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The integration of ecosystem services into computable general equilibrium modesling: State of the art and ways forward

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ABSTRACT

Reversing the loss and degradation of nature requires changes in how economies operate. However, economic models guiding policy fail to fully reflect nature's contributions to the economy as well as the economic and welfare consequences of ecosystem degradation. Here we review efforts to link ecosystem services (ES) models or estimates with Computable General Equilibrium (CGE) models. We found that provisioning ES with clear market values (like timber and fish) are relatively often linked to CGE models, while regulating and cultural ES are less so. Moreover, studies typically consider only a few direct drivers of ES change, such as land use, which risks underestimating ecological and economic impacts of nature degradation. Most examples lack a temporal dimension and often examine single ES in single regions. We identify four ways forward towards more integrated Earth-economy modeling: 1) more comprehensive integration of ES in CGE models, 2) improving ES models to capture relevant ecological processes, 3) improving CGE models to better capture the consequences of changes in ES, and 4) improving the representation of direct drivers of biodiversity and ES change. Given the urgent and visible effects of environmental degradation, moving towards integrated Earth-economy models is essential to the design of sustainability policies.

1. Introduction

Globally, the state of biodiversity and ecosystems is deteriorating at unprecedented rates due to human activities (Bellard et al., 2022; IPBES, 2019). Species extinction rates are significantly higher than natural background rates (Ceballos et al., 2017; IPBES, 2019), with over one million species threatened by extinction (IPBES, 2019). Biodiversity loss and ecosystem degradation affect the ability of ecosystems to provide essential services to people, such as the provisioning of food, water and air, the mitigation of natural disasters such as floods, and opportunities for recreation (Cardinale et al., 2012; Pereira et al., 2024). Despite the recognition that more than half of global gross domestic product (GDP) is moderately or highly dependent on nature (WEF, 2020), human activities remain a significant threat to biodiversity through habitat loss,

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pollution and over-exploitation, particularly in intensive production systems (Ellis, 2021; Hoskins et al., 2016; IPBES, 2019).

Addressing these threats and reversing the loss and degradation of nature require fundamental changes of economic and social systems and institutions globally (Dasgupta, 2021; IPBES, 2024). This includes challenging prevailing approaches that measure economic development using indicators of economic growth or productivity without considering nature's contributions to the economy or externalities in terms of natural capital and biodiversity loss (Banerjee et al., 2016; Dasgupta, 2021; Stiglitz et al., 2009). To facilitate the design of policies that enable sustainability transformations in economic systems, decision-makers need tools that provide quantitative evidence of how policy and investment interventions affect the contribution of ecosystem services (ES) to the economy (Johnson et al., 2025; Johnson et al., 2020; NGFS, 2023; Ranger et al., 2023). Changes in ES supply matter in many ways for both producers and consumers and may thus cause regional and sectoral spillovers transmitted through market prices. This may trigger indirect economic effects that go far beyond the direct effects on consumers and producers, for example by triggering feedback effects on overall economic growth and stability (Anger et al., 2014; Banerjee et al., 2020a; World Bank, 2025).

Assessing the full social, macroeconomic and environmental impacts of policies requires integrated modeling frameworks that are able to capture the state and dynamics of the economic and ecological systems (NGFS, 2023; von Jeetze et al., 2023), as well as the feedbacks between them (Banerjee et al., 2020c; Johnson et al., 2025). Several types of integrated modeling frameworks are being developed to take account of interdependencies between ES and the economy, including environmentally-extended computable general equilibrium (CGE) models, input-output models and partial equilibrium models, as well as integrated assessment models (IAMs) (Chaplin-Kramer et al., 2024; Johnson et al., 2025; NGFS, 2023). Here we focus on CGE models, which are commonly used and powerful tools for estimating socio-economic impacts of policies and investments (Dixon et al., 1992; Hertel, 1997). CGE models use empirical economic data to parameterize a set of equations which aim to capture the structure of the economy and behavioral responses of various economic agents (industries, households, governments) to changes in factors supply affecting the economy (Dixon et al., 1992; Hertel, 1997). Because CGE models take into account the interdependencies between different sectors, economic agents and economic resources in the economy, they can be used to generate insights into the economy-wide effects of policies, investments and external shocks, including biodiversity loss and climate change (Arto et al., 2019; Banerjee et al., 2016; Fabregat-Aibar et al., 2022; Jin et al., 2012; La Notte et al., 2020; Lantz et al., 2022). As such, they represent a promising tool for assessing the economic consequences of changes in biodiversity and ES. While the original focus of CGE models is on economy-centered indicators such as GDP, income, employment and poverty, the integration of ES into a CGE model provides a basis for estimation of policy impacts on wealth (Hamilton and Clemens, 1999). By wealth, we refer to the concept of genuine savings, which is equivalent to net national savings adjusted for changes in natural capital stocks and environmental quality.

The integration of biophysical ES models with CGE models, where the information of consequences of changes in ES is passed on to the CGE model to simulate the economic consequences, is emerging (Banerjee et al., 2020c; Banerjee et al., 2022; Johnson et al., 2020, 2021; La Notte et al., 2020; Panagos et al., 2018; Steininger et al., 2016). For example, Johnson et al. (2020) integrated the ES model InVEST with a CGE model to evaluate the global economic consequences of reductions in pollination, coastal protection, water yield, forestry production, marine fisheries and carbon storage. Similarly, Banerjee et al. (2020a) developed a coupled ES-CGE model to assess the economic impacts of Rwanda's Green Growth Strategy via changes in land use and ES, including carbon storage, sediment regulation, nutrient regulation and water yields. Despite these recent advancements, however, studies demonstrating a coupling of ES and CGE models are still scarce, and challenges remain concerning the application of these integrated frameworks in decision making bodies of governments and other institutions. There is a need to consolidate learning from these studies to better understand how practices can be further advanced to improve the tools needed for policy support.

As a step towards a more comprehensive and systematic consideration of ES in macroeconomic assessments, we aim to describe the current state-of-the-art in integrating ES and CGE models, synthesize remaining gaps and propose a way forward for addressing these gaps, in order to provide the quantitative evidence needed by decision-makers to fully recognize the value of nature in economic systems. In doing so, we also aim to bridge the ecological and economic research communities by making explicit the concepts, terminology and modeling approaches used in each field, without assuming prior familiarity with either discipline. To set the scene, we first present a conceptual model framework that lays out the possible linkages between ES and CGE models. This is followed by a review of the state-of-the-art of linkages actually established between ES and CGE models. Our scope is defined by a methodological criterion: in our review, we focus on studies that explicitly linked a quantitative biophysical model or estimate of ES to a CGE model; that is, studies where biophysical ES model outputs or estimates were used to inform the CGE model. If studies fall outside this criterion but offer methodological insights relevant to the integration of ES and CGE models, we include them as illustrative cases and note their departure from the primary scope. We exclude studies that quantified the economic consequences of environmental change without explicitly representing the mediating role of ecosystems. The latter include, for example, studies assessing the economic impacts of climate change on labor productivity or agricultural yields, without modeling the buffering or regulating role of ecosystems. Based on the conceptual framework and the findings of the literature review, we outline ways forward for a more systematic integration of ES in macroeconomic modeling for policy support.

2. Conceptual model framework

The links between the Earth and economic systems can be described by mapping specific ES components onto the corresponding flow variables in a CGE model (Table 1, Fig. 1). We identify two main entry points for ES into CGE models, namely as utility generating final consumption and as value generating input factors. This adds more detail to previous definitions of ES, such as the flow of services from natural capital (Hernández-Blanco and Costanza, 2018), represented by the arrow from natural capital to ES in Fig. 1.

Firstly, the utility generating final consumption ES enter the CGE model as direct consumption goods for the household, modeled as variable n in the utility function $U(c, l, n)$, where c represents consumption and l leisure. In addition to the direct value that final consumption of ES generates in the form of utility, ES may be complements or substitutes for leisure or produced consumption goods. Thus, changes in final consumption of ES may affect labor supply and demand for produced goods, thereby indirectly influencing economic dynamics.

Secondly, the value generating ES input factors enter the economy as input factors. We split them into two types: marketed and non-marketed ES. Marketed ES flow through the factor market (which determines their price) and enter into the production function as variable N in $F(K,L,N)$, where K represents capital and L labor. Endowments K, L and N are owned by economic agents which in turn receive a factor payment. Many applications of CGEs that include the environment do so exclusively through the representation of “natural resources", such as mineral reserves, fish and forests, which would be included in N, and can be augmented with other ES-derived input factors. Non-marketed ES, in contrast, directly affect the production function without a market determined price. An example of this would be wild pollinators increasing crop yields. The non-marketed ES only have value through

Table 1
Brief description of ecosystem services and computable general equilibrium models. A more extensive description and explanation is provided in the Supplementary Information.

Ecosystem services
Ecosystem services (ES), in the context of this paper, can be defined as the contributions of ecosystems to human activities (United Nations, 2024). ES supply is dependent on the attributes of the ecosystem (e.g., its biodiversity) and its relationships with environmental factors (e.g., climate, water). ES are commonly divided into three categories; provisioning services, which include material and energetic outputs from ecosystems (e.g., wild plants or fibers); regulating and maintenance services, which represent ways in which organisms can mediate or moderate the environment that affect human health, safety and comfort (e.g., pollination or flood control); and cultural services, which are benefits of ecosystems (biotic and abiotic) to the physical and mental states of people (including through, e.g., recreation, sense of place or aesthetic inspiration).
Computable General Equilibrium models
Computable General Equilibrium (CGE) models are macroeconomic models that describe the economy as a whole as well as the interactions between the different economic agents. The term computable refers to the fact that CGE models are able to quantify the effects of specific shocks, or "what-if" scenarios, to the economy. General refers to fact that CGE models encompass all economic activities and linkages between them. Finally, equilibrium refers to the fact that CGE models' solution is found when supply and demand are in balance at a certain set of prices (Burfisher, 2021).

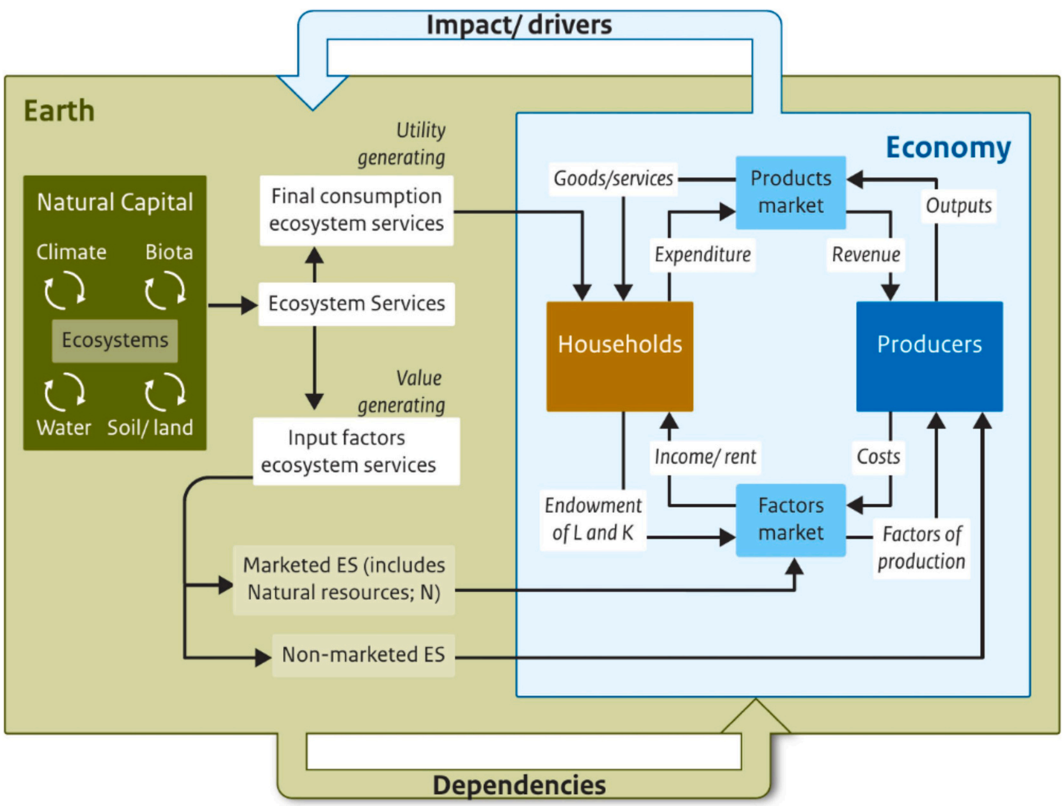

Fig. 1. Linkages between the Earth system and economic systems through input and output variables from ES and CGE models. For simplicity, only a single region is represented, and the government is not depicted. For a more detailed description of relevant ES concepts and CGE models see the Supplementary Information.

their effect on productivity. In CGE models, such effects are typically represented as shifts in production functions (e.g., factor-neutral or factor-specific productivity changes), with their magnitude parameterized based on empirical or literature-based evidence, as discussed in more depth in the next sections. The choice of functional form and parameterization strategy should be context- and ES-specific. Changes in the provision of non-marketed ES could be modeled in multiple ways, including factor-neutral productivity shifts (the A_0 in the production function), which is discussed in more depth in the next sections. Our description here is consistent with the previous definition of ES as the flow of value from natural capital, but is more specific by highlighting that some value is obtained through direct welfare enhancing use of ES while other value is obtained through its marketed and non-marketed effect on production.

3. Linkages established between ES and CGE models

In this section, we describe how ES have been linked to CGE models. To this end, we conducted a targeted review of the literature. This review was not intended to be systematic or comprehensive, but rather to identify representative examples that illustrate the range of approaches used to link quantitative biophysical ES models or estimates with CGE models (Table 2). We organize our examples by ES category. We found that, typically, the link is one-way (from an ES model or estimate to a CGE model) and that cultural ES have been less frequently linked than provisioning and regulating and maintenance ES.

3.1. Provisioning ES

Provisioning ES include all nutritional, non-nutritional material and energetic outputs from ecosystems (Haines-Young and Potschin, 2018). The consideration of provisioning ES in macroeconomic models has a

Table 2
Overview of linkages established between ES and CGE models (see Supplementary Information for a more in-depth explanation of CGE model parameters).

Type of linkage	Description and variable affected	References
Linkages on the production function		
Productivity shock (P)	*Changes in the ES are linked to the CGE model through changes in total output produced via productivity shocks. The productivity shock can be i) factor neutral if the shock is applied to total factor productivity, meaning that all primary factors are affected in the same way, or ii) factor specific if the shock is applied to specific primary factors of production.*	**Provisioning ES** ***Fish*** (Arto et al., 2019; Banerjee et al., 2016; Jin, 2012; Jin et al., 2012; Johnson et al., 2021; Johnson et al., 2020; Wang et al., 2020) ***Timber*** (Johnson et al., 2021; Lantz et al., 2022; Steininger et al., 2016) **Regulating and maintenance ES** ***Pollination*** (Bauer and Wing, 2016; Bauer and Wing, 2010; Johnson et al., 2021; Johnson et al., 2020) ***Soil erosion*** ((Banerjee et al., 2020b); Lal et al., 2020; Panagos et al., 2018) **Cultural ES*****Recreation*** (McDermott et al., 2013)
Shock to modified primary factors of production (F)	*Changes in ES are linked to the CGE model by modifying or disaggregating an already existing primary factor of production. This modification is usually implemented by creating a composite of primary factors (e.g. land-water composite).*	**Provisioning ES** ***Fish*** (Finnoff and Caplan, 2010) ***Timber*** (Alavalapati et al., 1997; Chang et al., 2012; Lantz et al., 2022; Withey et al., 2018) ***Water*** (Koopman et al., 2017; Liu et al., 2014; Taheripour et al., 2013; Wittwer, 2012; Wittwer and Griffith, 2011) **Regulating and maintenance ES** ***Carbon storage and sequestration*** (Golub et al., 2009; Hertel et al., 2008; Michetti and Rosa, 2012; Peña-Lévano et al., 2019) **Cultural ES** ***Recreation*** (Antoine et al., 2008; Finnoff and Caplan, 2010)
Shock to new factors of production (S)	*Changes in ES are linked to the CGE model through the creation of a genuinely independent new input factor with no prior representation in the model, for example by introducing water as a distinct factor of production in sectors where it was previously absent.*	**Provisioning ES** ***Water*** (Berrittella et al., 2007; Goodman, 2000; Peterson et al., 2005; Koopman et al., 2017) **Cultural ES** ***Recreation*** (Smajgl, 2007)
Direct adjustment/ depreciation to GDP or other flows (D)	*The changes in ES are translated to changes to total (aggregate) output.*	**Regulating and maintenance ES** ***Coastal protection*** (Johnson et al., 2020)
Linkages on the demand function		
Changing demand (U)	*ES are included in preferences, e.g. through willingness to pay for recreation in the utility function.*	**Cultural ES** ***Recreation*** (Antoine et al., 2008; Carbone and Smith, 2013)

Table 2 (*continued*)

Type of linkage	Description and variable affected	References
Linkages related to investment and/or public expenditures		
Induced demand change (C)	*Demand for a specific good changes due to ES being a substitute or complement (e.g. higher consumption of a recreational good due to increased environmental quality).*	**Provisioning ES** ***Wood*** (Banerjee et al., 2019b) **Cultural ES** ***Recreation*** (Banerjee et al., 2018)

relatively long history in the field of natural resource economics, owing to readily available data on natural resources with a market value (e.g., timber, fish) from the System of National Accounts (Banerjee et al., 2016). Marketable provisioning ES have also been integrated in CGE frameworks via biophysical models. For example, multiple studies have used biophysical models to quantify fish or crustacean (e.g., shrimp) stocks and changes therein and linked these to a production function in a CGE model (Arto et al., 2019; Banerjee et al., 2016; Finnoff and Caplan, 2010; Jin, 2012; Jin et al., 2012; Johnson et al., 2021; Johnson et al., 2020; Wang et al., 2020). Linkages have been established via the introduction of factors of production, including land and, less commonly, water, and via productivity shocks (Table 2). For example, Jin (2012) imposed a productivity shock on the fishing industry in response to changes in fish stock by shocking labor and capital inputs via the coefficient α (see the Supplementary Information for a description of most common CGE parameters).

Similarly, biophysical forest (re)growth models have been used to quantify changes in timber yield, due to factors like climate change or invasive pest species, which are then linked to production functions in CGE models by adjusting factor endowments (e.g., Chang et al., 2012; Lantz et al., 2022). In contrast, other studies represent these shifts through exogenous shocks to policy instruments or production factors without using a biophysical model. For instance, Alavalapati et al. (1997) simulated changes in stumpage fees/taxes as a policy shock, leading to endogenous changes in wood prices. Similarly, Withey et al. (2018) modeled conservation policies by constraining the total allowable cut, which acted as a direct reduction in the available primary production factor (land/stumpage) for the forestry and logging sectors. These modeling efforts aimed to evaluate the economic consequences of natural resource management measures or changes in or damage to natural resources. In a similar vein, Wang et al. (2020) used a coupled fish-CGE model to explore the effects on fish stock of policy measures diverting fishers to other sectors, thus targeting labor as a primary factor of production. A different perspective and approach were taken by Banerjee et al., (2019)), who modeled the economic consequences of changes in the demand rather than the supply of wood, based on scenarios of increases in the efficiency of wood-fueled stoves in households in Guatemala.

Compared to fish and timber, and usually in the absence of a functioning water market, water provision is more challenging to connect to a CGE model (Berrittella et al., 2007; Wittwer, 2012). While the sanitation and distribution of water is typically an industry sector in the System of National Accounts and thus is represented in a CGE model, the mere provision of water for agriculture and other consumptive uses is not easily captured as water abstraction is often not priced (Calzadilla et al., 2016; Koopman et al., 2017). The inclusion of water provisioning into CGE models has taken different forms (Wittwer, 2012). For example, water has been considered as a part of land, using a land-water composite as a primary factor of production, such that the value of the land depends partly on the water that comes with it (Gomez et al., 2004; Liu et al., 2014; Lofgren et al., 1996; Seung et al., 1998; Taheripour et al., 2013; Wittwer, 2012; Wittwer and Griffith, 2011). Similarly, water has also been integrated as a primary factor of production through a water-capital composite, which is more appropriate for sectors less reliant on land, such as the manufacturing and public water sectors (Koopman et al., 2017). Other modelers have included water as a new, exogenous factor of production based on statistical accounts rather than biophysical models (Berrittella et al., 2007; Goodman, 2000; Peterson et al., 2005). For example, Peterson et al. (2005) included irrigation water as a new endowment entering the production function at the top level of the nesting structure, where it is substitutable with the aggregate bundle of non-water inputs, through a constant elasticity of substitution (CES) function. This approach requires information on the productivity differential between irrigated and rainfed crops. Finally, a recent review concluded that most CGE models struggle to represent competing water uses across sectors and in particular the energy sector (Bardazzi and Bosello, 2021).

3.2. Regulating and maintenance ES

Regulating and maintenance ES are the ways in which organisms can mediate or moderate the ambient environment that affects human health, safety and comfort (Haines-Young and Potschin, 2018). So far, linkages between regulating and maintenance ES and CGE models have considered changes in pollination supply, control of soil erosion rates, climate regulation (through carbon uptake and storage), flood control, and water quality regulation (Table 2). Pollination and control of soil erosion rates were linked via changes in agricultural productivity (Banerjee et al., 2020b; Bauer and Wing, 2010, 2016; Johnson et al., 2020, 2021; La Notte et al., 2020; Lal et al., 2020; Panagos et al., 2018). For example, the consequences of a complete loss of pollinators for agricultural productivity have been quantified based on crop-specific pollination dependency ratios, which represent the proportion of yield that is pollinator-dependent (Bauer and Wing, 2016; Bauer and Wing, 2010). La Notte et al. (2020) assessed the impact on agricultural productivity of pollinator loss due to the presence of an invasive alien species using ES accounts. Some studies have gone beyond the assumption of complete pollinator loss by introducing a simplified pollinator abundance model based on the presence of pollinator habitat near cropland, thus allowing the evaluation of gradual economic impacts via crop pollinator dependency ratios (Johnson et al., 2021; Johnson et al., 2020).

The economic impacts of soil erosion were estimated by linking decreases in agricultural productivity, quantified with a soil loss model, to a CGE model (Panagos et al., 2018). Banerjee et al. (2020b) and Lal et al. (2020) integrated dynamic endogenous feedbacks between control of soil erosion and the economy through productivity loss in agriculture. This dynamic approach results in an estimate of the marginal value of the regulating ES in question that is entirely consistent with a country's System of National Accounts.

Coastal protection and carbon storage have been linked to CGE models via reductions of GDP (Table 2). Johnson et al. (2020) linked coastal protection services to a CGE model by using a biophysical model to determine areas at risk of flooding due to sea level rise. In these areas, GDP was considered to be at risk, and an overall estimated GDP loss was implemented as a shock in the CGE model by adjusting national-level productivity.

The role of forests as a carbon sink (carbon sequestration) has been integrated in CGE models mostly in the context of assessing climate-related policies. Such analysis has led to better representations of land and land dynamics within CGE models (see for example, Ahammad and Mi, 2005; Golub et al., 2009; Hertel et al., 2008). To capture the carbon sequestration and storage capacity of forests, Hertel et al. (2008) modified the production function of the forestry sector by including a carbon composite as a primary factor of production. Through this carbon composite, the forestry sector can sequester and store carbon by expanding or by managing forestry areas. This approach was also followed in other studies (Golub et al., 2009; Michetti and Rosa, 2012; Peña-Lévano et al., 2019). To characterize the responses of this new carbon composite, forest supply curves were generated exogenously through a global timber model (Sohngen and Mendelsohn, 2007) and used to calibrate the CGE model (Golub et al., 2009; Hertel et al., 2008; Peña-Lévano et al., 2019). Finally, the dynamics of carbon sequestration are enabled via the introduction of a carbon sequestration subsidy that ultimately influences land allocation and carbon sequestration strategies (Golub et al., 2009; Hertel et al., 2008; Peña-Lévano et al., 2019).

Water quality regulation was recently integrated into a CGE model in an application evaluating the wealth impacts of a program to enhance environmental quality in Uruguay (Banerjee et al., 2026). In this study, the authors modeled the downstream water quality effects of planting vegetation buffers along water courses to comply with existing legislation. The multi-regional CGE highlighted the economic consequences of establishing riparian buffers, as in most cases, planting trees along waterways implied withdrawing areas from existing agricultural production. The linkage to water quality was established through the quantification of nitrogen, phosphorous and sediment concentrations in the water courses connected to tourism demand and water treatment costs (Banerjee et al., 2026).

3.3. Cultural ES

Cultural ES are defined as all the non-material, and normally non-rival and non-consumptive, outputs of ecosystems (biotic and abiotic) that affect the physical and mental states of people (Haines-Young and Potschin, 2018). Cultural ES have been linked to CGE models through recreation or tourism, both via production and demand functions (Table 2). For example, Smajgl (2007) included the abundance of fish in the Great Barrier Reef region, as modeled with a biophysical food web model, as a factor of production for the tourism sector, reasoning that tourists visit the region in order to experience a certain environment and its biodiversity values. Similarly, Finnoff and Caplan (2010) used water bird population abundance in the Great Salt Lake ecosystem as a primary factor of production for the recreation sector, such that increases in bird abundance led to an increase in household demand for bird watching.

McDermott et al. (2013) included the costs of the replacement of ash trees in parks infested with the invasive alien emerald ash borer as an increase in primary costs for the recreation sector. While this study does not employ a biophysical model or estimate of ES, and thus falls outside the primary scope of this review, it offers a methodologically relevant illustration of how invasive species impacts on cultural ES can be captured in a CGE framework. A different approach was followed by Banerjee et al. (2018), who established a link between a cultural ES and a CGE model via tourism demand. They rely on contingent valuation estimates of international and domestic visitors' willingness to pay (WTP) for improvements in Rwanda's Nyungwe National Park. These WTP estimates were used to parametrize tourism demand functions in the CGE model, where improved environmental quality translates into increased foreign and domestic tourist arrivals, modeled through constant elasticity demand functions for tourism-related commodities. Similarly, this study does not formally link biophysical ES model outputs to the CGE, but illustrates a promising approach for capturing the demand-side effects of cultural ES. Antoine et al. (2008) introduced the recreation benefits of natural forests in a CGE model through the inclusion of an outdoor recreation demand function and changes in land as a primary factor of production, considering protected and non-protected forests. In protected forests, government expenditure maintains and improves the condition of these forests to supply ES.

Non-marketed cultural ES are challenging to link to a CGE model, because, by definition, these do not affect the market directly. Carbone and Smith (2013) proposed to model the non-market recreational value from fishing or other natural amenities via reductions in household demands for other activities or consumption. They reason that non-market ES can indirectly affect market activity by changing the preferences of the household sector and thereby the marginal utility of income. In other words, if people are able to enjoy nature, this can reduce their demand for other activities or consumption. However, while the framework of Carbone and Smith (2013) is promising, it has not yet been implemented.

4. Shortfalls in the integration of ES and CGE models

Our literature review revealed a relatively limited and biased integration of ES in CGE models (Table 2). In general, (marketable) provisioning ES are readily incorporated into CGE models as intermediate inputs to the production side of the economy with respect to fish, timber and, to a lesser extent, water provisioning. Moreover, the monetary transactions related to these ES are reported in the System of National Accounts of most countries and thus are included in the databases (social accounting matrices) that underpin CGE models. For regulating and maintenance ES, solid progress has been made in integrating non-marketed soil erosion control and crop pollination in CGE models through the introduction of productivity shocks, and recent work has linked natural water quality regulation to a CGE model through tourism demand and water treatment costs. The integration of other regulating and maintenance ES is less advanced. Few studies cover the integration of ES that contribute to disaster risk reduction, such as coastal protection (for example, Johnson et al., 2020). Cultural ES are rarely associated with CGE models.

Across the three major types of ES, links with CGE models are typically made on the production side of the economy, while linking non-marketed regulating and maintenance ES remains a challenge. The integration of non-marketed ES on the demand side, for example through changes in consumer preferences, is rare (but see Antoine et al., 2008). Furthermore, studies that have linked ES and CGE models often focus on a single ES (for example, Bauer and Wing, 2016; Bauer and Wing, 2010; Koopman et al., 2017; Panagos et al., 2018). The simultaneous integration of multiple ES in a CGE model remains uncommon (Banerjee et al., 2016; Johnson et al., 2021; Johnson et al., 2020), and the studies concerned are not comprehensive. For example, while Johnson et al. (2020) managed to couple six ES to the GTAP CGE, this represents only a fraction of the myriad ways that nature contributes to the economy (see Table 3). As such, existing studies provide conservative estimates of the economic value of nature or the economic losses associated with ES loss (Johnson et al., 2020).

Many studies linking provisioning ES to a CGE model focused on a single region or country (e.g., Arto et al., 2019; Banerjee et al., 2020a; Finnoff and Caplan, 2010; McDermott et al., 2013). Multi-regional models can provide critical insights into policy or investment impacts that span borders or where the specifics of inter-country trade are important (see Banerjee et al., 2026) for an example of a multi-regional model that highlights inter-regional trade-offs, costs and benefits). However, for multi-regional models to be meaningful, the regional disaggregation needs attention and must be tailored to the research question. In general, global CGE models tend to identify regions by economic relevance and similarity. Especially regions in the global south are usually highly aggregated. These high aggregation levels might fall short for tracking trade transmitted policy spillover effects on ES at national or subnational scales, which might be of particular interest for policy applications.

Many of the existing ES-CGE model integrations implemented a one-time (scenario-based) shock or change to the ES of concern. Recently, progress has been made in dynamic-recursive approaches that endogenize feedbacks between changes in ES supply and their effect on the behavior of economic agents (e.g., Banerjee et al., 2024). Dynamic-recursive approaches allow for the inclusion of the temporal consequences of changes in ES, but they do not fully capture the transient dynamics of nature-economy interactions. In a dynamic recursive CGE model, economic agents have “myopic expectations” about the future, which means that decisions are made based solely on the information available for past and current periods but not for the future (Babiker et al., 2009). For nature-economy interactions, this means that the potential future evolution of the state of nature cannot be taken into account.

Table 3
Examples of the macroeconomic relevance of additional ES to be included in CGE models.

Ecosystem services category	Ecosystem services	Macroeconomic relevance
Provisioning	Genetic material	Wild species contribute genes and genetic material to agriculture and manufacturing sectors. Examples include productivity-enhancing genes from wild relatives bred into crops, and genes mediating chemical compound production for industrial use.
Regulating and maintenance	Pest control	Nature deters agricultural pests and human-transmitted diseases, with consequences for agricultural productivity and health costs.
	Flood risk mitigation	Nature reduces peak runoff, which, at watershed scale, reduces flood hazard, risk, and impact. This can reduce investment in technical risk mitigation measures and reduce damage and related costs.
	Disaster risk reduction (e.g. avalanche and landslide regulation)	Vegetation stabilizes hillslopes, reducing destruction of transport infrastructure, lowering insurance costs, and preserving continuity in supply chains.
	Air quality regulation	Trees and ecosystems remove particulate matter (PM2.5), ozone and NOx from the atmosphere. This lowers respiratory disease burden, reducing health costs and increasing labor productivity.
	Biological nitrogen fixation	Legumes and soil microbes naturally fix nitrogen, reducing fertilizer demand and lowering agricultural production costs and import dependencies.
	Waste assimilation/ nutrient cycling	Wetlands, riparian zones, soils and microbial communities remove or transform nutrients, sediments and chemical pollutants. This reduces the need for engineered water treatment infrastructure and lowers operational costs for utilities and water-dependent industries. It can also reduce health impacts affecting labor productivity.
Cultural	Nature interaction	Nature enhances human health, with potential impact on private and public spending as well as number of hours worked.
	Spiritual, identity and heritage values	Landscapes contribute to national identity and community cohesion, influencing tourism, and place-based economic development.

5. Towards integrated earth-economy modeling

Based on the above, we identified four ways forward towards a more systemic and comprehensive integration of ES and CGE models. These include improvements focused on the linkages between ES and CGE models as well as improvements needed in the respective models themselves (Fig. 2).

5.1. More comprehensive integration of ES in CGE models

As highlighted in the previous section, a limited selection of ES has been linked to CGE models, and multiple ES remain to be integrated (Table 3). However, linking the biophysical ES model outputs or estimates to CGE models is not straightforward: it requires a unequivocal identification of how the service is used in the economy, who is using it and the different transmission pathways that link change in ES to variables in the CGE and to economic outcomes. A way to clearly and systematically report ES, including how they contribute to economic sectors and households, is offered by the System of Environmental Economic Accounting (SEEA) and specifically by the Ecosystem Accounting (EA) module. In the SEEA-EA, the translation of outputs of ES models into ES supply and use tables allows identification of how producers and households use specific ES and how services are provided to economic sectors by multiple ecosystems (United Nations, 2024). The accounting principles followed in SEEA and SEEA-EA also guarantee that double counting of ES does not occur (La Notte, 2022). However, it is important to note that the SEEA-EA has not been developed with the purpose of coupling biophysical ES models and CGEs, and its effectiveness in reconciling spatially explicit ecosystem data with the aggregated sectoral classifications and equilibrium constraints of CGE models still needs to be tested.

A more practical challenge is the limited availability of biophysical models for ES, probably resulting in an underestimation of the contribution of ES to the economy. There is a need to expand existing ES modeling frameworks, such as GLOBIO-ES (Schulp et al., 2012), InVEST (Natural Capital Project, 2025), ARIES (Villa et al., 2009) or INCA (Vysna et al., 2021), with new ES with macroeconomic relevance (see Table 3), thereby explicitly considering the potential link with economic activities. This will provide the necessary basis to integrate these models with CGE frameworks, thereby deepening our understanding of how specific ES underpin economic activity.

A challenge that existing ES models do not solve is the lack of knowledge of the full extent regarding the dependency of the economy on nature. As Dasgupta (2021) states, nature allows people to exist. Accordingly, the conceptual distinction between nature and humans has its limits, which implies that the distinction between nature and the human economy has limits too. A more comprehensive representation of the dependency of humans on nature in a CGE model could be achieved

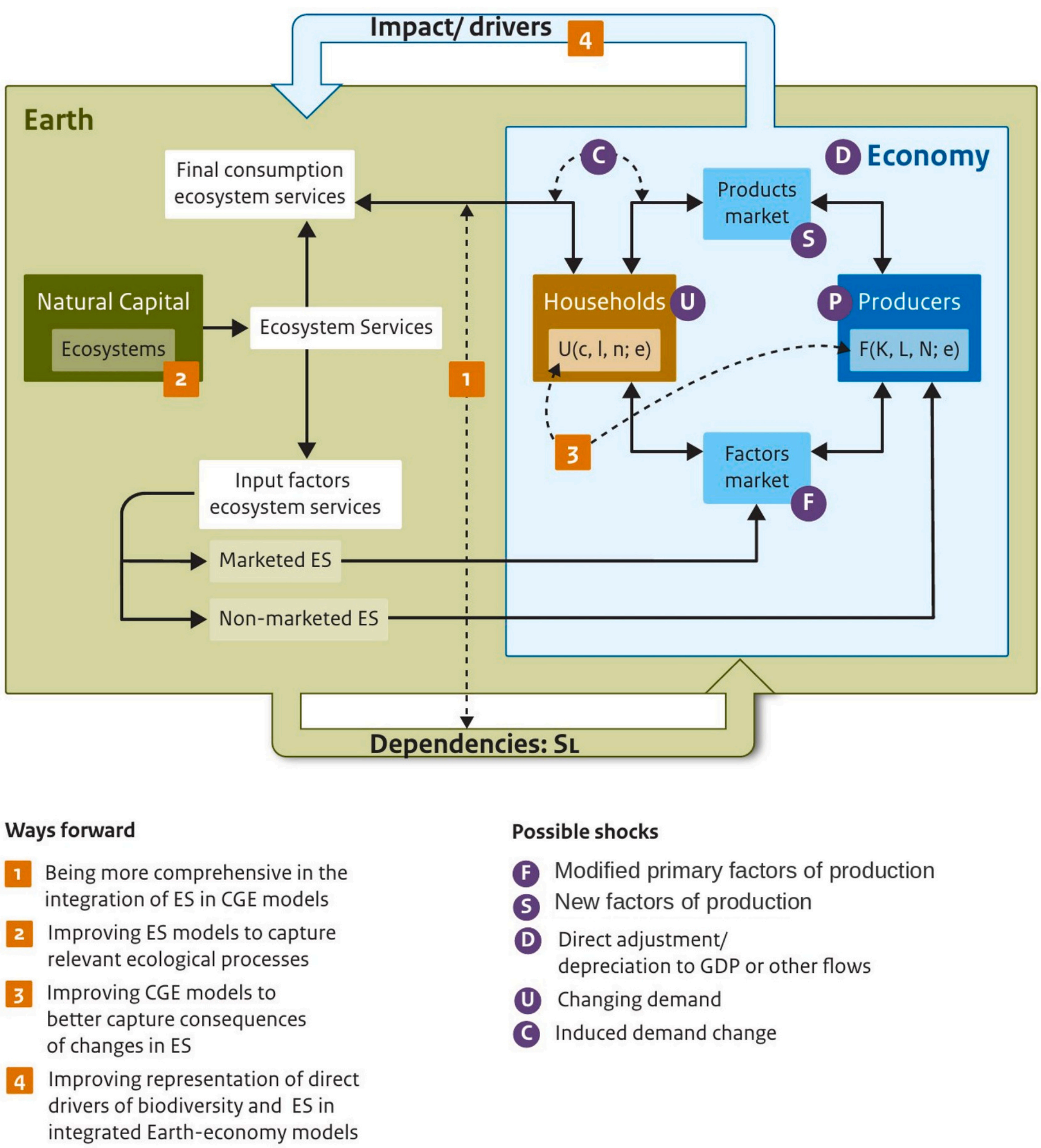

Fig. 2. Ways forward towards integrated Earth-economy modeling for policy support.

by including a term representing all the contributions that biophysical ES models cannot yet capture as a productivity shock (through inclusion in the definition of total factor productivity) (Dasgupta, 2021). We acknowledge, however, that the empirical estimation of such a term poses substantial challenges. Addressing this challenge represents an important direction for future research.

5.2. Improving ES models to better capture relevant ecological processes

The functional relationship between biodiversity and ES supply is complicated and can take various forms (Paul et al., 2020). A better empirical understanding of how biodiversity matters for ES supply and ecosystem resilience is therefore needed. Improved ES models that capture the implications of biodiversity change for ecosystem functioning would enhance understanding of the interlinkages between biodiversity, ecosystem functioning and ES supply, enabling better simulation of the impacts of changes in biodiversity on ES supply. This is of critical importance given the declining state of biodiversity, which may compromise ES delivery. Interlinkages could be incorporated in ES models through functional traits or species composition, and how changes therein propagate through interaction networks (Antunes et al., 2024). Alternatively, statistical biodiversity-ecosystem functioning relationships could be used to estimate changes in ES as a result of biodiversity change (e.g., Mori et al., 2021), with machine learning approaches opening options for considering the joint effects of biodiversity change on multiple ES (Manley et al., 2022). At the global scale, statistical approaches are probably the most tractable and have been used already (Mori et al., 2021; Weiskopf et al., 2024). Combined with better representation of the drivers of biodiversity loss (most importantly land-use change, overexploitation, and pollution; IPBES, 2019) in both CGE and ES models, this will allow for better simulation of feedbacks between biodiversity loss and the economy.

5.3. Improving CGE models to better capture the consequences of changes in biodiversity and ES

Expanding the number of endogenized impact pathways that connect ES to CGE models will require significant changes in the latter. On the production function, new factors of production expressing the ability of nature to supply ES should be introduced. ES that act as direct inputs to production, such as pollination, water provision, soil quantity and quality and pest control, could be introduced as additional primary factors nested within a new ES composite branch of the production function, alongside the conventional capital-labor-energy nest (Fig. 3). It is important to avoid double counting in CGE applications, because some ES contributions are already embedded in the value of marketed outputs such as agricultural production (Comerford, 2017). Land as direct input in the production function could be linked to the land's capacity to provide ES. Several CGE models already include land supply curves and track land use transitions in physical units (Banerjee et al., 2019b; Dixon et al., 2016; Lee, 2005), providing a basis for linking land dynamics to ES supply.

Many of the suggested improvements will require knowledge on the elasticities of substitution between ES and other factors of production. Moreover, as the contribution of ES as primary factors of production is sector-specific, substitutability of ES will differ across and within production sectors. Luchtenbelt (2019) has provided empirical estimates of elasticities of substitution for pollination, water provision, pest control and soil quality in different agricultural sectors. It is important to note that assuming a uniform elasticity of substitution across ES and between ES and other production factors would be an oversimplification: the appropriate elasticity will be ES-specific and context-specific. As highlighted by Comerford (2017), the nesting structure of the production function matters quantitatively, and choices about which inputs are substitutes or complements reflect fundamental assumptions about weak versus strong sustainability. Besides as primary factors of production, ES can be considered as intermediate input. For example, soil nutrient cycling can be considered as a substitute for synthetic fertilizer, or natural flood regulation as a substitute for artificial flood defenses. In such cases, the ES would need to be nested within the intermediate input branch of the production function rather than the primary factor branch (Fig. 3). While resolving these nesting and parameterization challenges is beyond the scope of this paper, empirical estimation of ES-specific elasticities of substitution, building on the work of Luchtenbelt

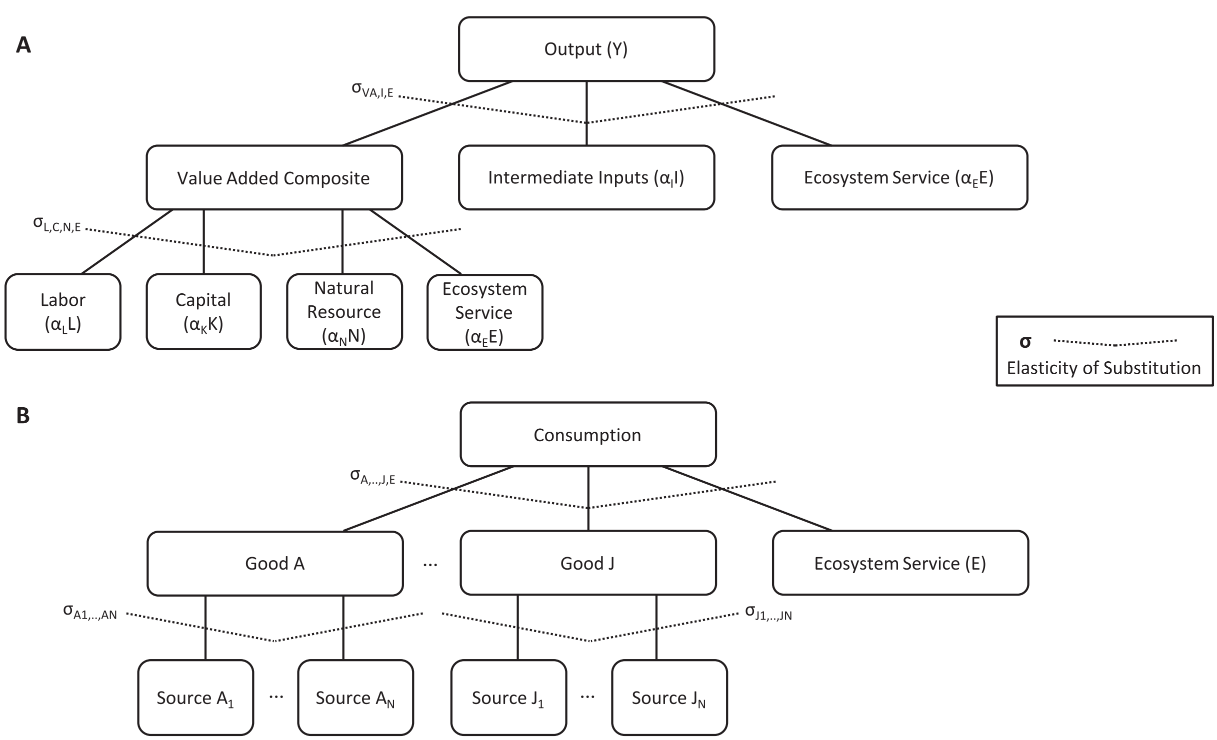

Fig. 3. Schematic representation of A) a production function and B) a utility or consumption function with ecosystem services at different nest levels.

(2019), will be essential for making progress in this direction.

At the utility function level, introducing the final use of ES allows the benefits people directly derive from nature to be captured. As these may be complements or substitutes for leisure activities and produced goods, changes in the availability of ES will affect demand. For example, access to natural recreation areas could be modeled as a substitute for purchased leisure activities. However, this approach overlooks the effort and costs households may incur to benefit from ecosystem services, such as the travel time required to access recreational areas like forests. Similarly, air quality regulation services could increase available income by reducing health costs. However, the empirical estimation of consumer preferences for ES remains very limited. Exceptions are Drupp (2018) and Heckenhahn and Drupp (2024), who estimated the substitutability between ES and manufactured goods, but their coverage is narrow in terms of ES types and geographic contexts. Expanding this empirical base is essential to expand demand-side representation of ES in CGE models.

Damage functions offer an important complementary approach to capturing the economic consequences of changes in biodiversity and ES in CGE models. Commonly used to represent the economic impacts of climate change (Banerjee et al., 2025; Nordhaus and Yang, 1996; Roson and Sartori, 2016; van der Wijst et al., 2023), damage functions describe the relationship between environmental variables and economic variables such as productivity or output. A recent example is provided by Nicita et al. (2024), who used regression analyses to estimate the effect of agrobiodiversity on farm net value added in five Mediterranean countries, and then parameterized changes in total factor productivity in a regionalized CGE model. Developing damage functions that link biodiversity and ES variables to economic variables can help to better represent the economic impacts of ES degradation in CGE models, particularly for ES where the mediating role of ecosystems is difficult to represent through explicit biophysical model linkages (e.g. habitat maintenance). Significant work is still required in the empirical estimation of such damage functions across a broader range of ES and regions.

Biodiversity loss and nature degradation may result in future scarcity of ES, which should be properly reflected in CGE models as it will affect ES values and consequently elasticities of substitution and consumer preferences (Drupp et al., 2024). Recursive-dynamic CGE models assume myopic expectations, where behavior depends only on current and past states of the economy. Forward-looking CGE models offer a way to incorporate expectations about the future state of biodiversity and ES into present day decisions. However, analytical and computational challenges associated with intertemporal optimization often require model simplifications, for example, reduced sectoral or economic agent detail, which in turn also limit the models' ability to fully capture complex Earth-economy dynamics (Babiker et al., 2009; Bröcker and Korzhenevych, 2013).

Further work is needed in identifying the multiple transmission pathways through which policies may affect future ES supply and in turn influence agent behavior in the CGE model. Transparency in scenario design is also essential: establishing a business-as-usual baseline that excludes specific shocks, and then implementing ES-related shocks on top of it, allows individual effects to be attributed and the macroeconomic mechanisms, including relative price changes, trade dynamics, and sectoral spillovers, to be revealed. Each new ES introduced expands the number of such pathways, adding to the complexity of model development and calibration. The choice of macroeconomic closure and theoretical paradigm also deserves attention in ES-CGE applications. Different assumptions about labor markets, for example, whether they clear through wages or unemployment, or about the endogeneity of government consumption and investment, will generate different economy-wide responses to the same ES shock. Future research should systematically explore how these paradigmatic choices affect the transmission and magnitude of ES impacts, building on broader efforts to mainstream nature into macroeconomic models (Arin et al., 2025).

Finally, it may be necessary to expand the types of economic models considered in ES-economy linkages. For instance, linking Dynamic Stochastic General Equilibrium (DSGE) models would allow representation of financial sectors, inflation, and other aspects typically excluded from CGEs, which would increase the relevance of such models to more stakeholders (e.g., central banks and finance ministries).

5.4. *Improving the representation of direct drivers of biodiversity and ES change*

In order to capture the full feedback loop between the Earth system and the economy, integrated Earth-economy models need to be comprehensive and adequate in their representation of direct drivers of biodiversity loss and ecosystem degradation (Johnson et al., 2025). Indeed, the central challenge is ensuring a genuine feedback loop between the Earth system and the economy, one in which shocks to land use, resource extraction, or other drivers are simultaneously transmitted from the CGE to biophysical ES models, and then back from the ES models to the CGE model (Section 5.1), generating economy-wide responses that adequately reflect the interdependencies between nature and economic activity. This full feedback loop remains the principal frontier of integrated Earth-economy modeling. To date, studies formally modeling this complete chain, from economic drivers through biophysical processes and back to economic outcomes, remain scarce, representing a critical gap in the literature.

To operationalize this loop in a way that remains consistent with physical constraints on land, the CGE model should be able to track the overall extent of land area to enable linkages between land-use change and the availability of land for different sectors. Land use and land cover modeling with built-in physical land accounting is required for representing land as a limited resource, assessing effects of land-use policies, and capturing feedbacks with land-related ES. Further, the CGE model must be able to model transitions of land between alternative uses in a way that preserves physical units of land, reflects the imperfect mobility of land between sectors, and accounts for the asymmetric ease of transitions between land uses (for example, the conversion of forest to pasture is historically more common than the reverse). Currently, these aspects are accounted for through land-use land-cover models that receive land-use projections from CGE models, typically reflecting sectoral composition changes driven by prices, trade, and policy, and produced at national or regional scales. Before they can inform ES models, these aggregate outputs must be translated into spatially explicit land-cover transitions. This is usually achieved through the use of downscaling tools such as the GLOBIO land-use downscaling tool (Schipper, 2020), the Spatial Economic Allocation Landscape Simulator (SEALS) (Johnson et al., 2023), or downscaleR (Bedia et al., 2020). Gridded CGE models provide a promising avenue to increase the level of spatial detail. For instance, the SIMPLE-G model (Haqiqi and Hertel, 2025) and the general-equilibrium extension GTAP-SIMPLE-G (Wang, 2024) greatly enhance the resolution at which economic equations are solved (including global, 10-km-resolution economic units).

While land use is indeed a major direct driver of current biodiversity loss, it is important to acknowledge that overexploitation, pollution, and the introduction of invasive alien species also pose significant threats (IPBES, 2019), and that anthropogenic climate change is becoming a progressively larger threat (Jaureguiberry et al., 2022; Maxwell et al., 2016; Pereira et al., 2024; Schipper, 2020). Accounting for these threats requires integrated ES–CGE models that move towards more comprehensive modeling approaches, capable of quantifying how economic activities (production, trade, consumption) generate direct drivers (for example, climate change induced by greenhouse gas emissions, or the introduction of alien species due to global trade) and how these, in turn, affect biodiversity and ecosystem services in order to proper represent a full feedback loop. It is important to note that the pathways from changes in these drivers to economic effects need to be well understood, as there can be overlaps between drivers. For example, the introduction of invasive species through international trade may affect production costs and factor allocations, which in turn influence land-use change endogenously. In addition, downscaling approaches for drivers other than land use, will also be needed.

6. Concluding remarks

Human activities rely on healthy ecosystems for an array of ES. As the consequences of environmental change are increasingly evident and the state of nature continues to decline, it is essential to understand the dependencies of the economy on nature, and design policies that take into account the system-wide consequences of nature degradation and loss. CGE models are widely used to understand the economy-wide consequences of different policy options (An et al., 2023; Devarajan and Robinson, 2013; Devarajan and Robinson, 2002). Accordingly, they provide a promising approach for assessing the economy-wide consequences of ecosystem change and policy options to halt biodiversity loss. Conceptually, ES and CGE models can be linked in different ways, depending on how economic decisions drive biodiversity change and how ES enter the economy (Fig. 1). ES can be directly used by households, can be used as factors of production with a market value or as factors of production without a market value. So far, only a limited number of ES have been incorporated in CGE models, with a focus on provisioning and (to some extent) regulating and maintenance ES. The dependency of the economy on ES has primarily been analyzed focusing on one ES at a time, which does not provide a comprehensive representation of the economy's overall reliance on nature. Further, until now, most of the links between ES and CGE models have been established at the production side of the economy. Improving the connection between ES and CGE models will result in a better understanding of the dependencies and feedbacks between nature and the economy, and potential early warning signs of approaching tipping points. Concrete ways to achieve this are increasing the number of ES linked to CGE models, improving ES models to capture relevant ecological processes, improving CGE models by introducing ecosystems and their services as well as their relationships with economic agents, and finally improving the representation of direct drivers of biodiversity and ES change. These advances will help the design of policies that take into account the overexploitation of nature, the costs of ecosystem degradation and consequent reduction in resilience, and nature's delayed responses to change.

It is important to note that the further integration of ES into CGE models comes with both conceptual and data-related challenges. Regarding the former, we recognize major challenges in particular regarding non-material ES that do not directly contribute to production yet are vital to people, such as spiritual or symbolic value, inspiration or sense of place. Regarding the latter, the increasing availability of high-resolution remote sensing datasets and machine learning methods can make it easier to link ES models to CGE models (Johnson et al., 2025), adding the possibility to tailor them to the specific context of their application. However, for many ES and CGE model parameters (e.g., elasticities), practitioners and researchers need to rely on global or default estimates. Acknowledging and working within these limitations is critical to maintaining and enhancing the credibility of integrated analysis among decision makers, given that it is still novel to many.

Increasingly, financial institutions and the private sector acknowledge their dependency on nature, and steps have been taken to understand the risks posed by nature loss to their activities (Boldrini et al., 2023; NGFS, 2023; Svartzman et al., 2021; TNFD, 2023; van Toor et al., 2020). For integrated modeling approaches to become mainstream for public policy and investment analysis, capacity building is critical. Integrated CGE and ES modeling is a multidisciplinary pursuit requiring foundations in the natural sciences as well as the social sciences. Integrated applications require the expertise of ecologists, geographers, economists, social scientists, statisticians, data scientists and others to build databases, model extensions and scenarios to intelligently formulate and answer increasingly complex questions. While expertise in these and other disciplines is necessary, so is interdisciplinarity, where individuals develop knowledge across disciplines that enable them to manage integrated workflows and push frontiers in some of the directions suggested in this paper.

CRediT authorship contribution statement

Alexandra Marques: Writing – review & editing, Writing – original draft, Project administration, Funding acquisition, Conceptualization. **Onil Banerjee:** Writing – review & editing, Conceptualization. **Lukas Eggert:** Writing – review & editing, Writing – original draft, Conceptualization. **Paula A. Harrison:** Writing – review & editing, Conceptualization. **Tobias Heimann:** Writing – review & editing, Conceptualization. **Justin Johnson:** Writing – review & editing, Conceptualization. **Alessandra La Notte:** Writing – review & editing, Conceptualization. **Alexander Popp:** Writing – review & editing, Conceptualization. **Martin Quaas:** Writing – review & editing, Conceptualization. **Catharina J.E. Schulp:** Writing – review & editing, Conceptualization. **Willem-Jan van Zeist:** Writing – review & editing, Conceptualization. **Patrick von Jeetze:** Writing – review & editing, Conceptualization. **Aafke M. Schipper:** Writing – review & editing, Funding acquisition, Conceptualization.

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.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.gloenvcha.2026.103213.

Data availability

No data was used for the research described in the article.

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