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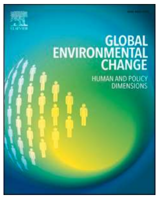

Integrated modeling of nature’s role in human well-being: A research agenda

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ABSTRACT

Integrated assessment models that incorporate biodiversity and ecosystem services could be an important tool for improving our understanding of interconnected social-economic-ecological systems, and for analyzing how policy alternatives can shift future trajectories towards more sustainable development. Despite recent scientific and technological advances, key gaps remain in the scientific community’s ability to deliver information to decision-makers at the pace and scale needed to address sustainability challenges. We identify five research frontiers for integrated social-economic-ecological modeling (primarily focused on terrestrial systems) to

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incorporate biodiversity and ecosystem services: 1) downscaling impacts of direct and indirect drivers on ecosystems; 2) incorporating feedbacks in ecosystems; 3) linking ecological impacts to human well-being, 4) disaggregating outcomes for distributional equity considerations, and 5) incorporating dynamic feedbacks of ecosystem services on the social-economic system. We discuss progress and challenges along each of these five frontiers and the science-policy linkages needed to move new research and information into action.

1. Introduction

We live in a period of profound global environmental, economic, and social change. While economic growth has increased material standards of living and reduced poverty rates overall, inequality has increased in many countries and uneven growth has left many in poverty (IPBES, 2019; World Bank, 2022). Consumption and production patterns have had detrimental environmental impacts through climate change, changes in nutrient and hydrological cycles, and loss of biodiversity (IPCC, 2021; Rockström et al., 2009; Steffen et al., 2015; UNEP, 2021). These negative impacts threaten human well-being and prosperity, especially for the poorest (Brauman et al., 2020; Díaz et al., 2018; IPBES, 2019; Johnson et al., 2023a).

Recognizing the severe threats posed by global environmental change, in 2015 countries agreed to global targets for the Sustainable Development Goals (SDGs) and adopted the Paris Climate Agreement. In 2022, under the Convention on Biological Diversity countries adopted the Kunming-Montreal Global Biodiversity Framework (GBF) that laid out long-terms goals and action-oriented targets for the conservation of biodiversity, including protecting at least 30% of terrestrial, inland water, marine and coastal areas by 2030, and ensuring the sustainable use of biodiversity and its contributions to people. The climate and biodiversity communities are growing increasingly interconnected in recognition of the fact that satisfactorily resolving either crisis requires addressing both (Pörtner et al., 2021).

Meeting multiple SDGs to maintain a livable planet and provide for the material and social well-being of a large and growing human population requires major transformations of societies and public policies (IPBES, 2019; IPCC, 2019, 2023; UNEP, 2021). Decision-makers and practitioners navigating sustainable development challenges require more complete information about current environmental, social, and economic conditions, and about potential transformation pathways. There is a pressing need to move beyond standard economic measures of progress that focus on growth in GDP (Costanza et al., 2014; Dasgupta, 2021; Stiglitz et al., 2010) to a broad set of environmental, economic, and social indicators to track progress across the SDGs (IPBES, 2019; Raworth, 2017; Steffen et al., 2015; Turnhout et al., 2021). An integrated and holistic approach is essential to address the interconnected social-economic- ecological system because of synergies and tradeoffs among SDGs and their drivers.

In recent years, science has made major advances in monitoring and modeling environmental change to enhance understanding of Earth systems, human impacts on Earth systems, and the potential consequences of changes in Earth systems for human well-being (IPBES, 2019; IPCC, 2018, 2019, 2021, 2022, 2023). Integrated assessment models (IAMs) are important tools for exploring the "linkages and feedbacks between different system components, including the social, economic and ecological implications of different natural or anthropogenic factors" (Hamilton et al., 2015). Increases in remote sensing capabilities, availability of long-term spatially explicit data, computing power, and analytical algorithms have improved the ability of the scientific community to undertake environmental assessments with a global extent while maintaining, and even increasing, fine spatial and process detail. Some IAMs have been applied to aspects of biodiversity and ecosystem services in addition to climate, and there are also a growing number of biodiversity models and ecosystem service models that could be linked to IAMs (Table 1).

Despite this scientific progress, significant gaps remain in our ability to undertake truly integrated assessments that incorporate biodiversity and ecosystem services. Past efforts have examined linkages and feedbacks between IAMs and Earth system models, which incorporate carbon, water and nutrient cycles (Calvin and Bond-Lamberty, 2018), but Earth system models are typically too coarse to capture fine-scale landscape dynamics relevant to biodiversity and ecosystem services (Batáry et al., 2017; Baude et al., 2019; Dainese et al., 2019; Johnson et al., 2023b; Le Provost et al., 2021; Sirami et al., 2019). Significant gaps also remain in using results from IAMs to inform management and policy decisions (Kim et al., 2023; Pereira et al., 2020, 2021; Scharlemann et al., 2020; Soergel et al., 2021). Reyers and Selig (2020) summarized several research challenges relevant in this regard: integrating the role of biodiversity in contributing to ecosystem services, capturing the feedbacks reinforcing biodiversity and ecosystem service loss and unsustainable outcomes, and accounting for ecosystem services in achieving societal goals including higher-level goals like justice and equality.

Here we present a research agenda for enhancing the integration of biodiversity and ecosystem services into global IAMs. This agenda outlines five priority research areas in integrated modeling of biodiversity and ecosystem services to better address urgent global sustainable development policy objectives (Box 1):

1. Downscaling impacts of direct and indirect drivers on ecosystems
2. Incorporating feedbacks in ecosystems
3. Linking ecological impacts to human well-being
4. Disaggregating outcomes for distributional equity considerations
5. Incorporating dynamic feedbacks of ecosystem services on the social-economic system.

Table 1

Examples of: a) Integrated Assessment Models (IAMs) that have been applied in biodiversity and ecosystem service assessments, b) biodiversity models, and c) ecosystem service models.

Model type	Models	Key References
a. **IAMs** with application to biodiversity and ecosystem services (see Kim et al., 2018; Leclère et al., 2020)	AIM	(Fujimori et al., 2014)
	GCAM	(Calvin et al., 2017)
	GTAP-InVEST	(Johnson et al., 2021; Johnson et al., 2020)
	IMAGE	(Stehfest et al., 2014)
	MESSAGE-GLOBIOM	(Havlík et al., 2014)
	REMIND-MAgPIE	(Baumstark et al., 2021; Dietrich et al., 2019; Soergel et al., 2021)
	BILBI	(Hoskins et al., 2020)
b. Biodiversity models		(Alkemade et al., 2009; Schipper et al., 2020)
	GLOBIO	(Janse et al., 2015)
	GLOBIO-Aquatic	
	InSiGHTS	(Baisero et al., 2020)
	PREDICTS	(Newbold et al., 2015)
	Co	(Mulligan, 2015a)
c. Ecosystem service models	$tingNature	
	DIVERSE	(Cheung et al., 2021; Cheung and Oyinlola, 2019)
	GLOBIO-ES	(Veerkamp et al., 2020)
	InVEST	(Natural Capital Project, 2023)

We highlight challenges and examples of promising research directions for each of these five frontiers. We also discuss the science-policy linkages needed to move new research and information into action. The aim of this research agenda is to make it routine to bring nature and its contributions to people into policy and decision-making. Our review of global integrated assessment modeling draws primarily from studies on terrestrial biodiversity and ecosystems. However, the outlined priority research areas are also relevant to modeling for marine biodiversity and ecosystems (Cheung and Oyinlola 2019; Tittensor et al. 2021).

2. Science frontiers for integrated social-economic-ecological assessment

Integrated assessment models have made rapid advances in recent years, but several key challenges remain for improving the ability of these models to accurately integrate biodiversity and ecosystem services and provide more useful information to decision-makers to achieve multiple SDGs (e.g., in contexts like those represented in Box 1). In what follows we describe five challenge areas in greater detail along with modeling and/or data advances that will allow progress on each challenge. The integrated social-economic-ecological system with the five key science frontiers highlighted is shown in Fig. 1.

2.1. Downscaling impacts of direct and indirect drivers on ecosystems

IAMs can be used to analyze global economic trade and market outcomes, national-level policy, and other indirect drivers of ecosystem change, but typically operate at a high level of spatial aggregation. Biodiversity conservation and ecosystem services, however, are driven by processes occurring at much finer spatial scales, such water flowing over a landscape as vegetation filters out pollutants, a pollinator using flowering or nesting resources in and around a farm, or coastal habitat attenuating storm surge near people and property. Modeling that is globally applicable yet still locally contextualized is challenging for many reasons (Meyfroidt et al., 2022). A key research frontier is to connect large-scale indirect drivers, such as changes in human demographics, government policies, or market conditions, with the finer-scale resolution of direct drivers like land-use change that affect specific locations in ways that impact ecosystem processes, the provision of ecosystem services, and biodiversity.

Downscaling indirect drivers to map land use change at the scale of ecosystem services. Models such as IMAGE, GLOBIOM and MAgPIE allocate demand for different land uses on a gridded, subnational resolution, relying on various downscaling algorithms (e.g., Dietrich et al., 2013 for MAgPIE; DownscalR for GLOBIOM) applied to detailed databases (e.g., the GEOBENE database in the case of GLOBIOM; Skalský et al., 2008) to translate indirect drivers (consumption, demand) to direct drivers like land-use change at a resolution of 30 arcmin (~50 x 50 km) or less. The SIMPLE-G model (Baldos et al., 2020) allocates gridded cropland, crop production, consumption, and trade to 5 arc min (~10 x 10 km) grid cells, which builds on the data-validated aggregate SIMPLE model (Simplified International Model of Agricultural Prices, Land use and the Environment; Hertel and Baldos, 2016). However, to match the scale needed to represent many fine-scale ecological processes such as water quality regulation or pollination, 10–50 km grid cells are still far too coarse. Further downscaling to individual land-use/land cover/ocean pixels with spatial resolution as fine-grained as 30–300 m is required for modeling many ecosystem services (Chaplin-Kramer et al., 2019; Kim et al., 2018). Several models can spatially allocate land-use change to this scale using machine learning trained on past land-use change (Johnson et al., 2021; Suh et al., 2020; Johnson et al., 2020; von Jeetze et al., 2023), simple allocation rules (Mulligan, 2015b; Schipper et al., 2020), or statistical modeling (Hoskins et al., 2016). These downscaling models have generally been applied to land conversion (e.g., from forest to agriculture), but similar approaches could be used to address changes in management within a land-use (e.g., differences in forestry intensity or changes in fertilizer use or mixed cropping methods (Alkemade et al., 2022; Moor et al., 2022). Integrating this finer spatial downscaling into IAMs is crucial for predicting impacts of large-scale drivers on biodiversity and ecosystem services, which depend on local context.

Verifying accuracy of spatial patterns. Validating downscaling against

Box 1
Illustrative examples of important policy questions requiring integrated social- economic-ecological assessment.

1) **Guiding coordinated action across multiple international sustainability agreements: how can biodiversity, climate, and human development targets be simultaneously achieved?** The Paris Climate Accord, the Kunming-Montreal Global Biodiversity Framework (GBF), and the Sustainable Development Goals (SDGs) represent an ambitious set of biodiversity, climate, and human development goals. A major question facing society is whether all of these goals can be achieved simultaneously. Current policies should be evaluated to determine whether the national-level targets for the GBF (National Biodiversity Strategy and Action Plans), Paris Climate Accord (Nationally Determined Contributions), and sustainable development policies for the SDGs, if fully implemented, are likely to achieve global biodiversity, climate and human development objectives, or whether there will be shortfalls, and if so, how to address them. Information is needed regarding synergies and tradeoffs in achieving multiple objectives and the distribution of benefits and costs across countries and within countries to determine whether policies are likely to be durable and equitable.

2) **Nature-based solutions for delivering climate mitigation and adaptation: what are the full benefits and costs, and how resilient are they to future climate change?** Nature-based solutions are investments in nature that provide multiple environmental, social and economic benefits. Nature-based solutions can conserve biodiversity, provide ecosystem services for climate change mitigation and adaptation (e.g., carbon sequestration, flood protection), and help attain other sustainable development goals, but careful design is needed. When selecting between nature-based solutions and technological solutions (often built infrastructure such as dams or water treatment plants), fair comparisons should include the broad range of non-market environmental and social benefits of nature. Considerations of the long-term resilience of nature-based solutions requires information about the security of nature-based investments under climate change, and where and how the ecosystems providing key benefits can be maintained into the future.

3) Financial and economic risk assessment: what do changes in biodiversity and ecosystem services mean for disruptions in business-as-usual? Financial markets routinely account for risk, but typically do not account for risks from loss of biodiversity or ecosystem services. Of particular concern are potentially catastrophic events, such as extreme climate events or ecosystem collapse, with large negative financial consequences. Nature-related risk is often characterized by distributions with “fat tails,” denoting higher probabilities of extreme events than the normal distributions typically used in risk assessments. Financial markets are beginning to alter their policies to account for the greater probability of extreme events under climate change. However, there is a need to better understand risks from deterioration of nature leading to a reduction of resilience and loss of valuable ecosystem services.

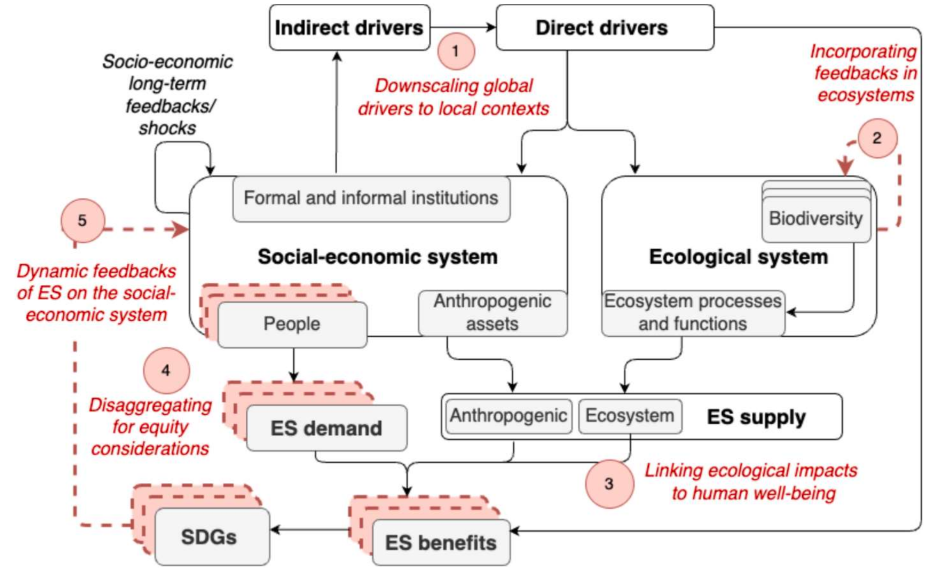

Fig. 1. Conceptual diagram for integrated social-economic-ecological assessment illustrating the five frontiers for modeling and data advances (identified in red text): 1) downscaling impacts of direct and indirect drivers on ecosystems; 2) incorporating feedbacks in ecosystems; 3) linking ecological impacts to human well-being, 4) disaggregating outcomes for distributional equity considerations, 5) incorporating dynamic feedbacks of ecosystem services on the social-economic system. Solid black lines represent linkages that already exist (but could be improved where red text appears), while dotted red lines represent linkages that, for the most part, are missing. Multiple stacked boxes for biodiversity represent different levels or elements of biodiversity. Multiple stacked boxes for people, ecosystem service (ES) demand, ES benefits, and Sustainable Development Goals (SDGs) represent groups in society that may experience impacts differently (shown in red as currently missing elements). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

observed land-use and economic and environmental outcomes is an important topic (Baldos and Hertel, 2013; Visconti et al., 2016). Hindcasting of downscaled predictions for GLOBIOM-Brazil has been compared with official statistics for deforestation, emissions, and production of major commodities such as soy, sugarcane and beef (Soterroni et al., 2023, 2019; Soterroni et al., 2018). Hindcasting and comparison with observed outcomes could be applied more widely as a check on validity of downscaling approaches. Validating model output is necessary for decision-makers to have confidence that the spatial pattern of land-use change and resulting impacts from indirect drivers is reasonably accurate.

Finding the right level of detail for land-use change. A limitation of many downscaling approaches is that they do not consider spatial feedbacks from effects of neighboring cells, interactions between land and ocean systems, economies of scale, or economic market factors. Some detailed land-use change models such as CLUMondo (Wolff et al., 2018) and DynaCLUE (Verburg et al., 2021; Verburg and Overmars, 2009) incorporate both bottom-up and top-down factors, allowing consideration of more complex land-use dynamics. These models have been used at the national level to link ecosystem service models to national-scale computable general equilibrium models of the economy (Banerjee et al., 2019). The downside of these detailed land-use change models, however, is the increased computational time and, relatedly, lower output resolution (e.g., CLUMondo produces 10 km resolution results globally). A key research frontier lies in coupling computationally efficient models capable of representing complex land-use dynamics with models that capture indirect drivers operating at larger scales (e.g., national policies and global markets).

Integrating other drivers. Other direct drivers of global biodiversity change beyond land-use change include climate change, pollution, overexploitation, and invasive species (IPBES, 2019). These drivers are often missing in integrated assessment models. Modeling of climate change is by far the most advanced. However, while some integrated assessment models are capable of teasing apart climate from land-use impacts on ecosystems (Davies-Barnard et al., 2015), predicted ecosystem-climate interactions are rarely included in ecosystem service modeling (but see Andriamanantena et al. 2022). Climate change may alter the policy and management options available (e.g, the likelihood of success of restoring ecosystems important for ecosystem services; expected range shifts of culturally important species), so improving climate-ecosystem interactions and making results available to decision-makers would be an important advance. The other direct drivers are currently less well represented in integrated assessment. Each may have a different scale at which it needs to be represented in order to translate the driver to changes in biodiversity and ecosystem services. For example, fine-grained species-level modeling has been used to map hunting-induced mammal defaunation across the tropics at a resolution of 30 arc-seconds (Benítez-López et al., 2019). Incorporating all drivers into a unified assessment would allow decision-makers to better understand which drivers are the most important to address.

2.2. *Incorporating feedbacks in ecosystems*

Biodiversity and ecosystem service models typically quantify responses to drivers of ecosystem change as a function of current conditions without considering feedbacks. For example, the long-term effects of climate change on ecosystems and biomes are typically not captured in ecosystem service models. Similarly missing from models are the long-term effects of degrading natural capital stock, such as declining soil organic matter or forest integrity, and the interactions between different aspects of biodiversity, different ecosystem services, or biodiversity and ecosystem services. Furthermore, most models are unable to capture cascading effects that may lead to tipping points: critical thresholds beyond which conditions deteriorate rapidly, such as deforestation followed by erosion, soil loss, and irreversible vegetation change (Armstrong McKay et al., 2021). Capturing ecological feedbacks may in some cases require building new ecosystem service models that are more responsive to changes in ecosystem integrity or diversity (Kim et al., 2023). Incorporating such feedbacks is necessary to address questions about the resilience of sustainable development strategies such as nature-based solutions (Box 1).

Reflecting ecosystem condition and long-term change. The current distribution of ecosystem types is likely to change under future climate. Some ecosystems may shift to new types (e.g., through afforestation, desertification, savanification) while others may change substantially in terms of condition or quality (Barnosky et al., 2017). These climate impacts on biodiversity, ecosystem structure and ecosystem function are relatively well understood (Weiskopf et al., 2020) but are seldom included in ecosystem services models, despite their influence on the provision of ecosystem services and the potential effectiveness of management to maintain biodiversity and ecosystem services. Likewise, the long-term feedbacks between soil quality and land productivity can have major impacts on ecosystem service provision as land degradation poses a major threat in some systems. Changes in soil quality and land productivity are largely ignored in current integrated assessment studies, due in part to uncertainty in evaluating the state and causes of soil degradation. An exception is the scenarios developed for the UNCCD's Global Land Outlook, that incorporated yield decline due to soil degradation, and its effect on land use, biodiversity and food security (van der Esch et al., 2022). To apply such approaches in an integrated modeling context, scenario development will be needed linking drivers (Frontier 1) to expected changes in ecosystem condition.

Assuming such scenarios could be generated, there is great potential in more explicit representation of continuous changes in ecosystem condition or function for driving changes in biodiversity and ecosystem services. While many marine ecosystem models include linkages between ecosystem condition, function, and services (Tittensor et al., 2018), terrestrial models, in contrast, have traditionally represented functions and conditions through categorical land cover (e.g., cropland, forest). Future development of land-use models could include variables such as continuous fractional covers of multiple vegetation functional types (Co$tingNature; Mulligan, 2015a) as well as continuous variables for productivity, structural complexity, diversity, and fertility (Ramirez-Reyes et al., 2019). Many efforts have mapped the natural heterogeneity within ecosystems across space and changes in ecosystem condition or quality resulting from changes in land management (Cord et al., 2014; Gábor et al., 2022; Hill et al., 2022; Leitão and Santos, 2019), which could be used in biodiversity and ecosystem service models to enable representation of degradation or restoration of ecosystem service provision occurring within an ecosystem type over time. Restoration of degraded lands is a major focus of the Global Biodiversity Framework and Paris Accord targets, and current ecosystem service modeling based on land-use/land-cover is insufficient for informing such efforts. Modeling using ecosystem quality or integrity as inputs rather than land cover would also enable better representation of naturally sparsely vegetated ecosystems like deserts, which provide important ecosystem services but are left out of many ecosystem services assessments because they are difficult to distinguish from barren lands (e.g., Chaplin-Kramer et al., 2023).

Coupling ecological models across realms. Many functional linkages between land, ocean and freshwater systems connect these three realms, including through the flows of water, energy, materials and organisms. Janssen et al. (2019) describe the outlines of a coupled global model system of land-use, hydrology, and lake ecosystem dynamics, which can then be linked to the ecosystem services provided by the lakes as a function of their ecological state (including local regime shifts; Janssen et al., 2021). Janse et al. (2019) perform a similar linking for inland wetlands, systems typically on the terrestrial-aquatic interface. A problem in linking across realms is that biodiversity and ecosystem services models in these three realms often use different schematizations and spatial resolutions, making it harder to model interactions between land, water, and ocean systems at scales relevant for these processes. Yet linking these models is essential for any integrated or coordinated management across these realms.

Coupling models for ecosystem-atmosphere linkages. Ecosystems shape the Earth's climate through regulation of water, energy, and biogeochemical flows, which affect hydroclimatic and ecohydrological conditions both locally and remotely. A wide range of land-atmospheric energy and water balance feedbacks can be represented through the coupling of land-surface modeling with modeling of atmospheric dynamics at varying details (Lawrence et al., 2022; Lawrence and Vandecar, 2015; Swann et al., 2015). Land-based changes to the atmospheric water balance can be accounted for by coupling a land-surface model to a data-driven moisture tracking scheme (or pre-processed moisture flow data; e.g., Tuinenburg et al., 2020). Such approaches have been used to assess potential for strategic positioning of reforestation projects for water-stress alleviation (Tuinenburg et al., 2022), to account for self-amplified feedbacks of forest loss in the Amazon rainforest (Zemp et al., 2017), and to quantify contributions of Indian irrigation to Chinese rainfall and river flows (Wang-Erlandsson et al., 2018). Vegetation-regulated moisture supply could be thought of as a keystone ecosystem service determining the supply of other ecosystem services through its impact on the ecosystems that provide those services (Keys et al., 2012, 2024), making it a key determinant of the resilience of nature-based solutions.

To account for other ecosystem impacts on the atmospheric system, such as energy balance, albedo, and atmospheric circulation, regional or global climate models that resolve for atmospheric dynamics are required (e.g., Swann et al., 2015), which comes at a high computational cost. Biogeochemical processes that create ecosystem-atmospheric feedbacks are not yet well captured by most Earth system models. For example, many global climate models underestimate carbon loss from tree mortality (Koch et al. 2021), warming impact on wetland methane emissions (Peng et al., 2022), and boreal treeline advance increase of biogenic volatile organic compounds and tropospheric atmospheric lifetime of methane (Boy et al., 2022). Holistic consideration of multiple types of ecosystem-atmospheric feedbacks are important, as different effects from land-based changes can cancel each other out or amplify in non-linear ways (Lawrence et al., 2022; Staal et al., 2015).

2.3. Linking ecological impacts to human well-being

Human well-being is multidimensional, including concerns about livelihoods, income, wealth, security, physical and mental health, social relations, and cultural experiences (IPBES, 2022). Nature influences human well-being in multiple ways and at varying scales (Brauman et al., 2020; Chaigneau et al., 2019; IPBES, 2019). However, most biodiversity and ecosystem service models stop short of measuring impacts on human well-being, often quantifying ecosystem services in biophysical terms (e.g., tons of carbon sequestered or cubic liters of water provided), and occasionally weighting these biophysical metrics by beneficiary populations (Mandle et al., 2021). Socioeconomic assessment of ecosystem services often has to be undertaken outside of the models, as a bespoke analysis, making it difficult to scale. This is a critical gap to fill; without the ability to easily link changes in ecosystem services to meaningful measures of impact on different social and economic dimensions of well-being, none of the policy questions posed in Box 1 (or others like them) can be fully addressed. Making clear the impact that changes in biodiversity and ecosystems have on different social and economic dimensions of well-being through fully linked ecosystem service model outputs greatly increases the probability that such information will be considered in public policy, community choices, and private sector investments and management decisions.

Scaling up local social-economic context for global assessment. At local and regional scales, ecosystem service models have made great progress in linking ecological impacts to social and economic impacts. Studies have analyzed the contributions of specific ecosystem services to human well-being in a particular location, such as the value of pollination for crop production (Klein et al., 2007; Ricketts et al., 2004) or the value of coastal protection from mangroves and other coastal habitats (Barbier et al., 2008, 2011). These studies often develop detailed site-specific information about the ecological conditions that determine service provision and the social-economic conditions that determine the benefits derived from service provision. Many of these local and regional scale studies use methods of market and non-market valuation from economics to estimate the values of ecosystem services in monetary terms (Freeman et al., 2014; National Research Council, 2005; Polasky, 2023). Estimates of monetary value are common for material ecosystem services (e.g., production of food, fiber, feed, and fuel), which often have a market price that can be used as a signal of value. Market prices can also be used to estimate the value of some regulating services that contribute to the provision of commodities, such as pollinators' contribution to agricultural crops, or that reduce harms to assets with market values, such as the value of coastal protection that increases property values. For many regulating and non-material ecosystem services, however, non-market valuation methods are the only available option, such as measuring the values people hold for a sacred forest or a culturally important species of fish (IPBES, 2022). An alternative approach that avoids using monetary and non-monetary valuation in order to put things into a common metric is ecological-economic viability analysis (Baumgärtner and Quaas, 2009; Béné and Doyen, 2018; Oubraham and Zaccour, 2018). This approach defines a set of components and functions of a dynamic stochastic system that are maintained above a specified probability (Baumgärtner and Quaas, 2009), making it consistent with "strong sustainability" principles aimed at preserving natural capital stocks, in contrast to monetary valuation approaches that are more associated with "weak sustainability" (Neumayer, 2014).

Whatever the approach, linking ecological impacts to social and economic impacts and human well-being done at the global scale remains a challenge. IAMs have been used recently to analyze the current status and potential future trends globally for land use, agriculture, and biodiversity (Leclère et al., 2020; Popp et al., 2017; Springmann et al., 2018; Stehfest et al., 2019), ecosystem services (Chaplin-Kramer et al., 2019; Kok et al., 2023), climate and energy (Riahi et al., 2017; Rogelj et al., 2018; Rose et al., 2020), and food security (Fujimori et al., 2022; Hasegawa et al., 2019). However, for the most part, these global studies have not delved into social-economic data needed to translate outputs into impacts on human well-being.

Three main challenges stand in the way of providing complete global-scale coverage of the value of ecosystem services. First, the need for detailed site-specific social-economic information makes it difficult to extend the coverage of local and regional studies to national or global extent. For example, IAMs can estimate water quantity and water pollution using globally available data, but without detailed information on water intake facilities and water use, it is not possible to accurately quantify the value of changes in water availability or water quality. A major effort is needed to increase the global availability of locally relevant contextual social and economic data to fill this gap. Second, the gap between the way ecologists and other natural scientists analyze ecosystem condition and function and the way economists and other social scientists analyze welfare can make it difficult to effectively link understanding of changes in ecosystems with changes in human well-being. Integrating natural and social science perspectives from the beginning in designing IAMs, along with extensive dialog in research design and analysis can help to close this gap (Yang et al., 2015). Third, the contribution of some ecosystem services to human well-being is difficult to evaluate in quantitative terms even apart from difficulties of data or effective links to ecosystems. The difficulties of measuring value are particularly great for cultural and social values (non-material ecosystem services), including learning and inspiration, spiritual values, social cohesion, and sense of place (Chan et al., 2012; IPBES, 2022). Although the task may seem daunting, progress along any one of these fronts would strengthen capabilities to account for ecosystem services in a variety of social, economic and financial policy and decision-making contexts where they are commonly ignored.

Ecosystem services and health. In addition to the growing literature on monetary measures of ecosystem service value, there is a growing body of research that demonstrates links between mental and physical health and a person's exposure to and experience in nature (Bratman et al., 2019; Ohly et al., 2016; Van Den Berg et al., 2015). For example, ecosystem service models can assess the contribution of upstream forests to reducing diarrheal disease downstream (Herrera et al., 2017) and of coastal/marine protected areas to childhood health (Fisher et al., 2017). Systematic review has shown evidence for positive impacts of greenspace on mental health, including mental affect (i.e., outward expression of emotion), and physical health, including a reduction of heat-related health impacts (van den Bosch and Ode Sang, 2017). The link between nature and human health is especially prominent in cities, where space for nature tends to be limited (Richards et al. 2022). A recent study quantified heat-related health impacts across nearly one hundred U.S. cities and estimated that urban tree cover annually contributes to saving 245–346 lives, avoids more than 50,000 doctor's visits due to heat, and provides heat-related benefits equivalent to $1.3–2.9 billion or $21–49 per capita (McDonald et al., 2020). Mental health impacts have been similarly quantified through gradients in exposure to nature, showing one per 1000 fewer antidepressant prescriptions for each additional street tree per kilometer of road (Taylor et al., 2015) and 9% lower rates of depression through nature visits of just 30 min per week (Shanahan et al., 2016). Empirical evidence of other improvements in mental health through nature exposure that can be similarly translated to such relationships (Bratman et al., 2019).

Several major challenges exist for including impacts of nature on mental or physical health in IAMs. Currently, there is only limited information about the strength or shape of the relationship between nature and health (i.e., 'dose–response relationship'), or the specific aspects of nature (amount, configuration, greenness, diversity, etc.) and scale (from meters to kilometers) that are relevant to people. For example, some studies find that the quality of nature is important, with more "natural" spaces tied to stronger health impact (van den Bosch and Ode Sang, 2017). A recent framework proposes ways of quantifying the different sensory dimensions of the aesthetic qualities of nature (Stoltz and Grahn, 2021), which could be used to further delineate the specific variables driving such health effects. Increasingly high-resolution satellite information makes it possible to map nature in cities at very fine spatial scales that may be relevant to mental and physical health impacts, capturing people's exposure to nature as they move between where they live, work, study, and socialize. Analysis of smartphone GPS information and other geocoded data could help fill this gap, but privacy and equity concerns complicate the uptake and widespread use of such data (Markevych et al., 2017). Understanding how other variables (age, gender, race, ethnicity, socioeconomic status, etc.) moderate the effect of greenspace on health is another important gap, especially because there is often highly uneven access to nature in cities, which may exacerbate other inequalities (see next section, on disaggregating beneficiaries). Furthermore, much of the work on mental health benefits of nature come from the Global North; this geographic bias needs to be corrected to better understand how to evaluate such benefits especially in developing countries (Bratman et al., 2019). Undesirable health effects like allergies or vector-borne diseases should also be recognized (van den Bosch and Ode Sang, 2017). It may be most productive to develop holistic or composite measures that capture a wide range of health-related outcomes through multiple pathways (Markevych et al., 2017).

Towards multidimensional well-being. It can be difficult to tease apart the effect of nature on different aspects of well-being, especially since so many of them interact with each other (e.g., greater ability to exercise as well as mood can affect cardiovascular disease). A key challenge for measuring and modeling multiple dimensions of well-being is that while approaches for material well-being are relatively advanced, methods for subjective and relational dimensions (e.g., life satisfaction, social relations/capital) remain underdeveloped (McGregor et al., 2015; McGregor et al., 2015b). Further, while modeling tends to rely on simplified observed (proxy) variables to represent more complex latent constructs (such as well-being), evidence shows that well-being dimensions are not all consistently correlated, so it is difficult to find a simple proxy for several dimensions. For example, while income, assets and wealth are commonly used as proxies for overall well-being, higher income is not necessarily correlated with better shelter, sanitation, or food security within a given community (Chaigneau et al., 2019). Similarly, life satisfaction is determined by much more than just income (Hojman and Miranda, 2018). Integrating subjective and relational dimensions of well-being in social-economic-ecological modeling is needed for supporting more holistic sustainable development. While there are no perfect measures of well-being, there are many measures of components of well-being, such as measures of health, income, livelihoods, and security, which can be measured and of interest to decision-makers. Incorporating such measures into ecosystem service models would improve integrated assessments.

2.4. *Disaggregating outcomes for distributional equity considerations*

Equity considerations lie at the heart of sustainable development. Many SDGs, including Goal 1 to eliminate poverty, Goal 2 to eliminate hunger, Goal 5 on gender equality, and Goal 10 on reduced inequality, focus explicitly on equity. The poor tend to depend more directly on nature and derive a larger share of their income from it (Angelsen et al., 2014). Yet, ecosystem service assessments rarely analyze the distribution of benefits or directly address equity issues (Langemeyer and Connolly, 2020). Social and economic data are often highly aggregated at province or national level. Many IAM results are based on averages (e.g., mean or median income), which by definition do not address those at the lower end of the distribution. Disaggregation among people or groups that differ by gender, age, livelihoods, income and other social and economic characteristics at finer spatial scale is needed to address these concerns, especially for representing the needs of Indigenous People and Local Communities (Forest Peoples Programme et al., 2020). Social and spatial disaggregation is also important for understanding how ecosystem services benefit different groups, and how the stewards of areas providing ecosystem services differ in their access to capital and land tenure security (Agarwala et al., 2014; Daw et al., 2011, 2016, Fisher et al., 2013, 2014). Advancing capabilities for representing how changes in biodiversity or ecosystem services will affect the well-being of different groups is a key consideration for guiding coordinated action across multiple international sustainability agreements (as described in Box 1), because understanding how reaching biodiversity or climate targets enable achievement of the SDGs requires an equity lens.

Integrating poverty and other vulnerabilities. An important challenge facing those seeking to link IAMs to household level outcomes, such as poverty, nutrition, and health, is finding meaningful linkages between IAM outputs and characteristics of individual households. The poor control few assets other than their own labor, so accurate modeling of labor markets is an important component of assessment of poverty and equitable sustainable development (Hertel and Winters, 2005). Hertel et al. (2010) assessed the poverty impacts of climate change, showing that low-income, agriculture-specialized households in some countries could benefit from adverse climate shocks due to the ensuing rise in commodity prices and agricultural wages, while urban poor would be made worse off. The GTAP-POV framework (Hertel et al., 2015) groups households below the poverty line into seven strata that could be used to analyze distributional effects of changes in ecosystem provision or access. Nature has also been highlighted as a fundamental constituent of well-being and poverty in contexts beyond labor, especially related to cultural values, access to natural spaces, and resilience and vulnerability to natural hazards (Schleicher et al., 2018). Detailed household-level data available in some regions might offer opportunities to delve into distributional concerns of this type of nature dependence (Fedele et al., 2021). Disaggregating population data into this finer demographic detail is also important for assessing poverty and displacement impacts of conservation and other environmental policies.

Using field studies and Earth observations to analyze distribution of benefits. An emerging set of large, household survey-based field studies used in disaggregating populations for modeling multiple well-being outcomes (Adams et al., 2020; Robinson et al., 2019; Smith et al., 2019) are increasingly being combined with satellite Earth observations to provide rich spatial datasets on social dimensions relating to well-being, poverty and inequality, at above-household but still very fine (e.g., village) scales (Chi et al., 2022; Jean et al., 2016; McBride et al., 2022). The IAM community has an opportunity to leverage these datasets and analyses for modeling the distribution of benefits (Hargreaves and Watmough, 2021; Watmough et al., 2019; Yeh et al., 2020). Despite this opportunity, incorporating disaggregated information by social group and well-being dimensions continues to face a number of challenges. Social differences (e.g. gender, ethnicity, religion, occupation, etc.) and their impact on well-being outcomes are highly variable and context specific (Daw et al., 2016). For example, the impact of environmental change on the vulnerability of female-headed households depends on how resource access is gendered in a particular culture and location (Fortnam et al., 2019). Modeling impacts on marginalized groups is also challenged by inherent limitations and biases in the data typically available to modelers. For example, the finest scale data is usually at household-level, which is sometimes too coarse to detect important mechanisms of marginalization that may occur within a household (Golden et al., 2016). Data are also likely biased towards the perspectives of dominant social groups, such as the prevalence of 'male data' (Perez, 2019) and WEIRD (Western Educated Industrialized Rich Democratic) data (Henrich et al., 2010). Still, even preliminary breakdowns of impacts by social groups that can later be contextualized would be a major step forward for incorporating equity into analysis and policy, flagging potentially unintended consequences for marginalized groups.

Fine-scale equity mapping in urban ecosystem service contexts. Urban planning is undergoing a revolution in thinking about investing in nature (green infrastructure), but the widespread interest is constrained by limited information on how the resulting changes in ecosystem services (e.g., urban cooling, urban agriculture, stormwater protection, recreation opportunities) provide benefits to different groups. Investments in parks and green spaces that may make neighborhoods more desirable can lead to gentrification forcing poorer residents to move (Keeler et al., 2019). Addressing the distributional consequences of green infrastructure investments in cities requires integrating ecosystem services with understanding of market feedbacks. Planning for equitable distribution of benefits likely requires a portfolio approach to green infrastructure decisions that can help planners choose the best set of locations for investment based on socioeconomic factors (Hamel et al., 2021; Lonsdorf et al., 2021; Nesbitt et al., 2019). The scale of "service-sheds", the area over which an ecosystem service is provided, may or may not align with the scale of decision-making, leading to externalities and likely underinvestment (Cortinovis and Geneletti, 2020). Insights generated by developing socioeconomic and land cover data libraries that are integrated with tools like urban InVEST (Hamel et al., 2021) could identify where coordination is needed between different scales of governance and where equity concerns may need special attention within urban systems.

2.5. *Incorporating dynamic feedbacks of ecosystem services on the social-economic system*

The final challenge we identify is incorporating the socio-economic impacts resulting from changes in biodiversity and ecosystem services into a dynamic representation of integrated social-economic-ecological systems. This modeling frontier brings all of the previously discussed frontiers into a final step feeding back on the social-economic system. It is this system that determines the drivers that cause changes in environmental conditions (Frontier 1) and ecosystem services (Frontier 2) that lead to differential benefits and costs (Frontier 3) accruing to different groups (Frontier 4) that ultimately feed back onto the overall social-economic system. This cascade could be modeled in a single time step with a static representation of impacts and the costs and benefits of those impacts for a single scenario. However, in each time step, impacts on the social-economic system can cause shifts in incentives for people to undertake certain activities, shifts in demands and supply of goods and services, the potential for social and cultural changes, all of which can lead to changes in behavior that can cause further environmental change. These types of feedback effects are not considered in most IAMs. However, such feedbacks are a key factor shaping human development, ranging from migration, shifts in livelihoods, investments in infrastructure, to fundamental shifts in cultural practices. In many contexts, these feedbacks are what is missing for this information to be most relevant to decision making. To assess the long-term social and economic consequences of any policies for sustainable development (such as those considered in Box 1 or others like them), these feedbacks that cause changes in underlying drivers of further change must be included.

Endogenizing ecosystems and climate in economy modeling. One way to assess feedback effects of changes in ecosystems and climate on the social-economic system is to incorporate ecosystem services into computable general equilibrium (CGE) models. Progress on this front has been made both at the national level with the Integrated Environmental-Economic Model (IEEM) (Banerjee et al., 2020), and at the global level, with the integrated GTAP-InVEST model linking the Global Trade Analysis Project's (GTAP) CGE with the InVEST ecosystem services model (Johnson et al., 2021, 2023a,c; Johnson et al., 2020; Johnson et al., 2023b). These models incorporate the impacts of changes in ecosystem services on the economy, including capturing indirect effects from changes in relative prices and subsequent changes in supply and demand in various economic sectors. To date, the set of ecosystem services incorporated has been limited (e.g., pollination, timber provision, carbon storage, marine fisheries in GTAP-InVEST), but in principle these models could include a much wider set of effects such as the effect on labor productivity from changes in urban heat islands or burden of disease from lower air or water quality. The current versions of these ecosystem-economy models do not incorporate climate impacts of changing ecosystems on the economy and resulting drivers of change. There are many climate models integrated into economy models (e.g., Nordhaus 2014, Hope 2013), but these are missing the intermediate effects of climate on ecosystems on ecosystem services and values.

In addition, while these models capture contributions to marketed goods and services, they miss many ways that biodiversity and ecosystems impact society and culture, notably through non-marketed ecosystem service benefits such as cultural or spiritual values. Measures of marketed goods and services also often fail to include informal economic sectors, such as subsistence farming or other household activities that do not show up in formal economic accounts. For this reason, other metrics that go beyond marketed goods and services may be necessary. One such metric linked to ecosystem service provision is Gross Ecosystem Product (GEP), which China is using as a measure of the aggregate value contributed by ecosystem services to track sustainable development progress and reward high-performing local governments (Ouyang et al., 2020; Zheng et al., 2023). Better integration of ecosystem service feedbacks on social-economic systems will better capture the long-term dynamics of sustainable development trajectories. A truly integrated assessment model must strive to capture the crucial elements and relationships of such an integrated social-economic-ecological system.

3. Pathways to impact: Linking improved science to policy

The advances reviewed above would push integrated modeling toward greater societal relevance, supplying the information needed to navigate towards a more prosperous, equitable, and sustainable future. But for such information to be truly transformative, the gap between science and action needs to be closed. The dangers posed by climate change and loss of biodiversity and the lack of meaningful policy or societal action on either front provide two compelling examples of how difficult this can be, even for phenomena that are relatively well understood. A number of studies have shown that the benefits of taking actions to reduce greenhouse gas emissions far exceeds the costs of doing so (Burke et al., 2018; IPCC, 2023, 2014; Moore and Diaz, 2015; Nordhaus, 2013, 2017; Stern, 2007, 2008). Similarly, there are many cases where the documented benefits of protecting nature far exceed the costs (Balmford et al., 2002; Bateman et al., 2013, p. 201; Dasgupta, 2021; IPBES, 2019; Johnson et al., 2021; Nelson et al., 2009; Polasky et al., 2011). And yet, each year emissions of greenhouse gases and loss of biodiversity continue.

One of the major reasons for the divergence between what is known by science and the direction of global society is the fact that the dominant economic system based on markets does not adequately account for the diverse values of nature, nor does it accurately account for the harm done by economic activity to those values (IPBES, 2022). The basic rules by which the global market economic system operates were formed in prior centuries when human influence on the biosphere was far less than it is now. Under these rules, businesses and consumers are incentivized to choose actions that are good for their immediate private needs, but actions taken under a narrow short-term focus cumulatively imperil the future health and well-being of all of humanity. Not fully incorporating the values of nature into social, economic and financial, and policy decision-making means we are ill-equipped for dealing with pressing 21st century problems that society currently faces (Folke et al., 2021; Polasky et al., 2019).

One of the great strengths of IAMs is to embed economic and social systems within integrated Earth systems models to show how economic and social drivers affect ecosystems, and in turn how changes in ecosystems affect human health, well-being, and prosperity. As such, IAMs can be powerful tools to help guide societal decisions towards sustainable development and away from destructive trajectories. Of course, the ability of these models to assess future consequences in a complex social-economic-ecological system will always be imperfect, but these tools offer insights and evidence that can be used to explore possible futures and chart more sensible policies. For IAMs to realize their full potential in improving societal decision-making, however, they must prove useful to decision-makers, and thereby be employed to inform decision-making. A perfect integrated assessment tool will not improve societal outcomes unless it is linked to decision-making in both public and private spheres. While the research frontiers we identified here were motivated by the intent of improving our capacity to answer urgent policy questions (such as those highlighted in Box 1), model development to address those challenges will likely be most successful if tested and discussed, and where possible co-developed, with decision makers and other stakeholders.

An important consideration for working with decision makers is finding the right level of model complexity to reveal important insights while still being easily understood. Throughout this paper, we have stressed the importance of integrated modeling of social-economic-ecological systems that is capable of incorporating ecological feedbacks, social-economic feedbacks, and the mutual feedbacks between social-economic and ecological systems. We have also stressed the importance of downscaling the impact of global processes to local contexts and considerations of equity and the distribution of benefits across different groups. However, incorporating all of these factors into an integrated model will increase the complexity of the model. If not done carefully, the increased complexity can be overwhelming, outstripping data availability and making results difficult to understand and interpret (Hertel et al., 2023).

Considering model complexity as one “cost” when choosing an approach is important to identify when, and where, additional complexity is needed. In many cases a compromise may be found in combining IAMs with simplified mathematical models or models of intermediate complexity (MICE), for example those that join bioeconomic models for fisheries (Plagányi et al. 2014; Doyen, et al., 2017) or land-use (Ay et al, 2014), or including *meso*-level models in between modeling scales (Johnson et al., 2023c). Model complexity can be addressed via reduced-form empirical models, especially with machine learning and artificial intelligence model emulation approaches (Liu et al., 2024; Yang et al., 2023). Such models are beneficial in the sense of improving insights with greatly reduced model complexity and faster computation time, enabling real-time model computation for integration with decision-making processes. An analysis of model uncertainties can help determine whether including additional capabilities improves models enough to be worth the added complexity, especially over longer timeframes (Rounsevell et al., 2021). Given the uncertainty of many modeled trajectories, one of the important contributions of IAMs may be to help decision-makers consider the probability and magnitude of impacts to identify "significant" risks. Using an uncertainty or risk lens to select from the many available models of intermediate complexity allows the identification of an appropriately complex model for a given research question, context, or spatial/temporal scope.

Refining models for decision relevance and uptake requires well-established channels to promote connection between science and decision-makers. Many of these already exist. At the global level, the IPCC and IPBES synthesize scientific understanding and communicate the science to national governments. At the national level, many governments have highly trained scientific staff in various agencies whose responsibility is to understand and communicate the latest science to high level decision-makers. In addition, climate, conservation and development NGOs play a vital role in promoting and communicating science to decision-makers, including practitioners and local citizens. Increasingly, corporations and financial institutions pay attention to sustainable development metrics and report on the impacts of their operations through the Taskforce on Climate-Related Financial Disclosures (fsb-tcfd.org) and the Taskforce and on Nature-Related Financial Disclosures (tnfd.global). Similarly, the Network of Central Banks and Supervisors for Greening the Financial System, a network of the financial systems of many of the world's largest economies, is increasingly concerned about the role of climate change and biodiversity loss as sources of systemic risk to the world's economies and currencies (ngfs.net).

Even with all of these positive developments, however, a significant gap remains between the science produced by IAMs and government and private sector decision-making. Working through the IPCC, IPBES, and the scientific staff of national governments to strengthen and improve science-policy linkages is of vital importance. At present, however, IPCC and IPBES reports have greater resonance in environment and natural resource ministries than they do in ministries of finance, agriculture, education, health, development, and other ministries concerned primarily with economic or social issues. The social-economic-ecological integration we are calling for here would facilitate translation of scientific findings into terms that resonate with finance ministers, business CEOs, and the general public, such as indicators of economy, health, jobs, income, and well-being, including socially relevant indicators such as impacts on physical and mental health. This is a key first step but must also be accompanied by structural changes in decision-making and accountability to bring about the kinds of transformative change needed for achieving a sustainable world.

4. Conclusion

In this paper, we have laid out a research agenda for integrated assessment modeling to provide understanding of connections between the social-economic and ecological systems over time and across local to global scales. Making progress on the five frontiers identified here would provide key insights into how global drivers play out locally, how to better anticipate the unexpected by accounting for long-term ecological change, how ecological change can impact the economy and human well-being, how these impacts play out across different socioeconomic groups, and how feedbacks from ecological systems may affect human behavior and drive long-run directions of the global social-economic-ecological system. Improving understanding in these areas is essential to evaluate policies and identify pathways toward sustainability.

Our review of the research gaps and key frontiers to fill them has a few key implications. First, more funding is needed to build these integrated assessment models, which do not necessarily represent significant advances in any individual domain but fundamentally advance holistic and systemic understanding relevant to decision-making. More opportunities and fora for international cooperation and collaboration are needed, especially given that most researchers working on IPCC and IPBES assessments are largely unfunded. The Belmont Forum is one avenue for such collaboration funding, where several countries' national science foundations agree to fund proposals by international teams, but the individual awards are often not large enough to undertake the substantial work needed to advance this type of modeling.

Second, it is important to provide training and capacity building to use these types of models within universities, agencies and NGOs, to enable wider adoption and application. Interdisciplinary departments or schools within universities, like those housing environmental science and policy programs, could include such models in their curriculum, building the familiarity and competency with ecological, social, and economic techniques needed to build the next generation of modelers and models, and providing trained people who can use these models across public and private sectors.

Third, open-access data and open-source models are crucial to facilitate model development and uptake. Advancing the research frontiers described here hinges on model integration, which requires interoperable data formats and easily accessible code to adapt the models in order to create the necessary linkages between them. Agreements on data standards and analysis protocols can also help to ensure quality and increase comparability across models.

Finally, enacting requirements for science- and evidence-based decision-making could help drive demand for this information. For example, recent US federal government guidance to all federal agencies to incorporate ecosystem services into cost benefit analysis will push more rapid development and use of ecosystem service models. Similar guidance on when and how to use integrated assessment models would help spread adoption and make analysis and results more useful. Part of this task may fall on the research community to demonstrate the value of this information, building understanding of how much better off society would be if decision-making used integrated assessment modeling; this would also help address questions around the right level of complexity to include in modeling.

Ultimately, if nature is not adequately represented in integrated assessment modeling, its contributions to the global economy and to human development will continue to be vastly underestimated. From evaluating how nature-based solutions could address loss and damages in upcoming climate negotiations, to setting up loans or debt relief that can promote more resilient development, to anticipating and avoiding threats posed by nature degradation and climate change to the economy and to international security, an array of policy opportunities are emerging that require better understanding of an integrated social-economic-ecological system. While information alone is never a guarantee of improved decision-making, it is clear that the current state of modeling is insufficient to meet decision needs. Advancing along the frontiers explored here would support the type of integrated decision-making we need to navigate the interrelated challenges in an interconnected world.

CRediT authorship contribution statement

Rebecca Chaplin-Kramer: Writing – review & editing, Writing – original draft, Project administration, Conceptualization. **Stephen Polasky:** Writing – review & editing, Writing – original draft, Conceptualization. **Rob Alkemade:** Writing – review & editing, Conceptualization. **Neil D. Burgess:** Writing – review & editing, Conceptualization. **William W.L. Cheung:** . **Ingo Fetzer:** Writing – review & editing, Conceptualization. **Mike Harfoot:** Writing – review & editing, Conceptualization. **Thomas W. Hertel:** Writing – review & editing, Conceptualization. **Samantha L.L. Hill:** Writing – review & editing. **Justin Andrew Johnson:** Writing – review & editing, Conceptualization. **Jan H. Janse:** Writing – review & editing. **Patrick José v. Jeetze:** Writing – review & editing, Conceptualization. **HyeJin Kim:** Writing – review & editing, Conceptualization. **Jan J. Kuiper:** Writing – review & editing. **Eric Lonsdorf:** Writing – review & editing, Conceptualization. **David Leclère:** Writing – review & editing, Conceptualization. **Mark Mulligan:** Writing – review & editing, Conceptualization. **Garry D. Peterson:** Writing – review & editing, Conceptualization. **Alexander Popp:** Writing – review & editing, Conceptualization. **Stephanie Roe:** Writing – review & editing, Conceptualization. **Aafke M. Schipper:** Writing – review & editing. **Tord Snäll:** Writing – review & editing, Conceptualization. **Arnout van Soesbergen:** Writing – review & editing, Conceptualization. **Aline C. Soterroni:** Writing – review & editing, Conceptualization. **Elke Stehfest:** Writing – review & editing, Conceptualization. **Detlef P. van Vuuren:** Writing – review & editing, Conceptualization. **Piero Visconti:** Writing – review & editing, Conceptualization. **Lan Wang-Erlandsson:** Writing – review & editing, Conceptualization. **Geoff Wells:** Writing – review & editing, Conceptualization. **Henrique M. Pereira:** .

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 paper.

Data availability

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