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Assessing Integrated Assessment Models for Building Global Nature-Economy Scenarios

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ABSTRACT

Policymakers are increasingly calling for the development of scenarios to explore the economic consequences of nature loss and transition policies, particularly at a global scale and macroeconomic level. In this paper, we review global integrated-assessment models (IAMs) linking nature and the macroeconomy and assess their suitability to help build such scenarios. We perform an in-depth analysis of both 'stylised' and 'applied' IAMs, and critically assess how they represent dependencies of the macroeconomy on nature, as well as policies to reverse nature loss. We find that applied IAMs are generally skewed to capturing the dependency of the economy to selected provisioning ecosystem services, with regulating and maintenance services less represented. As these models tend to focus on the land-use and climate drivers of biodiversity loss, the transition policies they capture only aim to mitigate those drivers and overlook other drivers of nature loss such as pollution or invasive alien species. We also find that some theoretical assumptions in the core macroeconomic part of applied models may tend to mitigate the potential macroeconomic consequences of nature loss and nature transition policies. This contrasts with the results of the 'stylised' models we review, which tend to represent the loss of natural capital and biodiversity as having significant impacts on the macroeconomy. However, stylised models make it hard to represent the impact of the loss of specific ecosystem services or specific policies to protect nature. Building on this analysis, we explore the challenges and identify future avenues for the use of IAMs in scenarios that account for the importance of nature and biodiversity for economic activity.

Keywords: Integrated Assessment Modelling; Biodiversity; Natural Capital; Nature Scenarios; Macroeconomic Impacts; Sustainable Development

JEL classification: C6, Q56, Q57, Q01, O11, O44

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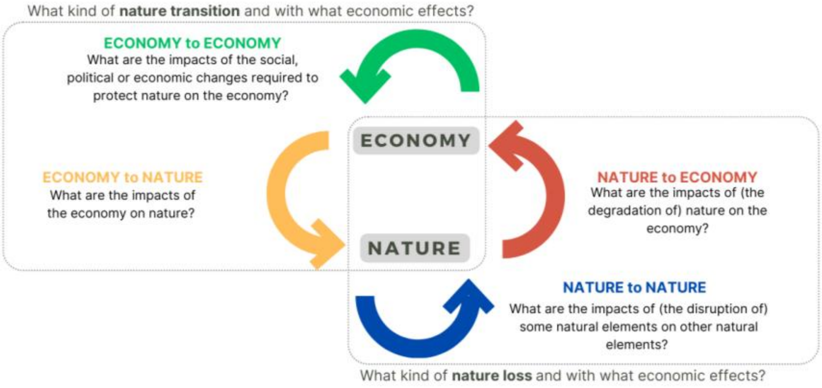
NON-TECHNICAL SUMMARY

Biodiversity, natural ecosystems, and the ecosystem services they provide (henceforth, 'nature') are declining at an alarming rate (IPBES, 2019). What consequences could this trend have for our economies, which are embedded in nature and depend upon it? In response, economies will have to undertake major "transformative" changes to halt and reverse nature loss by 2050 (IPBES, 2019; CBD, 2022). What will be the economic impacts of such transformations? Policymakers are increasingly calling for the development of scenarios to explore these questions, particularly at a global scale. Scenarios describe quantitative and/or qualitative representations of possible futures relating to trajectories of environmental change; based on a set of informed assumptions. This paper reviews and analyses the models that could help in the development of such nature-related scenarios.

Initially built to explore *climate*-economy interactions, some global integrated assessment models (IAMs) are now being adapted or developed to consider broader dimensions of nature. Whilst some are 'stylised' models – aggregated, with few equations and analytical solutions –, others are what we call 'applied'– large-scale, multi-module models that are typically solved numerically, representing multiple technologies and various detailed climate and other environmental impacts. This paper reviews those two types of emerging global IAMs and analyses their suitability to explore the macroeconomic impacts of nature loss and the transition in scenario analysis at the global level.

Figure 1. A framework for analysing nature-economy interactions in IAMs



We propose an analytical framework for assessing how models represent the complex interactions between nature and the economy (Figure 1). We sequentially explore how they represent (i) different aspects of nature, including feedbacks between natural elements, (ii) dependencies of the economy upon nature, (iii) impacts of the economy on nature, and (iv) policy interventions to mitigate nature loss (Figure 1). More precisely, we apply this framework to a set of recently published 'stylised' nature IAMs, and to six 'applied' IAMs model used initially to build scenarios linking the macroeconomy with climate (e.g., NGFS, 2020), but recently extended to broader dimensions of nature (e.g., Leclère et al., 2020; Johnson et al., 2021; 2023; DNB, 2023).

We find that applied IAMs are generally skewed toward capturing the dependency of the economy to selected provisioning ecosystem services, like food, water provision and bioenergy, while the economic dependency to regulating and maintenance services (like soil quality, pest and disease control, or flood protection) are less often represented, with the notable exception of pollination and climate regulation, accounted for more frequently. Regarding transition policies, the models only capture those aiming to mitigate the land-use and climate drivers of biodiversity loss, and overlook policies to mitigate other drivers of nature loss, such as pollution (e.g., plastics, pesticides, nutrient runoffs) or invasive alien species. We also find that some theoretical assumptions in the core macroeconomic part of applied models (e.g., on the possibilities for substitution between inputs and rapid technological change) may potentially minimise the macroeconomic consequences of nature loss and nature transition policies. This contrasts with the results of the 'stylised' models we review,

which tend to represent the loss of natural capital and biodiversity as having significant impacts on the macroeconomy, notably because they tend to endogenise the impact of nature loss on economic growth. However, the aggregated nature of stylised models precludes the representation of specific ecosystem services or specific policies to protect nature. Building on this analysis, we explore the challenges and identify future avenues for the use of IAMs in scenarios that account for the importance of nature and biodiversity for economic activity.

We contribute to the fields of macroeconomics and environmental economics by elucidating how emerging stylised and applied global models conceive of "nature", and its relationships with the macroeconomy. Our analysis also informs emerging policy applications of applied IAMs for understanding the economic impacts of nature loss and nature policies. Finally, we describe several avenues to continue the development of emerging 'nature-economy' models, in light of the theoretical literature.

Une évaluation des « modèles d'évaluation intégrée » pour l'élaboration de scénarios globaux liant nature et économie

RÉSUMÉ

Les décideurs politiques appellent de plus en plus au développement de scénarios pour explorer les conséquences économiques de la dégradation de la nature et des politiques de transition pour limiter l'érosion de la biodiversité, notamment à un niveau mondial et macroéconomique. Nous passons en revue les modèles d'évaluation intégrée (*integrated assessment models*, IAM) liant nature et macroéconomie à l'échelle mondiale, et évaluons leur aptitude à contribuer à l'élaboration de tels scénarios. Nous analysons deux types de modèles, "stylisés" et "appliqués", et explorons la façon dont ils représentent les dépendances de la macroéconomie aux services rendus par les écosystèmes, ainsi que les politiques visant à inverser la perte de nature. On trouve que les IAM appliqués capturent principalement la dépendance de l'économie à certains services écosystémiques d'approvisionnement, en négligeant la plupart des services de régulation. Comme ces modèles se concentrent principalement sur les facteurs de perte de biodiversité que sont le changement d'usage des terres et le changement climatique, les politiques de transition qu'ils intègrent visent seulement à atténuer ces pressions et négligent d'autres facteurs tels que la pollution ou les espèces exotiques envahissantes. On constate également que certaines hypothèses théoriques au cœur de la partie macroéconomique des modèles appliqués peuvent avoir tendance à minimiser les conséquences économiques potentielles de la perte de la nature et des politiques de transition. Cela contraste avec les modèles "stylisés", qui trouvent que la perte du capital naturel et de la biodiversité ont des impacts significatifs sur la macroéconomie. Cependant, le niveau d'agrégation important des modèles stylisés empêche de représenter la perte de services écosystémiques spécifiques ou des politiques de protection de la nature particulières. À partir de cette analyse, nous identifions les pistes futures et les défis associés à l'utilisation des IAM pour construire des scénarios qui tiennent compte de l'importance de la nature pour les activités économiques.

Mots-clés : modèles d'évaluation intégrée ; biodiversité ; capital naturel ; scénarios nature ; impacts macroéconomiques ; développement durable

1 Introduction

Policymakers are increasingly calling for the development of scenarios to explore the economic consequences of nature loss and transition policies, particularly at a global scale (NGFS, 2023; OECD, 2023; World Bank and BNM, 2022; DNB, 2023). Natural ecosystems and the ecosystem services they provide (henceforth, 'nature')[1] are declining at an alarming rate (IPBES, 2019), which may lead to catastrophic consequences for our economies, which are embedded in nature and depend upon it (Dasgupta, 2021). Additionally, economies will have to undertake major "transformative" changes to halt and reverse nature loss by 2050 (IPBES, 2019; CBD, 2022).

Investigating the economic impact of environmental change, and associated policy interventions, has been a topic of interest within macroeconomics at least since William Nordhaus' development of the first climate integrated assessment model (IAM), DICE, in the 1990s (Nordhaus, 1993). Sustainability issues have been explored at length with a particular focus on constraints relating to natural resources (e.g., Dasgupta and Heal (1974); Stiglitz (1974); Hartwick (1978)). Whilst many macroeconomic models have explored the interaction of growth with greenhouse gas emissions, there has been less engagement with the role of nature and biodiversity in enabling macroeconomic growth (Polasky et al., 2005; Eppink and van den Bergh, 2007; Dasgupta, 2021; Groom and Turk, 2021). However, recent years have seen a shift towards a re-conceptualisation of the economy as embedded in and dependent upon a functioning biosphere (Dasgupta, 2021), as Earth System scientists have emphasised the presence of planetary boundaries (Rockström et al., 2023; Steffen et al., 2015). Some economists have proposed that the finite carrying capacity suggests that there are ultimately limits to the scale and intensity of economic activity (e.g., Raworth (2012); Jackson (2017), reviving ideas introduced within ecological economics (e.g., Georgescu-Roegen (1975); Daly (1991)).

Alongside this resurgent interest in nature, several IAMs are now being adapted or developed to consider dimensions of nature. Initially built to explore in particular climate-economy interactions, IAMs offer a framework within which to investigate broader nature-economy interactions in a single integrated modelling framework. Whilst some of these IAMs are 'stylised' models - aggregated, with few equations and analytical solutions -, others have developed into what we call 'applied' models in this paper - large-scale, multi-module models that are typically solved numerically, representing multiple technologies and various climate and other environmental impacts at a sophisticated level of detail (IPCC, 2023; IPBES, 2016).[2]

This paper reviews emerging nature-economy integrated assessment models and analyses their suitability to explore the macroeconomic impacts of nature loss and the transition in scenario analysis. We start by proposing an analytical framework for assessing how models represent the complex interactions between nature and the economy. In particular, we propose to explore how models represent (i) different aspects of nature, including feedbacks between natural elements, (ii) economic dependencies upon nature, (iii) economic impacts upon nature, and (iv) policy interventions to mitigate nature loss. Using this framework, we evaluate how recent 'stylised' models represent these interactions. Next, we analyse in detail how six applied IAMs model the nexus between nature and the macroeconomy. These applied models have been used to build scenarios linking the macroeconomy with climate (e.g. NGFS (2020)), and, more recently, broader dimensions of nature (e.g., Leclère et al. (2020); Johnson et al. (2021); Johnson

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[1] In line with the emerging terminology in this field (e.g., NGFS (2023); Dasgupta (2021)), throughout this paper we use the umbrella term 'nature' to refer to the biotic and non-biotic elements of the biosphere that interact to form natural ecosystems and which provide flows of direct and indirect benefits for human wellbeing, also described as 'ecosystem services' (or 'nature's contributions to people') (Díaz et al., 2015). Biodiversity (defined as diversity within and between species and ecosystems) is a critical quality of functioning ecosystems that mediates the flow of ecosystem services (IPBES, 2019).

[2] These "applied" models are sometimes referred to as "computational" models. See also Tol and Fankhauser (1998) who make a similar distinction.

et al. (2023); DNB (2023)).

In order to assess how emerging nature IAMs could be used in macroeconomic scenario analysis, our review of applied models focuses in detail on how shocks to economic sectors that have dependencies on nature, or relating to transition policies, might feed through to affect the macroeconomy. As such, we determine model 'suitability' according to the nature-to-economy causal mechanisms captured and the credibility of their representation at the system-level. Whilst model realism is not always deemed a necessary condition for model robustness where more simple, conceptual models are concerned,[3] the IAMs that we review are widely used for policy and other applied purposes. If model results are to inform 'real world' decisions – as IAMs are increasingly positioned, this requires some evaluation of the extent to which the model system describes a plausible fictional world that is credible relative to our knowledge of the 'real world' (Mäki, 2009). Importantly, we focus on the credibility of the representation of the modelling system as a whole, rather than just the realism of individual transmission mechanisms.[4] A 'credible' system is one where the causal mechanisms linking nature loss/policies to the macroeconomy capture scientific consensus on the importance of ecosystem services to economic activity (i.e., adopting a 'fictionalist' perspective of models, as defined by Couix (2021); Parent (ming)). Most notably, the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) identifies as 'well-established' by the scientific literature that 'Most of nature's contributions are not fully replaceable, yet some contributions of nature are irreplaceable' (IPBES (2019), p.XXVI). The decline in nature's contribution to people is likely to affect in particular nutrition and health (IPBES (2019), Table 2.3.4) - and IPBES (2020) points for example to the rapidly increasing risk of pandemics driven by anthropogenic changes and biodiversity loss. A 'credible' model of the economic impact of biodiversity loss should therefore attempt to include such mechanisms.

The contributions of our paper are the following. First, we contribute to the fields of macroeconomics and environmental economics by elucidating how emerging stylised and applied models conceive "nature", and its relationships with the macroeconomy. Second, our analysis informs emerging policy applications of global IAMs for understanding the economic impacts of nature loss and nature policies - notably through the design of scenarios (NGFS, 2023; DNB, 2023). Such an in-depth review is both timely and relevant because such models are large and link the economy to the environment in various ways, hence the underlying mechanisms giving rise to results may not be easy for end users to interpret. Additionally, the mechanisms present in the models may constrain the type of nature scenarios that can be represented. Finally, we identify important limitations in current modelling approaches, related to underlying assumptions, structural constraints, and the treatment of modelling uncertainty, and we describe several avenues to continue the development of emerging 'nature-economy' models, in light of the theoretical literature.

The rest of this paper proceeds as follows. Section 2 proposes an analytical framework for assessing nature-economy interconnections in models, and presents our method for model selection and analysis. Section 3 analyses existing stylised models that link together macroeconomics and nature aspects. Section 4 presents the results of our in-depth review and analysis of six applied models. Section 5 discusses our results further in light of the insights drawn from the stylised models. Section 6 concludes.

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[3] For example, some economic philosophy scholars have argued that, where conceptual exploration is the key function of models, realistic representation of the real world is not relevant as a criterion for good modelling (e.g., Hausman (1992)). From a more instrumentalist perspective, Friedman (1966) has also argued that the unrealism of economic assumptions are irrelevant as long as resulting predictions are "valid and meaningful". For a full discussion on the philosophy of science of economic modelling, see Morgan and Knuuttila (2012).

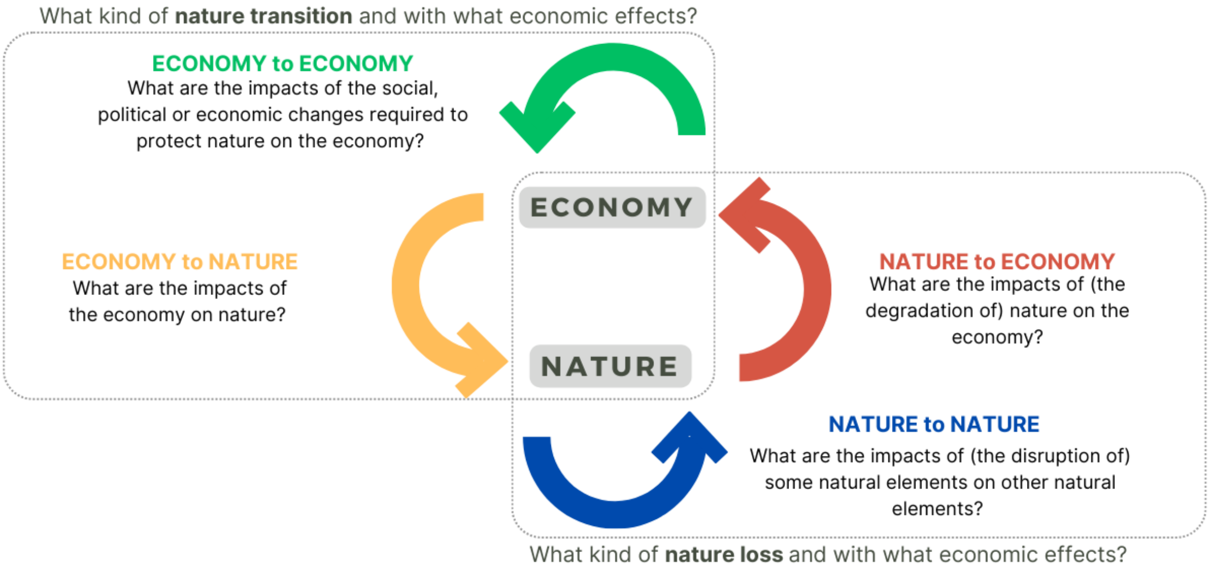
[4] Indeed, one of the findings of our review is that the spatially explicit and biophysically grounded detail of many nature IAMs does indeed enable a great degree of realism of specific transmission channels (e.g., spatially explicit dependencies of certain land uses on water systems).

2 Method and framework for analysing nature-economy interactions

2.1 Analytical framework

Nature-economy interactions are complex, but we propose that they can be explored in an integrated way using the framework depicted in Figure 1. On the one hand, exploring how the economy is dependent upon nature requires the model to capture both how nature provides ecosystem services and how these services could be disrupted (blue arrow), and the mechanisms by which different economic activities depend on those services, and hence can be negatively affected by nature loss (red arrow). For example, economic activity can depend on “provisioning” ecosystem services (e.g., of food, water, materials), “cultural” ecosystem services (e.g., beautiful landscapes for tourism activities), but also more indirectly on “regulation and maintenance” services (e.g., wild pollinators, protection against floods and soil erosion, air/water filtration etc) (Millennium Ecosystem Assessment, 2005).

Figure 1: A framework for analysing nature-economy interactions in IAMs



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We frame our analysis using the ecosystem services concept (rather than e.g., stocks of natural capital), because it allows us to disaggregate the multiple flows of benefits nature provides to people, and to easily connect nature with the economy - notably because of its utilitarian perspective.[5]

On the other hand, investigating transition-related aspects also requires the model to account for both the impacts of economic activity on nature (yellow arrow) and the impact on the economy of measures taken to protect nature (green arrow). The impacts of economies on nature are described by the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services, who identify the five main direct drivers of biodiversity loss as land-use change, overexploitation of species, climate change, pollution and invasive alien species (IPBES, 2019). Multiple policies can be implemented to halt nature loss (CBD, 2022), affecting multiple

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[5] For a discussion on alternative conceptual understandings of human-nature interactions see Muradian and Gómez-Baggethun (2021) and Kim et al. (2023).

economic sectors in various ways depending on the drivers that have to be mitigated.

2.2 Model section method

To identify relevant models, we applied the following search criteria to the Web of Science platform ("integrated assessment" OR macro-econom* OR macroeconom* OR "integrated model" OR “integrated strategy”) AND (biodiversity OR "natural capital" OR "ecosystem services") AND (model*) AND (global OR world) for “Topic” (Title, Abstract, Keywords) for peer-reviewed journal articles published between 2002 and 2023 – yielding 177 results.[6] The criteria for relevance were papers that proposed, extended, or reviewed integrated assessment models at a global level, with macroeconomic dimensions. After removing papers that employed the search terms in a way that is irrelevant, and those that did not fit the initial criteria, we were left with 28 results. At this stage, we identified the models in each paper as either ‘stylised’ or ‘applied’ models.

For ‘stylised’ models, this left us with seven relevant papers covering 3 different analytical models. As biodiversity is still a relatively recent topic in macroeconomics, we also chose to include the Bounded Global Economy (BGE) model proposed in the Dasgupta Review on the economics of biodiversity (Dasgupta (2021), Chapter 4*), as it fits our selection criteria even if it has not been published in a peer-reviewed journal. Table 1 summarises the model selection of stylised models.

For the remaining list of ‘applied’ models, we deployed some additional criteria to ascertain the relevance of the model for use in scenario exercises related to the assessment of nature-related physical and transition shocks. The criteria were: (1) the representation of ‘biophysical’ dimensions beyond climate change, i.e., ecosystem services and the dependence of the economy on those services; and (2) the representation of transition dimensions beyond climate change, i.e., drivers of biodiversity loss and potential policies to mitigate those drivers. In total, 12 papers fitted the criteria, comprising 6 applied integrated modelling frameworks, the details of which are summarised in Table 2.[7]

Whilst these applied models share many similarities, they differ in scope, objectives, and structure. Comparing them in a consistent manner for the purposes of this analysis necessarily requires making some simplifications. We loosely categorise the reviewed models modelling approach into two distinct groups. The first group (GTAP-InVEST, IMAGE-MAGNET, AIM-Hub) uses multi-sector general equilibrium macroeconomic models (CGEs), often then linked to suites of biophysical models. The second group links aggregated single sector general equilibrium models (with one aggregated production function) to partial equilibrium models focusing on land-use and agriculture and energy, which are themselves can be linked to biophysical vegetation models (REMIND-MAgPIE, MESSAGE-GLOBIOM, GCAM). As demonstrated by Figure 2, the various model components within these two loose groups differ in terms of detail of economic and biophysical representation.

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[6] Up to and including August 2023.

[7] The list of 12 articles of applied models fitting the selection criteria can be found in the Supplementary Information.

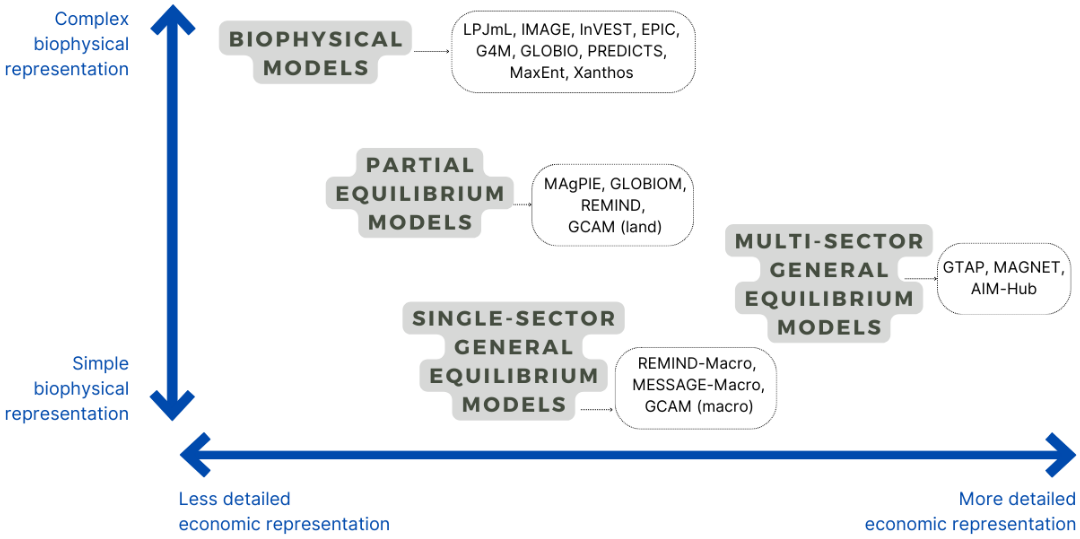
Table 1: Selected stylised models

Publ. date	Authors	Article title	Model
2014	Brooks and Newbold	An updated biodiversity nonuse value function for use in climate change integrated assessment models	FUND
2015	Hackett and Moxnes	Natural capital in integrated assessment models of climate change	DICE-NC
2018	Lanz et al.	The Expansion of Modern Agriculture and Global Biodiversity Decline: An Integrated Assessment	MAVA
2020	Fuss et al.	The economic value of tropical forests in meeting global climate stabilization goals	DICE
2021	Bastien-Olvera and Moore	Use and non-use value of nature and the social cost of carbon	GreenDICE
2021	Dasgupta	The Dasgupta Review on the Economics of Biodiversity	BGE
2022	Naso et al.	A macroeconomic approach to global land use policy	MAVA
2023	Kaushal and Navrud	Accounting for Biodiversity Costs from Climate Change in Integrated Assessment Models	FUND

Table 2: Selected applied models

Model name	Developed by	Macroeconomic component	Economic sector component(s)	Biophysical component(s)
GTAP-InVEST (‘Global Earth-Economy model’)	University of Minnesota, Purdue University, Natural Capital Project, World Bank	GTAP (multi-sector general equilibrium model - CGE)	GTAP (multi-sector general equilibrium model - CGE)	InVEST (ecosystem services model)
REMIND-MAgPIE	Potsdam Institute for Climate Impact Research (PIK)	REMIND-Macro (single sector general equilibrium model - optimal growth model)	REMIND (energy sector partial equilibrium (PE) model) & MAgPIE (land use PE model)	MAgPIE (land use PE model) & LPJmL (vegetation model)
IMAGE-MAGNET	Netherlands Environmental Assessment Agency (PBL), Wageningen University	MAGNET (multi-sector general equilibrium model - CGE)	MAGNET (multi-sector general equilibrium model - CGE)	IMAGE and various connected biophysical models (e.g. LPJmL vegetation model, GLOBIO biodiversity impact model)
AIM-Hub	National Institute for Environmental Studies (NIES), Kyoto University, Mizuho Information & Research Institute	AIM (multi-sector general equilibrium model - CGE)	AIM (multi-sector general equilibrium model - CGE)	Can be connected to PREDICTS and MaxEnt (both biodiversity impact models)
MESSAGE-GLOBIOM	International Institute for Applied Systems Analysis (IIASA)	MESSAGE-Macro (single sector general equilibrium model - CGE)	MESSAGE-Energy (PE model) & GLOBIOM (land use PE model)	GLOBIOM (land use PE model) & EPIC (vegetation model)
GCAM (version 7)	Pacific Northwest National Laboratory	GCAM-Macro (single sector general equilibrium model - CGE)	GCAM-Land and GCAM-Energy (both PE models)	Xanthos (global hydrology model)

Figure 2: Illustrative comparison of models according to level of biophysical vs. economic detail



Source: Authors

We assessed each applied model according to the same standardised criteria, based on reading official model documentation, peer-reviewed journal articles using the models, and oral interviews and written exchanges with modelling teams.[8]

3 Stylised models of nature-macroeconomy interactions

The stylized integrated assessment models linking "nature" to macroeconomic dimensions that we find can be classified in three main categories. We present them and investigate further how each model represents the four "arrows" of Figure 1, that together make up an "integrated assessment" framework. This will allow us to compare the choices made in those theoretical models to the applied models analysed in the next section.

A first category of models directly include "natural capital" aspects into traditional stylized climate integrated assessment models, such as DICE (Hackett and Moxnes, 2015; Fuss et al., 2021; Bastien-Olvera and Moore, 2021) or FUND (Brooks and Newbold, 2014; Kaushal and Navrud, 2023). Some of them (Brooks and Newbold, 2014; Kaushal and Navrud, 2023; Bastien-Olvera and Moore, 2021) represent the fact that climate change negatively impacts natural capital (blue arrow). Then, this leads to additional damages on economic output (the "use value of nature") and welfare (via the decrease in output, but also the "non-use values" of nature) (red arrow), as compared to the standard damages of the DICE and FUND models.[9]

In most of the models in this first category, the economy only impacts natural capital (yellow arrow) through climate change. One exception is the DICE-NC model, where Hackett and Moxnes (2015) introduce some direct damages from economic output to natural capital, and make those non-climate damages interact with climate damages on the economy. In terms

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[8] The interviews were used to check our interpretation of the documentation, and understand current or future developments of the model regarding nature/biodiversity issues. Each modelling team was given the opportunity to verify the content of the relevant model ID card, but the final assessment remains the responsibility of the authors.

[9] Efforts to account for ecosystems' contributions to welfare also feature in the literature exploring the relevance of non-market goods for optimal climate policy. In particular, Drupp and Hänsel (2021) introduce a subsistence level of non-market goods in the welfare function of the DICE model.

of policies to mitigate nature loss (green arrow), Bastien-Olvera and Moore (2021) include investments in "adaptation" aiming to limit climate impacts on natural capital (including some quite abstract policies, such as "relocating species"), or investment to directly increase natural capital. The model developed by Fuss et al. (2021) mostly focuses on changing the climate mitigation policies in the DICE model (which only considers abatement of GHG emissions from fossil fuels), to include a possibility for land use-based abatement through halting deforestation or reforestation. The authors highlight the possible co-benefits for biodiversity of such mitigation options, but do not tackle biodiversity nor natural capital as such in their model. Overall, we find that papers introducing natural capital in standard stylized climate IAMs have mostly conceived of nature only within the narrow focus of its interactions with climate change, especially via the damage function. All find that accounting for natural capital leads to an optimal pathway with lower temperature rises and higher carbon prices.

Instead of using the broad notion of "natural capital", we find that another model called MAVA (Lanz et al., 2018; Naso et al., 2022) chose to represent biodiversity-macroeconomy interactions by focusing on the interactions between biodiversity, the agriculture sector and the rest of the economy in an endogenous growth framework. Using their model, Lanz et al. (2018) show that, as cropland expansion leads to biodiversity loss and to a subsequent reduction of agricultural productivity, the optimal use of land is lower when one accounts for this "biodiversity negative externality" than if one doesn't. The optimal growth path of the economy is also affected. In this model, the driver of nature loss (yellow arrow) is therefore restricted to land-use change for the expansion of cropland. It is notable that the impacts of cropland expansion on biodiversity (which would correspond to the blue arrow of Figure 1) are not modelled. Indeed, the surface of cropland is assumed to directly affect (negatively) the total factor productivity of the agriculture sector (red arrow). Finally, the model allows for several actions to limit the externality (green arrow), such as changes in the fertility choices and limitations in land conversion imposed by the social planner, but also increases in the TFP of the agriculture sector induced by an increase in the workforce dedicated to R&D in agriculture. Note that the model assumes that only cropland expansion leads to biodiversity loss, but not the intensification of land use - which leads to recommending mitigation policies focused mainly on increasing agricultural productivity to limit the needs for expansion. An interesting feature of the model is that it explicitly represents a food constraint. Overall, the model conceives of nature-economy interactions only through land and its interactions with agricultural productivity.

Finally, the BGE model (Dasgupta, 2021) attempts to be more holistic, and represents "nature" or "the biosphere" as a whole biophysical system in which the economy is embedded. In this model, the economy impacts the biosphere through two main channels: by drawing natural resources (R) for production, and by using nature as a sink for waste (yellow arrow). This affects the evolution of the biosphere (a stock S) over time (blue arrow). The primary problem outlined by the Dasgupta Review is that demands placed on the biosphere exceed its regenerative capacity. The degradation of the biosphere then feedbacks on GDP (red arrow). Indeed, production in the model relies on capital, labour and natural resources, following a standard functional form in resource economics, where "resources" can also include provisioning ecosystem services. However, a multiplicative term, the biosphere stock S, is also added to the production function: it represents regulating and maintaining services, without which production is not possible. Investing in total factor productivity can help increase the efficiency with which resources are extracted to produce GDP, just like the efficiency to which GDP is converted to waste can be improved (green arrow). However, because the biosphere is bounded and can reach 'tipping points', where negative changes become irreversible, these efficiency gains are bounded. Hence, so is economic growth.

The comparison of these three types of stylised models provides some interesting findings. First, they all come with a discussion regarding the need to account for limited substitutability when linking nature to the economy. For example, the GreenDice model focuses on the limited substitutability between use and non-use values of natural capital in the utility function of agents, while Lanz et al. (2018) stress the role of the substitutability between land and other factors of production in determining the results of the model. Only Dasgupta tends to avoid the discussion on substitutability, by placing the emphasis on the "embeddedness" of the economy in nature. Another finding is the common discussion on the strong uncertainty of functional forms and parameters in the papers providing calibrated models. They strongly emphasise the difficulty of calibration, a problem which is also pervasive in the climate-IAM literature (Pindyck, 2013). This raises the question of how applied models manage to face this uncertainty.

Overall, we find that there have been few stylized models that have seriously engaged in the interplay of macroeconomic growth and environmental pressures related to the loss of nature and biodiversity. Those which have help understand transmission channels from nature loss to the macroeconomy, and highlight the sizable macroeconomic impacts that nature loss and nature protection policies can have. However, as those models conceptualise nature-to-economy feedback channels in a highly aggregated and abstract fashion they can hardly be used to explore the macroeconomic implications of the degradation of particular ecosystems or specific transition policies - both highly relevant questions to decision makers. The multi-dimensional nature of biodiversity loss and of the human activities implicated in it calls for models to represent multiple different economic sectors and their interaction with multiple different ecosystem services or aspects of biodiversity (IPBES, 2016; Spangenberg, 2007). Applied macroeconomic models, that we explore in the following section, offer a framework within which to investigate nature-to-economy interactions in this more granular way.

4 Nature-macroeconomy interactions in applied models

To date, what we call 'applied nature IAMs' in this paper have mainly been used within the biodiversity and ecosystem services (BES) literature to model the environmental impacts of particular economic trajectories (yellow arrow in Figure 1), as part of broader modelling frameworks also encompassing various biophysical models (e.g., Kim et al. (2018); Leclère et al. (2020); Janssens et al. (2020,0)). However, applied nature-economy modelling of the economic impacts of various environmental and transition policy trajectories remains far less developed than in the climate space (Maurin et al., 2022; Banerjee et al., 2020). There have been studies using partial equilibrium models to estimate the effects of transition policies on selected economic dynamics, such as food security and food prices, but without assessing macroeconomic impacts (e.g., Leclère et al. (2020); Prudhomme et al. (2020)). Emerging applied nature-economy models incorporate various direct and indirect mechanisms that transmit nature-related shocks or policies into economic impacts, based on the scope and detail of economic sectors represented, and which biophysical dynamics are accounted for. By shedding light on these 'nature-to-economy transmission mechanisms', we seek to identify the current state of emerging applied models, and assess their suitability for scenario analysis of the economic impacts of nature loss and transition policies.

4.1 How are economic dependencies upon nature represented in the models?

In the first stage of analysis, we investigate (i) which ecosystem services are represented in the model (blue arrow), and (ii) how the economy depends on those ecosystem services to function (red arrow). Table 3 details how each model represents those two aspects, for a list of ecosystem services identified in the Common international classification of ecosystem services (CICES[10]). Splitting dimensions (i) and (ii) enables us to assess the level of detail of the models. For

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[10] https://cices.eu/

example, some models represent the supply of ecosystem services like wild pollinators, but do not explicitly describe how the economy, e.g. food production, depends on those.

Our main finding is that the applied models represent the supply of a significant range of ecosystem services, with a skew towards provisioning services, although not all are connected to an economic variable to represent an economic dependency on that aspect of nature. A particular strength in several models relates to connections to biophysical models providing spatially-explicit detail on hydrological dynamics (e.g., Xanthos), pollinators (e.g., InVEST), vegetation and soil fertility (e.g., LPJmL).[11] The economic dependencies included are similarly skewed towards provisioning ecosystem services, with regulating/maintenance, and cultural ecosystem services being far less well accounted for - with the notable exceptions of pollination and climate regulation. Furthermore, provisioning ecosystem services tend to focus on the provision of food crops and livestock, with some models also representing water withdrawals and consumption required for production (although only relating to agriculture or energy). Other provisioning services are neglected, in particular those relating to fish, possibly due to their lower share of GDP and to a focus on terrestrial ecosystems. Reasons for this skew may also relate to the fact that these models are drawing from a long line of applied models detailing economic production of crop and livestock sectors and land use allocation. Additionally, regulating/maintenance ecosystem services may be far more complex to model - requiring additional levels of biophysical modelling (Stehfest et al., 2014), or particular assumptions about non-use values of ecosystem services that are hard to draw from empirical data (Carbone and Kerry Smith, 2013).

4.2 Policy interventions to mitigate nature loss in the models

For the second stage of our analysis, we investigate how the models represent: first, the impacts of economic activities on nature - ‘drivers’ of nature loss (yellow arrow); and second, policy options to mitigate those impacts (green arrow). Understanding the scale of negative environmental impacts gives an indication of the exposure a particular sector might have to future policies or mitigation measures that may result in economic consequences. Table 4 details how each model represents transition policies related to the direct drivers of biodiversity loss identified by the IPBES (2019), (Chapter 2.1).

Our main finding is that drivers and policies aiming to mitigate land use change and climate change are captured by the models in the most detail. This is likely explained by the models’ history as climate-economy models, with land-use modelling included to estimate land-based emissions and bioenergy capacity. The policy interventions most commonly represented are protected areas, REDD+, payments for ecosystem services, and different agricultural management systems. There is a strong tendency for the models to represent ‘land-sparing’ approaches over ‘land-sharing’ (Phalan et al., 2011). Land price increases resulting from reduced agricultural land availability stimulate greater use of capital as a production input (i.e., a shift to more capital intensive farming) to maintain output levels. Yet, the negative effects on ecosystems from intensive agriculture (e.g., due to pollution flows from increased use of pesticides and fertiliser, water withdrawals) (Bommarco et al., 2013) are not explicitly accounted for. More nuanced policies that could be explored include ‘sustainable intensification’ methods (e.g., Godfray and Garnett (2014)) and a range of ‘land sharing’ approaches, such as organic farming and agro-ecology (e.g., Muller et al. (2017)).

Policies relating to other land-based drivers (urban expansion, habitat fragmentation) or pollution-related drivers of biodiversity loss are not captured in any comprehensive detail by any of the models reviewed. Pollution flows are difficult to include within global models due to their spatial mobility and involvement of multiple sectors. Transition policies are also tricky

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[11] The spatial resolution of the reviewed models ranges from 30 arc minutes (e.g., GLOBIOM - equivalent to a 50x50km grid at the equator) to 10 arc seconds (e.g., InVEST - equivalent to a 300x300m grid at the equator).

Table 3: Representation, in the reviewed models, of (i) the supply of ecosystem services and (ii) the economic dependency on ecosystem services

		How is (i) the supply of the ecosystem service (background colour) and (ii) the dependency of the economy on the ecosystem service (symbols) represented in:					
	Ecosystem services	GTAP-InVEST	REMIND-MAgPIE	AIM Hub	IMAGE MAGNET	MESSAGE-GLOBIOM	GCAM
Provisioning services	Surface- and Ground- Water provision		▓ *		▓ *	▓ *	▓ ✓
	(Food) crop provision	░ ✓	▓ ✓	░ ✓	▓ ✓	▓ ✓	▓ ✓
	(Food) livestock provision	░ ✓	▓ ✓	░ ✓	▓ ✓	▓ ✓	▓ ✓
	Fish provision	░ ✓		✓	✓		
	Timber provision	░ ✓	▓ ✓	░ ✓	▓ ✓	▓ ✓	░ ✓
	Fibres provision	░ ✓	▓ ✓		▓ ✓	▓ ✓	▓ ✓
	Bioenergy		▓ ✓	✓	▓ ✓	▓ ✓	░ ✓
	Genetic material						
Maintenance and regulation services	Pollination	▓ ✓	▓ *		▓ *		
	Climate regulation	*	▓ ✓		▓ *	▓ *	▓ *
	Mass stabilisation and erosion control		░ *		▓ *	░ *	
	Soil quality		░ *		▓ *	░ *	
	Flood and storm protection				▓		
	Water flow maintenance		▓ *		▓ *	▓ *	▓ ✓
	Water quality		▓		▓		
	Pest control				▓		
	Disease control						
	Dilution by atmosphere & ecosystems						
	Filtration						
	Ventilation						
	Buffering and attenuation of mass flows						
	Bioremediation						
	Maintain nursery habitats						
	Mediation of sensory impacts						
	Protection against fires				▓		
Cultu--ral	Tourism				▓		

(i) Supply of ecosystem services by nature:
▓ Modelled in quite detailed way
░ Modelled in less detailed way
☐ Not modelled
(ii) Economic dependency on ecosystem services:
✓: Multiple and/or direct transmission mechanisms included
* : Incomplete compared to other models, or indirect mechanism
Blank: Not included
NB: assessment is relative to the other models.

to represent, given that the governance of polluting activities is determined as much by regionally diverse institutional arrangements as by markets. The invasive species driver shares these challenges and is not captured by any of the approaches reviewed. Another important finding is that some transition policies are modelled by adjusting set parameters or exogenous variables to match scenario narratives. This ‘ad hoc’ approach means that the costs of implementing the policies are sometimes not accounted for.

While this section has focused on how models represent the drivers of biodiversity loss, we conclude by noting that some models also include biodiversity metrics in various ways, allowing to some extent to produce ‘target-seeking’ scenarios (IPBES, 2016). On the ‘nature-to-economy’ side, we find that the MAgPIE model is original because it can impose a constraint on the amount of biodiversity loss permitted (measured with the Biodiversity Intactness Index (BII) associated with land use maps) and then compute the costs associated with the satisfaction of this biodiversity constraint. This approach appears close to what many climate models do (imposing a CO2e target and computing the cost associated with reaching it), but represents transition policies in a very aggregated way. However, MAgPIE appears to be an exception, as most models are limited to producing biodiversity metrics as an output - focusing on the ‘economy-to-nature’ relationship (yellow arrow) - without necessarily computing the costs associated with a biodiversity constraint. The IMAGE-MAGNET can for example be connected to the GLOBIO modelling framework to capture impacts of economic pathways on terrestrial and aquatic biodiversity (using the Mean Species Abundance biodiversity metric) and ecosystem services. Similarly, AIM-Hub has been linked to the PREDICTS model (using the BII metric) and MaxEnt (a detailed species distribution model) (Leclère et al., 2020; Ohashi et al., 2019). However, as a multidimensional concept, biodiversity cannot be captured reliably by a single indicator, making it a difficult measure to convincingly integrate into a macroeconomic modelling framework (Maurin et al., 2022).

4.3 How do changes in aspects of nature feed through to affect the macroeconomy?

For the third stage of our analysis, we explored how shocks to economic sectors that have dependencies on nature, or relating to transition policies, might feed through to affect the macroeconomy.

None of the models reviewed have an explicit ‘biodiversity damage function’ as is featured in Lanz et al. (2018); our analysis therefore focused on careful elucidation of the nature-to-economy feedback mechanisms included in each model. A key finding is that all the models reviewed focus exclusively on the ‘land channel’ to connect changes in nature/policies to the macroeconomy via land-based sectors such as agriculture, forestry and energy. None of the applied models attempt to include regulating and maintenance services as a factor in the production function without which economic activity is not possible - as is theorised in Dasgupta’s BGE Model - perhaps due to the challenges in modelling these identified in the previous section. Table 5 summarises the multiple nature-to-economy transmission channels captured in the applied models.

For the multi-sector general equilibrium models, each sector contributes to macroeconomic production and land is explicitly included as a production factor for agricultural sectors. The production function, which represents how different inputs are combined to produce output, adopts a ‘nested’ structure. Shocks affecting, for example, agriculture, therefore feed through directly to affect macroeconomic output through changes in sector productivity and output, and changes in the cost of land. Constraints on the availability of land for production result in higher relative land prices, increasing factor costs for land-based sectors and feeding through to the macroeconomy through higher relative prices for goods, and its subsequent effects on production and consumption choices.

In the modelling frameworks relying on single sector general equilibrium models, however, land is not included in the aggregate production function. Because only labour, capital and

Table 4: Representation, in the reviewed models, of (i) the impacts of the economy on nature and (ii) policies to mitigate the drivers of nature loss

		How are (i) the impacts of the economy on nature (background color) and (ii) the policies to mitigate these drivers of nature loss (symbols) represented in:					
	Drivers of biodiversity loss	GTAP-InVEST	REMIND-MAgPIE	AIM Hub	IMAGE-MAGNET	MESSAGE-GLOBIOM	GCAM
Land and sea use change	Expansion of cropland and pastureland	▓ ✓	▓ ✓	▓ ✓	▓ ✓	▓ ✓	▓ ✓
	Expansion of managed forests	▓ ✓	▓ ✓	▓ ✓	▓ ✓	▓ ✓	▓ ✓
	Expansion of cities	□	░	░	░	□	□
	Fragmentation	□	□	□	▓	□	□
	Land use intensification	░	▓ ✓	░	▓ ✓	▓ ✓	▓ ✓
	Sea use intensification	░	□	□	░ *	□	░
	Land degradation	□	▓ *	□	▓ ✓	□	□
Resource extraction	Rates of extraction of living materials from nature (e.g. biomass)	▓ ✓	░ *	░ *	▓ ✓	░ *	▓ *
	Rates of extraction of non-living materials (e.g., metals, minerals)	░	░ *	░ *	░ *	░ *	░ *
	Freshwater withdrawals	□	▓ *	▓	▓ ✓	▓ *	▓ ✓
Climate change	Greenhouse gas (GHG) emissions	░ *	▓ ✓	▓ ✓	▓ ✓	▓ ✓	▓ ✓
Pollution	NOx	□	▓	▓	▓ *	▓ *	▓ *
	SO2	□	▓	▓	▓ *	▓ *	▓ *
	PM2.5	□	□	░	▓ *	▓ *	▓ *
	Mercury	□	□	□	□	□	□
	Nitrogen/nutrient runoffs	□	▓	□	▓ ✓	□ *	□ *
	Noise	□	□	□	░	□	□
	Untreated wastewater	□	□	□	░ ✓	□	□
	Pesticides	□	□	□	□	□	□
	Pharmaceutical residues	□	□	□	□	□	□
	Plastics	□	□	□	□ *	□	□
	Dissolved metals	□	□	□	□	□	□
	Oil spills	□	□	□	□	□	□
	Salinization	□	□	□	□	□	□
Invasive alien species		□	□	□	□	□	□

(i) Impacts of the economy on nature:
▓ Modelled in quite detailed way
░ Modelled in less detailed way
□ Not modelled
(ii) Policies to mitigate the drivers of nature loss:
✓: Multiple and/or direct transmission mechanisms included
* : Incomplete compared to other models, or indirect mechanism
Blank: Not included
NB: assessment is relative to the other models.

Table 5: Illustrative summary of nature-to-economy transmission channels within applied models

	GTAP-InVEST	REMIND-MAgPIE	AIM-Hub	IMAGE-MAGNET	MESSAGE-GLOBIOM	GCAM
Production / Supply side:						
Sectors (number of sectors/technologies)						
– Agriculture (crops)	✓(6)	✓(20)	✓(6)	✓(9)	✓(30)	✓(5)
– Agri (livestock)	✓(2)	✓(5)	✓(3)	✓(10)	✓(4)	✓(3)
– Fishery	✓(1)	-	✓(1)	✓(6)	-	-
– Forestry	✓(1)	✓(1)	✓(1)	✓(4)	✓(1)	✓
– Energy	✓(2)	✓(>50) Including bioenergy	✓(19) Including bioenergy	✓(7) Including bioenergy	✓ Including bioenergy	✓ Including bioenergy
Are those sectors connected to macro output?						
	✓	No, except for the energy sector	✓	✓	No, except for the energy sector	No, except for the energy sector
Factors of production in macroeconomic production function						
– Labour	✓	✓	✓	✓	✓	✓
– Capital	✓	✓	✓	✓	✓	✓
– Energy	✓	✓	✓	✓	✓	✓
– Land	✓for agricultural and forestry sectors	-	✓for agricultural and forestry sectors	✓for agricultural and forestry sectors	-	-
Consumption / Demand side:						
Are the impacts of food prices on final consumption currently accounted for?						
	-	-	✓	-	-	-
Are the impacts of nature loss on human health accounted for?						
	-	-	-	-	-	-
Indirect effects:						
– Trade	✓	✓	✓	✓	✓	✓
– Sector inter-linkages	✓(CGE model)	Not included (only link is between agriculture and energy)	✓(CGE model)	✓(CGE model)	Not included (only link is between agriculture and energy)	Not included (only link is between agriculture and energy)

energy are production factors at the macro level, changes in agricultural output only affect macroeconomic production indirectly through changes in the prices of bioenergy and carbon. The agricultural sector is detailed in a connected partial equilibrium model that can represent the impact of shocks upon agricultural commodity yields and output. Nature loss and transition policies can affect bioenergy capacity and price. Additionally, land use policies will affect carbon sequestration in soils and therefore the amount of GHG emissions that need to be abated, hence influencing the price of carbon and then the price of energy. As the latter is a production factor at the macroeconomic level, production will be affected by land-related shocks through this specific energy channel.[12] One exception is REMIND-MAgPIE, where the costs to reach the demand addressed to the agricultural sector (in MAgPIE) are directly subtracted from total output (in REMIND) - a way through which land use-related constraints (e.g. due to protected areas or decline in productivity due to water scarcity) feedbacks on macroeconomic product.

Finally, we note that some transmission channels linking nature to macroeconomic variables are absent from most of the models reviewed. Apart from GTAP-InVEST where a drop in pollination affects total factor productivity in agriculture, factor productivity is not endogenously captured by the models reviewed: the degradation in ecosystem services so far does not result in lower labour or capital productivity in most models. In addition, the shocks on food production due to transition policies (e.g. protected areas, see Leclère et al. (2020)) or nature degradation (as in Lanz et al. (2018)) have surprisingly limited impacts on the demand side of the economy. Indeed, when food prices increase, one would expect demand to fall for other non-essential goods as consumers reallocate their budgets to prioritise food as an ‘essential good’. However, with the exception of AIM-Hub, the models reviewed do not currently include non-homothetic preferences - the typical function form to account for the essential ‘survival necessities’ of certain consumption goods (Echevarria, 2000). This means that the economic importance of food, health, and sanitation services is likely to be underestimated, especially in higher income nations where consumers do not dedicate a large part of their budgets to purchasing food. Other potential demand-side nature-to-economy transmission channels, such as the economic consequences of human health impact, are not modelled by any of the models reviewed. This is an important limitation if one wants to represent the economic damages of biodiversity loss, as the IPBES found that the alarming decline in biodiversity could entail an “era of pandemics”.

4.4 Model features mitigating the macroeconomic impact of nature-related shocks

Of the few studies estimating such macroeconomic effects, reported results have been low - even for severe losses in ecosystem services and transition policies. For example, using GTAP-InVEST, Johnson et al. (2021,0) estimate that the partial collapse of three ecosystem services (wild pollinators, marine fisheries, and timber provision by forests) would result in only a 2.3% reduction of global GDP in 2030, relative to a business-as-usual scenario. Using the MAGNET model, the Dutch central bank (DNB, 2023) finds that a 100% collapse in pollination would increase Netherlands’ agricultural output by 23%, due trade substitution effects that favour the Dutch agricultural sector. These results are somewhat at odds with the insights from the theoretical models presented in our literature review. Both Lanz et al. (2018) and Dasgupta (2021) emphasise that the loss of nature has significant impacts on economic growth, with the latter going as far to argue that economic growth may be ultimately bounded. These results also contrast strongly with consensus among earth systems scientists, for whom continuing current trajectories of nature loss presents an existential threat to the continued stability of human activity (Lenton and Ciscar, 2013; Rockström et al., 2023).

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[12] A future version of GCAM should include agriculture as a production factor in its aggregate production function.

One important reason for such results is that, regardless of how well the transmission channels between nature-related shocks and the economy are captured, macroeconomic models have several structural features and underlying assumptions that are likely to mitigate the economic impacts of nature-related or transition-related shocks.

First, economies are assumed to have a high degree of adaptability to shocks. Given that shocks affect the economy through relative price changes (e.g., of factor inputs or sector output), producers and consumers are able to adapt through substitution and trade. If the price of one production input (e.g. land) or consumption good (e.g. food) increases relative to another, that option can be substituted for an alternative, with the ease of switching governed by 'elasticity' parameters. This typical feature of neoclassical general equilibrium models is often a strength in understanding, for example, innovative technological problems to resource scarcity (Solow, 1973). However, it also conflicts with an understanding of the economy as 'embedded' within the biosphere. If the 'finiteness' of certain aspects of nature is represented by shadow prices rising to infinity, as is suggested by Dasgupta (2021), substitution possibilities in the model may mitigate the magnitude of economic impacts resulting from the loss of ecosystem services that are critical to human wellbeing.

Indeed, a subset of the environmental economics literature has argued that substitution possibilities may be limited or even impossible when considering 'critical' aspects of nature (Bergman, 2005; Traeger, 2011; Neumayer, 2013; Dasgupta, 2021; Cohen et al., 2019). In particular, Baumgärtner et al. (2017) show that accounting for a subsistence requirement in the consumption of ecosystem services decreases the elasticity of substitution between ecosystem services and manufactured goods. There are also good reasons to believe that these adaptation possibilities might be temporarily or even chronically impaired in the aftermath of severe shocks (see e.g. Geerolf (2022)). Recognising this, Johnson et al. (2021) ran a sensitivity analysis with GTAP-InVEST to limit price-induced substitution possibilities, finding that the drop in agricultural and forestry output was twelve times larger than under the business-as-usual scenario.[13] Such sensitivity of modelling results demonstrate the difficulty of choosing appropriate parameter values for unprecedented global environmental change, not least because substitution elasticities are typically calibrated according to historical data. Whilst CGEs can adjust substitution elasticities to a point, 'limited' or 'no substitutability' assumptions can prevent the model from solving under more extreme scenarios.[14]

The significance of the high adaptation capacities for producers and consumers in the models is that the final economic impact obtained may not be higher than the sector's share in value added. Importantly, for the main transmission channels included in the models (summarised in the previous section), the relevant sectors' share in value added often does not reflect the importance of the particular aspect of nature (e.g., food provision) for human wellbeing.[15] This limitation can be found in the results of Johnson et al. (2021), where the estimated economic impacts of the loss of three ecosystem services are largely skewed towards low-income countries (where agriculture represents 25% of GDP on average) but represents only a limited share (3%) of global GDP.

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[13] The authors reduced by 50% relative to baseline values the (1) constant elasticity of substitution between land, labour, capital (primary production factors); (2) the ease of transformation between land uses; and (3) ease of transforming land uses between different types of crops.

[14] As indicated by Johnson et al. (2023) in a later study using GTAP-InVEST: "We found, however, when running the GTAP-InVEST model with both the partial ecosystem collapse and limited substitutability that the model would not solve." (p. 4). Indeed, 'solving' the model refers to achieving an equilibrium where supply equals demand.

[15] For example, the agricultural sector only represents a small proportion of GDP in high- and middle-income countries (4.3% of global GDP, 1.3% in high income countries, and 8.8% in middle income countries, according to 2022 World Bank data) - portions which don't reflect the importance of the food sector for any economy (https://data.worldbank.org/indicator/NV.AGR.TOTL.ZS?name_desc=false)

Finally, economies are also assumed to maintain a rapid pace of technological development, captured by exogenous scenario assumptions. Current applied models typically calibrate total factor productivity so that, when the model is run without being shocked, the GDP path obtained reproduces an exogenous GDP taken from Shared Socioeconomic Pathways (SSPs – usually SSP2 and coming from Dellink et al. (2017)). Some models also take exogenous labour and land productivity and sectoral technological change as inputs. This means that a portion of GDP growth is assumed to always increase regardless of the magnitude of any transition or nature shock. This type of analysis aims to assess marginal changes, i.e., impacts holding all other things equal. Whilst such an approach can be useful for comparing different incremental policy approaches, its suitability is called into question when exploring scenario narratives of radical and structural changes. For instance, high-impact nature-related shocks or transformative policy changes implied by the Global Biodiversity Framework (GBF) targets will both influence long-term growth trajectories and cause structural changes, rather than marginal ones.

Taken together, the interplay of the mitigating factors summarised here suggest that the applied modelling approaches reviewed in this paper are likely to deliver very conservative estimates (i.e., underestimates) of the economic consequences of nature-related shocks.

5 Discussion

Our analysis has revealed an important discrepancy between how the stylised models and applied IAMs represent nature's contribution to the macroeconomy. Stylised models have tended to include highly aggregated aspects of nature, but have linked the dependence of the economy on nature in an endogenous way. For instance, the inclusion of 'critical' ecosystem services as a necessary input to the production function (as in Dasgupta (2021); the relevance of use and non-use values of nature, in determining utility (as in Bastien-Olvera and Moore (2021)); and the connections between ecosystem quality and agricultural productivity growth, as well as food availability and population (Lanz et al., 2018). Stylised models have also explored the relevance of substitutability assumptions - demonstrating in various ways that limited substitutability can dramatically impact the magnitude of impacts upon the economy. By contrast, the applied global IAMs reviewed in this paper capture more detailed, disaggregated ecosystem services and nature-related policies, but with a rather implicit connection to the determination of macroeconomic output. Is there a way of reconciling these two distinct approaches to modelling nature-economy interactions? We identify a number of avenues for the use of models for nature scenarios.

First, existing applied global models could explore options to develop more explicit nature-to-economy transmission channels, building for example on the endogenous feedback mechanisms between nature and the macroeconomy developed within stylised models. Another possibility - potentially more short term - is to calibrate the applied models on a broader range of exogenous growth pathways, including more less optimistic future growth pathways (instead of SSP2, which is the most widely used and which makes substantial growth assumptions). Applied global models could also explore possibilities for incorporating a more dynamic understanding of substitution (Drupp, 2018).

Second, we suggest that global nature scenario modelling should also be complemented by disaggregated economic models (e.g., focusing on specific localities) which aim to assess specific nature-related shocks (e.g., specific ecosystem services / transition policies). Whilst such an approach would eschew the more systemic perspective of applied global models, it would enable more precise calibration of economic impacts in a particular area, addressing some calibration limitations of global models.

Finally, nature-economy modelling is distinguished from climate-economy modelling by its enhanced complexity and uncertainty. This calls for an evolution in how applied models are used by end users for nature scenario analysis. Whilst climate-economy modelling is already a complex exercise, our analysis has identified that the mechanisms by which nature loss and transition policies can impact upon the economy are multi-dimensional, interconnected, and difficult to quantify with certainty. Indeed, the unprecedented and highly uncertain trajectory of nature loss means that certain functional forms and behavioural parameters will always have to be chosen arbitrarily. Applied models hence may never provide empirical estimates of economic impacts within the conventional parameters of certainty (Kedward et al., 2022). As a result, policymakers should be aware that applied nature-economy models cannot convert 'unknown unknowns' into 'known knowns', and that policy decisions may have to be informed by a combination of qualitative and quantitative approaches. One potential avenue could involve the use of stylised nature-economy models to build and explore qualitative scenarios at a global level.[16] Overall, the complexity of nature loss calls for a multi-dimensional approach to nature scenarios, rather than a 'one model fits all approach'.

6 Conclusion

In this paper, we review how different ecosystem services, drivers of nature loss, and mitigation policies are represented in global integrated assessment models that incorporate aspects of nature loss. We have also assessed the precise mechanisms by which nature-related shocks translate through to macroeconomic impacts. Importantly, many of these applied models were not initially designed to estimate the impacts of nature loss or policies upon the economy. However, growing demand by policymakers for nature scenarios (e.g., NGFS (2023)) has seen the use of applied global models shift towards attempting to estimate the economic impacts of nature-related shocks (Johnson et al., 2023; DNB, 2023; Banerjee et al., 2021).

First, we find that applied global IAMs represent economic dependencies on only a subset of ecosystem services (mostly provisioning services, in particular food and water) and capture selected drivers of biodiversity loss (mainly climate and land use–related). Only a few models represent regulating and maintenance ecosystem services (focusing mainly on pollination and climate) albeit with only partial connections to the economy. Consequently, this partial coverage constrains the types of nature scenarios that can be run in global IAMs, with a bias in particular towards scenarios of land-based transition policies and rather limited dimensions of nature loss (e.g., DNB (2023)).

Second, we find that the representation of nature/policy dimensions in applied models is linked to macroeconomic variables by limited and in some cases indirect mechanisms. Important nature-to-economy transmission mechanisms are missing, such as those involving the role of critical ecosystem services to production (e.g., Dasgupta (2021)) and human health and nutrition. Further assumptions within the macroeconomic core of applied models, notably exogenous growth pathways and substitutability assumptions, further tend to mitigate the economic impacts of nature-related shocks. As a result, applied global models are likely to underestimate the economic impacts stemming from nature-related shocks. Simply adding additional ecosystem services or nature-related policies is therefore insufficient for improving the suitability of global applied models to nature scenarios; it is also necessary for these models to better represent the crucial contribution of nature to the macroeconomy.

Emerging nature-economy models offer potential in helping to illuminate the complex socio-ecological problem of nature loss, when deployed in the appropriate context. The challenge for future research will be to keep applied nature-economy models aligned with ecology and earth systems science, as well as recent developments in environmental macroeconomic theory (Dasgupta, 2021), highlighting the centrality of a functioning biosphere to human activity. More detailed investigation of the economic consequences of the multiple biodiversity policies needed

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[16] For more on the interaction between quantitative and qualitative approaches to scenario modelling, see Jahel et al. (2023).

to halt and reverse nature loss is also crucial to advancing policymaker-relevant scenarios.

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7 Supplementary information

7.1 Method

Table A1: Articles of applied IAMs identified in the systematic review

Year	Authors	Title	Model(s)
2005	Alcamo et al.	Changes in nature's balance sheet: Model-based estimates of future worldwide ecosystem services	AIM, IMAGE
2013	Stehfest et al.	Options to reduce the environmental effects of livestock production - Comparison of two economic models	GTAP-IMAGE
2014	Harfoot et al.	Integrated assessment models for ecologists: the present and the future	AIM, MAGNET, GCAM, MESSAGE
2015	Van Vuuren et al.	Pathways to achieve a set of ambitious global sustainability objectives by 2050: Explorations using the IMAGE integrated assessment model	IMAGE-MAGNET
2017	Hasegawa et al.	Global land-use allocation model linked to an integrated assessment model	AIM
2017	Popp et al.	Land-use futures in the shared socio-economic pathways	REMIND-MAgPIE, AIM, IMAGE, GCAM, MESSAGE-GLOBIOM
2019	Wu et al.	Land-use futures in the shared socio-economic pathways	AIM
2019	Wu et al.	Biodiversity can benefit from climate stabilization despite adverse side effects of land-based mitigation	AIM
2020	Leclère et al.	Bending the curve of terrestrial biodiversity needs an integrated strategy	MAgPIE, AIM, IMAGE, GLOBIOM
2022	Doelman et al.	Quantifying synergies and trade-offs in the global water-land-food-climate nexus using a multi-model scenario approach	MAgPIE, IMAGE
2023	Johnson et al.	Investing in nature can improve equity and economic returns	GTAP-InVEST
2023	Kok et al.	Assessing ambitious nature conservation strategies in a below 2-degree and food-secure world	IMAGE-MAGNET, GLOBIO

7.2 Results - Stylised models

Table A2: Nature-economy interactions in Stylised models - Details

Model	Economy to Nature	Nature to Nature	Nature to Economy	Economy to Economy	Results
DICE with forest Fuss et al. (2021)	GDP leads to CO2 emissions accumulating to reach a constrained carbon budget	None (cost-efficient approach)	None (cost-efficient approach)	Abatement : (i) traditional *(ii) limiting deforestation, and reforestation ("biodiversity co-benefits" mentioned but not modelled)*	Reducing deforestation and reforesting lowers the cost of reaching given climate target
GreenDICE Bastien Olvera and Moore (2021)	GDP leads to CO2 emissions	CO2 emissions lead to climate change (temperature rise). *Climate damage on natural capital N, and decrease in N affects production of ecosystem services E*	*(i) Decrease in N affects production (ii) decrease in E affects utility function, (iii) Decrease in N affects utility function*	Abatement of CO2 emissions, plus *investment in natural capital: (i) offsetting damages from climate change to N, (ii) direct investment in N*	Introducing damages from N decreases optimal emissions and temperature, and significantly raises optimal carbon tax
DICE-NC Hackett and Moxnes (2015)	GDP leads to (i) CO2 emissions and *(ii) direct impacts on N*	CO2 emissions lead to climate change (temperature rise). *N is decreased by* climatic effects and *non-climatic effects. Synergies: climate-induced degradation of N interacts with non-climatic loss of N*	Climate damages made of (i) direct climate impacts on economy and *(ii) impact on the economy of loss of N due to climate change. Plus, damages from non-climatic loss of N*	Only traditional abatement of CO2 emissions	Non-climatic effects on N imply lower savings rate and more abatement. Synergy between climatic and non-climatic effect further increase costs of climate change: even more abatement
MAVA Lanz et al. (2018), Naso et al. (2022)	Population growth requires more *agriculture (food constraint, increasing with per capita income), leads to land use change*	*Land-use change via agricultural expansion impacts biodiversity (narrative, not modelled)*	*Biodiversity loss (narrative, not modelled) depreciates TFP of agricultural sector via a random shock. Agricultural production takes land as an input*	Transition policies: *(i) reduce food demand* via (a) fertility reduction or (b) a decrease in manufacturing consumption via less factors in manufacturing sector or higher saving rate, and *(ii) increasing population share employed in the agriculture R&D sector to increase agricultural TFP (agriculture intensification)*	Optimal area of cropland and optimal growth path are lower when accounting for cropland expansion leading to biodiversity loss and a subsequent reduction in agricultural productivity
Bounded Global Economy model Dasgupta (2021)	*GDP impacts the biosphere S through (i) resource extraction and (ii) pollution sink*	*Stock of biosphere S depreciates with impact and has a regeneration rate (function of the biosphere stock S, with a limit L below which there is no regeneration)*	GDP is a function of capital, labour, *a flow of provisioning ecosystem services (somewhat substitutable), and the biosphere stock S (reflecting regulating and maintenance services)*	Investment: (i) traditional investment in produced and human capital, (ii) research and development to increase total factor productivity (A). *TFP affects the intensity with which GDP requires resources from the biosphere and use biosphere as a pollution sink (but bounded efficiency gains), (iii) "waiting" (pure GDP loss to let the biosphere regenerate)*	As the economy is embedded in the biosphere (which has a safety zone L that must not be crossed) and efficiency gains to limit impacts are bounded, so is economic growth.

7.3 Results - Applied models

The detailed justification for Tables 3 and 4 in this paper can be found in Annex Table 3 and Annex Table 4 of NGFS (2023), *Recommendations toward the development of scenarios for assessing nature-related economic and financial risks*, `https://www.ngfs.net/sites/default/files/medias/documents/ngfs_nature_scenarios_recommendations.pdf`