

INTEGRATING ECOSYSTEM MODELING INTO ECONOMIC MODELS: APPLICATIONS TO EFFICIENCY ANALYSIS, GROSS ECOSYSTEM PRODUCT, AND POLICY ANALYSIS

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Unless you are one of the 676 people who have traveled to space as of November 2023,¹ you will have spent your entire life living within the biosphere, a relatively thin layer above and below the Earth's surface, where life exists. Spending our entire existence surrounded by the biosphere, it can be easy to take it for granted. But a livable biosphere is crucial for the health and well-being of humanity. One way to see the fundamental importance of the biosphere is to imagine living outside of it. In the science-fiction novel *The Martian*,² an astronaut finds himself alone on the surface of Mars and must figure out how to survive in an unforgiving environment, including meeting basic requirements like providing food and maintaining a breathable air supply. *The Martian* drives home a basic point: the Earth, unlike Mars or anywhere else in the universe as far as we know, provides humans with an essential life support system. When an article published in *Nature* estimated that the total annual value of the Earth's ecosystem services was \$33 trillion,³ economist Mike Toman wryly commented that it was a "serious underestimate of infinity."⁴

1. See Hobbs (2023).

2. See Weir (2014).

3. See Costanza and others (1997).

4. See Toman (1998).

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For most of human history, human actions did not appreciably change the biosphere except for some localized effects.

However, since the Industrial Revolution and particularly since the “Great Acceleration” in economic activity that began in the 1950s, humanity has had massive global impacts.⁵ We now live in an era in which humans are the dominant force driving change in the biosphere.⁶ Changes in the biosphere, including global climate change and loss of biodiversity, now threaten current and future prosperity and well-being.⁷

Maintaining a livable biosphere in which humanity can thrive will require large-scale changes in economic activity, including shifting energy production away from carbon-emitting fossil fuels and changes in agriculture, forestry, mining, development, industrial production, and other sectors that directly affect biodiversity. Harnessing economic incentives is essential for making changes in economic activity on the scale and at the speed necessary to address the climate and biodiversity crises. In 2005, the Millennium Ecosystem Assessment reported on global trends in biodiversity and ecosystems and focused attention on the concept of “ecosystem services,” defined as goods and services provided by nature that benefit people. This assessment found that the provision of the vast majority of important ecosystem services had declined over the previous 50 years. The only exceptions to the general pattern of decline were the production of crops, livestock, and aquaculture, which are all private goods for which economic incentives for production are in place, along with net carbon sequestration.⁸ This pattern of decline in the majority of the ecosystem services, except for the provision of material services that are private goods, was also found more recently in the Global Assessment Report of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES).⁹ Virtually all other ecosystem services are characterized by being provided by forms of natural capital that are public goods. Economic theory predicts the under-provision of public goods without some type of policy intervention. In reviewing the trends in ecosystem services, Kinzig and others (2011) noted “you get what you pay for” and, conversely, “you don’t get what you don’t pay for.” These works highlight the urgent need to bring the values

5. See IPBES (2019); IPCC (2023).

6. See Crutzen and Stoermer (2000).

7. See IPBES (2019); IPCC (2023); UNEP (2021).

8. See MA (2005).

9. See Brauman and others (2020); IPBES (2019).

of nature into economic accounts and to provide economic incentives to preserve the natural capital that generates the flow of ecosystem services.

The primary motivation for developing integrated ecosystem-economic models is to bring information about ecosystem services and natural capital into economic and policy decision-making. Integrated ecosystem-economic modeling can be used to analyze the impacts of human actions on ecosystems, the resulting changes in the provision of ecosystem services, and the consequent impacts on the economy and human well-being. With this information, it is possible to assess the benefits and costs of various economic activities, including their effects on ecosystem services. By linking these impacts on ecosystem services to incentives—either through green subsidies (i.e., payments for ecosystem services), brown taxes (i.e., carbon and pollution taxes), cap-and-trade, or other policy mechanisms—the proper economic incentives can be given to businesses and households to maintain or enhance an efficient level of natural capital and provision of ecosystem services. Doing so would reorient economic activity towards maintaining a livable biosphere in which humanity can prosper well into the future.

The next section lays out the framework guiding the development of integrated ecosystem-economic models and their basic building blocks. The following section contains descriptions of various applications of integrated ecosystem-economic modeling. These applications include: i) local-regional scale benefit-cost analysis of policies or projects, ii) development of efficiency frontiers (production possibility frontiers) showing feasible combinations of outputs across multiple objectives, iii) private-sector disclosure of dependencies and impacts, iv) Gross Ecosystem Product (GEP), which aggregates the value of ecosystem services similar to GDP accounting of marketed goods and services, and v) global general equilibrium analysis that incorporates natural capital and ecosystem services.

1. AN INTEGRATED ECOSYSTEM-ECONOMY MODELING FRAMEWORK

The purpose of integrated ecosystem-economic modeling is to bring ecosystem services and natural capital into economic and policy decision-making. One framework for bringing the value of nature into decision-making was laid out in Polasky and Segerson

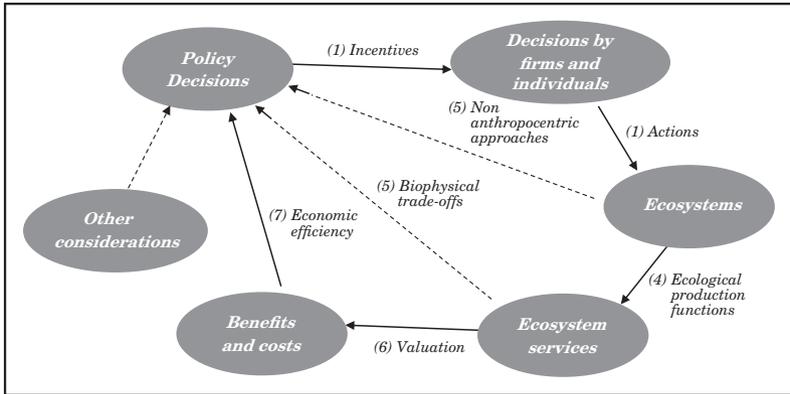
(2009), shown in Figure 1. Since the purpose of integrated ecosystem-economic modeling is to inform decision-making, the framework starts (and ends) with policy decisions, as depicted in the upper left oval in Figure 1. Policy decisions, such as whether to institute a carbon tax or payments for ecosystem services, affect incentives faced by businesses and households and can thus influence their decisions, as shown by arrow (1) in Figure 1. Businesses and households take actions that can impact ecosystems, for example, clearing land for crop production or grazing, harvesting biological resources (hunting, fishing, and gathering), changing nutrient flows through fertilizer application, changing hydrological cycles from irrigation and other water uses, and emitting air or water pollutants and greenhouse gases, as shown by arrow (2) in Figure 1. A branch of the environmental sciences analyzes impacts on nature from various economic activities, such as the impact of habitat loss on biodiversity or the greenhouse gas emissions on climate change and their subsequent impacts on ecosystems. Environmental science often stops at this point, showing how actions impact the environment in biophysical terms. Sometimes this is sufficient for policy decisions, as for example, demonstrating that an action causes harm to an endangered species listed under the U.S. Endangered Species Act or that pollution emissions into a waterbody violates water quality standards under the U.S. Clean Water Act. A major disadvantage of this approach, however, is that it doesn't determine whether a regulatory prohibition will result in an increase or decrease in social net benefits because there is no calculation of benefits or costs. There may also be impacts on other sectors or geographic regions, such as when strict regulations in one country cause a shift in production to other countries with less strict regulations, which also typically do not get factored into the analysis.

Impacts on ecosystems may or may not cause impacts on human well-being. For an ecosystem function to be considered an ecosystem service, it must generate a benefit to some person. If eliminating the function does not affect the well-being of any person, whether present or future, then the ecological function is not an ecosystem service. Going beyond ecological functions and biophysical impacts, ecosystem service modeling uses "ecological production functions" to determine the provision of ecosystem services as a function of the condition of ecosystems, as shown by arrow (4) in Figure 1. For example, the extent and condition of vegetation within ecosystems affect the degree to which the ecosystem can filter pollutants, regulate pests and pathogens, modulate floods or droughts, provide habitat for

charismatic species, or provide other valuable benefits that people care about. Ecological production functions for multiple ecosystem services can be used to identify tradeoffs among ecosystem services such as between expanded food production and maintaining water quality and carbon sequestration, as shown by arrow (5) in Figure 1.

Ecological production functions defining the provision of ecosystem services can be combined with economic valuation to determine the value of the contribution of ecosystem services to human well-being, as shown by arrow (6) in Figure 1. The value of the provision of ecosystem services can be estimated in monetary terms by using market and nonmarket valuation methods. The great advantage of using economic valuation is that it puts the contribution of all ecosystem services into a common (monetary) metric, making it easier for decision-makers to determine which policy alternatives or management choices deliver the highest net benefits, as shown by arrow (7) in Figure 1.

Figure 1. Framework for Integrated Ecosystem-Economy Modeling Connected to Decision-Making



Source: Polasky and Segerson (2009).

Currently, the monetary valuation of all ecosystem services is difficult to achieve in practice. Because many ecosystem services are not traded in markets and therefore do not have market prices, nonmarket valuation methods must be used to assess value. Nonmarket valuation methods work quite well for some ecosystem services, such as assessing the value of recreation by using random utility travel cost methods or the value of natural amenities on property value by using hedonic property price methods.¹⁰ Other ecosystem services are inputs into marketed goods and services, and their value can be imputed by using the marginal value product along with the market price of the marketed good or service. For example, the value of pollination can be imputed by estimating how pollination contributes to the quantity and quality of agricultural crop production and the consequent increase in crop revenue.¹¹ Some ecosystem services, though, are difficult to measure in monetary terms, especially nonmaterial ecosystem services such as those that contribute to cultural or spiritual values, sense of place, or experience.¹² It is also difficult to get an accurate estimate of the present value of the flow of future ecosystem services caused by changes in natural capital. Besides the normal difficulties of knowing how to discount future values, there is also the difficult task of predicting how much of each ecosystem service will be provided in the future and the value of those services to future generations.

In part because of the difficulty of getting fully accurate estimates of the value of all ecosystem services, comparing the net benefits of policy or management alternatives using ecosystem service valuation should be viewed as an important input into decision-making, but not determinative of the decision itself.¹³ Additional factors such as distribution or equity concerns or information about values that are difficult to quantify or monetize may also be important to consider in decision-making (Figure 1).

Many components of the integrated ecosystem-economic framework described above are well-developed in the natural sciences and economics. Ecosystem ecology studies ecosystem functions and many environmental sciences study how the environment is impacted by various human actions. Environmental economics has developed methods of market and nonmarket valuation that can be applied

10. See Freeman and others (2014).

11. See Ricketts and others (2004); Ricketts and Lonsdorf (2013).

12. See Daniel and others (2012); IPBES (2019).

13. See Arrow and others (1996).

to value ecosystem services. Economists have also studied a wide variety of policies and incentive mechanisms and how these influence decisions, including decisions that have an impact on the environment.

While these components are often available, what is more often missing is the integration of these parts into a complete analysis—one that connects a policy or management change to its impacts on ecosystems, to subsequent changes in ecosystem services, and ultimately, to changes in human well-being. The parts of this integration that have drawn the least attention typically occur at the junctures linking natural sciences and economics. Natural scientists are comfortable doing natural science, and economists are comfortable doing economics. It takes a concerted effort to overcome disciplinary silos to combine natural science and economic analysis into a single integrated analysis. The first of these key junctures between natural science and economics comes from connecting the way in which policies and incentives translate to actions, which is largely in the realm of economic analysis, to their effects on ecosystems and environmental impacts. Most of the information to establish this connection exists but often work is needed to translate economic decisions into changes in ecosystems that can then be used in ecological production functions. Changes in land use or emissions of greenhouse gases have received the most attention and are furthest along in this regard. At a more micro level, how agricultural practices and management affect ecosystems is well studied, as are the impacts of many particular industrial practices. The second key juncture between natural science and economics comes from the need to link changes in ecosystem structure and function to the provision of ecosystem services that benefit people, and ultimately to their value to people. Ecological production functions are well understood for some ecosystem services, such as carbon sequestration and storage, or the contribution to material goods, such as agricultural crops, timber, and fisheries. For many other ecosystem services, such as the physical and mental health benefits of exposure to nature, the production functions are still works in progress.

Even with imperfect knowledge of some ecosystem service values, analysis incorporating what is currently known about ecosystem services can provide useful information to inform decisions. The next section presents example applications that illustrate this point.

2. APPLICATIONS OF INTEGRATED ECOSYSTEM-ECONOMY MODELING

Information about the value of ecosystem services can be used in a variety of contexts to inform public- and private-sector decisions. This section describes five types of applications of integrated ecosystem-economy modeling and provides illustrative examples, starting with local- to regional-scale benefit-cost applications of policy or project alternatives and ending with global-scale general equilibrium models.

2.1 Local-Regional Scale Benefit-Cost Analysis

Benefit-cost analysis is a useful tool for helping to inform policy and management decisions, but the results are only as good as the inputs used. Leaving out major categories of benefits or costs can result in biased information and poor decisions. Including information about ecosystem services and the impacts of alternative policy or management decisions on ecosystem services can improve benefit-cost analysis and the information it provides for decision-making. Over the past two decades, The Natural Capital Project—a partnership between Stanford University, the University of Minnesota, the Chinese Academy of Sciences, the Royal Swedish Academy of Sciences, the Stockholm Resilience Center, The Nature Conservancy, and the World Wildlife Fund—has developed the InVEST (Integrated Valuation of Ecosystem Services and Tradeoffs) software package, which is a suite of ecosystem service models using biophysical, land use, and land management inputs, to predict provision of a set of ecosystem services.¹⁴ At its core, InVEST is a set of ecological production functions that take biophysical inputs characterizing the extent and condition of ecosystems and generate outputs describing the provision of ecosystem services. The InVEST software has been downloaded thousands of times and has been used in countries around the world.

Polasky and others (2011a) used an early application of the InVEST software to analyze the benefits and costs of alternative land-use policies on several important ecosystem services. Using data from the state of Minnesota, they parameterized InVEST, and several other models to analyze the impact of alternative land-use plans covering the period from 1992 to 2001 on carbon sequestration, water quality

14. See website of The Natural Capital Project, Standford University.

(phosphorus contributions to rivers and streams), habitat quality for grassland and forest birds and general terrestrial biodiversity, agricultural crop and timber production, and the value of land use in urban development. The authors found that incorporating the values of several ecosystem services (carbon sequestration and water quality) changed the ranking of net benefits among alternative land-use policies compared to the case without incorporating ecosystem service values. When just considering the private returns to landowners, the agricultural expansion scenario, in which all highly productive land for agriculture was put into crop production, generated the highest net market returns among the scenarios (bottom row in Table 1). The agricultural expansion scenario, however, generated the lowest net social benefits across all scenarios considered when ecosystem services were included because of the large losses in stored carbon and negative impacts on water quality in this scenario (top row in Table 1). Further, this scenario resulted in the largest decline in habitat quality for general terrestrial biodiversity and forest songbirds. Values associated with biodiversity conservation were not monetized and not included in Table 1. Inclusion of biodiversity values would only worsen the relative outcomes for the agricultural expansion scenario. In contrast, the no agricultural expansion scenario with no new cropland generated the highest net social returns when the value of carbon sequestration and water quality were included. This alternative and the conservation scenario, in which lands within 100 meters of streams and agricultural lands with marginal soils were restored to natural vegetative, were the only two scenarios with a positive net social benefit relative to the no change in land use scenario (column 2 in Table 1).

The results in Polasky and others (2011a) show the importance of including the benefits and costs associated with changes in ecosystem services for policy decisions. The finding that the inclusion of ecosystem service values changes the ranking among policy alternatives is consistent with other studies, including comparing the social net benefits of maintaining natural habitat versus land conversion,¹⁵ alternative land uses in the Willamette Basin, Oregon, USA,¹⁶ and alternative policies affecting land use for the U.S.¹⁷

15. See Balmford and others (2002).

16. See Nelson and others (2009).

17. See Lawler and others (2014).

Table 1. Value of Ecosystem Services and Private Returns to Land under Land-Use Change Alternatives

	<i>Actual land use in 1992</i>	<i>No agriculture expansion</i>	<i>No urban expansion</i>	<i>Agriculture expansion</i>	<i>Forest expansion</i>	<i>Conservation</i>
Change in total value: carbon, water quality, agriculture & forest production, and urban development using actual prices (million 1992 US dollars)	\$3,328	\$3,407	\$3,040	\$2,742	\$3,300	\$3,380
Change in returns to landowners: agriculture & forest production, and urban development using actual prices (million 1992 US dollars)	\$3,320	\$3,343	\$3,027	\$3,418	\$3,292	\$3,221

Source: Polasky and others (2011a).

2.2 Efficiency Frontiers

Even when information about the value of some ecosystem services is unavailable, information about the quantity of ecosystem services can still be useful for decision-making. Ecological production functions define the quantity of ecosystem services that can be produced with available inputs. Using optimization techniques along with ecological production functions, an efficiency frontier (production possibility frontier) can be derived showing Pareto-efficient combinations of ecosystem services that can be achieved with a given set of resource

inputs.¹⁸ The efficiency frontier shows the biophysical tradeoffs between services; i.e., the slope of the efficiency frontier is the marginal rate of transformation between ecosystem services. The efficiency frontier can also show the degree of inefficiency of various alternative resource allocation plans including the current allocation and what changes can be made in allocations that would lead to Pareto improvements.

In recent work involving colleagues from the Natural Capital Project and the World Bank, landscape efficiency frontiers showing Pareto-efficient land-use patterns were derived for 146 countries.¹⁹ For each country, the landscape efficiency frontier shows how land should be allocated to different uses, which in this analysis included crop production, livestock grazing, timber production, and conservation as natural habitat, in order to generate Pareto-efficient combinations of multiple ecosystem services, which in this analysis included carbon storage in terrestrial ecosystems, biodiversity conservation, and the value of net returns to crop production, livestock grazing, and timber production. The analysis showed that the current land-use pattern in many countries was far from the efficiency frontiers, indicating that large environmental and economic gains were possible, even when factoring in transition costs for switching land use. For example, in Haiti, it is possible to improve carbon storage, biodiversity, and the net value of agricultural crops, livestock, and timber production, relative to the current landscape by large percentages (panel A in Figure 2). Not all countries can simultaneously improve outcomes in multiple dimensions, such as Iceland (panel B in Figure 2). Many sparsely populated low-income countries, such as Gabon, can greatly increase the value of market returns while maintaining high levels of biodiversity and carbon storage (panel C in Figure 2). Many highly developed and densely populated countries, like Japan, can improve biodiversity and carbon storage without loss of market value. However, restoring environmental outcomes to anything close to what they once were would require large sacrifices in the value of market returns (panel D in Figure 2). Across all 146 countries, improved land use and land management can increase carbon storage by 233 billion metric tons of CO₂ (23 percent increase from current levels) while also increasing biodiversity without loss of net production value from crops, grazing, and timber, or increase the net value of production by

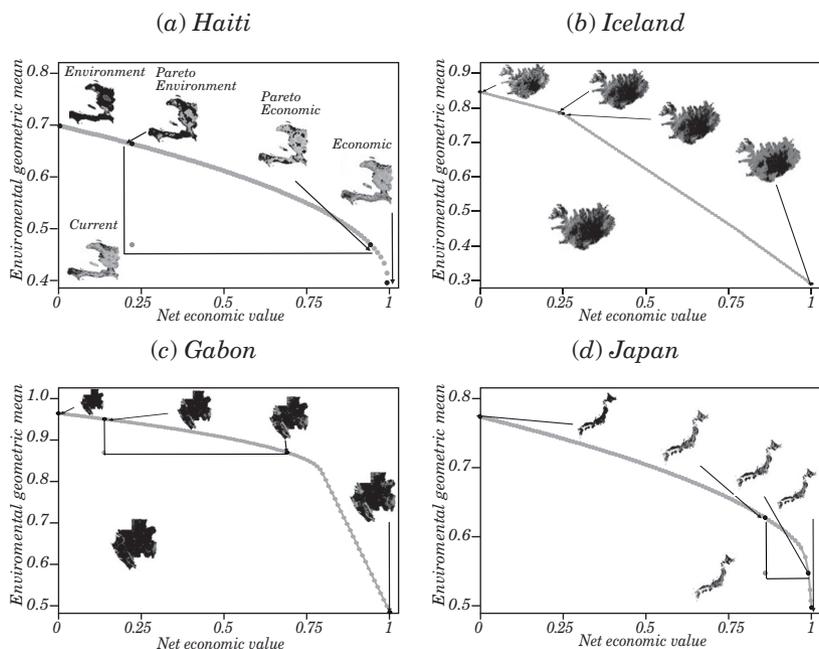
18. See Polasky and others (2008).

19. See Damania and others (2023); Polasky and others (2023a).

367.7 billion U.S. dollars (83 percent increase) without loss of climate mitigation or biodiversity benefits.²⁰

An advantage of efficiency frontiers is that they highlight potential efficiency gains, the actions that can be taken to realize efficiency gains, and the unavoidable tradeoffs between various ecosystem services and between ecosystem services and other goods and services. Efficiency frontiers also do not rely on prices or values, which can be difficult to obtain for some (nonmarket) ecosystem services. The disadvantage of efficiency frontiers is that there is no obvious best outcome. Rather, decision-makers need to contribute their own value judgments to decide which Pareto-efficient outcome is viewed as best.

Figure 2. Landscape Efficiency Frontiers and Current Performance



Source: Polasky and others (2023a).

Notes: The figure shows potential simultaneous gains for environmental and economic outcomes and tradeoffs for illustrative countries. The horizontal axis measures the net production value from agricultural crop production, livestock grazing, and forestry. The vertical axis is the geometric mean of carbon storage and biodiversity scores. Minimum and maximum scores in each country for each outcome are normalized to 0 and 1 with maximum environmental geometric scores often occurring at negative production values because of transition costs from the current landscape that outweigh positive production value at the landscape that maximizes environmental outcomes.

20. See Polasky and others (2023a).

2.3 Private-Sector Disclosure of Dependencies and Impacts

While most ecosystem services evaluations to date have been focused on public-sector decision-making, a similar analysis can be done to inform private-sector decision-making. The major difference between the ecosystem information relevant to private-sector and public-sector decision-making is the scope of the accounting. For a business, the appropriate scope for accounting can include the direct impact of the business's operations on the provision of ecosystem services (Scope 1) or the impact of the business through its entire supply chain—from purchased inputs through to impact from consumer use and the end of the life of the product (scopes 2 and 3). Like public-sector applications, business applications measuring impacts can be done in both biophysical and monetary terms and, like public-sector applications, measurement in a common monetary metric facilitates comparisons of the profitability and/or social net benefits of alternative business strategies. Measures of impact are also of interest to financial analysts evaluating businesses or investment portfolios.

To measure the impacts of a business on ecosystem services, information is needed on the location of company operations (“where”), the production processes at each location (“what”; i.e., what products are produced and by what processes), and the scale of activities at each location (“how much”).²¹ This type of information is often proprietary. However, using publicly available information on the location and size of business operations, along with life-cycle analyses by industry, dependencies and impacts can be estimated even without access to proprietary information.

Currently, there is great interest in the disclosure of business impacts on nature, spurred by impending mandatory disclosure rules in the European Union under its Corporate Sustainability Reporting Directive (CSRD). In addition, there are voluntary disclosure rules published by the Taskforce on Nature-Related Financial Disclosure (TNFD), similar in spirit to carbon disclosure rules published by the Task Force on Climate-Related Financial Disclosure (TCFD), and the Methodological Assessment of the Impact and Dependence of Business on Biodiversity and Nature's Contributions to People by IPBES.

21. See Polasky and others (2023b).

2.4 Gross Ecosystem Product (GEP)

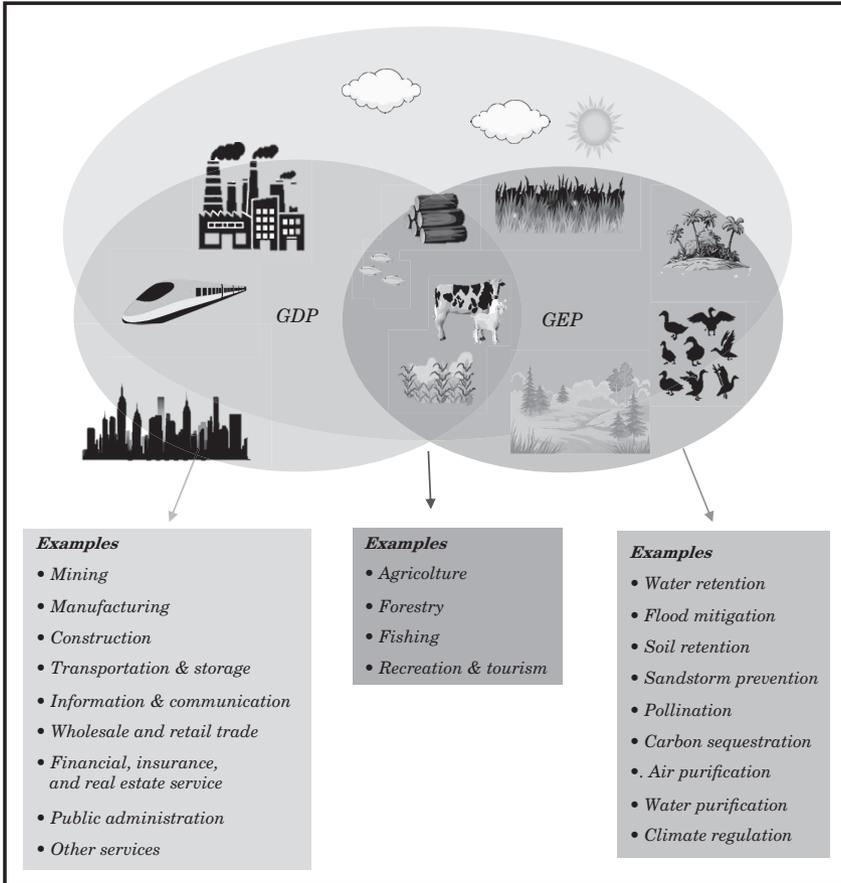
The development of Gross Domestic Product (GDP) within an agreed-upon standardized System of National Accounts provided government leaders with a clear macroeconomic measure of economic performance. There is currently no similar agreed-upon and widely quoted number for environmental performance and its contribution to human well-being. However, when market prices for ecosystem services or calculable shadow prices for nonmarket ecosystem services are available, it is possible to aggregate the value of all ecosystem services into a measure of “Gross Ecosystem Product” (GEP) in a manner similar to the aggregation of the value of final goods and services measured by GDP. Accordingly, GEP is defined as the aggregate monetary value of ecosystem services in a given region (city, county, province, country) in a given accounting period, typically a year.²² GEP is calculated using methods that parallel the methods used to calculate GDP. Just as GDP summarizes the complex operations of an entire economy in a single monetary metric that is readily understood by decision-makers, GEP summarizes the aggregate value of nature’s contributions to the economy in a single easily understood number. There is overlap between GDP and GEP because both measure the value of marketed ecosystem services, so GDP and GEP cannot simply be summed together to derive anything meaningful, as shown in Figure 3. GEP is meant to complement, not replace, GDP by providing different but related information.

Although calculating GEP is challenging for the reasons discussed above regarding the difficulties of understanding ecological production functions as well as of using nonmarket valuation, it is possible to calculate GEP with existing data for a set of important ecosystem services. Ouyang and others (2020) calculated GEP for Qinghai province in China using data from the China Ecosystem Assessment for the years 2000 and 2015. Qinghai is known as the “water tower of Asia” because it contains the source of the Mekong, Yangtze, and Yellow rivers. The authors found that water-related ecosystem services made up nearly two-thirds of the value of GEP. Water runoff from Qinghai contributes to hydropower generation, agricultural irrigation, and industrial and household consumption. They also found that GEP more than doubled from 2000 to 2015. Part of this increase in value was due to large-scale investment in ecosystem restoration that increased the

22. See Ouyang and others (2020).

supply of some ecosystem services. The larger part of the increase in value was due to increases in the per-unit value of ecosystem services arising from a greater demand for ecosystem services through time, such as the greater value of downstream water use from increased population and economic activity.

Figure 3. The Relationship between GDP and GEP



Source: Zheng and others (2023).

The government of China has supported the development and use of GEP by county, city, and provincial governments and has adopted a common set of guidelines for calculating and reporting GEP. The goal in China is to have all levels of government report GEP alongside GDP on a regular basis. GEP can be used to reveal the contribution of ecosystems to the economy and human well-being, to show the ecological connections among regions, to be the basis for compensation from beneficiaries to suppliers of ecosystem services, and to serve as a performance metric for government officials.²³ GEP is also being used to support “Two-Mountains Banks,” which provide favorable loans to enterprises that invest in activities that promote ecosystem services.²⁴

2.5 Macroeconomic Analysis: GTAP-InVEST

At a macroeconomic scale, ecosystem service information can be integrated with computable general equilibrium models to show how economic activity drives changes in ecosystems, changes in the provision of ecosystem services, and in turn, how changes in ecosystem services affect the economy, including impacts on economic production and employment in various sectors, trade, and GDP. This integrated “earth-economy” model can be used to analyze likely trajectories for ecosystems and the economy under business-as-usual policies and can also show the economic consequences of gains or losses in ecosystem services. The integrated model can also be used to analyze the effects of policies, such as carbon taxes or payments for ecosystem services, on ecosystem services and economic performance.

Johnson and others (2023) integrate a computable general equilibrium model of the economy from the Global Trade Analysis Project (GTAP) with the InVEST model of ecosystem services. The resulting integrated earth-economy model jointly determines land use, environmental conditions, ecosystem services, market prices, supply and demand across economic sectors, trade across regions, and aggregate performance metrics like GDP. In an initial application of the earth-economy model, the authors included four ecosystem services: crop pollination, timber provision, marine fisheries, and carbon sequestration, and showed that under a business-as-usual scenario, economic activity would cause a decline in these four ecosystem services leading to a reduction in annual GDP of \$75 billion. They also

23. See Ouyang and others (2020).

24. See Zheng and others (2023).

analyzed outcomes under five policy options: removing agricultural subsidies and giving lump-sum payments to landowners, removing agricultural subsidies to fund increased investment in agricultural research and development, instituting Payments for Ecosystem Services (PES) financed by international transfers from high-income to low-income countries, instituting a national-level PES where each country funds its own PES program, and a combination policy that removes agricultural subsidies to fund increased investment in agricultural research and development along with an international transfer PES program. Johnson and others (2023) find that these policies increased GDP by \$100 to \$200 billion annually relative to the business-as-usual scenario. As noted above, however, GDP fails to capture the full value of ecosystem services by failing to capture the value of nonmarket ecosystem services. Adding in the benefits of additional carbon sequestration by using a social cost of carbon of \$185 per ton of carbon²⁵ raises the value of annual benefits for the combination policy to almost \$350 billion annually.

Work on global-scale earth-economy models is only just beginning. Global-scale modeling of ecosystem services using globally consistent data and methods has only started to be done recently,²⁶ and links between ecosystem service models and computable general equilibrium models are also fairly recent.²⁷ Only a small number of ecosystem services have been included to date. Even so, this work already makes a compelling “economic case for nature,”²⁸ which will likely become more so with the addition of more complete models including more services, and as natural capital becomes scarcer.

3. DISCUSSION

Economic activity is causing rapid changes in the biosphere. Accurate accounting of the provision of ecosystem services and their value, along with policy mechanisms to provide economic incentives to maintain the natural capital that supplies valuable ecosystem services, is needed to halt, and reverse, the deterioration of natural capital. Providing accurate information on the value of natural capital and ecosystem services that leads to improved policy and management

25. See Rennert and others (2022).

26. See Chaplin-Kramer and others (2019, 2023).

27. See Banerjee and others (2019, 2020); Johnson and others (2020, 2021).

28. See Johnson and others (2021).

decisions can in turn lead to large improvements in human well-being and biodiversity over the long run.

The agenda of accurate accounting tied to economic incentives has already gained traction in the climate policy community. Over the past several decades, much effort has gone into getting ever more refined carbon accounting along with efforts to better understand the social cost of carbon, which at least in theory, measures the present value of damages from emitting one ton of carbon to the atmosphere. As of the end of 2023, fifty-two national governments and 42 subnational (state and local) governments have adopted some form of carbon pricing—whether a carbon tax, emission-trading system, or government credit mechanism—,²⁹ and there is abundant literature containing estimates of the social cost of carbon.³⁰ Though coverage of climate policies is far from complete and many of these policies have prices well below current estimates of the social cost of carbon, the principles of what an efficient climate policy should look like have been laid out, and important steps towards efficient climate policy have been taken.

Ecosystem service accounting is, unfortunately, far more complex than climate accounting and valuation. While there is a single carbon budget, there are numerous ecosystem services. For virtually all ecosystem services, the location of where things occur matters much more than for greenhouse gas emissions because greenhouse gases globally mix in the atmosphere. Despite these difficulties, as shown in the applications in the previous section, many of the parts of what is needed to accurately account for ecosystem services and the knowledge of how to create economic incentives for continued provision of ecosystem services already exist. Understanding the ecological production functions is well advanced for many of the most important and valuable ecosystem services, as is understanding the market and nonmarket value of many important ecosystem services.

There is, of course, no shortage of ways in which accurate accounting and policymaking for ecosystem services could be, and should be, improved. Incorporating ecosystem services into economic and policy decision-making is still in its infancy, and many frontiers of analysis remain to be more fully developed. Further improvements are needed for ecological production functions as well as for market and nonmarket valuation, particularly for the many ecosystem services

29. See World Bank (2023).

30. See, for example, Barrage and Nordhaus (2024); Rennert and others (2022); Rode and others (2021).

that have not received as much attention to date. Some impacts of economic activity on ecosystems and ecosystem services that have not received much attention may turn out to be quite important. For example, the costs associated with air pollution from land use and land management (particularly agriculture) tend to be large, often larger than the direct monetary benefits from the economic activity.³¹ The present value of the global social cost of eutrophication-driven methane emissions from lakes between 2015 and 2050 was estimated to be between \$7.5 and \$80 trillion.³² There are probably other important ecosystem services still waiting to be quantified and valued.

Other areas where improvements are needed are the handling of uncertainties, of which there are many, and issues involving dynamics. Many ecosystem service analyses, including several discussed in this paper, report point estimates. While these may be the best guesses of value, they are likely to have significant errors because of both biophysical and economic uncertainties. One area for improvement involves better reporting and communicating important uncertainties to decision-makers, as well as improving decision-making under uncertainty.³³ Climate change, soil degradation, population declines, and species extinctions are all examples where state variables in biophysical systems change through time, potentially causing large changes in ecosystem service provision. Changes in manufactured capital, human capital, and institutions can similarly have large impacts on future values of ecosystem services. Developing integrated models with dynamic feedback effects between ecosystems and economic systems is another high priority for modeling improvements. Combining uncertainty with feedback effects can be particularly daunting, as ecological-economic systems may undergo regime shifts involving rapid fundamental shifts from small changes in initial conditions.³⁴ Finding methods of early warnings for potential catastrophic regime shifts³⁵ and taking the potential for regime shift into account in management³⁶ are two strategies for addressing this challenge.

Improving integrated ecosystem-economy models and generating reliable information for public- and private-sector decision-makers is

31. See Goodkind and others (2023).

32. See Downing and others (2021).

33. See Polasky and others (2011b).

34. See Scheffer and others (2001).

35. See Biggs, Carpenter, and Brock (2009); Carpenter and others (2011).

36. See Polasky and others (2011c).

a vitally important task for addressing the rapid decline of natural capital and ecosystem services. These models are improving and can be applied to a variety of contexts from micro- to macroeconomic scales. Economists have a central role to play in developing integrated ecosystem-economy models, just as economists played a central role in developing integrated assessment models to provide policy-relevant information on climate change. Even though integrated ecosystem-economy models are currently far from perfect, the pressing need to reverse the decline in natural capital and ecosystem services means there is no time to waste. The best way to improve rapidly on many fronts is to get started without waiting for perfection.

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