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Integrating Quantitative Macroeconomic and Ecosystem Service Modeling Methods to Assess Conservation Programs in Mexico

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Abstract
Conveying the importance of public conservation programs to Government decision makers is challenging given the long-term nature of investments in conservation and competition for scarce public resources. The effectiveness of conservation programs in terms of their impact on ecological and socioeconomic outcomes has been evaluated in the literature though not typically in an integrated way that enables the assessment of trade-offs across environmental, economic and social objectives. Through a novel approach that uses macroeconomic tools that incorporate land use-land cover change and ecosystem services, we conduct policy scenario analysis to investigate the economic, natural capital and ecosystem service impacts of three conservation programs in Mexico. We show their combined impact on Gross Domestic Product and wealth in 2035 to be US$856.9 and US$492.3 million, respectively and that the programs reduce poverty by 1,800 individuals. In addition to macroeconomic effects, our approach illustrates that by accounting for changes in regulating ecosystem service flows, cumulative Gross Domestic Product would be 1.34 times higher. Our results build a business case for ongoing investment and expansion of these conservation programs by demonstrating the benefits to biodiversity, natural capital and the economic well-being of Mexican society. The case study allows for replication in other countries as the tools and data employed are openly available for much of Latin America and the Caribbean, Southeast Asia and increasingly worldwide.

Keywords Conservation financing · Integrated economic-environmental modeling (IEEM) · Computable general equilibrium model (CGE) · Natural capital · Ecosystem services modeling and valuation

Extended author information available on the last page of the article

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1 Introduction

Since the late 1990s, Mexico has implemented several public policy instruments whose objective is the conservation of terrestrial and marine ecosystems. Among the legally binding instruments, the system of Protected Natural Areas stands out, which covers an area of approximately 21.3 million (about 10% of Mexico's total area) and 70 million hectares (ha) of terrestrial and marine ecosystems, respectively (CONANP 2021). Another set of instruments consists of voluntary initiatives that promote conservation based on compensation or by promoting activities that encourage conservation and the sustainable management of biodiversity under the "steward earns principle," which rewards the creation of positive environmental externalities (Gómez-Baggethun et al. 2010; Gómez-Baggethun and Ruiz-Pérez 2011).

Voluntary instruments are especially relevant in Mexico, where most land is private or communal property and the populations inhabiting natural areas are often poor and dependent on natural resources for their livelihoods. Given this context, tax instruments, which disincentivize negative environmental externalities (Gómez-Baggethun et al. 2010) are often not the most appropriate and effective (Clements et al. 2010). Three key voluntary instruments are (i) Payment for Environmental Services programs (PSA by its Spanish acronym), (ii) Environmental Management Units for the conservation of wildlife (UMA) and (iii) programs to incentivize sustainable agriculture and forestry including agroforestry and silvopastoral systems and the certification of sustainable management practices (e.g., forest certification and organic agriculture certification). The PSA and UMA programs are two flagship programs of Mexican environmental policy. Impact analysis of both programs has shown that they can be most effective through simultaneous application of several conservation instruments (Ezzine-de-Blas et al. 2016). An example of the third modality is the Initiative for Sustainable Forest Landscapes (IPFS) which considers a portfolio of conservation and sustainable management programs (World Bank 2018).

In Mexico and around the world, sustained public funding is a critical determinant of the long-term success of environmental programs, as financial resources influence both implementation capacity and policy continuity. Moreover, public financing insulates conservation efforts from shifting philanthropic priorities and market-driven volatility that private sector initiatives may face. Consistent funding has been deemed essential for maintaining program effectiveness and ensuring that initiatives achieve their intended outcomes (Balmford et al. 2015; Schell et al. 2013; Watson et al. 2014). In the context of climate finance, financial commitments from government entities have been shown to significantly shape the success of climate mitigation and adaptation strategies, as these resources enable the scaling and long-term viability of interventions (Bhandary et al. 2021). Additionally, well-structured funding mechanisms play a role in bridging the gap between research and practice, emphasizing that financial support is necessary to sustain knowledge-based decision-making and environmental governance (Nyboer et al. 2021).

The ability to translate program outcomes to economic terms understood by policymakers is critical to their survival. Macroeconomics, its models and the variables it describes are a fundamental part of the lingua franca of economic and fiscal policy. Conventional economic sectors such as energy, transport and manufacturing are well-represented in these models and public investment proposals for these sectors are readily modeled with results expressed as impacts on Gross Domestic Product (GDP), income, employment and other indicators that enable decision making and budget allocations by Ministries of Finance.

In contrast, the environment, natural capital and ecosystem services (ES) are minimally represented in most macroeconomic models (Banerjee et al. 2016; IDB 2020). When it comes to evaluating public investment aimed at enhancing environmental outcomes, there are significant challenges in estimating economic benefits and in expressing these benefits in a manner consistent with the accounting frameworks, for example, the System of National Accounts (European Commission et al. 2009), that enable calculation of impacts on GDP, sectoral output and other key indicators used by decision makers. Moreover, GDP is a measure of income flow, which speaks little to how those flows affect either produced capital or other forms of capital stocks. At the same time, investments in the environment often impact stocks of natural capital and their capacity to generate future ES flows, which are poorly captured in standard GDP accounting.

In response to this challenge, modeling frameworks that integrate natural capital and ES in economy-wide, Computable General Equilibrium Models (CGE) have emerged (Lotze-Campen et al. 2008; Valin et al. 2013; Banerjee et al. 2025; Ray and Hertel 2025). This new class of models has been increasingly adopted by governments in the economic analysis of public investment (Wittwer 2012; Wittwer and Banerjee 2015) and by multilateral development institutions for generating strategic policy guidance across economic sectors (World Bank 2023a, 2023b), economic analysis of development loans and grants (IDB 2015, 2019) and to inform regional dialogue (Banerjee et al. 2021b, 2022).

With better tools has come the ability to report on changes in more robust metrics of sustainable economic development, namely wealth, which accounts for changes in human capital, natural capital and manufactured capital (Dasgupta 2021). The ability to express changes in natural capital and ES flows and their interaction with socioeconomic variables in macroeconomic terms is powerful for informing financing decisions and national budgets. Doing so can generate compelling arguments to justify investment in maintaining and enhancing conservation programs and their inclusion in national development plans and budgets.

In this study, we demonstrate the application of an integrated analytical framework to building the business case for investing in the environment in Mexico, focusing on the PSA, UMA and IPFS Programs. Our approach centers on assessing the socioeconomic returns of these investments by uncovering the hidden economic gains and losses associated with natural capital use. Specifically, our methods extend conventional macroeconomic modeling by incorporating natural capital and natural capital-specific environmental modeling modules through the Integrated Economic-Environmental Modeling (IEEM) approach (Banerjee et al. 2016, 2019b).

The IEEM approach is further enhanced by linking IEEM with the spatial modeling of changes in LULC and ES flows (IEEM + Ecosystem Services Modeling, abbreviated as IEEM + ESM; Banerjee et al. 2022, 2024b; World Bank 2023b). This integration is important since it allows us to estimate indicators such as Genuine Savings which reflect changes in comprehensive wealth, including natural capital assets, often omitted from conventional analyses. The traditional economic tools, which we aim to complement, focus heavily on monetary valuation and market prices, overlooking valuable but unpriced regulating ES. This omission can lead to inefficient resource allocation and degradation (Stiglitz et al. 20092010; European Commission et al. 2014). By providing a more complete picture of economic performance that incorporates natural capital and ES, we strengthen the economic rationale for continued and enhanced investment in these conservation programs.

In section 2, we present the IEEM+ESM modeling approach and the Social Accounting Matrix used to calibrate IEEM for Mexico. Next, the dynamic IEEM+ESM workflow is presented, which integrates IEEM, LULC and ES models and enables endogenous estimation of the value of various ES, which in this study, focuses on soil erosion mitigation ES. Section 2 also defines the business-as-usual and policy scenarios simulated. Section 3 presents the results. Section 4 provides a discussion of key results and policy insights and section 5 concludes the paper.

2 Methods, Data and Scenarios

2.1 The IEEM Model and Data

The IEEM model for Mexico takes as its starting point the theoretical and mathematical modeling framework described in: Banerjee et al. (2016); Banerjee et al. (2019a, b) and Banerjee and Cicowiez (2020). IEEM has some relatively standard features of CGE models (see, for example Robinson et al. 1999; Lofgren et al. 2002) and other less conventional features described in Section 2.2 that make it particularly useful for assessing the effects of policies on the interactions between the economy, natural capital assets (various LULC types, fisheries, water resources and others) and ES supply. IEEM represents a wide range of economic flows, including income flows in one direction and flows of products or factors of production (labor, capital and land) in the opposite direction (Fig. 1). Supplementary Information (SI) Section 1 provides further details of IEEM methods and SI section 8 presents the IEEM mathematical model statement.

IEEM builds upon the well-established tradition of dynamic CGE models used for macroeconomic and environmental policy analysis, extending their capabilities through explicit integration of natural capital assets and ES. IEEM employs a recursive dynamic framework

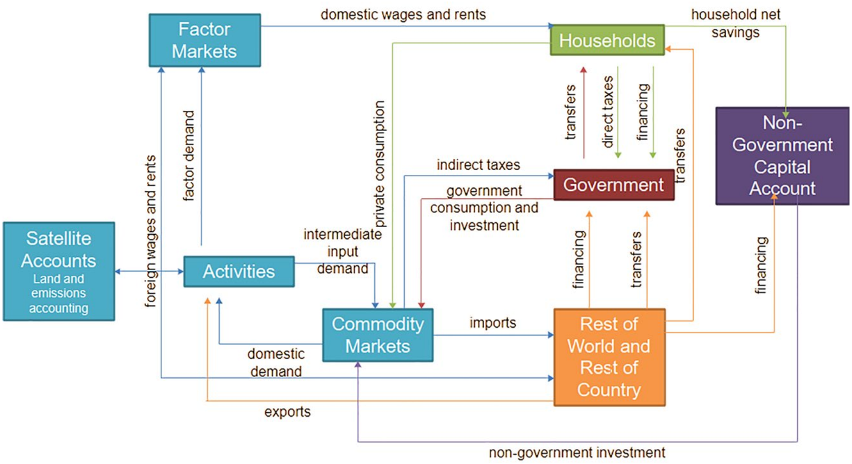

Fig. 1 The circular flow of income in Integrated Economic-Environmental Modeling (IEEM). Source: Authors' own elaboration

where production functions incorporate not only labor and physical capital but also natural resource factors using nested constant elasticity of substitution structures. Specifically, natural capital - such as land, water, and ecosystem services - is integrated into sectoral production through constant elasticity of substitution functions that allow for substitution between conventional inputs and natural capital assets (Banerjee et al. 2016; Banerjee and Cicowiez 2020). This enables IEEM to capture the productivity effects of changes in stocks of natural capital assets and ES flows, as well as the trade-offs between economic activity, growth and natural capital depletion (Banerjee et al. 2019). Moreover, IEEM introduces a land-use transition module that dynamically links land allocation decisions with economic incentives and ecological constraints and incorporates multi-factor mobility functions to reflect realistic adjustment processes (Banerjee et al. 2020a). These refinements ensure that IEEM provides a more comprehensive representation of economy-environment interactions than conventional CGE approaches, particularly in policy assessments that require spatially explicit results of land and resource dynamics (Banerjee et al. 2024a, 2025).

Economic sectors, such as agriculture, forestry, tourism, manufacturing and financial services, are represented by activities that maximize their benefits in competitive markets. The goods and services that these activities produce are traded in the commodity markets domestically and can be exported. IEEM identifies households, enterprises, government and the rest of the world as institutions (Fig. 1). Households obtain their income from the productive factors they own (labor, capital and land) as well as from the transfers they receive from other institutions. Households use their income to buy the goods and services they consume, save, pay direct taxes and make transfers to other institutions. The government receives tax income and consumes and supplies goods and services, makes transfers to households and saves. The rest of the world demands exports and supplies imports.

In terms of foreign trade, it is assumed that goods and services are differentiated according to the country of origin (Armington 1969). Thus, trade is modeled in two directions where the same good or service can be imported and exported simultaneously. The combination of national and imported products is carried out at the border of the modeled country. In other words, the domestic and imported composition of consumption is the same regardless of the destination (intermediate consumption and/or final consumption) of the products.

IEEM integrates temporal dynamics that are characterized as dynamic recursive where it is assumed that economic agents are myopic, so their expectations are static and they expect future prices to be identical to those of the present period. IEEM includes four sources of dynamics: capital accumulation, labor force growth, growth or contraction in the supply of natural capital assets and changes in factor productivity. At the beginning of each period, the sectoral capital stocks are modified based on the investment of the previous period and depreciation. The endowments of the other factors of production grow exogenously.

In the labor market, it is assumed that there is unemployment. A wage curve describes the negative relationship between the level of wages and the unemployment rate (Blanchflower and Oswald 1994, 2005). In all cases, labor is perfectly mobile between sectors. Capital, once installed, is immobile across sectors. To estimate impacts on poverty and inequality, IEEM is linked to a microsimulation model. Results from IEEM for the per capita income of each of the representative households identified in the Social Accounting Matrix are used to modify per capita income of each of the households registered in the latest household survey available (Vos and Sanchez 2010; Cicowiez and Ordonez 2021).

We construct a new database for the IEEM model for Mexico, which is a Social Accounting Matrix with the base year of 2018, using the most recent supply and use tables and integrated economic accounts published by the Experimental Statistics division of the National Institute of Statistics and Geography (INEGI 2023). Information from the Agro-Food and Fisheries Information Service of the Ministry of Agriculture and Rural Development of Mexico was used to regionalize the agricultural, livestock and forestry sectors for Mexico's 31 federal states and the Federal District of Mexico City. In the database, the production of goods and services is disaggregated into 27 activities and products. An overview of the Mexican economy from the perspective of the Social Accounting Matrix is provided in SI Section 2.

IEEM generates detailed macroeconomic impact reporting, including indicators such as GDP, private consumption, investment, imports and exports, detailed sectoral impacts, employment and household income. With regards to natural capital and ES, IEEM can be applied directly to estimate impacts on material ES (IPBES 2019) or provisioning services (Haines-Young and Potschin 2012; European Environment Agency 2018), most of which have a market price (e.g. wood, fuel and food). With some customization of the IEEM database, mainly by integrating tourism demand, IEEM can also be used to directly estimate impacts on some cultural and recreational services that also have market prices. To capture policy impacts on those ES that do not have a market price, specifically, regulating or non-material ES, we link IEEM with spatial LULC and ES modeling as described in the section that follows.

2.2 The IEEM + ESM Workflow: Linking IEEM, Land Use Land Cover Change and Ecosystem Services Modeling

In the basic IEEM + ESM workflow, the policy scenarios are implemented in IEEM, which produces economic indicators and a projection of demand for land, for each Mexican state in this study, as outputs. LULC change modeling is the necessary bridge between IEEM and the spatial modeling of ES. The Dyna-CLUE modeling framework (Verburg et al. 1999, 2002, 2021; Veldkamp and Verburg 2004) is used to spatially allocate IEEM projected demand for land to new LULC maps for future years for the business-as-usual (BASE) and policy scenarios. Dyna-CLUE spatially allocates demand for land based on a binomial logit step-wise regression of driving factors (biophysical, economic and social) which generates probabilities of occurrence of each land use in each grid cell in the maps. SI Section 1 describes the process in detail and SI section 7 presents LULC modeling metadata.

The Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST version 3.14.0; Natural Capital Project 2023) ES models are used in this study. InVEST is open source, well documented and used worldwide for ES modeling. We use four InVEST ES models:[1] erosion mitigation (Sediment Delivery Ratio Model); carbon storage (Carbon Storage Model); water regulation (Annual Water Yield Model) and water purification (Nutrient Delivery Ratio Model)[2] ES models. These ES models are run using the LULC maps for the initial and final year of each scenario. The difference between the supply of ES in each scenario

[1] These specific ES were chosen for their relevance to the conservation programs analyzed in this study.

[2] To parameterize these models, we use the ES model datapackets developed by the authors (IDB 2021) which contains country-specific data and parameters required to implement these four ES models. These datapackets are available on the IEEM website: www.rmgeo.org

and the BASE in the final period is the impact of the policy on the flow of ES. The basic IEEM+ESM workflow thus generates results in terms of impacts on macroeconomic indicators and natural capital and ES metrics in biophysical units (tons of soil loss in the case of erosion mitigation; tons of carbon for carbon storage; millimeters per pixel in the case of water yield and; kilograms of nitrogen per pixel per year in the case of water purification). SI section 6 provides all ES model parameters and metadata used.

In the more advanced dynamic IEEM+ESM workflow with endogenous feedbacks, we sequentially and iteratively run IEEM, Dyna-CLUE and InVEST in 5-year periods in the case of this study (i.e., 2020, 2025, 2030, 2035). The first step in the dynamic IEEM+ESM workflow is to generate a baseline projection for the first 5-year period. The desired output from this IEEM model run is the projection of demand for land. In the next step, the projected demand for land for the first period is spatially attributed with Dyna-CLUE and a LULC map is produced for the beginning of period t and for the end of period $t+5$, for example.

The main variable of change in the ES modeling is the LULC projections generated with IEEM and Dyna-CLUE. New LULC maps are produced for each scenario and time period and are then used as inputs in the ES models. Scenario-driven changes in ES flows in a given year are calculated as differences between the ES in the scenario for year t and in the BASE scenario for that same year.

2.3 Modeling Feedback between Ecosystem Service Models and IEEM to Value Regulating Ecosystem Services

The basic IEEM+ESM workflow generates monetary values for provisioning ES (in this study, plant-based foods, meat, fish and timber and non-timber forest products) and cultural ES (recreation) but does not generate economic values for regulating ES. Economic values for regulating services may be estimated based on stated preference studies (Johnston et al. 2017), benefits transfer (Boyle et al. 2010; Brander et al. 2023) and other environmental economic methods (Brander 2010). The advanced dynamic IEEM+ESM workflow implemented in this study, however, enables the estimation of economic values for regulating ES while maintaining consistency with the country's System of National Accounts (United Nations 1993; European Commission 2009), the internationally accepted framework for reporting economic progress. The dynamic IEEM+ESM workflow incorporates endogenous feedbacks through time between natural capital, ES and the economic system (Banerjee et al. 2024a, 2025). Figure 2 presents the interactions between IEEM and the LULC change and ES modeling and transmission pathways that link changes in ES flows to variables in IEEM.

This dynamic approach has two important characteristics that make it cutting-edge in the integrated economic-environmental analytical literature: (i) producers and consumers in IEEM adjust their behavior by taking into account the changes in the flows of ES throughout the analytical period, and; (ii) the marginal value of ES is calculated endogenously. Point (i) is important if changes in ES flows are expected to have an impact on decisions made by producers and consumers. The practical result of point (ii) is that no a priori decisions are made about the value and economic contribution of ES. The valuation method of regulating ES in IEEM+ESM is the production function approach which maintains consistency with the System of National Accounts and is characterized as a tier 3 valuation method in

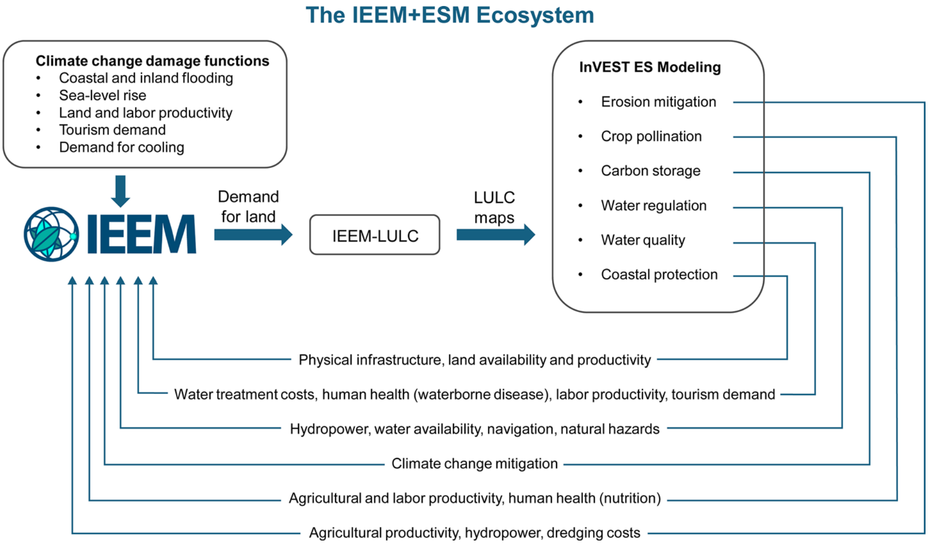

Fig. 2 The Integrated Economic-Environmental Modeling and Ecosystem Services Modeling (IEEM+ESM) Ecosystem. ES: ecosystem services; InVEST: Integrated Valuation of Ecosystem Services Tradeoffs; LULC: land use-land cover. Source: Authors' own elaboration

the System of Environmental-Economic Accounting Ecosystem Service Accounting Framework. Tier 3 methods are considered to provide the greatest accuracy and spatial resolution (NCAVES, MAIA 2022; UN et al. 2024).

The assumptions about observability and information in IEEM+ESM are rooted in the recursive dynamic nature of the model. Producers and consumers adjust their behavior over time based on changes in the flows of ES, which are incorporated into sectoral production functions via nested constant elasticity of substitution structures. These changes are observable to economic agents through their influence on factor productivity, prices and availability of natural capital inputs. Specifically, the model assumes that agents have perfect information regarding the marginal value of ES as it is calculated endogenously based on observed economic and environmental conditions. This approach ensures consistency with the System of National Accounts (European Commission 2009) and the System of Environmental-Economic Accounting (European Commission 2014) while allowing dynamic adjustments to reflect changes in ES availability and productivity over time. However, the model does not assume that agents anticipate future changes perfectly; rather, they respond to information embedded in past and current market signals and economic conditions. In other words, it is assumed that producers and consumers are myopic.

Our policy scenario analysis estimates impacts on carbon storage, erosion mitigation, water regulation and water purification ES and reports them in biophysical units and as percentage differences from the BASE for each Mexican state. In addition, we estimate the economic value of erosion mitigation ES with the dynamic IEEM+ESM framework. To link the change in erosion mitigation ES to the economy, an economic shock is calculated to represent the economic impact of the change in the flow of ES. Increased soil erosion reduces agricultural productivity (Borrelli et al. 2017; Panagos et al. 2018; Pimentel 2006; Pimentel et al. 1995) and can affect water quality, which may have implications for water treatment costs, human health and tourism values (Paerl and Huisman 2008; Keeler et al. 2012; O'Neil et al. 2012; STAC 2013; Aguilera et al. 2018; Banerjee et al. 2019).

In this study, we focus on the impact of changes in erosion on agricultural productivity. Based on our review of the scientific literature and following Organisation for Economic Co-operation and Development (OECD) Guidelines (Parris 1999), we define severe erosion as soil loss greater than 11 tons/ha/yr (Panagos et al. 2018; Sartori et al. 20192024). Also based on this evidence, severe erosion is associated with an 8% reduction in agricultural productivity (Pimentel et al. 1995; Pimentel 2006; Borrelli et al. 2017; Panagos et al. 2018).[3] To model the impact of changes in erosion mitigation ES, the InVEST sediment delivery ratio model is run for the period *t* and *t* + *5* based on the LULC maps for the baseline scenario and the policy scenarios produced with Dyna-CLUE. The erosion model calculates soil loss per pixel across the country (tons/pixel/yr). The impact of the scenario on the flow of ES is calculated as the difference between the scenario erosion map in year *t* + *5* and the BASE erosion map in year *t* + *5* using a raster calculator in a Geographic Information Systems (GIS; ArcGIS Pro 3.1.3) software package.

To estimate the economic impact of changes in erosion mitigation ES, the area per Mexican state that exhibits erosion greater than 11 tons/ha/yr at the start of the time period is identified (using zonal statistics and the raster calculator in a GIS software package) for the BASE and for each scenario. If the area of erosion greater than 11 tons/ha/year is larger in a given scenario compared to the BASE scenario, this indicates that erosion has increased because of the policies implemented.

To create a dynamic feedback between changes in erosion mitigation ES and the economy represented by IEEM, the following equation is applied to the BASE and policy scenarios:

$$LPL_{rg} = \frac{SER_{rg}}{TAA_{rg}} \cdot 0.08 \tag{1}$$

Where:

LPL_{rg} is the agricultural productivity loss by subscript *rg* for each Mexican state;

SER_{rg} is the area of land (ha) that is subject to erosion greater than 11 tons/ha/year in each state;

TAA_{rg} the total agricultural area, both livestock and crops by state and;

0.08 is the agricultural productivity shock.

The erosion shocks are introduced into IEEM in each 5-year period. The analytical period begins in 2020 with shocks implemented in the years 2025, 2030 and 2035. Between-period shocks are calculated by simple linear interpolation. With erosion shocks implemented on a periodic basis and the three models iterating every 5-year period, agents in IEEM respond to changes in ES flows and adjust their production and

[3] Based on our review of the literature (Banerjee and Cicowiez 2022), Panagos et al. (2018) have to date provided the most comprehensive survey of the literature on the relationship between changes in erosion and agricultural productivity. Their paper reviewed 16 studies reporting results of experimental trials on the loss of crop productivity due to soil erosion. The studies were well-distributed geographically, including results from the United States, Canada, Europe, Africa and Indonesia. Panagos et al. (2018) and Sartori et al. (2024), Sartori et al. (2019)) identified a threshold of 11 tons/ha/yr after which agricultural productivity can be meaningfully affected. This threshold was based on the Organization for Economic Cooperation and Development (OECD) indicators (Parris 1999) and has support in the literature from, for example Montgomery (2007) and others. The use of such thresholds in the soil science literature is relatively common while studies that estimate productivity losses due to severe erosion are few as they typically require multi-year field trials.

consumption decisions. New LULC maps for each 5-year period reflect these decisions as they affect LULC. The multi-sectoral linkages in IEEM and the results at the end of the analytical period thus include how changes in erosion mitigation affect decisions and ultimately, economic outcomes expressed as changes in GDP, wealth and other economic indicators.

2.4 Measuring Economic Development: Wealth

It is now well established that GDP is not an appropriate metric of economic development and well-being since it represents an income flow that does not consider changes in natural capital assets. Measures of wealth are more robust metrics of economic development (Stiglitz et al. 2010; Lange et al. 2011; Polasky et al. 2015; Banerjee et al. 2021b). Our estimation of wealth is based on the concept of genuine savings (Hamilton 2000; Arrow et al. 2010), which in this study is calculated as net national public and private savings adjusted for changes in natural capital stocks[4] and environmental damage proxied for by greenhouse gas emissions. This calculation follows the approach taken in the World Bank's Changing Wealth of Nations flagship report series (World Bank 2021, 2024).[5]

The calculation of wealth is presented in equation 2:

$$GenuineSAV_t = GNSAV_t - DeprCapStock_t - DeplForStock_t - DeplMinStock_t - EmiVal_t \quad (2)$$

Where:

$GNSAV_t$=Gross National Savings ($GNDI_t - PrvCon_t - GovCon_t$)

$GNDI_t$=Gross National Disposable Income;

$PrvCon_t$=Private Consumption;

$GovCon_t$=Government Consumption;

$DeprCapStock_t$=depreciation of reproducible capital stock;

$DeplForStock_t$ = depletion of forest stock;

$DeplMinStock_t$=depletion of mineral stock;

$EmiVal_t$=Cost of damage from CO_2 emissions; US$20 per ton of CO_2 (following (Lange et al. 2018; World Bank 2021). Note that we consider changes in carbon capture through LULC change as well as changes in emissions from the consumption of fossil fuels driven by economic activity.

[4] Standing forest, for example, is the natural capital asset considered in this study. Changes in the standing stock of forest are calculated as the net present value of forgone forest harvest revenues. This valuation method is consistent with the guidance provided in the System of Environmental-Economic Accounting Ecosystem Service Accounting Framework (UN 2021; NCAVES, MAIA 2022).

[5] It is acknowledged that this cost is calculated on a global scale and thus does not necessarily reflect the social cost of carbon in Mexico. The guidance on discounting from the most recent (at time of publication) Changing Wealth of Nations flagship report (World Bank 2024) advocates for using a country-specific discount rate to better reflect national circumstances. However, the Changing Wealth of Nations report itself applies a 4% discount rate for consistency with previous editions. Moreover, Groom et al. (2022) identify substantial variation in social discount rates across countries and institutions, ranging from a rate as low as 1% used in Germany to the 12% discount rate used by the Inter-American Development Bank in its economical appraisal of development loans and grants. Considering this broad range, we maintain the use of 4% as a balanced, internationally recognized benchmark suitable for assessing long-term social returns, particularly in studies emphasizing sustainability and intergenerational equity. Furthermore, adhering to this rate ensures comparability with prior IEEM analyses, enhancing the robustness and coherence of our findings.

For natural capital, the value of depletion is defined as:

$$\sum_{i=t}^{t+T-1} \frac{qdepl_t \cdot unitrent_t}{(1+intrat)^{i-t}} \tag{3}$$

Where:

$qdepl_t$ = quantity of the resource extracted

$unitrent_t$ = unit rent in year t

$intrat_t$ = interest rate (4% as applied in (Lange et al. 2018; World Bank 20212024)

As an example with t = 2014, …, 2035 and T = 22

$$\frac{qdepl_{2014} \cdot untrent_{2014}}{(1+intrat)^0} + \frac{qdepl_{2015} \cdot untrent_{2015}}{(1+intrat)^1} + \ldots + \frac{qdepl_{2035} \cdot untrent_{2035}}{(1+intrat)^{21}}$$

Note that in IEEM, the value for $unitrent_t$ is endogenous.

2.5 Scenarios

2.5.1 Base Scenario

In the BASE scenario, IEEM replicates the observed trajectory for GDP growth from 2018 to 2021. For the period 2022–2035, estimations from the World Economic Outlook are used as the main source of information to project the evolution of the Mexican economy (IMF 2021). The BASE scenario imposes an annual deforestation rate of 0.3%, calculated from the average annual area deforested for the period 2008–2018 (212,070 hectares per year; CONAFOR, 2021). In addition, based on the evidence presented in Mexico's land accounts (INEGI 2021), it is assumed that deforested areas are used for agriculture (i.e., agriculture and/or livestock; we do not explicitly model deforestation for the creation of new urban spaces). In turn, the distribution of land between agriculture and livestock is endogenous in IEEM and responds to relative economic returns to these activities. Thus, all else being equal, an increase in the relative profitability of crops will result in more land being reallocated from livestock to crops.

2.5.2 Policy Scenarios

The design of the conservation policy scenarios is based on extensive discussion of Mexico's conservation programs with government officials from the National Institute of Statistics and Geography and the Secretariat of Environment and Natural Resources, as well as the United Nations Statistics Division and United Nations Environment Programme. These discussions took place between January 2020 and December 2021. The sources of program funding in the scenarios are consistent with current funding structures and while the scenarios are simplifications of the conservation programs they represent, they are factual in their detail with regards to areas, costs and other key variables. The areas established and costs associated with each policy scenario are presented in SI Section 3. The initial investments in each program are made over the period 2020–2024 while the programs remain active for the entire analytical period until 2035.

PSA: This scenario simulates increasing the coverage of the PSA Program. This program essentially consists of an annual payment to the owners of forest lands through an agreement to preserve a specific area of forest on their property (Engel et al. 2008; Pagiola 2009; Ramirez-Reyes et al. 2018; Wunder 2005). The amount of the payment is based on the type of forest, risk of LULC change, the area enrolled and any investments required for forest restoration or protection. For compliance, beneficiaries must meet the socioeconomic, forest condition and reinvestment requirements as defined in annually published program rules. The payment is made when the National Forestry Commission (CONAFOR) has determined that the conditions of the agreement have been met.

In the modeling of this scenario, each new hectare of PSA is assumed to result in avoided deforestation of half a hectare (Alix-Garcia et al. 2012; Von Thaden et al. 2019; Banerjee et al. 2023). This scenario establishes 1,313,483 ha of new PSA area across the country for the period 2020–2024. PSA payments are made from the government to households. On average for 2020–2024, the cost of the program is equivalent to 0.001% of GDP in the baseline scenario.

IPFS: In this scenario, we focus on the Emissions Reduction in Agriculture, Forestry and Other Land Uses program component of the IPFS. This program promotes the reduction of greenhouse gas emissions and increased carbon sequestration through the improvement of land management practices and strategies aimed at reducing the loss of forest ecosystems. Important program components include restoration of degraded areas and the promotion of sustainable agroforestry, silvopastoral and agro-silvo-pastoral systems.

In this scenario, we simulate the reduction of greenhouse gas emissions in the agriculture, forestry and other land uses sectors, which are components of the IPFS. Based on government plans and targets, this involves increasing the area allocated to forest restoration and silvopastoral systems for the period 2020–2024 by 16,332 ha. The areas destined for restoration correspond to degraded areas that are transformed into forest areas that are not commercially managed. The areas allocated to silvopastoral systems include enhanced livestock productivity. More specifically, based on empirical evidence from similar programs, it is conservatively assumed that the total factor productivity of livestock with silvopastoral systems is 50% higher than that of livestock with traditional systems (Chará et al. 2019).

UMA: This scenario simulates the refinancing of a total of 37,085,854 ha of UMAs, which were created to regulate the sustainable use of wildlife. The UMA program was designed to create incentives to align pro-conservation private and public interests by promoting sustainable landscape management. Private landowners are incentivized to participate by receiving authorization to harvest natural resources on their property according to an approved management plan. Due to uncertainties around continued financing, however, the UMA program has had variable and limited support, despite being efficient in achieving conservation objectives (Gallina and Escobedo-Morales 2009; Gallina et al. 2009; Hernández et al. 2011).

In this scenario, returns associated with recreational hunting in UMAs are considered. Based on the projections reported by Retes Lopez et al. (2010), it is estimated that each hectare of UMA for hunting purposes generates an income of 57.5 Mexican pesos per year (approximately US$2.00 in 2020). This additional income is applied to 25% of the new areas that obtain an UMA permit each year.

COMBI: This scenario is the simultaneous implementation of all previous scenarios, and since IEEM is a non-linear model, this scenario includes interaction effects between scenarios. The total cost from 2020 to 2024 of this scenario represents 0.01% of GDP in 2018.

COMBI*: This scenario includes all elements of COMBI with the difference that the dynamic IEEM + ESM framework is implemented to capture the effects and contribution of soil erosion mitigation ES as well as provisioning and cultural and recreational ES, which are endogenous to IEEM.

In implementing IEEM + ESM, each scenario is simulated independently and then simultaneously in the case of COMBI. This enables us to identify the contribution of each individual scenario to economic outcomes. This also holds true for the modeling of erosion mitigation where we model it as its own scenario. In the case of COMBI*, this scenario includes the impacts of each individual scenario, including erosion mitigation, whereas COMBI does not include the impact of erosion.

3 Results

3.1 Land Use-Land Cover

The BASE LULC is presented in Fig. 3; the annual deforestation rate in the BASE is 0.3%. The distribution of land use in the BASE is presented in SI Section 1. Scenario impacts are reported as changes with respect to the BASE projection of deforestation. Of the scenarios implemented, only the PSA scenario affects the total area of standing forest. This is the result of the avoided deforestation of 0.5 ha for each 1 ha of PSA established which is exogenously determined. To a much smaller extent, the IPFS scenario, which implements 16,332 ha of sustainable agroforestry, silvopastoral and agro-silvo-pastoral systems, affects the distribution of land between crops and livestock on 16,332 ha. Specifically, in the combined scenarios (COMBI and COMBI*), the forest area would be 285,195 ha larger than in the BASE scenario and in the COMBI* scenario, 2,609 ha would move from livestock uses to crops.

3.2 Economic Impacts

Table 1 summarizes the macroeconomic effects of the scenarios as a difference from BASE in 2035 and cumulative GDP and wealth, which is the sum of the annual difference from BASE for GDP and wealth until the end of the analytical period. A systematic sensitivity analysis is reported in detail in SI Section 5. Results of this sensitivity analysis show, for example, that in the COMBI scenario, it is almost certain that wealth in 2035 would increase relative to the BASE, by between US$26.2 and US$30.4 million.

Table 1 Impacts on macroeconomic indicators as the deviation from the business-as-usual (BASE) in 2035 in millions of 2020 U.S. Dollars (USD). GDP: Gross domestic product; PSA: Payments for environmental services; IPFS: Initiative for sustainable forest landscapes; UMA: Management Units for the conservation of wildlife; COMBI: PSA, IPFS, UMA combined; COMBI*: COMBI, plus economic contributions of ecosystem services

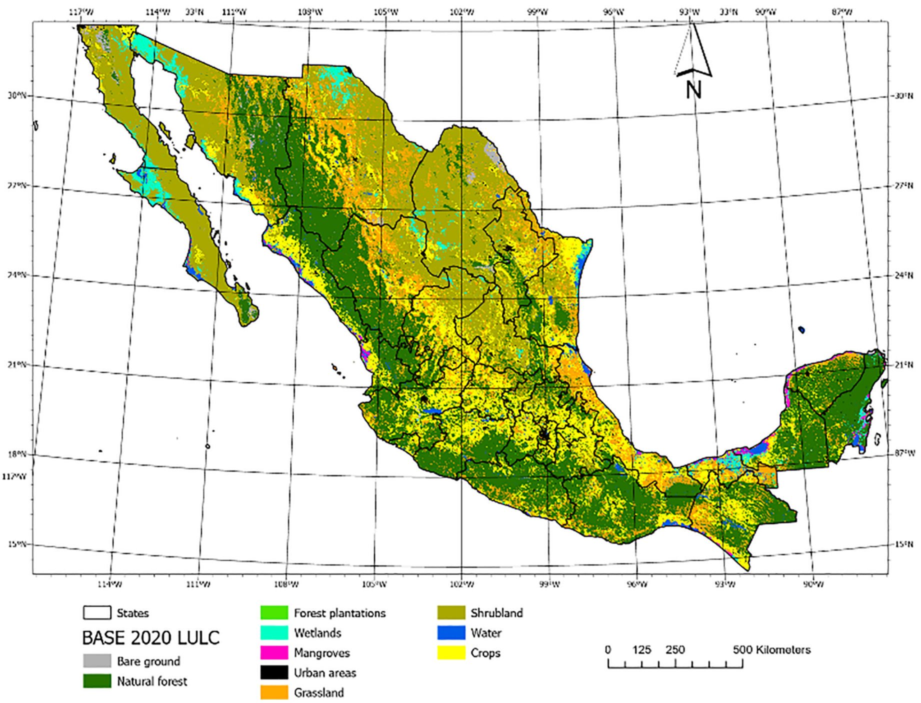

Fig. 3 Land Use-Land Cover (LULC) in the BASE (2020). Source: Original Land Use Land Cover Base map sourced from CONABIO (2020). Modified through the application of Integrated Economic-Environmental Modeling + Ecosystem Services Modeling (IEEM + ESM) results

In general, all scenarios would have positive macroeconomic impacts. The contribution of regulating ES is important, as its inclusion would result in a cumulative GDP that is 1.34 times higher (COMBI* vs. COMBI), equivalent to a US$219.2 million impact on cumulative GDP. Note that it is primarily the PSA scenario with its increase in standing forest relative to the BASE that drives the positive contribution of erosion mitigation ES.

In terms of wealth, the COMBI* scenario would enhance wealth the most, by US$492.3 million[6] in cumulative terms. Figure 4 shows the trajectory of GDP (left) and wealth (right) until 2035. The peaks and troughs in the trajectory of GDP and wealth are attributable to the effects of conservation program financing and implementation, which occurs between 2020 and 2025. Also of note in Fig. 4 is that COMBI (without regulating ES) and COMBI* (with regulating ES) begin to diverge in the year 2025 due to the lag between changes in LULC from the conservation programs' implementation and their impacts on erosion and agricultural productivity.

[6] IEEM is a non-linear model and therefore each individual scenario, when implemented simultaneously, interacts. The overall impact of multiple scenarios implemented simultaneously (i.e. COMBI and COMBI*), will be greater than the sum of their individual contributions to an indicator. In the case of the scenarios considered here, however, the interaction effects are extremely small due to the nature of the scenarios themselves and the size of the policy interventions. The interaction effects are thus not evident in Table 1 where impacts are reported at the level of one significant figure.

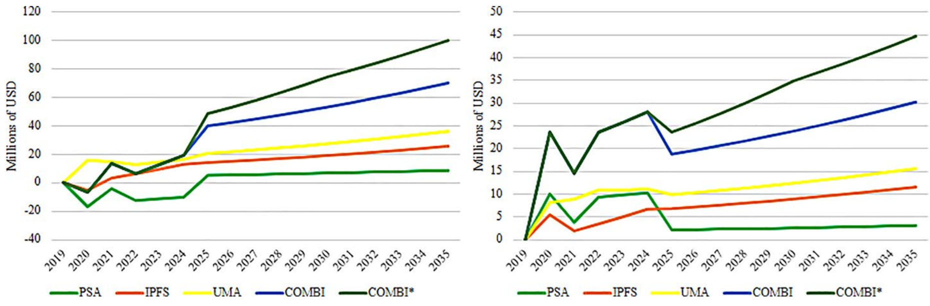

Fig. 4 Gross Domestic Product (left) and wealth (right) trajectory as a deviation from the business-as-usual (BASE) in millions of 2020 U.S. Dollars (USD). PSA: Payments for environmental services; IPFS: Initiative for sustainable forest landscapes; UMA: Management Units for the conservation of wildlife; COMBI: PSA, IPFS, UMA combined; COMBI*: COMBI, plus economic contributions of ecosystem services. Source: Integrated Economic-Environmental Modeling + Ecosystem Services Modeling (IEEM + ESM) results

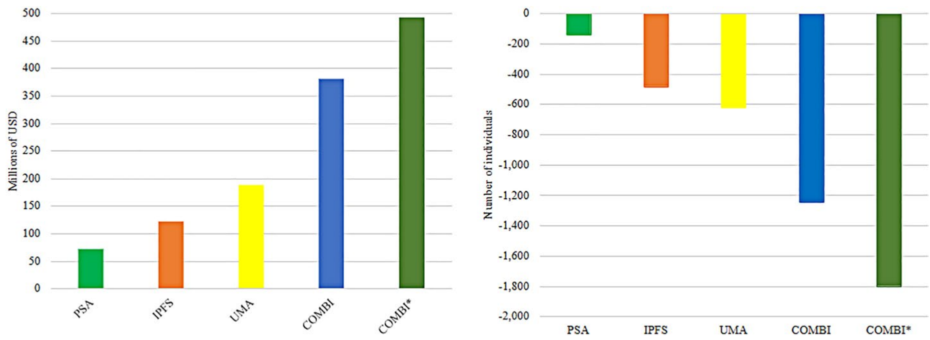

Fig. 5 Cumulative wealth in 2020 U.S. Dollars (USD, left) and poverty (right) in 2035 as a deviation from business-as-usual (BASE). PSA: Payments for environmental services; IPFS: Initiative for sustainable forest landscapes; UMA: Management Units for the conservation of wildlife; COMBI: PSA, IPFS, UMA combined; COMBI*: COMBI, plus economic contributions of ecosystem services. Source: Integrated Economic-Environmental Modeling + Ecosystem Services Modeling (IEEM + ESM) results

Reduced deforestation increases the stock of natural capital relative to the BASE and would have positive effects on wealth. The UMA scenario, due to its positive impact on the level of economic activity, would also contribute to increasing wealth (Fig. 5, left). The distributional analysis shows that the COMBI* scenario would lift 1,800 individuals out of poverty, with the IPFS and UMA programs making the greatest contribution (Fig. 5, right).

Relative to the BASE, the Agricultural and Food processing sectors would experience the largest increases in production, along with the Construction and Commerce sectors (Fig. 6). The positive agricultural sector impacts are largely due to the enhanced management of silvopastoral systems arising from the IPFS scenario. The PSA scenario's negative impact on Other services in Fig. 6 stands out; this result is a function of a reduction in government expenditure on Other services as the government reallocates expenditure to fund the PSA program. In terms of percentage change with respect to the BASE, this reduction would be small (between 0.0013% and 0.0043% with respect to the BASE) and would be limited to the first four years of the simulation (2020 to 2024).

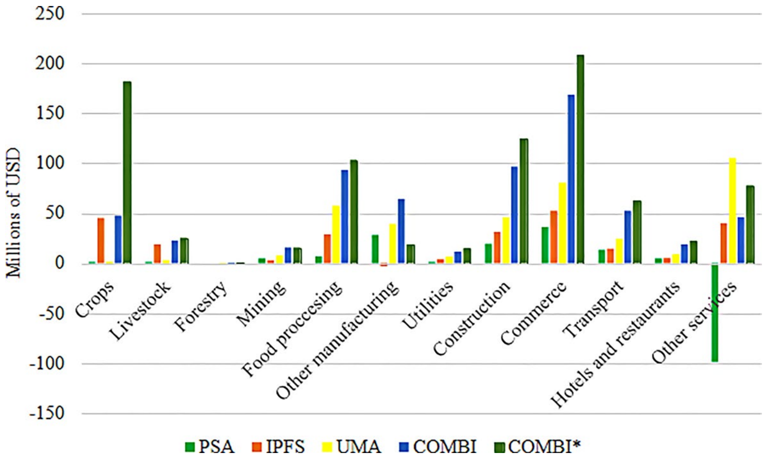

Fig. 6 Cumulative output in 2035 by activity as a deviation from the business-as-usual (BASE) in millions of 2020 U.S. Dollars (USD). PSA: Payments for environmental services; IPFS: Initiative for sustainable forest landscapes; UMA: Management Units for the conservation of wildlife; COMBI: PSA, IPFS, UMA combined; COMBI*: COMBI, plus economic contributions of ecosystem services. Source: Integrated Economic-Environmental Modeling + Ecosystem Services Modeling (IEEM + ESM) results

3.3 Impacts on Ecosystem Services

Table 2 shows the impacts of the scenarios on monetary values of ES, considering provisioning, cultural and recreational and regulating ES. The IPFS program contributes the greatest economic value through provisioning services, plant-based foods in particular, followed by meat and fish. Avoided deforestation does not increase the area of forests commercially managed, only the area under conservation, so there is no significant increase in forest sector activity. There is, however, a significant increase in cultural and recreational ES with the greatest contribution attributed to the UMA scenario, which promotes recreational hunting activities.

Table 2 Impacts on CICES and IPBES-coded ecosystem services as a deviation from the business-as-usual (BASE) in millions of 2020 U.S. Dollars (USD)

Even more important are regulating services, specifically erosion mitigation ES, which would contribute US$219.2 million in cumulative value to the economy. In this case, avoided deforestation and the consequent increase in the stock of natural capital would have the effect of decreasing erosion across the landscape and increasing agricultural productivity as less soil would be lost to erosion. It is worth noting that the value of erosion mitigation regulating ES as modeled by IEEM is additive to the value of food provisioning ES thus avoiding any issues with double counting (La Notte et al. 2021).

Figure 7 (left) presents changes in carbon storage ES for the COMBI* scenario in 2035. All Mexican states would experience an increase in carbon storage, as high as 1.5% in 2035 compared to the BASE in the same year. This effect is mainly due to the PSA scenario and its contribution to avoided deforestation. On a national scale, carbon storage would increase by 0.28% with respect to the BASE in 2035. IEEM also calculates emissions from fossil fuel consumption attributable to changes in economic activity. In this case, there would be an increase of 20,000 tons of CO_2 equivalent in the COMBI* scenario due to the increase in

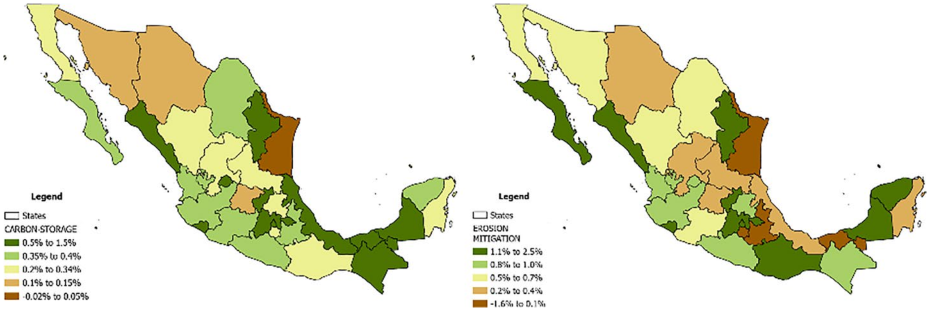

Fig. 7 Combination plus ecosystem services (COMBI*) scenario, impact on carbon storage (left) and erosion mitigation (right) expressed as a percent deviation from the business-as-usual (BASE) in 2035. Source: Integrated Economic-Environmental Modeling + Ecosystem Services Modeling (IEEM + ESM) results

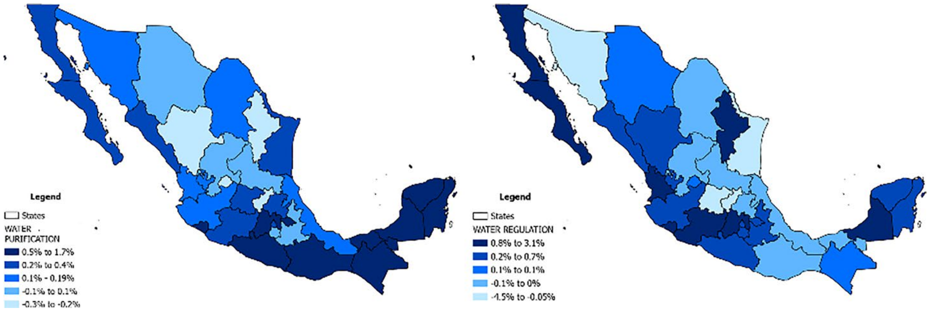

Fig. 8 Combination plus ecosystem services (COMBI*) scenario, impact on water purification (left) and water regulation (right) expressed as a percent deviation from the business-as-usual (BASE) in 2035. Source: Integrated Economic-Environmental Modeling + Ecosystem Services Modeling (IEEM + ESM) Results

economic activity, in the absence of new emission mitigation measures. SI Section 4 presents detailed state-by-state changes in ES flows.

Figure 7 (right) presents changes in erosion mitigation ES for the COMBI* scenario in 2035. All but three states would experience an increase in erosion mitigation ES of up to 2.5% in 2035. The greater flow of this ES has important effects on GDP and wealth due to its contribution to improving agricultural productivity. On a national scale, erosion mitigation ES would increase by 0.84% with respect to the BASE in 2035.

Figure 8 (left) presents the estimated impact of the COMBI* scenario on water purification and water quality ES in 2035 as a deviation from the BASE. Most of the states (all but eight) would experience an improvement (positive deviation with respect to the BASE) in the flow of water purification ES with some states in the south of the country showing the greatest positive impacts. Negative impacts in the eight states would be small and are attributed to an increase in agricultural activity and the use of fertilizers that later reach water bodies. On a national scale, water purification ES would increase by 0.31% with respect to the BASE in 2035.

Figure 8 (right) presents the impact of the COMBI* scenario on water regulation ES in 2035 as a deviation from the BASE. In this case, water regulation would improve in all but eight states, up to 3.1% and on average, by about 0.5%. On a national scale, water regulation would improve by 0.26% with respect to the BASE in 2035. With a larger forested area in the COMBI* scenario, evapotranspiration and infiltration within ecosystems would be greater, thus reducing the extremes in terms of rapid, rainfall-driven runoff towards rivers and other water bodies.

4 Discussion

In this study, the IEEM + ESM framework was applied to assess the economic, natural capital and ES impacts of the PSA, UMA and IPFS conservation programs in Mexico over a 15-year time horizon. We set out to illustrate how the extension of economic analytical tools to include economic contributions from natural capital and ES generates more robust information for the improved allocation of public resources from a public finance perspective and better decisions from a policy-making perspective. Indeed, the evaluation of the impacts of these conservation instruments on both economic and environmental variables is necessary in the context of increasingly scarce public resources, demonstrating their substantial economic benefits beyond the fulfillment of their primary conservation objectives. All three programs were assessed to have strong positive economic impacts individually, while the simultaneous application of these programs had the greatest impact on GDP and wealth. When the economic value of regulating ES is considered, GDP would be 1.34 times higher (Banerjee and Cicowiez 2022; Banerjee et al. 2023, 2025).

The strong positive impacts of Mexico's conservation programs on GDP and private investment are attributed to two main drivers. The first is a result of the productivity gains generated by the IPFS and UMA programs. These productivity gains are due to the increase in silvopastoral systems and recreational hunting activities. The second main driver is an improvement in the efficiency of the public sector that finances the conservation programs, which in turn has a positive impact on the overall level of economic activity. In the case of the PSA program, its positive economic impact is attributed to the combination of avoided deforestation and the increase in the flow of erosion mitigation ES, which in turn catalyzes an increase in agricultural productivity. In the case of the IPFS program, its contribution to economic growth is derived from its diversity of actions and the value chains produced by them, in particular, restoring degraded lands and expanding sustainable silvopastoral systems for the multiple economic and conservation benefits generated. These positive impacts translate into gains in household income, which are reflected in the reduction in poverty levels.

The IEEM + ESM framework captures the linkages and dependencies between economic sectors and institutions (households and the government). These linkages are demonstrated in Fig. 6, for example, where the COMBI* scenario stimulates all economic sectors. This result is explained by the fact that economic sectors produce intermediate goods and services that are then used in the production of a final output. With the COMBI* scenario affecting the overall level of economic output, one sector's dependency on another boosts demand across the economy. As an example, COMBI* increases upstream forest sector activity which then stimulates downstream processing activities related to processed wood and paper production.

These linkages and dependencies are also exemplified by impacts on poverty levels which are directly affected by changes in household income. In the PSA scenario, for example, transfer payments are made from the government to households for forest conservation. In addition, the deforestation avoided with the establishment of PSAs indirectly impacts household income. Here, it is the increase in forested area relative to the baseline and its interaction with agricultural productivity that indirectly affects household income. Equation 1 shows the relationship between forested land and agricultural productivity. With greater forestland relative to the baseline in the PSA scenario, erosion decreases which has the effect of increasing agricultural productivity. With a higher level of productivity, overall economic output increases, which generates additional income for households. Thus, in the case of the PSA scenario, it is the combined impact of the transfer payments from the government and the mitigation of erosion that generates an increase in household income which explains the reduction in poverty in this scenario.

In general, the three conservation programs contribute positively to all types of ES, including provisioning, cultural and recreational, erosion mitigation, carbon storage, water purification and water regulation ES. Impacts are spatially heterogeneous across the landscape (Figs. 7 and 8), suggesting that, as has been observed by others, there is enormous potential for spatial targeting of the conservation policies analyzed, which would contribute to maximizing various economic, social and environmental objectives (Izquierdo and Clark 2012; Crossman et al. 2013; Mokondoko et al. 2018; Blackman et al. 2019; Guo et al. 2020; Ribeiro de Souza et al. 2021).

In quantitative terms, the COMBI* scenario, which combines the three conservation programs, had the greatest impact on ES, first on regulating ES and second on provisioning ES (Table 2). The three programs, and especially UMA, also positively contributed to recreational and cultural ES. Our overall results align with the evidence from other studies that examine the interactions between climate and conservation policy instruments where there may be multiplicative effects in reducing emissions, conserving biodiversity and enhancing ES supply (Ibarraran Viniegra et al. 2015; Elizondo et al. 2020).

5 Conclusions

It is widely accepted that GDP is not a suitable indicator for measuring sustainable economic development (Stiglitz et al. 2009, 2010; Polasky et al. 2015; Lange et al. 2018; HM Treasury 2020; Banerjee et al. 2020a, 2021b). Consequently, this analysis considered the impacts of the conservation programs on wealth, which is based on more robust metrics of sustainable economic development including public and private savings, natural capital stocks and environmental degradation. The positive impact of the three programs on wealth is attributed to the: increase in economic activity; the way in which this increase in activity impacts net national savings and natural capital stocks, for example, by enhancing the stocks of natural capital (PSA program) and; through returns from hunting activities that drive wealth generation through net national savings (UMA program).

While the IEEM + ESM framework has been previously applied to development scenarios in various parts of the world that include conservation components (for example, Colombia: Banerjee et al. 2023b; Brazil, Bolivia, Colombia, Ecuador and Peru: Banerjee et al. 2022; Rwanda: Banerjee et al. 2020), this study is novel in its linkage of IEEM and spatial models of LULC change and ES to three existing national-scale conservation programs. The approach developed in this paper is replicable and applicable to any country with a strong System of National Accounts (European Commission 2009). Indeed, the IEEM + ESM approach has been applied thus far to over 30 countries and all models and data are openly available on the IEEM website.[7]

Based on the results presented in this study, market and non-market ES can contribute substantially to macroeconomic indicators and human well-being. Future applications can build on this approach through the integration of other regulating ES in the dynamic IEEM + ESM framework, including crop pollination, water purification and coastal vulnerability (Banerjee and Cicowiez 2022; Banerjee et al. 2024a). This IEEM + ESM application has demonstrated that the inclusion of natural capital and ES metrics can tip the scales for Ministries of Finance in making decisions and allocating funds toward conservation goals given the triple dividends to the economy, environment and society.

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Data Availability Data will be made available upon reasonable request.

Declarations

Competing Interests 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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