minimum consumption thresholds for each category of goods (e.g. GEM-E3). Above these thresholds, households can substitute between consumption goods. Some heterodox models (e.g. Eurogreen, IFs) allow for substitution between consumption categories and base this consumption per category on historical data. In general, there is a gap in how consumption can be linked to needs satisfaction, and which other factors (e.g. social norms, government policy) affect consumption patterns.

5.3. Biophysical limits

Only a few of the models surveyed include biophysical limits as feedback mechanisms from the environment back to the economy. In the Dasgupta model the depletion of the stock of natural capital hampers its regeneration, eventually leading to economic collapse. In MEDEAS, Eurogreen, and iSDG, increasing climate change affects economic activity in certain sectors or in the whole economy, but these mechanisms are implemented differently. This diversity aligns with a study by Rose et al. (2017), who found significant differences in how climate damage functions are implemented in IAMs.

The inclusion of limits and feedback mechanisms, although important, is a non-trivial endeavour because of the large uncertainties regarding their estimation. For instance, cost-based IAMs have been criticised because the economic damages can be implausibly low for large increases in global temperatures (Ackerman et al., 2009; Diaz and Moore, 2017; Keen, 2021). When limits are ambiguous, or difficult to quantify, their implementation may introduce large uncertainties in the behaviour of the model.

5.4. Drivers of productivity growth

Technological progress and productivity growth are an important part of many ESE models, as they are seen as a core driver of economic growth. Our results suggest that the drivers of productivity growth included in different models may be partially attributable to the different pre-analytic visions of the modellers. We see the use of social variables as drivers of productivity as an inverted approach that instrumentalises social outcomes. It makes social outcomes serve economic output instead of treating economic output as a means to achieve social outcomes. Framing technological progress or productivity increases in this way further entrenches the problematic depiction of GDP growth as an end in itself and reinforces the hegemony of a growth agenda in the modelling community.

5.5. Model documentation

In our analysis, we encountered a wide diversity in the quality and format of model documentation, hampering the transparency required for the critical assessment of these models. The most accessible documentation consisted of visual representations of the most important relationships, followed by concise, precise, and clear mathematical formulations of these relationships. IFs provides a good example of this best practice (e.g. Rothman et al., 2017). To improve reproducibility of results, we suggest that future generations of models should aim to use open-source software and programming languages (e.g. Python or Julia).

5.6. Contributions and implications

This study contributes to the research field of ESE modelling in three ways. First, we show which social and environmental indicators have received the most attention, and which ones are underrepresented in current ESE models. Second, we analyse the general approaches that are used to model these indicators. Lastly, we investigate which variables are commonly used as underlying drivers. These three insights can help facilitate the inclusion of important social and environmental indicators into new and existing models, and also direct modellers towards including indicators that are currently not well-represented.

Post-growth research focuses on how positive social outcomes can be achieved or maintained in the absence of growth. Models that use economic variables such as GDP or disposable income as the guiding indicators are not well suited to this purpose. Models that instead use environmental and social indicators as a compass may come to radically different conclusions about which pathways or policies are most desirable. For example, a policy such as working-time reduction would not appear to be a good option in a model where GDP growth was the main goal, but in a model where health and life satisfaction were considered important goals, the policy evaluation could be very different.

In general, the Doughnut framework encourages policymakers to adopt a more diverse set of interconnected social and environmental goals that are not expressed in monetary terms. Using such a framework, and modelling tools that are compatible with it, policymakers would be able to assess policies in terms of what really matters, namely the achievement of a good life for all within planetary boundaries.

5.7. Limitations of this research

Our research has two main limitations. First, our analysis is based on a sample of 50 models, from which we investigated 15 models in depth, so our results and conclusions are necessarily biased towards this sample. However, by including the models with the broadest coverage of indicators, our conclusions should be quite representative. Furthermore, we included a diversity of model categories and theoretical underpinnings to avoid underrepresenting certain approaches.

Second, we focus on how ESE models represent our list of environmental and social indicators. Our intention is not to understand the complex, system-wide interactions between the different parts of a model, or its detailed economic foundations. The creation of the indicator archetypes is a step of reductionism necessary to highlight common elements and approaches between models. We want to stress the complexity of the environmental, social, and economic systems under study, and caution against interpreting our results as a linear depiction of cause-and-effect relations. Furthermore, we acknowledge that every model is designed with a specific purpose, which may be quite different from our focus, namely the representation of the Doughnut framework and SDGs.

6. Conclusion

Our study highlights the need to model what matters in Environment–Society–Economy models. It reveals important gaps in the coverage of critical Doughnut indicators and Sustainable Development Goals. While some environmental aspects such as climate, energy, land, and water are well-represented, others, notably biosphere integrity (i.e. biodiversity loss and HANPP) and soil quality remain inadequately addressed. Similarly, including less tangible social indicators is particularly challenging, because the quantification of these indicators and their drivers is subject to large uncertainties, even if they are understood well. However, not including them in models risks invisibilising critical societal goals. We acknowledge that many models to date have not been designed to have the broad coverage needed to evaluate policy spaces delineated by the Doughnut or SDGs, but nevertheless, we assert that these gaps remain and should be addressed in future research.

The prevalent focus on monetary flows in current models limits understanding of the interconnections between environmental, social, and economic systems. Relying on economic variables like income per capita as the primary determinant of social outcomes also stands in the way of understanding how to decouple wellbeing from consumption and biophysical resource use. Modelling provisioning systems in more detail would require the inclusion of biophysical, socioeconomic, political, and infrastructural variables, thus reducing the dependency on income as the main driver of social outcomes in ESE models. It would also contribute to a new generation of models that are able to explore post-growth futures and thereby move beyond growth-dependent historical trajectories and incumbent policy approaches.

Finally, our findings reveal a lack of integration and feedback mechanisms from the environmental and social realms back to the economy. ESE models would be improved by embracing a more holistic approach that better incorporates these feedbacks, although we acknowledge that doing so is not an easy task. Such work could be aided by moving beyond the confines of monetary measurements towards models that directly link social provisioning to biophysical and socioeconomic inputs. By embracing this comprehensive perspective, modelers can help pave the way for sustainable futures, and empower policymakers to make informed decisions that prioritise the wellbeing of our societies and our planet.

CRediT authorship contribution statement

Rob Van Eynde: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization, Project administration. **Daniel Horen Greenford:** Writing – review & editing, Writing – original draft, Validation, Methodology, Investigation, Formal analysis, Conceptualization, Project administration. **Daniel W. O'Neill:** Writing – review & editing, Supervision, Project administration, Investigation, Funding acquisition, Formal analysis, Conceptualization, Methodology, Visualization. **Federico Demaria:** Writing – review & editing, Project administration, Funding acquisition, Conceptualization, Investigation, Methodology.

Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work the authors used ChatGPT 3.5 to reduce the word count of the introduction. After using this tool/service, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this article.

Data availability

The data are added as supplementary information.

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Appendix A. Supplementary data

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