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Investing in nature can improve equity and economic returns

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Sustainable development requires jointly achieving economic development to raise standards of living and environmental sustainability to secure these gains for the long run. Here, we develop a local-to-global, and global-to-local, earth-economy model that integrates the Global Trade Analysis Project (GTAP)-computable general equilibrium model of the economy with the Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST) model of fine-scale, spatially explicit ecosystem services. The integrated model, GTAP–InVEST, 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. We use the integrated model to analyze the contribution of investing in nature for economic prosperity, accounting for the impact of four important ecosystem services (pollination, timber provision, marine fisheries, and carbon sequestration). We show that investments in nature result in large improvements relative to a business-as-usual path, accruing annual gains of $100 to $350 billion (2014 USD) with the largest percentage gains in the lowest-income countries. Our estimates include only a small subset of ecosystem services and could be far higher with inclusion of more ecosystem services, incorporation of ecological tipping points, and reduction in substitutability that limits economic adjustments to declines in natural capital. Our analysis highlights the need for improved environmental–economic modeling and the vital importance of integrating environmental information firmly into economic analysis and policy. The benefits of doing so are potentially very large, with the greatest percentage benefits accruing to inhabitants of the poorest countries.

ecosystem services | economics | computable general equilibrium | sustainable development | climate change

Sustainable development requires jointly achieving economic development, to address poverty and improve human health and well-being, along with environmental sustainability, to conserve nature to maintain vital ecosystem services and the life-support systems provided by a hospitable environment. How to achieve sustainable development is arguably the central challenge facing global society in the 21st century (1). To address this challenge, we develop a unique earth-economy model that integrates a computable general equilibrium model of the global economy with a fine-scale spatially explicit ecosystem services model. We apply this integrated model to show that investing in nature can increase conventional measures of economic development, including higher gross domestic product (GDP), as well as improve measures of environmental sustainability.

In contrast to the emphasis on jointly achieving both economic and environmental goals is a narrative about trade-offs between economic development and environmental sustainability: That economic growth is a key factor in environmental degradation and that environmental protection imposes economic costs. Recent reports on the declining state of the environment have documented the effects of rapid economic growth on climate change and biodiversity loss (2–5). On the contrary, arguments against taking action to address climate change or biodiversity loss often emphasize the economic costs of environmental policy including the loss of income, jobs, and competitiveness. In the short run, there often is a negative correlation between economic activity and environmental protection. For example, the outbreak of the COVID-19 pandemic in early 2020 led to a decline in economic activity with reductions in GDP but also air quality improvements and reduced greenhouse gas emissions (6, 7). The bulk of evidence points to there being very modest economic costs of environmental regulation, with little effect on aggregate economic performance (8). More importantly, however, conventional methods of assessing economic performance have left out many of the ways in which the economy is impacted by the environment. There are potentially large longer-term benefits from environmental protection that maintain natural capital and reduce damages from climate change, biodiversity loss, or other harmful environmental change (2–4, 8–10). In the long run, investing in natural capital, like other forms of investment, often pays economic dividends and there

Significance

Growing the economy while also protecting the environment is essential for achieving sustainable development. To provide better understanding about what policies might achieve both goals, we combined a global economic model with ecosystem service models, showing how markets and policy drive ecosystem change, and in turn how changes in ecosystem services affect the economy. We show that the degradation of nature causes large losses to the economy and that these damages hurt low-income countries the most. We also show that policies that invest in nature can greatly improve economic and environmental outcomes.

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are strong economic arguments for investing in natural capital as an essential component of continued economic prosperity (2, 4). To date, however, comprehensive quantification of the long-term benefits of investing in natural capital has been lacking.

Here, we develop a local-to-global, and global-to-local, earth-economy model that integrates the Global Trade Analysis Project (GTAP)–computable general equilibrium (CGE) model of the economy (11, 12) with the Natural Capital Project's spatially explicit Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST) model of ecosystem services (13). The integrated GTAP–InVEST model can be used to analyze how macroeconomic conditions and government policies affect local environmental conditions that determine the provision of ecosystem services, and in turn, how changes in ecosystem services affect market outcomes that determine GDP, employment, trade, and other macroeconomic outputs. The integrated model jointly determines environmental conditions, ecosystem services, market prices, supply and demand across economic sectors and regions, GDP, and trade across regions, accounting for market adjustments in a way that is consistent, calculable, and credible. The model has a large number of market regions (n = 341), sectors (n = 17), and inputs (n = 22), which allow us to better link fine-scale ecosystem services with global economic activity than more aggregated models. The integrated GTAP–InVEST model is described in *Methods and Materials*, with further details provided in *SI Appendix*. Prior work that links economic and ecosystem models focuses on the country level and is not currently capable of running at the global level (14), uses aggregate regional data rather than spatially explicit data (15–17), or uses partial equilibrium rather than general equilibrium analysis (18–21). Past work that focuses on the value of carbon sequestration uses greatly simplified representations of the economy compared to the global general equilibrium economic framework we use here (22–25).

Many types of natural capital are common property resources and market outcomes often fail to provide adequate investment in maintaining or enhancing natural capital. This type of market failure has been shown in a wide variety of settings including fisheries, forestry, environmental protection, and ecosystem services (2, 26–28). We apply the GTAP–InVEST model to analyze general equilibrium effects of market failure and five policy options that could increase investment in natural capital and improve sustainable development outcomes: removing agricultural subsidies and giving lump-sum payments to land owners (labeled Subs Land); removing agricultural subsidies to fund increased investment in agricultural research and development (Subs Ag R&D); instituting a payments for ecosystem services (PES) financed by international transfers from high-income to low-income countries (Global PES); instituting a national-level PES where each country is responsible for funding its own program (National PES); and instituting a combination policy that combines Subs Ag R&D and Global PES (labeled Combined Policies) (29, 30). In this analysis, we include four ecosystem services with strong evidence of economic benefits: crop pollination by wild pollinators, timber provision from forests, food provision from marine fisheries, and carbon sequestration. We evaluate the impact of investing in nature under these policies on GDP. We also present results in terms of regional welfare measured by equivalent variation (31), which is a better metric of welfare than GDP because it accounts for the value to final consumers rather than just the market transaction value of economic production. Regional welfare can also include impacts from transfer payments. For carbon sequestration, we report the impact using a social cost of carbon value rather than fully endogenizing its linkage to the economy. In addition to GDP and regional welfare, we generate results for a wide range of output variables, both from the economic model and from the biophysical model, that allow exploration of different policy simulations from a wide variety of perspectives, beyond just the provision of GDP and welfare.

1. Results

1.1. Business-as-Usual Trends: Declining Ecosystem Services Lead to Reduced GDP, Hitting Low-Income Countries Hardest. Under a business-as-usual (BAU) scenario that maintains current policies, we find that natural capital and the provision of ecosystem services decline over time, owing to loss of natural habitat from expanded economic production. We compare GDP in 2030 under BAU for the full version of our model that includes predicted declines in natural capital and ecosystem services to a version that ignores these declines. We find that annual GDP is 75 billion (2014 USD) lower in 2030 when we include the negative impacts from reduced ecosystem services compared to the 2030 BAU simulation that excluded ecosystem service impacts. Conventional accounting that ignores declines in natural capital, and the consequent decline in ecosystem services, will be too optimistic about future economic growth (32).

This analysis also shows that low-income countries will be hit hardest by the loss of ecosystem services (Fig. 1*A*). The percentage loss in regional welfare in low-income countries is nearly three times larger than that in high-income countries. The economies of low-income countries rely more heavily on sectors that depend on natural capital, making them particularly vulnerable to its degradation (2, 33). However, there is great heterogeneity across countries, even within the same income group, ranging from a 2.4% loss of regional welfare in Bangladesh (due to large projected losses in marine fisheries) to a 1% increase in the Middle East and North African region (see *SI Appendix*, section S.7 for details). Some countries see an increase in GDP when ecosystem services are included, either because of projected increases in ecosystem service provision in the country, or from commodity price increases that raise the value of ecosystem services produced. Global price increases can occur because of declining production so that a country with small reductions in supply can actually increase revenue. However, the provision of most ecosystem services in most countries shows declines under BAU (Fig. 1*B*).

1.2. Investing in Nature-Smart Policies Increases both Economic Welfare and Natural Capital While Benefitting Low-Income Countries Most. All the five policies we analyzed increase global GDP relative to the BAU scenario. These policies resulted in gains relative to BAU in 2030 ranging from $100 billion per year for the National PES policy to nearly $200 billion per year for increasing investment in agricultural R&D relative to BAU in 2030 (Fig. 2*A*). These gains more than offset the $75 billion loss in BAU in 2030, generating increases of $25 to $125 billion in 2030 relative to current GDP (USD 2014). Increasing agricultural R&D improves GDP by increasing agricultural productivity (34) and by reducing agricultural expansion into natural habitats, thereby maintaining larger flows of other ecosystem services (35). In addition to the benefits that are captured in GDP, these policies also result in larger amounts of carbon sequestration. Valuing this additional carbon sequestration using a recent estimate of the social cost of carbon [$185 per ton carbon, (9)] increases the estimated benefits of each policy by $10 billion to $150 billion. Policies with the Global PES scheme have the largest carbon benefits, resulting from reduced agricultural expansion in locations with high carbon storage.

Global PES, Subs Ag R&D, and Combined Policies generate the largest percentage gains in regional welfare in low-income countries (Fig. 2*B*). The welfare gains come both from efficiency

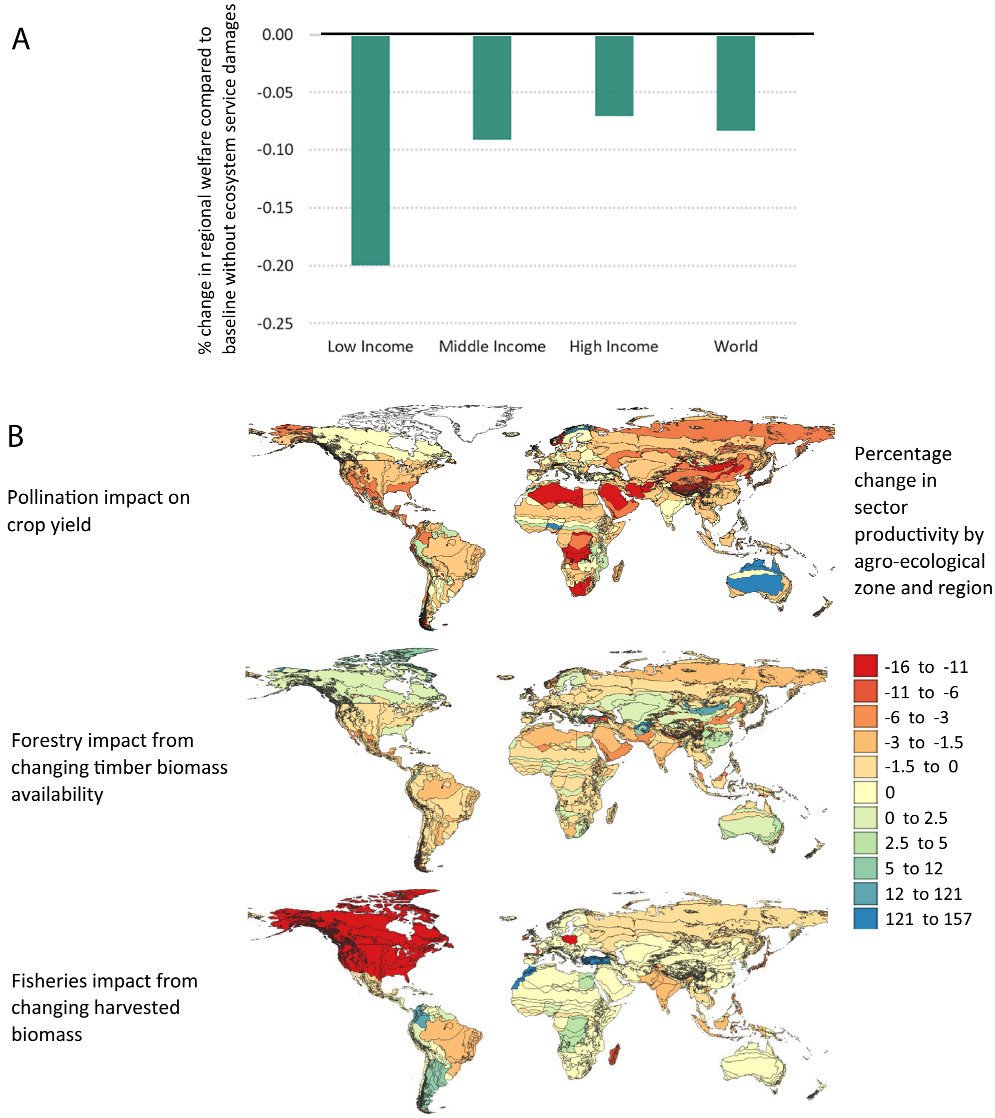

Fig. 1. (*A*) Losses in regional welfare from loss in ecosystem services. The negative impacts of declining natural capital and reduced flow of ecosystem services have the largest negative impact on welfare in low-income countries, more than twice as high in percentage terms compared to middle-income countries, and almost three times as high compared to high-income countries. (*B*) Ecosystem service impact by agro-ecological zone and region. Most ecosystem services in most regions show a decline under BAU.

gains (with Subs Ag R&D) and/or international transfer payments (with Global PES). Global PES results in a small loss in welfare in high-income countries because the adverse impacts of international transfer payments outweigh the positive impacts from increased ecosystem services.

Many ecosystem services, such as climate regulation and pollination, are closely related to the amount of natural habitat remaining in the landscape (4, 36). We find that the Combined Policies approach results in the largest increase in the amount of natural habitat relative to BAU (Fig. 3). This policy may be preferred to the policy of only investing in Agricultural R&D, even though the latter policy has the largest increase in GDP. Similarly, we find that the Combined Policies outperform Subs Ag R&D when we add in the value of carbon sequestration using the social cost of carbon (Fig. 2*A*). Global PES results in less agricultural expansion (Fig. 3, *Top Inset* map) compared to the scenario where these payments are absent (Fig. 3, *Bottom Inset*). Moreover, the payments in the Global PES policy are targeted to specific locations that have a high ratio of carbon sequestration to potential agricultural yield, thereby resulting in little loss in GDP.

1.3. Consideration of Ecological Tipping Points and Economic Rigidities. Coupling models of ecological processes and economic activity involves integrating information about a range of diverse processes, many of which are only incompletely understood, have partial or limited data, and are subject to large uncertainties. Of particular concern is whether integrated approaches can model tipping points and regime shifts (37, 38) rather than simply modeling marginal changes in ecological conditions, and whether existing computable general equilibrium models overestimate the ability of the economy to mitigate large environmental shocks through price-induced substitution and trade.

To address these concerns, we modified the GTAP–InVEST model to consider ecological regime shifts and reduced economic substitution possibilities. In the "partial ecosystem collapse" scenario characterized by widescale land-use change and large reductions in ecosystem services, we ran the model with a widespread shift of tropical forests to savanna and shrubland (specifically, converting forests to shrubland in the tropical AEZs), a 90% reduction in the ability of wild pollinators to pollinate crops, and a 90% reduction in total catch biomass of marine fisheries (see

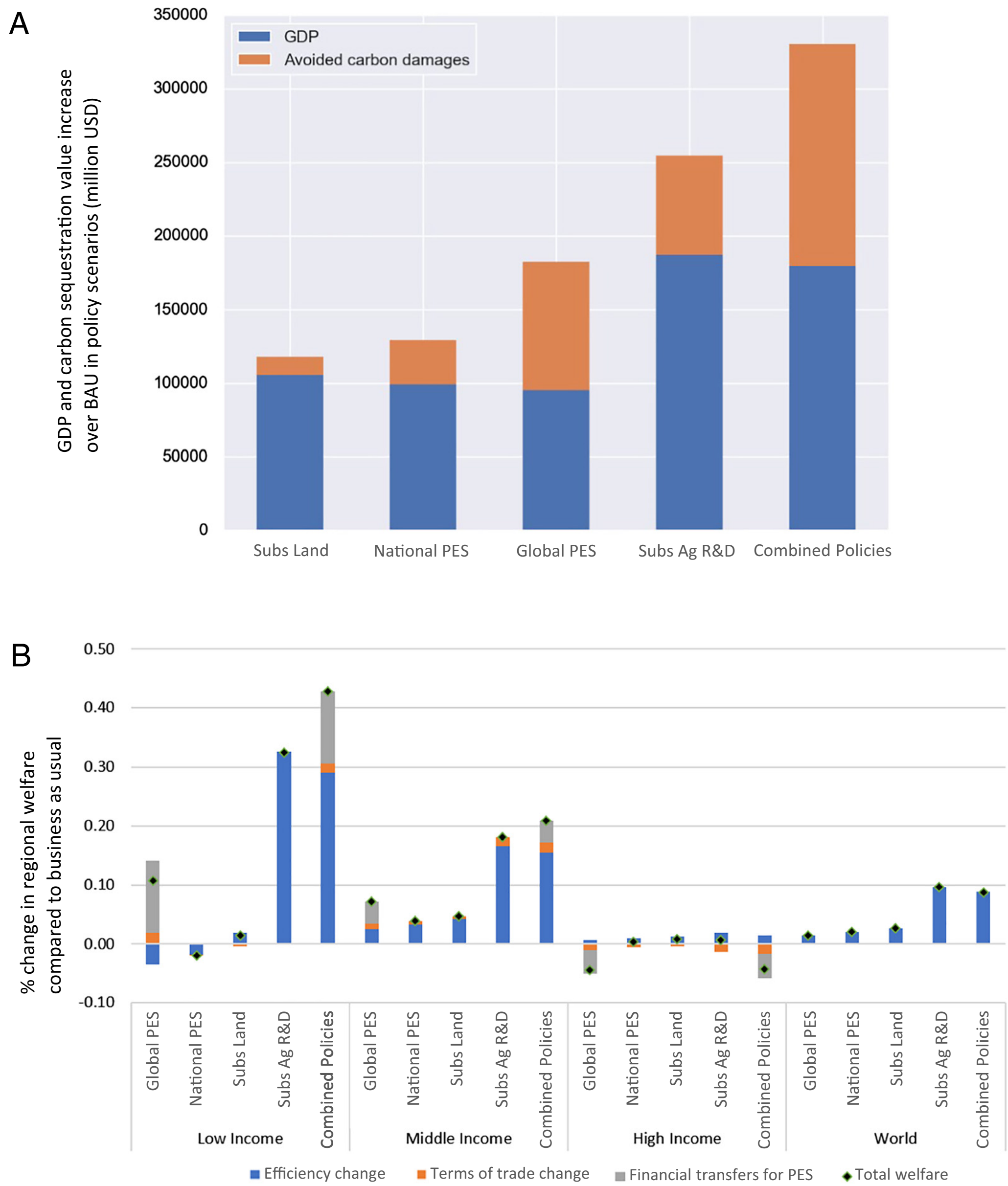

Fig. 2. The impact of policies on GDP, carbon, and regional welfare. (*A*) Increase in GDP and carbon sequestration value over BAU in policy scenarios. Investing in nature increases GDP compared to BAU. The Subs Ag R&D policy generates the largest increase in GDP, almost $200 billion annually, but the other policies also generate large increases of approximately $100 billion annually, relative to BAU. Additionally, these policies generate carbon benefits of $10 to $150 billion, with the Global PES and Combined Policies generating the largest carbon benefits. (*B*) Regional welfare improvement over BAU in policy scenario. Low-income countries have the largest percentage gain in regional welfare under Global PES, Subs Ag R&D, and the Combined Policies. Low-income countries have slightly reduced benefits with National PES as investments in nature do not yield as large returns on scarce resources for the country itself as do other investments.

SI Appendix, section 3.1.2 for a detailed description of the regime changes). These kinds of regime shifts cause large economic costs. In the partial ecosystem collapse scenario, we find estimated losses of $2.0 trillion GDP compared to $75 billion GDP lost under BAU. This result illustrates the potential for large to catastrophic economic impacts when there are large declines in natural capital. The impact of degraded ecosystem services was again most severe for low-income countries, mirroring previous findings generated from this model (e.g., ref. 2).

We also ran the GTAP–InVEST model with much lower elasticities of price-induced substitution for key parameters. We reduced by 33% relative to the default values in the GTAP database: 1) elasticity of transformation between land cover types for crop, livestock, and forestry sectors; 2) elasticity of cropland transformation among crops; and 3) constant elasticity of substitution (CES) parameter between primary factors of production (land, labor, and capital). We use the lower 5th percentile rather than the 50th percentile estimate used in standard GTAP model runs (39) for the elasticity of substitution between imported and domestic inputs into production. Reduced substitutability in the absence of partial ecosystem collapse increased losses under BAU, but only from $75 to $79 billion (see *SI Appendix*, section 3.1.1. for details). We found, however, when running the GTAP–InVEST model with both the partial ecosystem collapse and limited substitutability that the model would not solve.

2. Discussion

This integration of a global general equilibrium model (GTAP) with a fine-scale, spatially explicit model of ecosystem services capable of being run globally (InVEST) expands the scope of earth-economy modeling beyond what could be accomplished previously. Prior

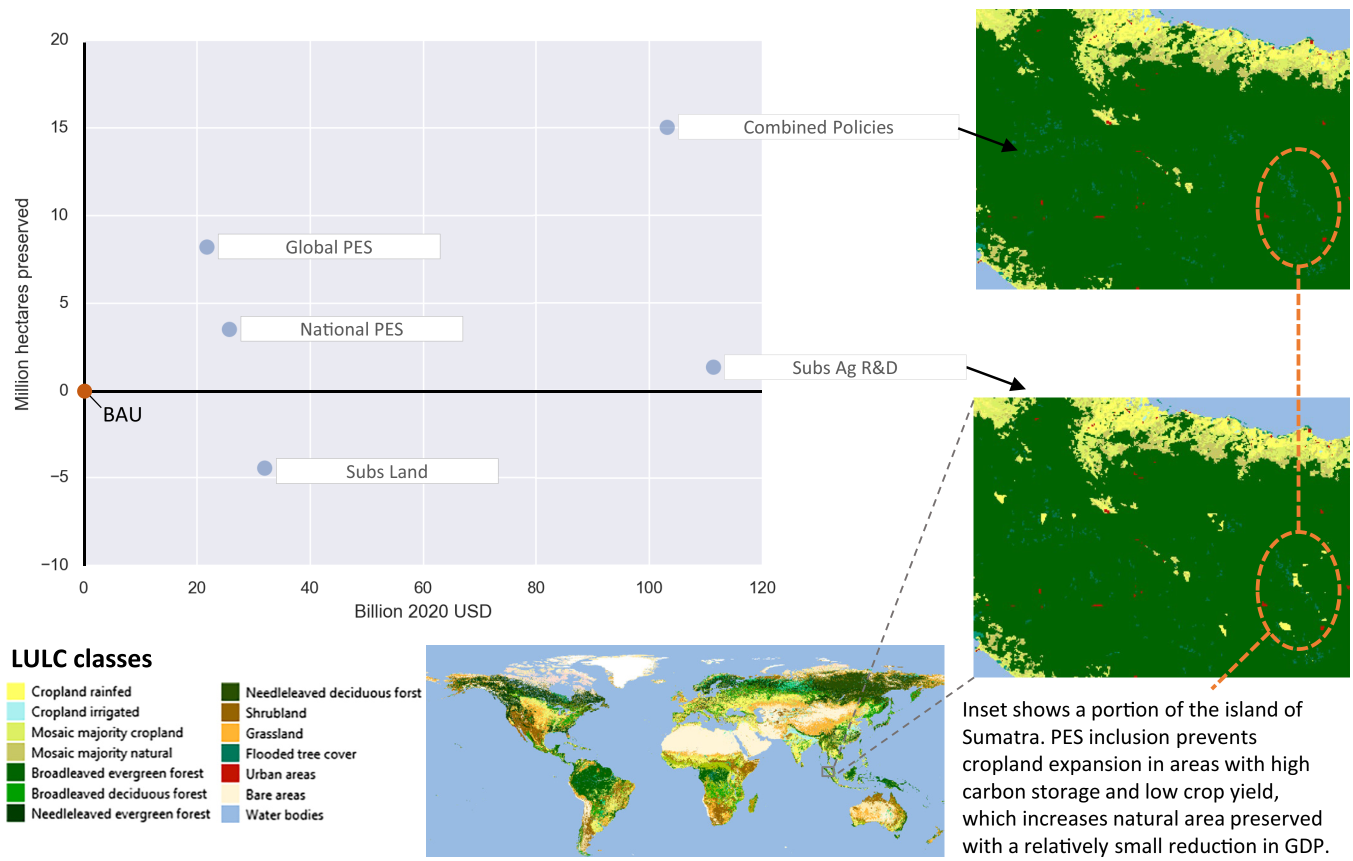

Fig. 3. The impact of policies on the amount of natural habitat preserved and GDP relative to BAU. All policies except Subs Land result in increases in both natural habitat preserved and GDP relative to BAU. Policies with Global PES result in large increases in natural habitat preserved but slightly lower GDP relative to other policies.

general equilibrium models ran at a larger aggregated spatial scale that did not permit modeling of fine-scale ecological processes. Most ecosystem service analyses have been run at local or regional scales and were not linked to general equilibrium models.

Applying the integrated GTAP–InVEST model, we find that continuing on a BAU path results in further degradation of natural capital with large negative impacts on GDP. Natural capital is often a common property and market outcomes will typically fail to provide adequate incentives to maintain it. We find that policies that increase investment in nature can generate large increases in GDP relative to BAU, as well as improve measures of environmental sustainability. Our findings are consistent with recent high-level summary reports that investing in natural capital is an essential component for attaining current and future economic prosperity (2, 4, 10). We also find that investing in nature is an equitable strategy, as evidenced by the greater increases in regional welfare for low-income countries under these policies.

Implementing policies that increase investment in nature faces significant challenges. A growing literature has emerged analyzing the performance of PES and other policies (40–43). While such policies can be designed so that they efficiently protect natural capital (44), this is difficult to achieve in practice, due to limitations in information and governance (42, 45). There are also often very high transaction costs associated with reaching the poorest households—particularly when land is communally held or where property rights are not clearly defined—resulting in low PES participation rates by the poor (46). Given the spatial heterogeneity of ecological systems, accurate measurement of ecosystem services can be costly, leading to the challenge of asymmetric information that gives rise to both moral hazard and adverse selection problems (42, 47). Despite these challenges, many policies have resulted in increased investment in natural capital (40).

The future scenarios presented in this work are not predictions about the future but instead are plausible and consistent possible future pathways. This fact, coupled with multiple sources of uncertainty, means that our results should be used to assess the relative merits of different policies but should not be taken as a forecast of values. There are at least five important sources of uncertainty in our model: 1) the underlying default parameters in the GTAP model (we address some of this uncertainty in the sensitivity analyses conducted above); 2) our modification of GTAP to add a land–supply curve along with measurement of agricultural suitability for each AEZ region; 3) the process of downscaling relatively coarse, regional land-use change estimates to high-resolution grid cells; 4) the biophysical parameters within InVEST especially given the global application of these models; and 5), the linkage between changes in ecosystem service provision and the subsequent effect on inputs to the GTAP model. Further sensitivity analysis should be conducted to systematically test all of the important input parameters.

The results in this paper represent an initial step toward fully incorporating the contributions of nature into the measures of economic performance. Much more remains to be done. The current approach assesses changes in a comparative-static framework, comparing values in the base-year equilibrium to the 2030 equilibrium. Future work could incorporate dynamics so that changes in the economy affect ecosystem conditions, which in turn affect the economy, in an ongoing set of feedbacks, allowing for analysis of the evolution of ecological–economic systems through time. Additionally, further work could be undertaken to integrate local-level phenomena by using the global results as boundary conditions of more detailed local models, which could then be integrated back into the global model (48).

The current effort incorporated only a small subset of ecosystem services, the impacts of three ecosystem services on GDP, plus the value of carbon sequestration measured by the social cost of carbon. This list does not capture the majority of ways that nature contributes to economic activity (4, 49). Recent work has expanded the set of ecosystem services that can be evaluated globally (50), but further work is needed to link these services with the general equilibrium economic model. A more complete accounting of ecosystem services would likely lead to much larger increases in the estimated value of investing in nature (51, 52). Accounting for the full contribution of nature to human well-being will also need to go beyond the value of marketed goods and services included in our measures of GDP and regional welfare to also include the value of nonmarketed ecosystem services. Some nonmarketed ecosystem services, such as pollinators, do get measured indirectly in conventional economic accounts through their contribution to marketed goods and services such as agricultural crop production. Other ecosystem services do not show up in GDP or other conventional economic measures even indirectly, though they make fundamental contributions to human well-being. These ecosystem services can be measured in other ways including in biophysical terms, impacts on health or other measures of well-being, or in monetary terms using various methods of nonmarket valuation. This latter approach was taken recently in calculating gross ecosystem product, which is an attempt to provide an aggregate monetary measure of all important ecosystem service benefits (51).

Our analysis strengthens the case to be made for improved environmental–economic modeling and the vital importance of integrating environmental information firmly into economic analysis and policy (53). The benefits of doing so are potentially very large, with the greatest percentage benefits accruing to inhabitants of the poorest nations on earth.

3. Methods

The integrated GTAP–InVEST model builds on and extends results from work initiated for reports published by the World Bank (30) and the World Wildlife Fund (29, 54). GTAP–InVEST connects three underlying models: The first is the GTAP CGE model (11, 12), based on foundational work on applied general equilibrium models (55–57) that incorporate model production, consumption, and trade at the scale of the macroeconomy. GTAP combines a carefully curated database of global trade, financial, and input/output relationships with a general equilibrium theoretical model that has been validated via back-casting (58, 59). The data for the economic components of our model come from ref. 60. For our analysis, we augment the base GTAP model with specific agro-ecological zones (AEZs) in order to specify biophysical production parameters, make explicit the use of environmental resources (e.g., water), and endogenously calculate the use of different land resources (for forestry, agriculture, and grazing) as documented in ref. 61. Using GTAP–AEZ allows us to specify hectares of land as a capital input (rather than just in monetary terms), which is critical for modeling ecosystem services that depend heavily on land use. We further extended GTAP–AEZ to allow for the conversion of natural land to economic use via a land supply function (following the methods of ref. 62) but extended to include high-resolution data on cropland suitability and land use (see *SI Appendix*, section 2.3 for details). Consistent with general equilibrium modeling, our policies are explicit about the source of funding and the impact of transfer payments. For example, the Global PES program includes the negative impact on donor countries and the positive impact on recipient countries of fund transfers (see *SI Appendix*, section 3 for detailed specification of the policies).

Our model does not calculate climate change endogenously, but rather assumes the level of temperature and precipitation changes under Representative Concentration Pathway 4.5 (RCP4.5) from the Intergovernmental Panel on Climate Change (IPCC). Additionally, we align our input data on exogenous factors (such as population growth) to the scenarios from the Shared Socioeconomic Pathway (SSP) scenarios, specifically SSP2, as described in ref. 63.

The second model we include is the Integrated Valuation of Ecosystem Services and Trade-offs (InVEST) model (13). InVEST is a set of 24 open-source, ecosystem service production function models that use spatially explicit inputs [for variables such as soil, topography, precipitation, and land-use, land-cover (LULC)] to calculate process-based estimates of ecosystem service provision. To estimate ecosystem services from global marine fisheries, we augment InVEST with outputs from FISH-MIP (64) from the Inter-Sector Impact Model Intercomparison Project (65) (*SI Appendix*, section 6.3). Some of the ecosystem service models in InVEST calculate the monetary value of the service using methods such as replacement cost, contingent valuation, or hedonic analysis of property transactions (66, 67); however, these methods are all "bottom–up" approaches that calculate how much individuals value ecosystem service consumption (or, at least, replacing that consumption when it is lost). Our estimates, conversely, are "top–down" approaches, that instead calculate the value of ecosystem services by assessing their effect on the economic production of value. This research direction is separate but complementary to existing ecosystem service valuation techniques. To the authors' knowledge, only one other approach exists that reports a top-down valuation of ecosystem services using general equilibrium methods (14, 68), though this can only be calculated at a national scale.

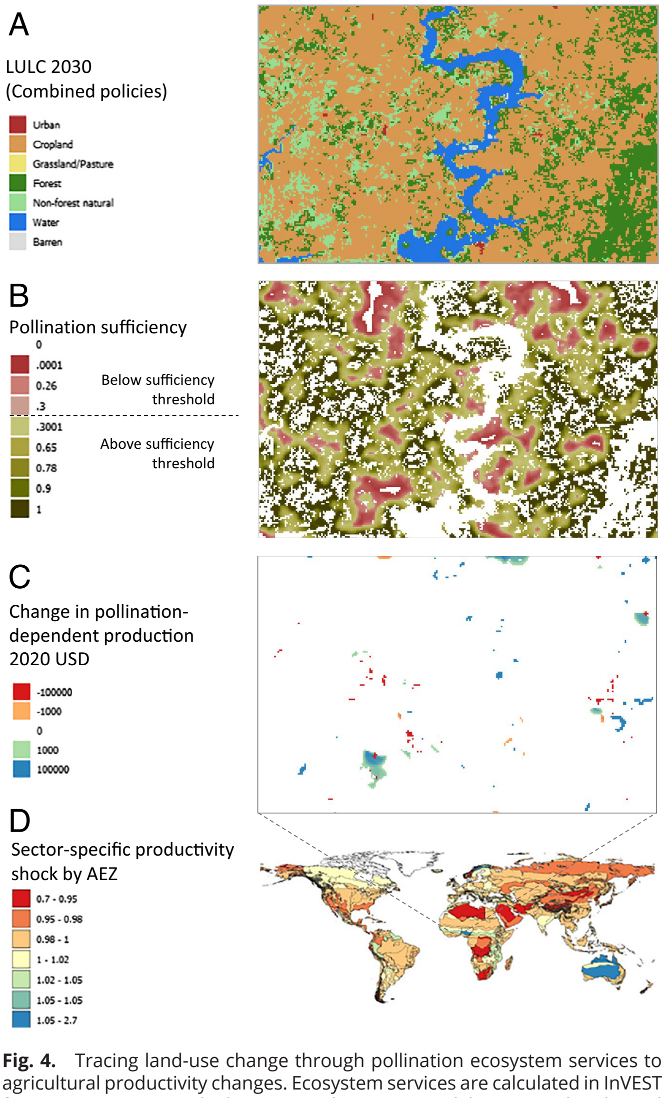

Fig. 4. Tracing land-use change through pollination ecosystem services to agricultural productivity changes. Ecosystem services are calculated in InVEST from LULC maps (*A*) and other inputs. The InVEST model generates biophysical outputs (*B*), which are processed into gridded impacts on productivity (*C*). These are converted to aggregate percentage change per AEZ (*D*), which is the input to the GTAP model.

For the three endogenous ecosystem services included in this model, we calculated a specific pathway by which changes in the InVEST outputs affect input parameters to the GTAP–AEZ model (*SI Appendix*, section 6). Fig. 4 illustrates one specific pathway, for pollination, indicating the modeling steps that were necessary. The primary input to the pollination model is a map of LULC in 2030 (Fig. 4, *Top*), which was endogenously calculated for each AEZ in GTAP–AEZ. The output of the InVEST model is the relative sufficiency of pollinators to pollinate nearby pollination-dependent crops (69). This model considers the spatial configuration of the landscape and whether a patch of cropland is within the flight range of wild pollinator habitat. Klein et al. (69) identify a threshold for pollination sufficiency of 30% wild pollinator habitat within the flight zone, below which pollination-dependent crops will experience reduced yield (second panel). Next, we calculate the reduction in agricultural yield, assuming the crop distribution in each pixel. For 175 crops (70), we use the pollination dependence of each crop [from Klein et al. (69)] to calculate reduced yield in each pixel as a function of the pollination sufficiency deficit. We then aggregate this up to the GTAP–AEZ agricultural sectors according to the loss in production value from lost pollination (third panel). This is then aggregated up for each AEZ and converted to a sector- and region-specific percentage reduction in crop yield (*Bottom* panel). These percentage changes are the input to the GTAP–AEZ model (shown previously in Fig. 1).

The third model is the Spatial Economic Allocation Landscape Simulator (SEALS), a land-use change model capable of downscaling regional estimates of change to global, 300-m (or higher) land-use, land-cover (LULC) map (71). This step is necessary because the key input to InVEST is an LULC map of suitably high resolution. Details of the downscaling approach are presented in *SI Appendix*, section 2.4.

Data, Materials, and Software Availability. Code, tabular outputs and raster data are freely available (72).

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