ARTICLE IN PRESS

Engineering xxx (xxxx) xxx

Contents lists available at ScienceDirect

Engineering

journal homepage: www.elsevier.com/locate/eng

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# Modeling the Earth System: Enhancing Representation of the Climate and Natural Capital Nexus

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## 1. Introduction

Scientific observations and analysis over many decades have led to increasing recognition of the urgent need for humanity to respond to this issue. The impacts of these changes on humanity and the rest of our world are already significant and growing. Similarly, during this time, concerns about biological diversity have brought increasing attention to species extinctions. On a broader level, during this time frame, natural capital arose as a more general term for land and water-based natural resources regarded as having economic value or providing a service to humanity. For a specific region, natural capital is generally defined as including the concerns about biodiversity, ecosystem function, land use change, freshwater availability, and air and water quality, along with other effects on natural resources.

The science based on observations and other analyses indicates that the changes occurring in climate and in biodiversity and other areas of natural capital are almost entirely due to human activities (e.g., see the series of international assessments of the science, with the most recent being from Intergovernmental Panel on Climate Change (IPCC) [1] and Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) [2,3]). The changes occurring in the Earth's climate also have important interactions with and effects on the components of natural capital. By definition [4], natural capital includes the world's stock of natural resources, for example, geology, soils, air, water, and living organisms. These resulting impacts on natural capital can also affect the climate system, both locally and globally.

The Earth's climate, the multi-decadal prevailing weather conditions throughout the world, is changing and changing much more rapidly than our planet has seen in many thousands of years [1,5,6]. The increasing ocean and atmospheric temperatures across many decades have been well documented, with each decade warmer than the prior one. The globally averaged temperature in 2024 was the highest in thousands of years and the last decade was the warmest decade on record [7]. Correspondingly, precipitation patterns are changing throughout the world. Many observations throughout the world demonstrate a warming Earth—most glaciers plus the large ice masses of Greenland and Antarctica are dramatically melting, winter snow cover is decreasing, sea ice is decreasing, sea levels are increasing at an accelerating rate, our ocean pH is decreasing due to the increasing levels of carbon dioxide, and water vapor in the atmosphere is generally increasing as expected from fundamental physics [1]. Humanity has long witnessed natural disasters due to extreme weather, but the increasing energy in the atmosphere because of climate change is driving an increasing intensity in extreme weather events (e.g., heat waves, floods, droughts, wildfires, and severe storms) [1]. These trends are expected to continue for many decades as the climate continues to change.

Scientific analyses demonstrate that human activities, especially the emissions from fossil fuel burning for energy, transportation and industry (i.e., use of coal, oil, and natural gas) and from changes in land use (e.g., destroying forests), have significantly been driving changes in climate throughout the world [1,5]. Analysis of satellite and other observational datasets in combination with detection and attribution analysis techniques shows that the connection between climate change and human activities is essentially certain [1]. Further risks, more damage, and greater economic losses are expected with further changes in climate. In addition, the risk of unforeseen and possibly catastrophic consequences also increases with the additional changes in climate, in many instances leading to compounding effects [1,6].

Natural capital is also being affected by human activities. Changes occurring in the landscape, freshwater resources, and air and water quality are well recognized, along with the corresponding loss in biodiversity and in ecosystem function. Biodiversity—the variety of all living things—has been declining at an alarming rate along with the corresponding reduction in ecosystem function, producing another major issue for our planet [2,3]. Biodiversity ensures the health and stability of ecosystems by providing a diverse range of organisms that play interconnected roles. Biodiversity also has significant economic, cultural and aesthetic value to humanity. For example, biodiversity supports various industries, including tourism, agriculture, and pharmaceuticals [8].

The trends of decreasing biodiversity, and resulting effects on ecosystem function and services, are projected to continue, either at current rates or higher, in the future in response to the effects

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https://doi.org/10.1016/j.eng.2026.05.001

Please cite this article as: D.J. Wuebbles, Modeling the Earth System: Enhancing Representation of the Climate and Natural Capital Nexus, Engineering, https://doi.org/10.1016/j.eng.2026.05.001

of a variety of stresses, including changes in human population, consumption, and technology [3]. However, efforts in sustainability and resiliency could reduce these trends [3].

Climate change is clearly a significant factor in either loss of biodiversity or reductions in ecosystem function. The changes in climate, including the long-term changes in annual and seasonal local temperature, the changes in patterns of precipitation, and the changes occurring in the ocean, affect biodiversity and ecosystem function, including effects on species ranges and effects on the various water and chemical cycles that are key to ecosystems. Although this impact has long been recognized, it is generally not fully considered in the analyses of biodiversity and ecosystem function. At this time, the full extent of these interactions is not fully represented in studies of climate change and biodiversity, or for that matter in studies of the landscape, water resources, and air and water quality. The models used to study biodiversity and/or ecosystem function generally consider limited aspects of the changing climate, but without fully considering the full complexity of the changes in severity of major weather events or changes in coastlines and ocean processes.

We propose that the two science communities studying the climate and biodiversity issues come together to more effectively consider more, and if possible, all of the interactions involved. Through these interactions, these communities can more effectively develop and understand these issues and how they affect each other.

Fig. 1 [9] shows that there is a strong relationship between humanity and human society, climate change and the various components of natural capital—for example, biodiversity, ecological services, landscape, freshwater resources, and air and water quality. As an example of the relevant complexity of the interactions, the inclusion of the slowing down of the Atlantic Meridional Overturning Circulation (AMOC) [1,9] is aimed at showing that understanding and preventing tipping points, irreversibly permanent or semi-permanent impacts, must be considered because of the extremely large effects they could have both on biodiversity and on humanity and human social systems. In addition to the interactions between climate change and natural capital, integrating natural and social science knowledge is needed to more effectively inform action on climate change and on natural capital policies and practice. The human dimensions are essential—to ensure a sustainable future, the intricate interactions between environmental and social change must be addressed.

## 2. Earth system models

Complex computational models that solve partial differential equations representing the physical, chemical, and biological processes occurring on land, in the ocean and in the atmosphere are used to understand past changes in climate and to study its future evolution. These digital twins of the Earth's climate are typically run on state-of-the-art supercomputers. These models, often referred to as Earth System Models (ESMs), are primarily aimed at studying climate change, but also get applied to concerns about atmospheric composition and to studying a variety of processes affecting the atmosphere and ocean.

There are now over 30 global ESMs being used in the international assessments of climate change [1]. While representing important inputs from different countries, many of these models are not fully independent and are basically versions of other ESMs. These models are regularly evaluated relative to past observed changes in climate and generally compare quite well with the observed trends in climate (scientists have long said no model is perfect but some are useful). To study future changes in climate, these models are evaluated for a range of emissions scenarios that examine various possible choices for human and natural emissions, as well as potential natural factors, affecting the forcing on the Earth's climate system [1]. The scenarios evaluated are based on

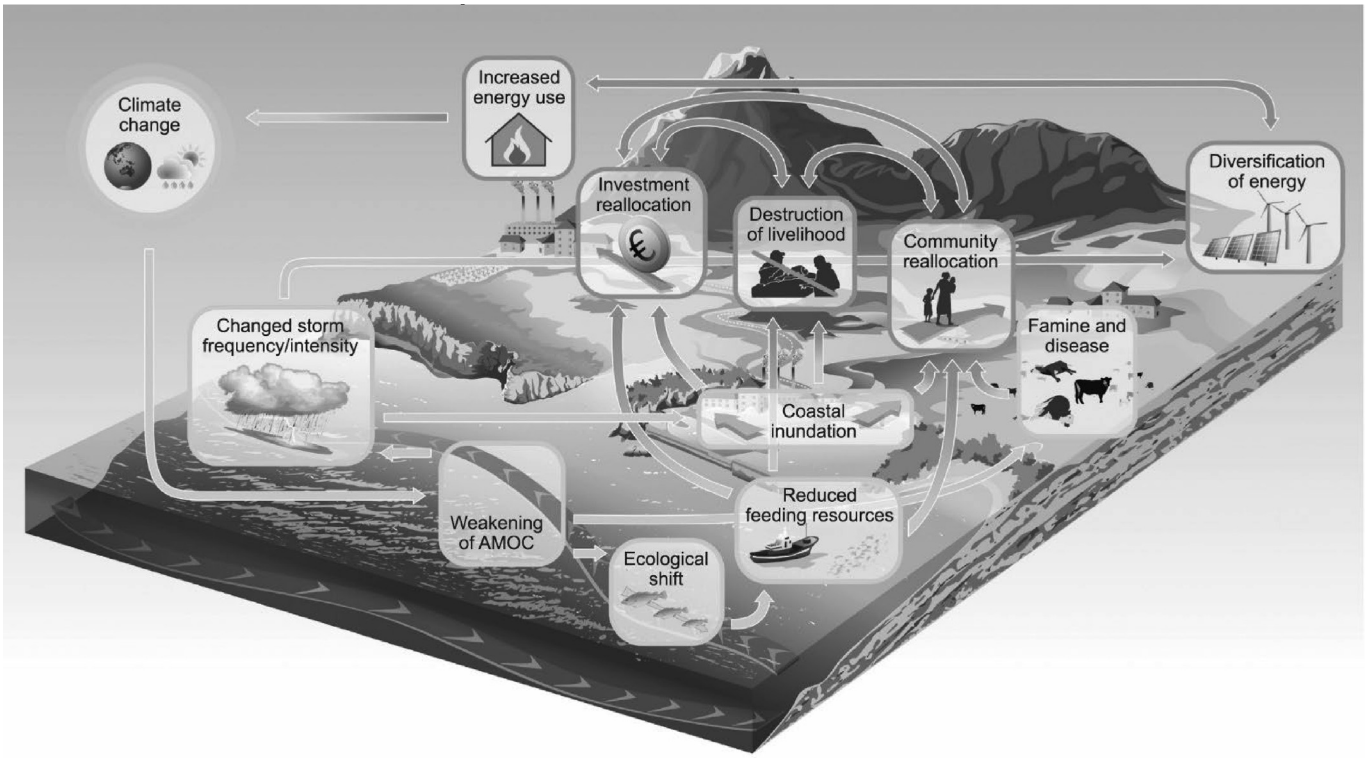

**Fig. 1.** Examples of interconnected social, climate and ecological systems that drive and are impacted by a weakening of the AMOC. Environmental and social systems and their interactions (arrows) are shown. Reproduced from Ref. [9].

assumptions of changes in population and economic development, as well as possible choices in future energy and transportation systems, along with other human activity considerations. Current ESMs are often run for periods of hundreds of years towards comparing with past observations and projecting future climate conditions over this century and beyond for this range of emissions scenarios.

The ESMs are aimed at studying the Earth's climate but have not been aimed at examining changes in biodiversity or ecosystem services to the same degree. ESMs do treat the major processes affecting atmospheric composition, temperature, and weather patterns and the similar set of processes affecting the oceans; and how all these components store and transport heat, carbon and other key components that drive and affect the Earth's climate [1]. These models also represent the processes affecting carbon and other important biogeochemical cycles, including the nitrogen cycle and its important effects on surface soils [10]. Some ESMs also can consider atmospheric chemistry, especially the effects of the ozone layer, because of the influence of these processes on the climate system. All of these processes are included in the model through a series of equations, many of them partial differential equations, that are then solved to determine the changing values of major variables like temperature and precipitation over spatial boxes as a function of latitude, longitude, and altitude.

The ESMs do put a significant effort into treating land surface processes, but not to the extent of fully considering biodiversity and ecosystem services [1]. As an example, the Community Land Model (CLM) is the primary land surface component of the Community Earth System Model (CESM) at the US National Center for Atmospheric Research (NCAR) as well as being used in several European ESMs. CLM is used to understand how natural and human changes in vegetation affect climate [11]. Land surface submodels like CLM represent the many processes by which terrestrial ecosystems affect and are affected by climate across a variety of spatial and temporal scales [11].

The inclusion of terrestrial ecosystems that cycle energy and water along with resulting effects on atmospheric composition, is important influences on climate. CLM is aimed at representing major processes affecting the land surface, with biogeophysical and biogeochemical processes being resolved at a subgrid scale resolution (meaning a finer spatial grid than the overlying atmosphere in the ESMs) with each subgrid unit maintaining its own prognostic variables [8]. The surface variables and fluxes required by the atmosphere are obtained by averaging the subgrid quantities weighted by their fractional areas [11]. Fig. 2 [11] shows a schematic representation for CLM version 5.0. Land surface models like CLM are continually improving so this discussion is a snapshot. The newest version 5.0 improves upon many processes and parameterizations and adds new capabilities, as discussed in Ref. [11].

As discussed above, representations of energy, water, and biogeochemical (e.g., carbon, nitrogen) cycles to study climate must be analyzed at high spatial resolution to sufficiently capture land surface changes and processes. Recently, the US Department of Energy's Energy Exascale Earth System Model (E3SM) Land Model (ELM) model [12,13] has been redeveloping CLM to have much higher spatial resolution, as fine as 1 km spatially. The goal of these analyses is to better account for ecosystem function and to reveal responses in ecosystems with the changing climate. Going to such high resolution has required essentially redesigning CLM to better account for all aspects of the treatments of processes within the land surface model. ELM is also adding new features and functionality, including plant hydraulics, radiation–topography interaction, subsurface multiphase flow, and more explicit land use and management practices [12,13]. Although its full impact is still not determined by the existing studies, the new ELM model already indicates the importance of treating processes at the right spatial resolution to capture the interactions with the Earth's climate system.

Despite the extent of their treatments of the land surface, current ESMs are limited in the degree to which they consider land use change or changes in hydrology and water resources or the impacts from changes in air or water quality [14]. Vegetation and vegetation changes associated with climate change are considered in these models, but they still do not fully consider or represent the complexity of biodiversity and ecosystem function. Much of the variety of life on Earth and associated impacts, including effects on biodiversity and potential feedbacks are generally not considered in today's ESMs [1,14].

Similarly, the complexity of ocean biodiversity and ecosystem function is not represented to the same degree in ESMs as the land surface processes. Marine Ecosystem Models (MEMs) are being developed that represent the nonlinear processes affecting marine species and the interactions within marine food webs [15]. At this point, submodels of MEMs are generally run using input from ESMs but are not generally an interactive part of ESMs in studying climate change.

## 3. Modeling of biodiversity and ecosystem function

Specialized computational modeling tools are also being used to study the responses of biodiversity and ecosystem function to environmental change. The approach generally used for addressing this complexity is often to reduce the diversity to a few meaningful dimensions representing key aspects of biodiversity complexity: biological organization levels (species, populations, ecosystems, etc.) and biodiversity attributes (composition, structure, and function) [2,16].

Models studying biodiversity are generally aimed at analyzing the current state of the biology components of ecosystems or at analyzing the effects from human activities or other forcings or stresses on the system [3]. These models, most of which either focus on global terrestrial ecosystems or on marine ecosystems, not both, most commonly are used to assess changes in species distribution, abundance, or community structure [2,16]. These modeling tools are also being adapted to looking at projected changes in ecosystems associated with climate change.

Modeling capabilities are crucial for understanding and addressing the impacts of climate change on biodiversity. Species distribution models (SDMs) and dynamic global vegetation models (DGVMs) are especially important tools [17]. These modeling capabilities are used to project how species distributions, habitat suitability, and ecosystem dynamics will change under various climate change scenarios, allowing for better informed conservation planning and adaptation strategies.

SDMs [18], also sometimes called environmental or ecological or habitat models, evaluate the distribution of a species spatially and temporally using environmental data. SDMs are used to examine the relationships between climate change and species distributions. They can use environmental variables and species presence data to project species locations relative to changes in climate.

DGVMs [16,17] are process-based computational models for analyzing various biogeochemical, biogeophysical and hydrological processes, including photosynthesis, heterotrophic respiration, autotrophic respiration, evaporation, transpiration, and decomposition. These are advanced tools for estimating the impact of climate change on vegetation and vegetation dynamics. DGVMs capture the transient response of vegetation to a changing climate or other effects on the local environment by representing key ecological processes relating to trees and other vegetation including processes affecting establishment, tree growth, competition, death and nutrient cycling [16]. Fig. 3 [16] shows the basic structure of a

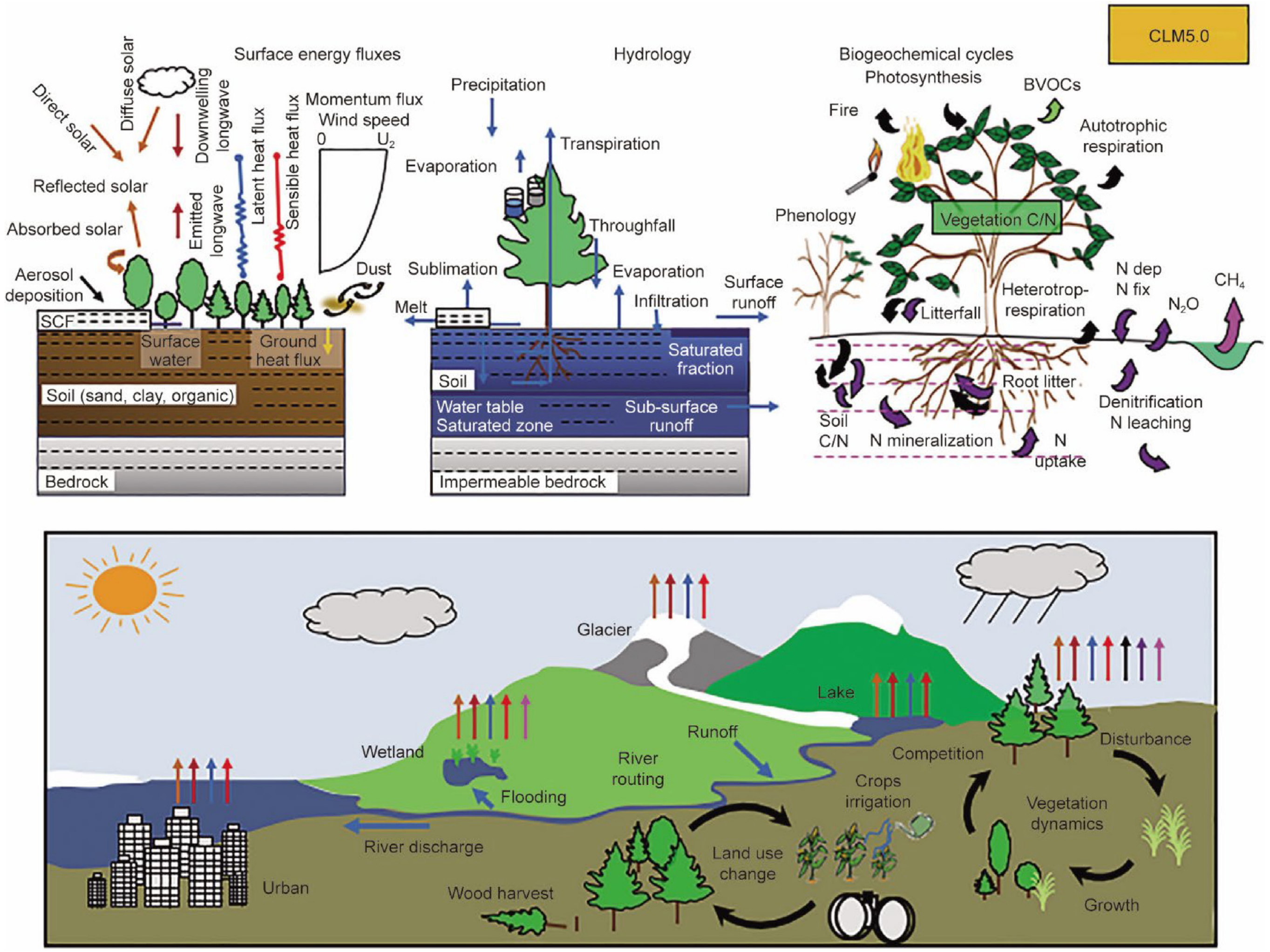

**Fig. 2.** Schematic representation of primary processes and functionality for land biogeophysical, biogeochemical, and landscape processes simulated by CLM, version 5.0. SCF: snow cover fraction; BVOC: biogenic volatile organic compounds; C/N: the ratio of carbon and nitrogen. For biogeochemical cycles, black arrow denotes carbon flux, and purple arrow denotes nitrogen flux. Note that not all soil levels are shown. Not all processes are depicted. Reproduced from Ref. [11].

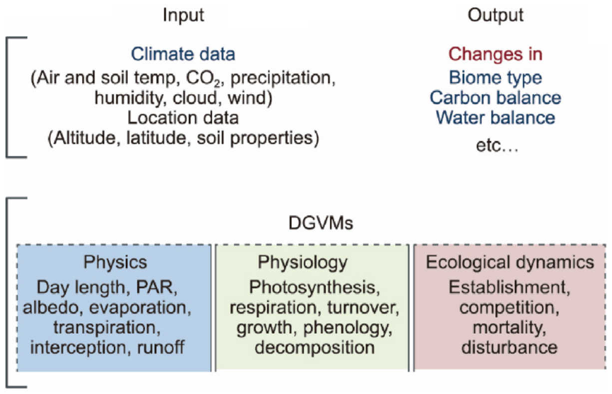

**Fig. 3.** Structure of DGVMs. PAR is photosynthetically active radiation. Reproduced from Ref. [16].

DGVMs. As discussed earlier, land surface models used in ESMs have adopted many of the processes and characteristics of DGVMs.

Ecosystem function models [19,20] are different, perhaps even aimed at going a step further, by modeling the interactions capturing important ecological processes—these models represent both biotic and abiotic ecosystem components, and they include the relevant processes affecting species interactions, productivity, and nutrient exchanges. Ecosystem services models [21,22] take these interactions even further by focusing on human well-being, including the forests, fish, and water resources that provide goods and services to people. Such capabilities for connecting natural capital and people will be discussed more in a later section.

Given the differences in their treatments of processes, it is not surprising that many, if not most, ecosystem function models do not include biological diversity in their analyses [19]. Also, global biodiversity and ecosystem service models tend to be run independently [19]. The biodiversity and ecosystem function models tend to be operated at different scales both spatially and temporally, affecting the ability to integrate these modeling tools [19,23,24]. Weiskopf et al. [19] reviewed 29 different models, including biodiversity models (most of which are focused on terrestrial, and one is focused on marine), ecosystem function models, and one ecosystem service model. As a result of their analysis, Weiskopf et al. [19] developed a framework for integrating these different types of models that include two pathways: ① Using relationships derived from empirical data to bridge biodiversity and ecosystem service models; and ② using outputs from biodiversity models to parameterize effects in ecosystem function models. Integrating these modeling capabilities would be a major step forward in modeling of the Earth's biosphere and the ongoing changes in biodiversity and ecosystem services, especially towards enhancing the understanding of impacts from human activities and climate change on ecosystem richness, intactness, and composition. Not only would these provide better projections but also could lead to better policy development.

Current biodiversity and ecosystem models do consider a range of scenarios for future drivers and forcings, including the effects of different scenarios for future climates. Many of the currently available studies use integrated assessment models (IAMs) [16] that provide a useful overview of climate change at a large regional scale and generally focus on temperature, precipitation, and limited representation of other impacts. As seen in Fig. 4 [16], IAMs are aimed at using a parameterized approach to evaluating the interactions and relationships between environmental, social and economic factors affecting climate change and other environmental issues, with the purpose of getting policy-relevant insights [2,16]. IAMs have proven to be especially useful for studying relationships between modeling climate change relative to considering various options for policy directed at limiting climate change and its impacts on human society. IAMs need further development to be fully considered for evaluating biodiversity dynamics under different stresses.

While climate change is not just about changes in temperature and precipitation, these are the primary variables considered in current models used to study biodiversity and ecosystem function [2,16–18]. As a result, the damaging effects of major storms and sea level rise, and other key aspects of climate change, are either not considered at all or are not considered adequately. There is a clear need to much more accurately consider all aspects of climate change—for example, the changing intensity of extreme weather events and the changes occurring in weather patterns and ocean circulation, in these studies. Ocean relationships in general need to be better considered, including sea level rise and storm surge effects on coastal systems. Extreme weather events and storm surges in rising seas likely have significant impacts on biodiversity and ecosystems that are not adequately addressed in current studies, especially at the spatial resolution required to fully understand changes in biodiversity and ecosystem services. Invasive species in part related to the changing climate are adding additional stresses.

## 4. Factoring in the human dimensions

While changes in both climate and biodiversity are largely being driven by human activities, it is also clear that human responses to the changes occurring are also leading to feedbacks on climate and biodiversity [1,2]. For example, human behavioral responses by adding more home insulation or adding solar panels in a warming climate, lead to changes in energy use, with resulting feedbacks on climate. Correspondingly, changes in land use in response to wildfires or changing intensity of extreme weather (e.g., increased flooding concerns) could also affect climate and biodiversity. Various studies have shown that reshaping natural habitats to make way for farmland, or to obtain natural resources (e.g., the search for rare earth metals or various minerals), is not only a huge threat to biodiversity but also indicate that there will be a growing impact on ecosystems as the climate continues to change [25].

Environmental protection and restoration require accurate analyses of ecosystem functions and effects of nature on people. However, the contributions of nature to people currently rely on biophysical variables while the tendency has been to ignore the effects of a changing biodiversity [26]. Models used for studying biodiversity can be key tools in understanding these relationships. Advances in the modeling of biodiversity can significantly enhance our understanding of the relationships of ecosystems with people and the various sectors of our society [26]. These advances could also help ensure that future biodiversity protection schemes are well informed and effective [26].

Our wellbeing and wealth also rely on natural capital, including biodiversity. Natural ecosystems provide services, including modulating climate, reducing flood risk, purifying water, and pollinating plants and crops we depend on. The world's ecosystems can be seen as major assets to our well-being. All too often, however, the importance of natural capital is poorly understood and under-

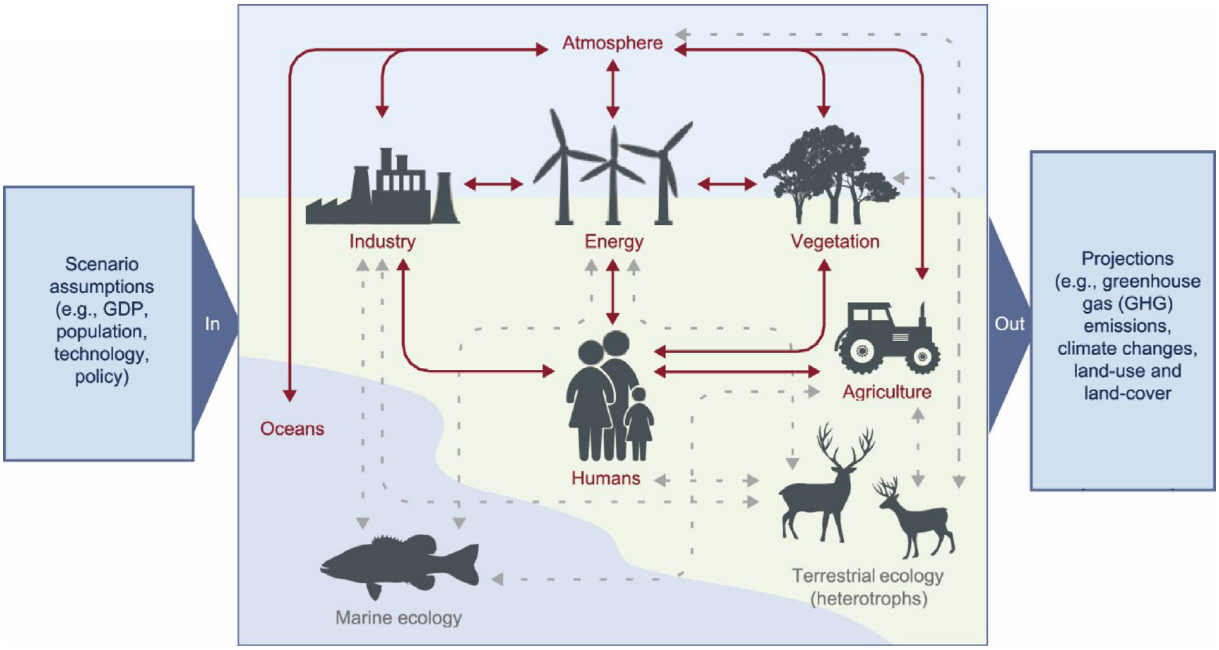

**Fig. 4.** Schematic representation of a typical full-scale integrated assessment model. Red labels and arrows represent existing model components and interactions, while gray labels and gray dashed arrows indicate important components and interactions not currently included. Reproduced from Ref. [16] with permission.

appreciated, resulting in degradation. All too often, we seem to only appreciate the benefits that nature has generated when they are gone.

One of the most important modeling efforts in understanding natural capital, biodiversity and the relationship of related issues to human activities comes from the Natural Capital alliance. The Natural Capital Alliance is a joint effort of Stanford University with other universities, organizations, and partners (including the Nature Conservancy, the Chinese Academy of Sciences, and the Stockholm Resilience Center). It is aimed at enhanced understanding of nature and its value. Through advanced modeling and analysis tools, the Natural Capital Project, by integrating the value nature provides to people, is aimed at helping decisionmakers understand where and how to safeguard nature with a special focus on biodiversity and ecosystem services. Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST) and other modeling tools are being used to analyze and evaluate interactions and connections between human activities, ecosystem services and biodiversity. Enhancing the understanding of these connections benefits us all. But as we discussed above, there is much more to do to further enhance these capabilities.

It is well recognized that changes occurring in climate and natural capital are already affecting humanity [1,2]. These changes affect our social systems, our economies, and our businesses. Projected future changes in climate and natural capital are likely going to lead to much larger impacts. Major actions can slow this down but are not likely to fully eliminate these impacts. Stakes are especially high for societal sectors with more direct, higher-value impacts and dependencies on nature and climate. Analyses show that the agriculture, food and beverage, and energy sectors are on the frontlines of stakeholder interest and engagement on climate and nature [27]. These sectors are major factors in the changes in climate and natural capital. For example, electricity production for household and business energy currently accounts for around 40% of the emissions of the gases and particles leading to the changes in climate [1,28]. Land use change, especially that associated with increasing food and vegetable oil production, is the primary driver of biodiversity loss, accounting for an estimated 30% of biodiversity decline globally [24]. Another 20% of biodiversity loss comes from overexploitation (overfishing, overhunting, and overharvesting) to help meet human needs for food, medicines, and timber. The single greatest cause of terrestrial biodiversity loss comes from meeting human needs for food and other goods, which is also responsible for 80% of deforestation and 70% of freshwater use globally [24].

Major human economic sectors, such as those related to food production, medicines, and timber, and the many corporations connected with them, not only are affecting the changes in climate and natural capital—these sectors are also being affected by these changes. Adaptation and resilience are needed along with reducing their effects on climate and natural capital. In addition to impacts on their assets, the responses of these sectors also affect the general populace—for example, land use change as a response, and resulting loss of natural habitats, increases the frequency of contact between wildlife and humans, and raises the likelihood of pathogens passing from one to the other. An increased emphasis on sustainability and on environmental, social, and governance (ESG) strategies can benefit these sectors and the general populace.

Governments and associated policies are generally given the most responsibility for dealing with these issues, but companies can also help to resolve climate and natural capital issues while addressing their own potential risks and hazards. To accomplish this, governments and companies need solution-based approaches that integrate nature, biodiversity, climate, and social issues into their sustainability and ESG strategies. While governments and companies can lead the way in addressing climate change and protecting nature, they also need scientific analyses and data analytics that will help them fully understand the pathway to solutions. This brings us back to the value of models that integrate human, natural capital, and climate interactions.

Numerical modeling of the Earth system that considers all of these interactions is necessary and could be valuable in helping determine the right policy and solution actions. The ESMs being used to study climate change, and the biodiversity and ecosystem function models currently account for some key aspects of human activities, such as the role of agriculture and resulting impacts from climate change [29,30] through their land surface modeling, but the adequacy of these treatments requires further analysis. They also account for some major processes affecting hydrology and freshwater flows in rivers. However, these models still need to more fully represent the feedbacks affecting the food–energy–water nexus [31,32], including the effects of responses of human society to changes in climate and natural capital.

## 5. The path forward

The primary objective resulting from this study is to encourage further enhancement of the modeling capabilities used to study climate and biodiversity. By having the science communities studying these issues coming together, the aim is to more effectively develop the modeling capabilities used to understand these issues and the interactions between climate change and natural capital. Numerical modeling of the complex systems affecting climate change and biodiversity can provide important insights for resiliency and a sustainable future. While it is well recognized that climate change and natural capital are intertwined, the modeling of these important issues does not adequately consider these interactions and resulting feedbacks. In addition, interactions with human society also provide important feedbacks; these models also need to more fully treat these interactions.

Changes in biodiversity and ecosystems affect the changing climate, and vice versa, at least locally and regionally through the resulting feedbacks on the landscape, water resources, and radiatively relevant emissions of gases and particle precursors. More complete understanding of the interactions occurring in climate, biodiversity, and ecosystem function and services requires the development of models that more fully represent digital twins of the Earth. While researchers are already enhancing the representation of these linkages, the communities of scientists studying Earth System Modeling and the study of biodiversity and ecosystem function and services likely do not interact sufficiently. Much more effort is needed to enhance these linkages while also better connecting with the human dimensions. These linkages need to also more fully consider other aspects of natural capital and associated changes in natural resources such as effects occurring from land use change, water resources, and air and water quality. Some of these improvements are limited by current computer resources. Increasing interactions between the climate and ecosystem/biodiversity communities could greatly enhance our understanding of relevant processes along with resulting in more powerful tools to study these important issues, while also addressing the spatial resolution really required in associated submodels.

Higher spatial resolution in Earth system modeling is likely required to more effectively consider the land surface, urban development, agricultural and soils relationships, changes in hydrology affecting water availability, and the interactions with ecosystems and biodiversity. Computational capabilities have limited the ability to fully consider all of these linkages and interactions in the past, but recognizing their importance brings a new priority to more fully understanding the entire Earth system. Specialized and/or dedicated computers may be needed. Machine learning and learning from artificial intelligence analyses can also provide important insights into the feedbacks and processes needing to be considered and could greatly assist in developing better overall understanding of these relationships and interactions.

## CRediT authorship contribution statement

**Donald J. Wuebbles:** Writing – review & editing, Writing – original draft, Visualization, Validation, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization.

## Acknowledgments

Thank you to Wei Gao of Colorado State University and Xin-Zhang Liang of the University of Maryland for reading the draft of this paper.

## Compliance with ethics guidelines

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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