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Banking on Strong Rural Livelihoods and the Sustainable Use of Natural Capital in Post-Conflict Colombia

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Banking on Strong Rural Livelihoods and the Sustainable Use of Natural Capital in Post-Conflict Colombia

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Declarations

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Competing Interests

The authors have no competing interests to declare that are relevant to the content of this article.

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Banking on Strong Rural Livelihoods and the Sustainable Use of Natural Capital in Post-Conflict Colombia

Abstract

In post-conflict Colombia, the government has prioritized resettlement of displaced people through development of strong rural livelihoods and the sustainable use of natural capital. In this paper, we considered government proposals for expanding payment for ecosystem services (PES) and sustainable silvopastoral systems, and private-sector investment in habitat banking. We coupled the Integrated Economic-Environmental Model (IEEM) with spatially explicit land use and land cover change and ecosystem services models to assess the potential impacts of these programs through the lens of wealth and sustainable economic development. This innovative workflow integrates dynamic endogenous feedbacks between natural capital, ecosystem services and the economic system, and can be applied to other country contexts. Results show that PES and habitat banking programs are strong investment propositions (Net Present Value of US$4.4 and $4.9 billion, respectively), but only when moving beyond conventional economic analysis to include non-market ecosystem services. Where a portfolio investment approach is taken and PES is implemented with sustainable silvopastoral systems, investment returns would reach US$7.1 billion. This paper provides a detailed evaluation of the benefits of investing in rural livelihoods and enhancing Colombia’s natural capital base, with empirical evidence to inform the spatial targeting of policies to maximize economic, environmental and social outcomes.

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1.0 Introduction

The government of Colombia signed a Peace Accord with the Revolutionary Armed Forces of Colombia in November of 2016, after over 50 years of civil conflict. Drawing from the experience of other post-conflict countries, the return of displaced people following the resolution of conflict, coupled with ineffective land use planning, often intensifies unsustainable natural capital use and drives deforestation and other environmental degradation (Calderon et al., 2016; Suarez et al., 2017). On signing the Peace Accord, the Colombian government focused public investment on security and social and economic recovery, which may further intensify pressures on natural capital (Bustos & Jaramillo, 2016; Conca & Wallace, 2009; McNeish, 2017).

About 19% of Colombia's population is rural (World Bank, 2021b) and remains strongly reliant on agriculture. Growth in this sector has been stagnant due to a lack of incentives, land tenure and inappropriate land management practices. Climate change and increased weather-related disasters affect the rural poor disproportionately and the intensity and frequency of these events are only expected to increase (IFAD, 2016). With the Peace Accord, there were renewed hopes for improving the prospects of the rural poor through integrated rural reform including provisions for investing in public services, measures to enhance agricultural productivity and granting land to small farmers. The implementation of these measures, however, has been progressing relatively slowly (Cobb, 2022).

Colombia is home to 10% of the planet's biodiversity and is the second most biodiverse nation on Earth (CONPES, 2017; Moreno et al., 2019). Over half of the country is forested and it has the greatest abundance of water resources among all countries in Latin America and the Caribbean (World Bank, 2015). In the past 25 years, Colombia lost 5.2 million hectares of forest cover, 3 million hectares of which were deforested in municipalities affected by the armed conflict (DNP, 2017). Colombia's protected areas have not been spared, with deforestation spiking in the post-conflict period and accounting for 11% of the national total in 2017. Deforestation, land degradation and soil erosion were estimated to cost on average 0.7% of gross domestic product (GDP) annually (Sanchez-Triana et al., 2007).

Clearing land for agriculture and livestock is the main driver of deforestation, accounting for 65% of the deforestation over the previous decade (Etter et al., 2006; Hanauer & Canavire Bacarreza, 2018; Prem et al., 2020; UNODC, 2019). Deforestation is also closely related to illegal activities, which have proliferated due to weak governance. Forests in some areas have been replaced with illicit crops or illegal mining and logging, with access made possible by informal roadbuilding. Since the Peace Accord, Colombia's coca production has tripled, accounting for 70% of the global harvest (UNODC, 2019). With the onset of peace, vast swaths of tropical forest and other ecosystems and the valuable ecosystem services they provide are now accessible and in some areas, this accessibility is spawning a frontier mentality (Hanauer & Canavire Bacarreza, 2018; Prem et al., 2020).

More recently, the Colombian government has come to view its natural capital base as an asset and opportunity for developing strong rural livelihoods to generate sustainable economic development opportunities in the countryside and mitigate climate change. Various policies and programs demonstrate this commitment. In 2019, the government established the multi-donor Sustainable Colombia Fund, which includes funding for Payment for Ecosystem Services (PES) to integrate biodiversity conservation with productive projects that will benefit post-conflict zones (CONPES, 2017; DNP, 2019a). PES programs have had positive household welfare impacts in some contexts while PES effectiveness can be enhanced where conservation and equity objectives are pursued simultaneously (Börner et al., 2017). Colombia's Green Growth Strategy is supporting the efficient use of natural capital through the development of strong bioeconomies (CONPES, 2018). The commitment to green growth was reaffirmed in Colombia's National Development Plan, which is aligned and consistent with the Paris Agreement, Colombia's National Climate Change Plan and the Sustainable Development Goals (DNP, 2017, 2019b; Gobierno de Colombia, 2017). Reducing deforestation is a critical element of these national strategies and plans, along with reducing greenhouse gas emissions by up to 30% by 2030 (DNP, 2016).

To measure progress toward sustainable economic development, like that now pursued by Colombia, metrics are required that gauge impacts on its three dimensions, namely social, economic and environmental outcomes. While GDP has been misused for this purpose (Banerjee et al. 2021; Lange, Wodon, and Carey 2018; Polasky et al. 2015; Stiglitz, Sen, and Fitoussi 2009, 2010), better methods and data are now available to measure and track more robust metrics such as wealth (HM Treasury, 2020; UNEP, 2018). Our innovative approach brings the value of biodiversity and ecosystem services into economic decision making by linking the Integrated Economic-Environmental Model (IEEM) (Banerjee et al. 2016, 2019) with high resolution spatially explicit land use land cover (LULC) change and ecosystem services models (IEEM+ESM; Banerjee, Bagstad, et al. 2020). This framework enables estimation of indicators that more accurately measure sustainable economic development, all consistent and compatible with a country's System of National Accounts (European Commission et al., 2009) thus lending a high degree of credibility to the results.

The IEEM+ESM workflow integrates dynamic endogenous feedbacks between natural capital, ecosystem services and the economic system. This approach considers the interdependencies between the economy and natural capital and enables the estimation of ecosystem service values based on their contribution to the economy. This contrasts with welfare-based ecosystem service valuation approaches prevalent in the literature (Boyle, 2017; Hanley & Czajkowski, 2019; Johnston et al., 2017; Rolfe, 2006). While welfare-based stated preference approaches estimate values that individuals may be willing to pay for a change in ecosystem service provision, the use of willingness to pay estimates is not feasible in an economy-wide framework such as IEEM where a transaction must occur such that for every expenditure, there is an equal income.

Instead, the IEEM+ESM approach developed here links these ecosystem services with economic outcomes making it possible to derive their marginal economic contribution to the economy and society. We apply this approach to the analysis of post-conflict strategies for the development of strong rural livelihoods and enhance natural capital, specifically: (i) expansion of Colombia's PES program; (ii) development of more productive and sustainable silvopastoral systems; and (iii) expansion of habitat banking for natural capital restoration and conservation.

2.0 Materials and Methods

Scenarios

We designed five scenarios to assess Colombian government and private sector plans to promote the development of rural livelihood opportunities and enhance natural capital and ecosystem service flows. Specifically, these scenarios simulate the expansion of the PES program, investment in sustainable silvopastoral systems (CONPES, 2017; DNP, 2019a), and private-sector investment in expanding habitat banking for environmental offsetting (Fundepúblico & Terrasos, 2020). We compared these policy scenarios to a business-as-usual scenario defined by current trends. The general features of each scenario follow (see Supplementary Information (S2) for more details).

(i) Business-as-Usual (BASE): In this analysis, all scenarios are compared to a business-as-usual scenario (abbreviated as BASE). In the BASE, Colombia's economy is projected to the year 2040 without the implementation of any new public policies or investments. Economic growth projections are based on the International Monetary Fund's World Economic Outlook (IMF, 2018). Labor force and population growth rates are drawn from the United Nations' Population Prospects projections (UN, 2019; see S2 for additional details on the BASE scenario).

(ii) Payment for Ecosystem Services (PES): This scenario simulates the establishment of 500,000 hectares (ha) of PES for strict preservation, beginning in 2021 and concluding in 2034. This area is equivalent to 0.84% of Colombia's total forested area. We assumed that each hectare preserved avoids the deforestation of one hectare of forest in perpetuity, assuming payments and compliance are maintained, which are prerequisites of a PES program (Börner et al., 2017; Engel et al., 2008; Wunder, 2005; Wunder et al., 2008. See Figures S1-S5 in S2).

(iii) Silvopastoral Systems (SPS): This scenario simulates the restoration of 125,000 ha of degraded pasture areas with more productive silvopastoral systems. This area is equivalent to 0.36% of Colombia's total livestock area. Expanding sustainable silvopastoral systems can reduce demand for agricultural land and reduce deforestation pressures (see Figure S6 in S2). Productivity gains and investment costs are based on previous Colombian studies (Rodríguez, 2017).

(iv) COMBI: The COMBI scenario is the joint implementation of the PES and SPS scenarios.

(v) PES and endogenous estimation of livestock Total Factor Productivity (PES+SPSe): This scenario simulates the establishment of 500,000 ha of PES and endogenizes livestock productivity such that GDP in the scenario tracks the GDP in the business-as-usual scenario. This scenario identifies the increase in the level of livestock productivity that would be required for the investment in PES to be GDP-neutral. Recent assessments of the productivity potential of enhanced silvopastoral systems show a large potential range to the upside (Chará et al. 2019; Mahecha et al. 2011;).

(vi) Habitat Bank Scenario (HAB): This scenario simulates the expansion of 500,000 ha of Colombia's habitat banking system where 80% of this area would be designated as strict preservation of existing intact ecosystems and 20% would involve restoration of degraded ecosystems. Habitat banking has been used in Colombia to enable firms to offset conservation liabilities by undertaking activities that generate positive environmental externalities (Fundepúblico & Terrasos, 2020).

Overview of IEEM

We used IEEM as the basis for this analysis because it allows for the quantification of the effects of public policies on standard indicators such as GDP, income and employment, as well as the impacts on stocks of natural capital, environmental quality, wealth and well-being, which are central to the discussion on post-conflict development prospects for Colombia (see S1 for more details on IEEM). Our measure of wealth is an adjusted form of genuine savings, which considers household savings, natural capital stocks and environmental quality. IEEM integrates natural capital accounts in the System of Environmental-Economic Accounting (SEEA) (United Nations et al., 2014) format, has environmental modeling modules to capture the dynamics of each environmental asset and ecosystem services, and generates indicators that enable assessment of impacts on the three pillars of sustainable development – society, economy and environment.

At the core of IEEM is a dynamic computable general equilibrium (CGE) model. The theory, structure and strengths and limitations of CGE modeling for public policy and investment analysis are discussed in a body of literature that has developed over the last four decades (Burfisher, 2021; Dervis et al., 1982; Dixon & Jorgenson, 2012; Kehoe, 2005; Shoven & Whalley, 1992). The IEEM conceptual framework and natural capital-specific modeling modules are described in Banerjee et al. (2016) while its mathematical structure is documented in Banerjee and Cicowiez (2020). IEEM's database is an environmentally extended Social Accounting Matrix (SAM; Banerjee et al. 2019). The main sources of data used in constructing the extended SAM are Colombia's National Accounts Environmental-Economic Accounts, Integrated Economic Accounts and Agricultural Census data (DANE, 2015, 2016, 2017, 2018). A user guide for a generic version of IEEM, applicable to any country with the corresponding database, is available (Banerjee and Cicowiez 2019). IEEM models for over 20 countries and various other resources are open source and available online on the OPEN IEEM Platform: https://openieem.iadb.org/

Linking IEEM with Spatial LULC and Ecosystem Services Modeling

In this application, we linked IEEM with LULC change and ecosystem services modeling (IEEM+ESM) to represent the economy, natural capital and ecosystem services as one integrated and complex system. To more accurately capture regional LULC dynamics and enable the spatial targeting of policies, we disaggregate IEEM's agriculture, livestock, and forestry sectors according to Colombia’s 32 departments. We used the IEEM-Enhanced version of the Dynamic Conversion of Land Use and its Effects (Dyna-CLUE) model (Veldkamp and Verburg 2004; Verburg et al. 2021; Verburg et al. 2002; Verburg and Overmars 2009) to spatially allocate the LULC change projected by IEEM. LULC allocation is implemented based on empirically quantified relationships between land use and location factors (e.g., climate, topography, soil and socioeconomic factors), in combination with the dynamic modeling of competition between land use types (see S3 for more details on the application of Dyna-CLUE).

We modeled changes in future ecosystem service flows using the Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST) suite of models and the IEEM+ESM ecosystem services modeling datapackets (IDB, 2021). Data collection and processing is the most time consuming and resource-intense aspect of ecosystem services modeling. The IEEM+ESM datapackets were developed to enable rapid deployment of ecosystem services models to support real time decision making. Datapackets were developed for these four InVEST ecosystem services models as well as the coastal vulnerability model for all countries of Latin America and the Caribbean, including Colombia. InVEST combines LULC maps and biophysical information to calculate ecosystem service flows. We used four models: the sediment delivery ratio model, used to calculate the Revised Universal Soil Loss Equation and sediment export (as well as soil erosion mitigation – the amount of soil held in place by vegetation); the carbon storage model, used to calculate carbon storage and carbon sequestration potential; the annual water yield model, used to calculate water supply, and; the nutrient delivery ratio model, used as a proxy for the water purification potential of landscapes in absorbing nitrogen and phosphorus (see S3) (Sharp et al., 2020).

In addition to the above-mentioned ecosystem services, the impact of policy scenarios on biodiversity was evaluated by calculating composite Biodiversity Intactness Indices (BII) (Hudson et al., 2017; Newbold et al., 2016). The BII is a coefficient based on the average abundance of species originally present across undisturbed habitats (Newbold et al., 2016). Our estimates are based on the Projecting Responses of Ecological Diversity In Changing Terrestrial Systems (PREDICTS) database, an extensive database collecting case study information on the relationship between land use and biodiversity, with over 32 million observations from 32,000 locations and covering 50,000 species (Trustees of the Natural History Museum, 2020). For Colombia alone, the database had a collection of 285 locations (Echeverría- Londoño et al., 2016) where the relationship between LULC and biodiversity have been monitored and assessed. Using calculated mean BII values, which are based on undisturbed natural habitats, we assigned BII coefficients to the land use types considered in this analysis. For each scenario and year, we then recalculated the composite BII across scenarios and through time based on LULC change.

Integrating Dynamic Endogenous Feedbacks between the Economy and Ecosystem Services

IEEM+ESM can be used directly to estimate economic impacts of changes in the supply of most provisioning ecosystem services (European Environment Agency, 2018; Haines-

Young & Potschin, 2012) that have a market price. These provisioning services include benefits to people in the form of food, timber/fiber/biomass, and mineral and non-mineral subsoil extracts. IEEM+ESM can also be used directly to estimate economic impacts of changes in the supply of some cultural ecosystem services such as tourism and recreation (Banerjee et al., 2018). A key contribution of this work is the development of a methodology for integrating LULC-driven changes in regulating and maintenance ecosystem services into IEEM+ESM and CGE models more generally. In contrast to provisioning and some cultural ecosystem services, regulating and maintenance services usually do not have a market price; examples of these services include erosion mitigation, water purification, water regulation, microclimate regulation (temperature, precipitation and humidity) and regulation of extreme events such as floods and landslides. We achieve this integration of regulating and maintenance ecosystem services into IEEM+ESM through the modeling of dynamic endogenous feedbacks between natural capital, ecosystem services and the economic system represented by IEEM+ESM.

Feedbacks from changes in ecosystem service supply affect agent behavior in the economy through various mechanisms. For example, a reduction in soil erosion mitigation ecosystem services reduces agricultural productivity and thus affects prices, returns to factors of production, producer demand for factors of production and the levels and composition of household demand (Borrelli et al., 2017, 2017; Panagos et al., 2015, 2018; Pimentel, 2006; Pimentel et al., 1995). Reduced soil regulation functions that moderate nutrient run-off can affect water quality which in turn can impact water treatment costs, human health and the quality of water-based recreational experiences. The resulting higher water treatment costs, health risks and changes in recreational quality affect agent behavior and demand (Aguilera et al. 2018; Keeler et al. 2012; O’Neil et al. 2012; Paerl and Huisman 2008; STAC 2013).

While it is possible to endogenize the impact of a range of ecosystem services in IEEM+ESM, in this application we focus on soil erosion mitigation services to demonstrate the methodology. This also enables us to isolate effects and identify how changes in erosion mitigation ecosystem services interact with the economy through their impact on agricultural productivity and in turn, producer and household behavior in response to changes in prices. Furthermore, more research is required to enable the integration of other ecosystem services in IEEM and other CGE models; for each regulating and maintenance ecosystem service, the pathway between changes in the supply of that ecosystem service and the economy must be first identified and then operationalized for each specific country context[1].

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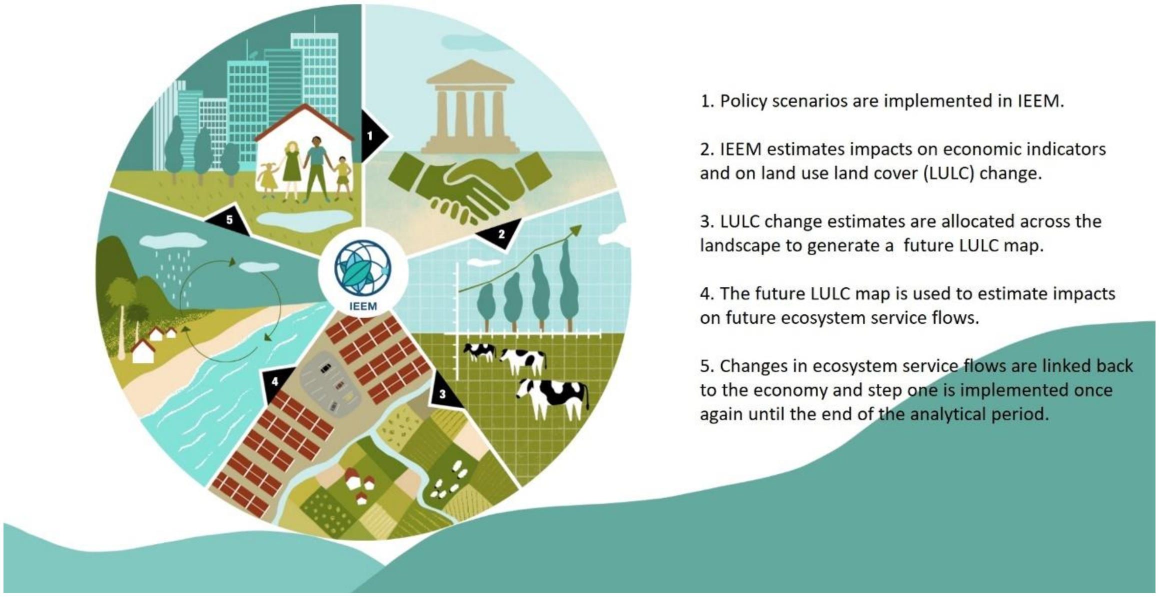
[1] While for some ecosystem services, the pathways to impact can be relatively straightforward to identify, the numerical estimation of the amount by which IEEM model variables should be adjusted poses challenges and in many cases, the science to support such estimations are incipient. For example, consider changes in forest cover that can affect microclimate regulation ecosystem services, including precipitation patterns and transpiration. In terms of identifying the pathway to impact, one pathway could be related to the productivity of rainfed agriculture. The main challenge in operationalizing this integration relates to estimating a quantitative relationship between forest cover and precipitation for a specific study area. Once this relationship is established, then the relationship between changes in precipitation and rainfed agricultural productivity can be estimated. This estimation could follow an approach similar to that described in Banerjee, Cicowiez, Macedo, et al. (2021).

To endogenize feedbacks between the economy and ecosystem services, we ran the three models (IEEM, Dyna-CLUE and InVEST models) iteratively in 5-year time steps. IEEM produces a projection of demand for land for the first time period which we spatially allocate with Dyna-CLUE to produce a LULC map for the beginning of the period (t) and the end of the period (t+5). We modeled each of Colombia's 32 departments individually over a 300-meter spatial grid. We run the soil erosion mitigation model for the period t and t+5 based on the Dyna-CLUE-generated LULC maps. Based on the changes in ecosystem service supply calculated as the difference between each scenario and business-as-usual, an economic feedback is estimated to account for the impacts of changes in future soil erosion mitigation ecosystem service supply. This feedback is introduced in IEEM in t+6 to t+10 which results in a new projection in demand for land accounting for changes in agent behavior estimated in the previous period. This new IEEM-based projection of demand for land is again spatially attributed with Dyna-CLUE and the iteration cycle begins again continuing in 5-year steps until the end of the analytical period in 2040 (Figure 1).



1. Policy scenarios are implemented in IEEM.

2. IEEM estimates impacts on economic indicators and on land use land cover (LULC) change.

3. LULC change estimates are allocated across the landscape to generate a future LULC map.

4. The future LULC map is used to estimate impacts on future ecosystem service flows.

5. Changes in ecosystem service flows are linked back to the economy and step one is implemented once again until the end of the analytical period.

Fig. 1. The Integrated Economic-Environmental Modeling + Ecosystem Services Modeling (IEEM+ESM) workflow with dynamic endogenous feedbacks.
Source: Authors' own elaboration.

We establish a relationship between changes in soil erosion mitigation ecosystem services and agricultural productivity based on a survey of the literature (Panagos et al., 2018). Severe erosion is considered to occur where erosion is greater than 11 tons per hectare per year; we relate the presence of severe erosion to an 8% reduction in agricultural productivity. The feedback introduced in IEEM in the second and subsequent periods to account for changes in soil erosion mitigation services is calculated as described in equation 1, where the area of severe erosion as a difference from business-as-usual is a function of the total area of agricultural land in each department and the relationship between soil erosion mitigation services and agricultural productivity (see S3 for additional details).

$$LPL_d = \frac{SER_d}{TAA_d} \cdot 0.08 \qquad \text{equation 1.}$$

Where:

- LPL_d is the land productivity loss by subscript d department;
- SER_d is the agricultural land area (hectares) subject to severe erosion of >11t/ha/year in each department as a difference from business-as-usual;
- TAA_d is the total agricultural area, both crop and livestock, by department, and;
- 0.08 is the agricultural productivity shock estimated based on the literature (Panagos et al., 2018).

Estimating Changes in Colombia's Wealth

The estimation of how the policy alternatives affect wealth is a key element of this work. For this, we used an adjusted form of genuine savings to focus on the economic and environmental impacts on changes in wealth. This is reasonable, since changes in human capital are often measured by changes in investments in education or lifetime earnings (Lange et al., 2018; World Bank, 2021a), which in our study, do not differ across the business-as-usual case and scenarios. Genuine savings is calculated as in equation 2 (Banerjee et al. 2021; Banerjee, Vargas, and Cicowiez 2020):

$$GenuineSAV_t = GNSAV_t - DeprCapStock_t - DeplForStock_t - DeplMinStock_t - EmiVal_t \qquad \text{equation 2.}$$

Where:

- $GNSAV_t$ = Gross National Savings ($GNDI_t - PrvCon_t - GovCon_t$). This term includes the scenario-impact of changes in ecosystem service supply;
- $GNDI_t$ = 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, and;
- $EmiVal_t$ = Cost of damage from CO_2 emissions; US$30 per ton of CO_2.

For natural capital, the value of depletion is defined as in equation 3.

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

Where:

$qdepl_t$ = quantity of the resource extracted;
$unitrent_t$ = unit rent in year t, the value of which is endogenous in IEEM, and;
$intrat_t$ = interest rate (4% as in (Lange et al., 2018)).

3.0 Results

Modeled land use-land cover and ecosystem services changes

Owing to the structure of the IEEM+ESM workflow, changes in LULC are reported first, followed by impacts on ecosystem service flows and economic impacts. We modeled LULC and ecosystem services at a spatial resolution of 300 meters for each of Colombia's 32 departments, enabling detailed analysis of LULC change - the primary determinant of changes in ecosystem service supply - across the landscape (see Figure S8 in the S3 section).

The main LULC change driver in Colombia is the conversion of forest to grazing land to meet growing demand for land, particularly along the Amazon Forest frontier. Although this is the predominant process of forest loss that we observed in our scenarios, we also observed some conversion of forests to grazing land near roads but far from the forest edge, for example, in the department of Amazonas. Encroachment of cropland into forests is more common in the Pacific regions. Other processes, such as conversion from cropland to grazing land and vice versa occurred though at a smaller scale and mostly in departments on the Pacific coast and in the Andes. Forest and shrub cover loss also occurred in the Llanos region in central Colombia towards the border with Venezuela.

At the national level by 2040, PES and HAB enhance soil erosion mitigation ecosystem services by 3.3% and 16.7%, respectively. The SPS and COMBI scenarios *reduce* erosion mitigation services by 12.5% and 4%, respectively, due to different shares of cropland and grassland, despite similar deforestation trends (Table 1).

Table 1 National-level impacts on ecosystem services supply compared with business-as-usual in percent in 2040.

	PES	SPS	COMBI	PES+SPSe	HAB
Soil erosion mitigation	3.3	-12.5	-4.0	11.4	16.7
Carbon storage	6.3	0.01	6.1	6.8	7.2
Nutrient (nitrogen) retention	7.3	4.9	10.3	6.0	29.4
Nutrient (phosphorus) retention	4.9	0.1	6.1	7.2	18.8
Regulation of annual water yield	6.4	0.6	5.4	6.3	4.8
Biodiversity Intactness	6.4	0.1	6.6	7.3	8.2

PES: Payments for ecosystem services, SPS: Silvopastoral systems, COMBI: PES + SPS, PES+SPSe: PES + endogenized livestock productivity, HAB: Habitat banking. Source: Integrated Economic-Environmental Modeling + Ecosystem Services Modeling (IEEM+ESM) results.

Cropland can have higher rates of erosion than grassland, which is mostly responsible for the reduction of erosion mitigation in the case of SPS and COMBI. Impacts, however, are spatially heterogenous; even in the PES scenario, some departments experienced a reduction in erosion mitigation services.

All scenarios resulted in increased carbon storage, with the HAB and PES+SPSe scenarios showing the greatest increase (Table 1; 7.2% and 6.8%, respectively). Overall, all scenarios except SPS increase water purification ecosystem services with HAB outperforming others in terms of increases in both nitrogen and phosphorus retention (29.4% and 18.8%, respectively). Relative to business-as-usual, all scenarios result in greater evapotranspiration, benefitting Colombia's hydrological systems (see S3). This results in less water runoff, thus reducing the impacts of floods, while maintaining better water quality and more water for dry-season flows and other important biological and ecosystem functions. Compared to business-as-usual, improvements to water regulation in other scenarios range from 0.6% in SPS, to 6.4% in the PES scenario (detailed ecosystem services impacts are shown in S3 and Figures S9-S18).

Economic impacts in 2040: Business-as-usual vs. scenarios

The economic impact of implementing these policies varied with the inclusion of ecosystem service values. When ecosystem service values are not included, the PES scenario would generate competition for crop and livestock land and would result in a US$276 million decline in GDP in 2040 compared with business-as-usual (Table 2). With the importance of agriculture to the incomes of many rural households, household consumption would contract by US$199 million; despite the policy's positive impact on natural capital, the decline in income and savings would push wealth downward by US$330 million. The implementation of SPS on the other hand would have a strong positive impact on GDP (US$694 million) and wealth (US$125 million). These gains are driven by the enhanced productivity of sustainable silvopastoral systems. When comparing the impact of SPS on GDP *when ecosystem services values are included*, positive economic returns to SPS would be over-estimated by US$53 million, due to the uncounted effects of worsening soil erosion.

Table 2 Impacts on macroeconomic indicators as difference between business-as-usual in 2040 in millions of (2019) U.S. Dollars. On the left, scenario impacts including ecosystem services values, and on the right, not including ecosystem services values.

	PES	SPS	COMBI	PES+SPSe	HAB	PES	SPS	COMBI	PES+SPSe	HAB
	Including ecosystem services					Excluding ecosystem services				
GDP	-262	694	549	0	188	-276	747	596	0	111
Genuine Savings	-325	125	-22	-216	1,607	-330	147	-3	-223	1,576
Private consumption	-188	725	444	-27	-237	-199	766	480	40	-299
Private investment	-244	76	-12	-130	134	-247	92	3	-182	114
Exports	-141	115	39	-69	237	-144	127	49	-80	217
Imports	-55	152	97	-1	166	-58	161	104	-3	151

GDP: Gross Domestic Product, PES: Payments for ecosystem services, SPS: Silvopastoral systems, COMBI: PES + SPS, PES+SPSe: PES + endogenized livestock productivity, HAB: Habitat banking. Source: Integrated Economic-Environmental Modeling + Ecosystem Services Modeling (IEEM+ESM) results.

With PES reducing deforestation and thus the supply of land available for crops and livestock, factor availability for agriculture is reduced. This result highlights the importance of investing in agricultural productivity and extension services, which in this case would have compensated for some of the negative economic impacts that arose in implementation of PES+SPSe. In Colombia in particular, there is large scope for enhancing agricultural and livestock factor productivity as it is considered low when compared to factor productivity in neighboring countries (Jiménez et al., 2018).

The joint implementation of PES and SPS in the COMBI scenario would boost GDP by US$549 million with a relatively small negative impact on wealth (US$22 million). In this scenario, double dividends would be achieved with increased income, consumption and savings through heightened economic activity, coupled with increased natural capital stocks and future ecosystem service flows. In PES+SPSe, where baseline GDP is tracked by endogenous adjustment of livestock productivity, the negative impact on wealth is driven by reduced crop and livestock output which negatively impacts household savings, a key component of wealth.

The establishment of habitat banking outperforms other scenarios across most economic indicators and would boost GDP by US$188 million and wealth by US$1.6 billion. The HAB scenario not only would increase natural capital stocks but would also show some additionality for ecosystem services provision. Comparing the HAB scenario's performance with and without the inclusion of ecosystem services values, it is evident that ecosystem services contribute significantly to the economy, by US$77 million and US$31 million to GDP and wealth, respectively.

Cumulative economic impacts in 2040: Business-as-usual vs. scenarios

Examining the cumulative value of wealth as the sum of the annual difference from business-as-usual provides a different perspective from that of Table 2. Where Table 2 shows a decline in wealth from 2020 to 2040 arising from PES (i.e., genuine savings), the cumulative impact on wealth vs. business-as-usual in 2040 is in contrast positive and would generate an additional US$14 billion in wealth (Figure 2). Combined with sustainable silvopastoral systems, wealth would increase by more than US$19.5 billion. Habitat banking again presents clear gains in wealth of over US$16.6 billion. While SPS alone generates important gains when considering the difference between 2020 and 2040, it does not perform as well from the perspective of cumulative wealth (i.e., compared to 2040 business-as-usual).

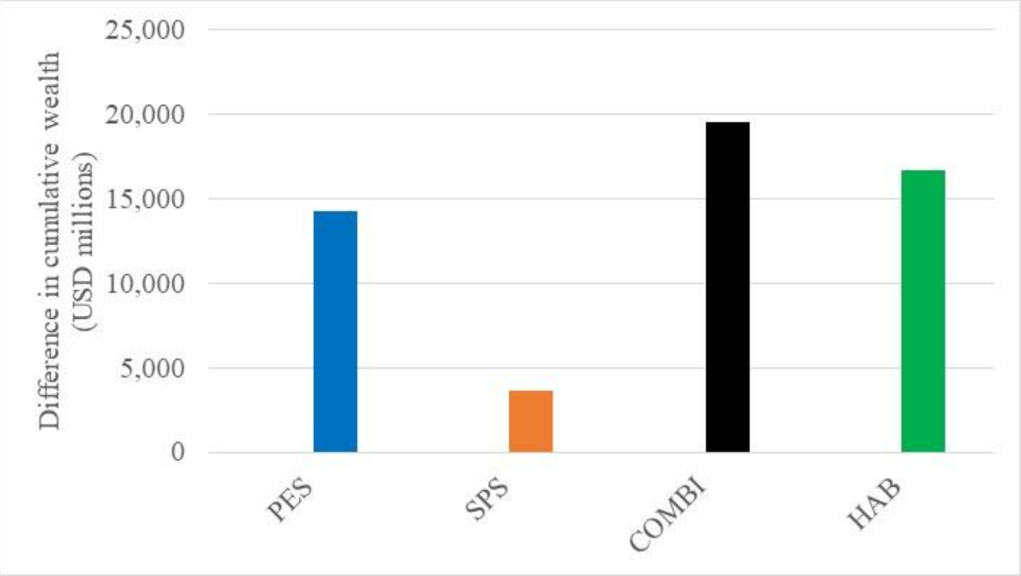


Fig. 2. Cumulative wealth, difference between scenarios and business-as-usual in 2040 in millions of (2019) U.S. Dollars (USD). PES: Payments for ecosystem services, SPS: Silvopastoral systems, COMBI: PES + SPS, PES+SPSe: PES + endogenized livestock productivity, HAB: Habitat banking. Source: Integrated Economic-Environmental Modeling + Ecosystem Services Modeling (IEEM+ESM) results.

Figure 3 shows a smooth trajectory for GDP in the SPS scenario and the offsetting impact of SPS on the downward pull of PES on GDP in COMBI. In the case of HAB, there would be an initial stimulus to the economy, a Keynesian effect from increased government expenditure, in the first two years during which habitat banking is established. This scenario shows gains that extend until 2035, after which there are no additional benefits as the program has achieved its purpose. Specifically, the drop in GDP in the HAB scenario in 2035 is explained by the fact that increases in productivity attributable to habitat banking and the Keynesian effect of increased public expenditure terminate in this year.

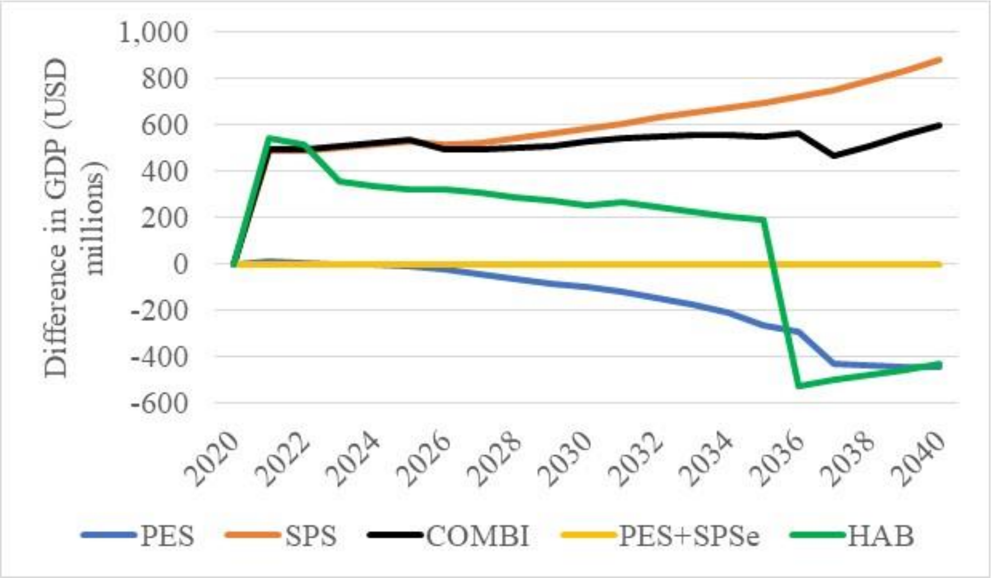


Fig. 3. GDP at factor cost, difference from business-as-usual in millions of (2019) U.S. Dollars (USD). PES: Payments for ecosystem services, SPS: Silvopastoral systems, COMBI: PES + SPS, PES+SPSe: PES + endogenized livestock productivity, HAB: Habitat banking. Source: Integrated Economic-Environmental Modeling + Ecosystem Services Modeling (IEEM+ESM) results.

For most scenarios, we can expect the return to business-as-usual levels in wealth once the investments have been fully implemented after 2034 (Figure 4). Some indicators such as wealth would drop slightly below business-as-usual due to the decrease in output, which in turn translates into a decrease in income, savings and investment. The explanation in terms of decreased investment is directly related to changes in household income. In later years, impacts on wealth tend to gravitate toward business-as-usual levels. That said, it is important to emphasize that over the analytical period, the positive deviations in flows of wealth would outweigh the negative ones and the overall impact of the policy scenarios on cumulative wealth, effectively the stock of Colombia's wealth, would be positive (Figure 2).

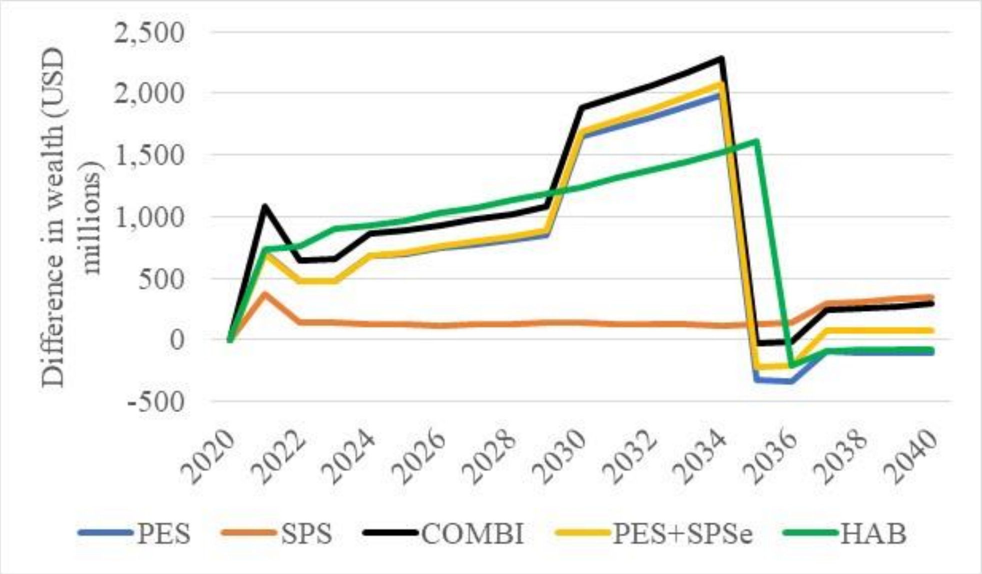


Fig. 4. Wealth, difference from business-as-usual in millions of (2019) U.S. Dollars (USD). PES: Payments for ecosystem services, SPS: Silvopastoral systems, COMBI: PES + SPS, PES+SPSe: PES + endogenized livestock productivity, HAB: Habitat banking. Source: Integrated Economic-Environmental Modeling + Ecosystem Services Modeling (IEEM+ESM) results.

The importance of including natural capital and ecosystem services values in public policy and investment decisions is unambiguous. In the case of PES, ecosystem services contribute an additional US$80 million in wealth (Figure 5). Silvopastoral systems create losses in ecosystem service-based wealth, on the order of US$295 million. Habitat banking outperforms other scenarios with an increase US$457 million in additional ecosystem service-based wealth.

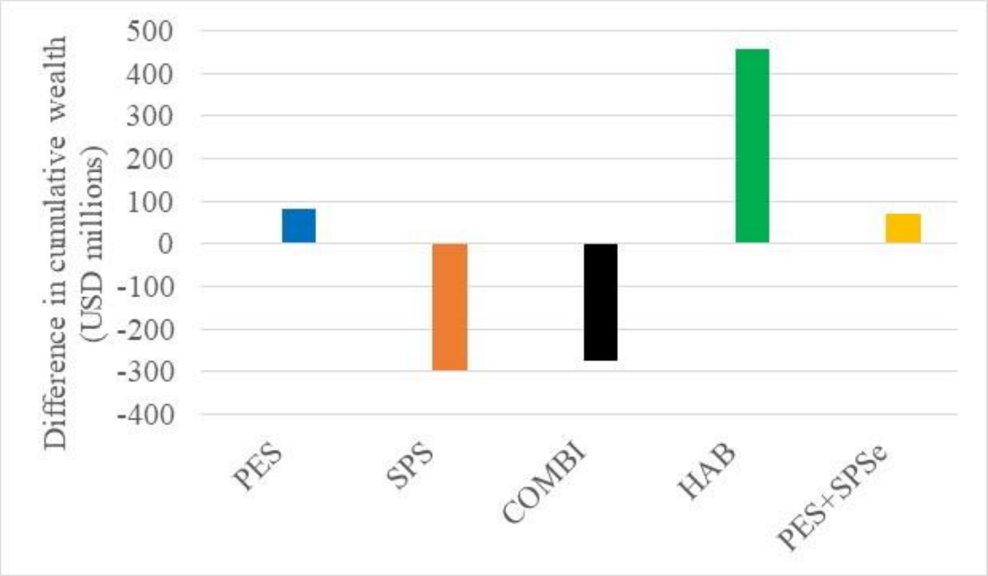


Fig. 5. Difference in cumulative wealth when ecosystem services are valued. Values are expressed as the difference between scenarios and business-as-usual until 2040 in millions of (2019) U.S. Dollars (USD). PES: Payments for ecosystem services, SPS: Silvopastoral systems, COMBI: PES + SPS, PES+SPSe: PES + endogenized livestock productivity, HAB: Habitat banking. Source: Integrated Economic-Environmental Modeling + Ecosystem Services Modeling (IEEM+ESM) results.

Calculating the Net Present Value (NPV) in a benefit-cost framework is a standard approach to assessing the economic viability of public investments. NPV is calculated here using a 12% discount rate, the standard discount rate used by some multilateral investment institutions. NPV is calculated based on equivalent variation, which is the amount of income an individual would need to receive to be as well-off had an investment project not been implemented (Banerjee, Cicowiez, and Moreda 2019). The costs used in the benefit-cost analysis are the investment costs related to the implementation of each of the scenarios as described in S2.

When considering household welfare alone, the implementation of PES results in an economically unviable project with an NPV of negative US$293 million (Figure 6). Coupling PES with silvopastoral systems results in a viable investment with an NPV of US$2.8 billion. The habitat banking scenario is not economically viable when ecosystem service values are not included, with an NPV of negative US$37 million. When the value of natural capital and ecosystem services are included, the outcomes change. The implementation of PES and HAB become strong investment propositions, with an NPV of US$4.4 billion and US$4.9 billion, respectively. The joint implementation of PES with silvopastoral systems results in a NPV of US$7.1 billion, capturing the benefits of both enhanced conservation as well as productivity and rural income opportunities.

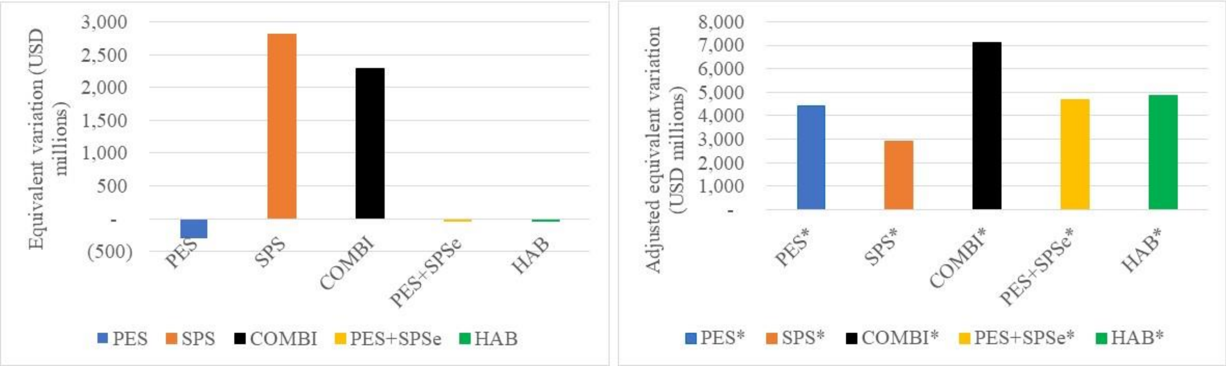


Figure 6. On the left, Net Present Value (NPV) calculated based on equivalent variation in millions of (2019) U.S. Dollars (USD); on the right, NPV calculated based on equivalent variation and adjusted for changes in natural capital and environmental quality in millions of (2019) USD. PES: Payments for ecosystem services, SPS: Silvopastoral systems, COMBI: PES + SPS, PES+SPSe: PES + endogenized livestock productivity, HAB: Habitat banking. Source: Integrated Economic-Environmental Modeling + Ecosystem Services Modeling (IEEM+ESM) results.

4.0 Discussion

We demonstrate the importance of including natural capital and ecosystem service values in public policy and decision making and the benefit-cost analysis used by governments and multilateral institutions around the world. If these values are included they can be expected to improve decision making and long-term socioeconomic outcomes through consideration of the contribution of all forms of capital, namely natural, manufactured and human, to sustainable economic development and wealth. Cumulatively, PES and habitat banking contribute an additional US$14 billion and US$16.6 billion in wealth, respectively, which can help sustain the peace in post-conflict Colombia for current and future generations. These results make the economics of biodiversity explicit and aligned to the assertion that "Economic valuation [of the environment] is always implicit or explicit; it cannot fail to happen at all" (Pearce, 2006).

The IEEM+ESM approach is the first integrated analytical framework to endogenize feedbacks between future changes in land use and ecosystem services and the economy, a research challenge posed in earlier work (Banerjee, Crossman, et al. 2020; Crossman et al. 2018). This approach is critical to account for how flows of ecosystem services have dynamic effects on the economy. It also provides an estimate of the marginal value of ecosystem services, consistent with a country's System of National Accounts, the primary accounting framework used by countries around the world to measure and monitor economic development. Enhanced ecosystem service flows from investing in habitat banking generated an additional US$77 million in GDP; this is effectively the marginal value of ecosystem services. This economic contribution is not trivial since in just one year, it amounts to 69% of the habitat banking scenario impact on GDP. Consistency with the country's System of National Accounts, provides a great deal of credibility to the IEEM+ESM approach compared with welfare-based valuation methods which have been the subject of some criticism.

A handful of earlier studies have explicitly considered the contribution of ecosystem services to economic development in an economy-wide framework. One such study examined how future changes in demand for agriculture would affect the European landscape (Verburg, Eickhout, and van Meijl 2008). A logical extension of this work is to consider how the change in land use would affect future ecosystem service supply. Another example with origins in the WWF's Global Futures project (Banerjee, Crossman, et al. 2020; Crossman et al. 2018; Johnson et al. 2020) linked a global static economy-wide model underpinned by the Global Trade Analysis Project (GTAP) database (Aguiar et al., 2019; Baldos & Corong, 2020; Fischer et al., 2012) with land use land cover and ecosystem services modeling (Chaplin-Kramer et al., 2019; Johnson et al., 2021). Integrating feedbacks between changes in ecosystem service flows and the economy using a dynamic modeling framework as implemented in this study is the next step for global approaches. At the same time, given the complexity of land use dynamics at the local scale, results of the implementation of global approaches require careful country-level validation.

Assessments of opportunities for enhancing natural capital and building strong bioeconomies in post-conflict societies are rare. Analyses are typically ex post and focus on political stability and socioeconomic development while considering the environment and natural capital as independent concerns (Bustos & Jaramillo, 2016; Suarez et al., 2017). This study has shown the importance of considering economy, society and environment as an integrated and inter-dependent system. With a focus on building strong bioeconomies, this assessment considers the contribution of natural capital and ecosystem services to the sustainability of economic development, and in particular, wealth. This emphasis supports a more equitable reconciliation and socioeconomic development process because rural households are the most acutely affected by policies that impact the quantity and quality of natural capital and ecosystem service flows (Fedele et al., 2021).

This study has shown that investment in PES and habitat banking would generate strong benefits in terms of future ecosystem service supply while sustainable silvopastoral systems on average would have a negative impact on ecosystem services. In light of these heterogenous outcomes and with the large rural livelihood development benefits that sustainable silvopastoral systems can provide, a portfolio approach combining these strategies would generate economic gains that are critical to economic stability that sustains the peace while simultaneously mitigating environmental harm and enhancing the productive natural capital base. The evidence presented in this study builds a strong business case for financing such an approach rooted in fostering the development of strong rural bioeconomies.

The IEEM+ESM approach provides critical information for the design of spatially targeted public policy and investment. The spatial distribution of impacts on one ecosystem service are not necessarily the same as those of other ecosystem services. In the case of carbon storage services, overall impacts across scenarios would be positive; however, some departments show a reduction in this service while others compensate with increases. Policy scenario impacts on water quality services would have differentiated spatial impacts, especially in the case of the implementation of sustainable silvopastoral systems.

Biodiversity intactness, while generally increasing across policy scenarios, also reveals spatially differentiated patterns. Knowing where the impacts are the largest and where communities may be most vulnerable can help policymakers target actions to strengthen the natural capital base and mitigate ecosystem service loss. As this study has demonstrated, stocks of natural capital and future ecosystem service flows are inextricably linked to economic outcomes and wealth.

Both PES and habitat banking aim to conserve half a million hectares. PES program distribution across the landscape was conducted based on the relative importance of deforestation in each of Colombia's 32 departments. In contrast, the HAB scenario targeted specific regions of Colombia with high conservation value forests, such as the Tropical Dry Forest, and regions with high ecosystem service supply potential. The results presented demonstrate that there are important advantages to spatial targeting for maximizing economic and ecosystem service outcomes. These increases in ecosystem service flows translate into hard currency when evaluated from an economic standpoint (i.e., in terms of increased farm revenue resulting from reduced soil erosion) and provide compelling evidence for increasing the importance of spatial targeting in PES design where the scientific underpinning of many programs is lacking (Naeem et al., 2015).

Net Present Value calculations represent the 'bottom-line' for public policy and investment evaluated by governments and multilateral institutions around the world. Public investments financed by multilateral development institutions need to generate returns on investment greater than the standard 12% discount rate used by some institutions such as the Inter-American Development Bank (Banerjee, Cicowiez, and Moreda 2019). With the relatively high discount rate used here, results in terms of returns on investment are conservative. A lower discount rate, such as the 3.5% proposed in the UK's Green Book, would result in a much greater contribution of ecosystem services and natural capital to investment returns and a yet more compelling investment case.

Results show just how fundamental the inclusion of the value of natural capital and ecosystem services is in benefit-cost analysis. Future research to understand linkages between additional ecosystem services and the economy in the form of modeled economic feedbacks (see Materials and Methods) will enable a fuller understanding of the economy's dependence on nature and more comprehensive valuation of natural capital. Investment in conservation through PES and habitat banking is not considered economically viable until the value of natural capital and ecosystem service is included. This is the difference between funding and not funding a project. Including the value of ecosystem services, PES and HAB become strong investment propositions with an NPV of US$4.4 billion and US$4.9 billion, respectively. The consequences of valuing ecosystem services and biodiversity in economic decision making are far reaching.

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Data Availability Statement

The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

Supplementary Information
Title: Banking on Strong Rural Livelihoods and the Sustainable Use of Natural Capital in Post-Conflict Colombia

Supplementary Information (S) 1: Overview of IEEM

The Integrated Economic-Environmental Modeling (IEEM) Platform is a Computable General Equilibrium (CGE) model designed for country-level analysis of medium- and long-run development policies with a focus on the environment (Onil Banerjee et al. 2016, 2019). In practice, conventional economic impact analysis quantifies the effects on standard indicators such as Gross Domestic Product (GDP), income, and employment. In addition to these indicators, IEEM captures impacts on stocks of natural capital, environmental quality, wealth, and well-being (Banerjee et al. 2021). IEEM is a future-looking framework that integrates natural capital accounts in the System of Environmental-Economic Accounting (SEEA) (United Nations et al. 2014) format, has environmental modeling modules to capture the dynamics of each environmental asset (Banerjee et al. 2016) and ecosystem services, and enables one to ask, 'what if' questions to estimate how a given policy will impact the three pillars of sustainable economic development—society, economy and environment.

Technically, IEEM is comprised of a set of simultaneous linear and non-linear equations (Banerjee and Cicowiez 2020). It is an economy-wide model, providing a comprehensive and consistent view of the economy, including linkages between disaggregated production sectors and the incomes they generate, households, the government (its budget and fiscal policies), and the balance of payments. It is an appropriate tool for analyzing changes in natural resources management and environmental policy given the fact that it, in an integrated manner, captures household welfare, fiscal issues, and differences between sectors in terms of household preferences, labor intensity, capital accumulation, technological change, and links to international trade and the domestic economy.

In each period, the different agents (producers, households, government, and the nation in its dealings with the outside world) are subject to budget constraints: receipts and spending are fully accounted for and by construction equal (as they are in the real world). The decisions of each agent – for producers and households, the objective is to maximize profits and utility, respectively – are made subject to these budget constraints: for example, households set aside parts of their incomes to pay direct taxes and save, allocating what is left to consumption with a utility-maximizing composition. For the nation, the real exchange rate typically adjusts to ensure that the external accounts are in balance; other options, including adjustments in foreign reserves or borrowing, are possible but may not balance accounts in the long run. Wages, rents and prices play a crucial role by clearing markets for factors and commodities (goods and services). For commodities that are traded internationally (exported and/or imported), domestic prices are influenced by international price developments. Given that Colombia is a small country, it is assumed that international markets demand and supply the country's exports and imports at given world prices.

Over time, output growth is determined by growth in factor employment and changes in total factor productivity (TFP). Growth in capital stocks is endogenous, depending on investment and depreciation. For other factors, the growth in employable stocks is exogenous. For labor and natural resources (with sector-specific factors for natural-resource-based sectors), the projected supplies in each time-period are exogenous. For natural resources, they are closely linked to production projections. For labor, the projections reflect the evolution of the population in labor-force age and labor force participation rates. The unemployment rate for labor is endogenous. TFP growth is made up of two components, one that responds positively to growth in government infrastructure capital stocks and one that, unless otherwise noted, is exogenous.

S2: Scenario design

This section provides details of the scenarios implemented in IEEM.

Business-as-usual scenario projection.

In this analysis, all scenarios are compared to a business-as-usual (abbreviated as BASE in figures and tables) projection. In the business-as-usual case, Colombia's economy is projected to the year 2040 without the implementation of any new public policies or investments. The base year of IEEM for Colombia is 2014, which is the most recent year for which complete National Accounts data are available. For the period from the 2014 to the year 2020, we draw on observed data on Colombia's economy, including observed growth rates for real GDP at factor cost. For the period 2020 to 2040, we draw on projections from the latest International Monetary Fund's World Economic Outlook (IMF 2019) to impose GDP growth rates.

In the business-as-usual scenario, GDP growth is exogenous and imposed by endogenously adjusting TFP. In all policy scenarios on the other hand, GDP growth is endogenous. In addition, we assume that government demand for government services, transfers from government to households, and domestic and foreign government net financing are all kept fixed as shares of GDP at their base-year values. Taxes are fixed at their base-year rates, which means that they will grow at a similar pace to the overall economy. Population projections were obtained from Colombia's National Administrative Department of Statistics. The supply of agricultural land grows by the rate of deforestation, which, for the base-year, varies between 0.02 and 1.8 percent per year across all of Colombia's 32 departments. The flows from extractive natural capital assets such as petroleum and minerals grow at the same rate as GDP, which captures the dynamics of new discoveries.

At the macro level, IEEM, like any other CGE model, requires the specification of equilibrating mechanisms known as model closures for three macroeconomic balances, namely the: (i) government closure; (ii) savings-investment closure, and (iii) balance of payments closure. For the business-as-usual projection, the following closures are used: (i) the government's accounts are balanced through adjustments in the direct tax rate; (ii) the savings-investment balance is achieved with private domestic investment equal to household savings as a fixed share of GDP at the base-year value. Private foreign investment is financed through the balance of payments. Government investment is a fixed share of the government budget, which in turn is a fixed share of GDP at its base-year value, and (iii) the real exchange rate equilibrates the balance of payments by influencing export and import quantities and values. The non-trade-related payments in the balance of payments, specifically, transfers and non-government net foreign financing and foreign direct investment, are non-clearing and kept fixed as shares of GDP.

Furthermore, in the BASE scenario, we impose exogenous projections for all non-trade items in the current account of the balance of payments, such as transfers. In the capital account, we impose exogenous projections for government and non-government foreign borrowing. In turn, this means that foreign savings follows an exogenous path, which is equal to the sum of government and non-government foreign borrowing and foreign direct investment. Consequently, the real exchange rate will adjust to balance the inflows and outflows of foreign exchange, and as a result, exports and imports will adjust.

Regionally disaggregated land areas are required to calibrate IEEM's land market module. Land Use Land Cover (LULC) in the business-as-usual scenario is derived from Colombia's Third National Agricultural Census (DANE 2016). The land use indicated in the census was compared with Colombia's LULC map for 2012, which is based on the CORINE Land Cover Inventory (Figure S). This inventory of 44 land cover classes has a spatial resolution of 25 hectares, was initiated in 1985 with a 1990 reference year, and updates have been produced in 2000, 2006, 2012, and 2018. It is common that there are differences in the land use areas in the census compared with the spatial information drawn from an LULC map. We calibrate the IEEM land market module based on census data (Table S1) but ensure that as far as deforestation is concerned, the rate of deforestation does not exceed the available standing forest for any given year in the base LULC at the Departmental level.

Figure S1. Land use land cover classes (2012)

Land use in the base year of IEEM is determined as follows. Crop areas reported in the agricultural census are equivalent to 8,476,711 ha. This area was regionally disaggregated to Colombia's 32 Departments according to data from local municipal evaluations (MADR 2019). The total livestock area is 34,426,622 ha (DANE 2016) and was regionally disaggregated according to data on herd size from the Livestock Census (ICA 2019). The total area of forest plantations and natural forests are 584,802 ha and 58,971,012 ha, respectively. Both were regionally disaggregated based on data from the Instituto de Hidrología, Meteorología y Estudios Ambientales (IDEAM) (IDEAM 2020).

Establishing the baseline projection of deforestation for each Colombian Department was undertaken in two steps. First, the Departmental distribution of deforestation was drawn from IDEAM for the period 2014 to 2018 (IDEAM 2020). This period was chosen to avoid the spike in deforestation that arose in the first few years of the post-conflict period. The forward projection of deforestation was based on IDEAM's projections from 2020 to 2030, which estimated average deforestation at the national level, equivalent to 389,154 ha in 2030. Based on this figure, we estimated the rate of deforestation by Department and applied it to the standing forest stock each year to project deforestation by Department to 2040 (

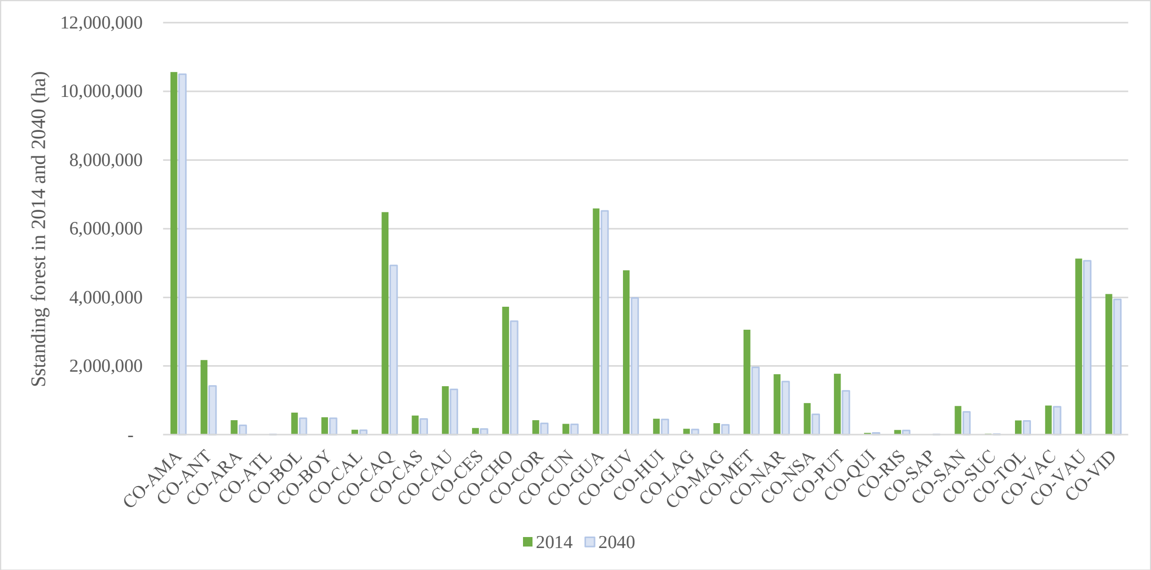
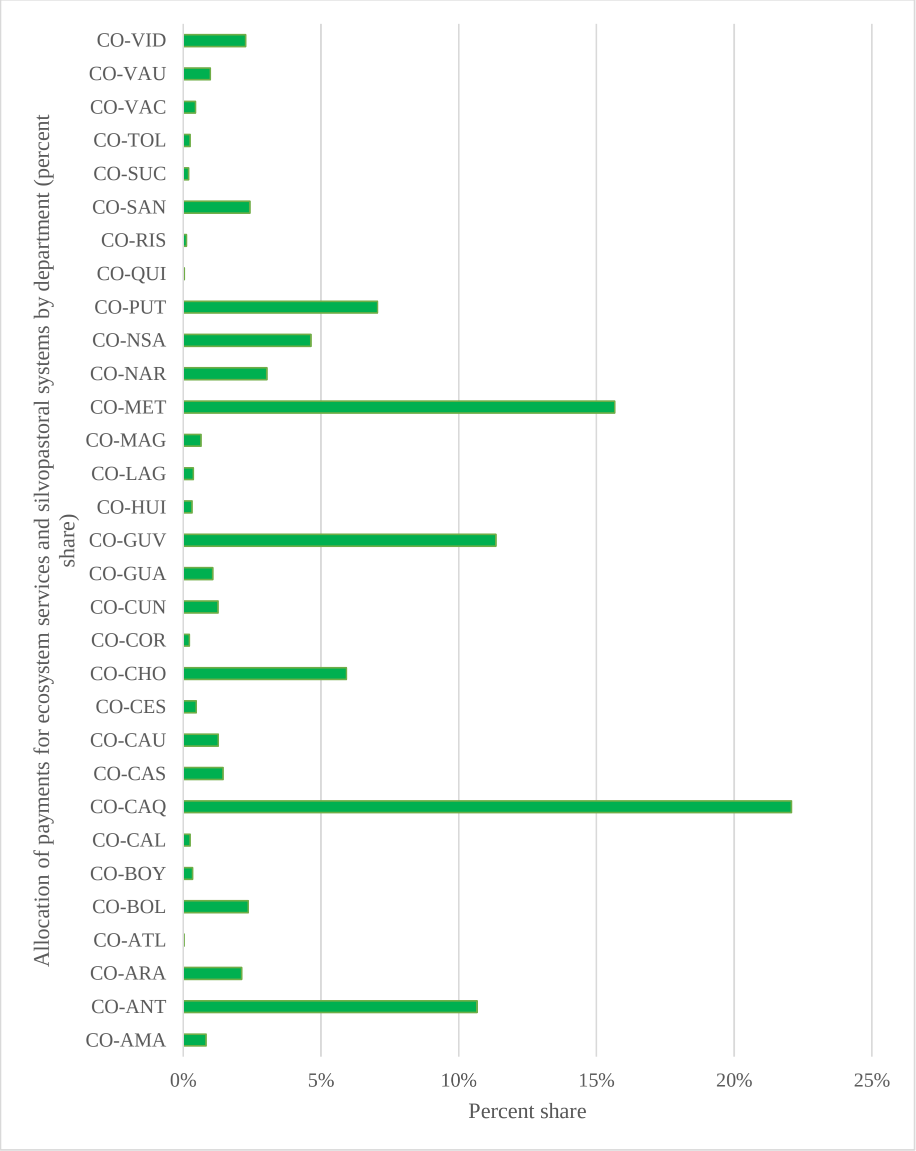


Figure S). Table S1 shows starting LULC in 2014 and projected land use in 2040.

Figure S2. Standing forest in the base year and 2040 in hectares

Policy scenario design

Four scenarios were designed and implemented in IEEM to assess a Government plan developed by the National Council for Social and Economic Policy (CONPES) to expand the Payment for Ecosystem Services (PES) Program (CONPES 2017; DNP 2019). The Program seeks to establish one million hectares of PES over the next 14 years, allocating half of the area to strict preservation and the other half to restoration and the implementation of more sustainable agricultural and livestock systems. Our scenarios simulate: (i) establishing 500,000 ha of PES across the country; (ii) restoring 125,000 ha of degraded pasture areas with more productive silvopastoral systems (SPS), and; (iii) the joint implementation of the two previous scenarios (PES+SPS and a variation of this, PES+SPSe described below). The PES program is funded by the government with landowners as the primary direct beneficiaries.



The allocation of PES and SPS across Colombian Departments follows the shares shown in Figure S3, which is proportional to the base levels of deforestation in each Department. A fifth scenario evaluates the impacts of a parallel conservation strategy for private investment in expanding habitat banking (HAB) following the Terrasos Habitat Bank model (Fundepúblico and Terrasos 2020).

Figure S3. Allocation of PES and SPS by Department in percent share

CONPES (CONPES 2017) has estimated the value of the payments for specific ecosystem services based on the opportunity cost of agriculture and cattle ranching as reflected in the Third National Agricultural Census (DANE 2016). Areas designated for strict preservation will receive between 318,000 and 477,000 Colombian Pesos (COP)/ha/year (between US$84 and US$126 as of May 2020) in PES payments while restoration activities will receive a payment of between 159,000 and 317,999 COP/ha/yr (between US$42 and US$84). Payments for strict conservation will pay up to 75% of the estimated opportunity cost of forgone land use while restoration activities will pay up to 50% of the opportunity cost of forgone land use.

The following describes the scenarios in greater detail:

(i) Payment for Ecosystem Services (PES): This scenario implements 500,000 ha of PES for strict preservation, beginning in 2021 and concluding in 2034 as shown in Figure S4. In this scenario, we take an optimistic approach and assume that one hectare of strict conservation of PES avoids the deforestation of one hectare of forest. This optimism is justified through the assumption that improvements in government allocation of resources to monitoring and enforcement of deforestation legislation will result in greater levels of efficacy in the contribution of PES to avoided deforestation. This means that 500,000 ha of PES will avoid deforestation of 500,000 ha of forest into perpetuity, assuming payments and compliance are maintained, which are prerequisites of a PES program (Börner et al. 2017; Engel, Pagiola, and Wunder 2008; Wunder 2005; Wunder, Engel, and Pagiola 2008). No additional avoided deforestation is assumed past the year 2034 once all PES agreements have been established.

Figure S4. Annual amount of PES established in hectares

The fact that the establishment of PES implies just a one-time reduction in deforestation highlights the importance of complementary measures that can have dynamic impacts on reducing deforestation. Such measures include reducing pressures for the expansion of agricultural land through more productive and sustainable productive practices, and mechanisms for funding additionality in conservation, including for example, habitat banking. Both mechanisms are explored in the scenarios that follow.

PES establishment costs are presented in Figure S5. These costs include establishment and maintenance costs and are treated in IEEM as direct transfers from the Government to property owners. PES design and administrative costs are also included and are financed by the Government. The CONPES Plan presents various mechanisms for financing PES, specifically: water use taxes; transfers from the energy sector; a 1% transfer of current income from municipal and departmental governments, which in 2019 was estimated as 900 billion pesos; a carbon tax, and; international grant financing (CONPES 2017).

Figure S5. PES program costs, millions of USD

(ii) Silvopastoral Systems (SPS): This scenario implements SPS to restore degraded pasture lands and enhance livestock productivity for meat and milk production. As the establishment of PES in some areas can result in a reduction in the current as well as potential future supply of land for crops and livestock, the purpose of this scenario is to explore investments that can reduce demand for agricultural land, reduce pressure for new deforestation and generate revenue to finance the PES program. The data and estimates used to inform the productivity gains and costs in this scenario are based on Rodríguez (2017) who conducted an economic analysis of investing in SPS to improve productivity and reduce greenhouse gas emissions in Colombia (Rodríguez 2017).

In this scenario, we implement a total of 125,000 ha of SPS with two levels of productivity gains considered to account for variability due to soils, climate, and other biophysical conditions. We implement 17,500 ha of high yielding SPS, which are expected to result in a milk production productivity gain of 2.9 times and meat productivity gain of 3.1 times. We implement 87,000 ha of average yielding SPS, which result in both a milk and meat productivity gain of 2.2 times. It is worth noting that the productivity gains found in Rodríguez (2017) are conservative compared to a number of other studies. For example, Chará et al. (2019) found that establishing SPS yielded between 74% and 314% higher milk production and between 683% and 1,116% more meat production. Mahecha et al. (2011) found increases of over 1,300% also in Colombia with similar increases found in Mexico.

Trees are sparsely planted throughout the total 125,000 ha, with their biomass being equivalent to 10,000 ha of an average-aged and stocked forest. The remaining 10,000 ha of the total 125,000 ha are assumed to remain under traditional livestock practices. Livestock producers are responsible for establishment, maintenance, and operational costs, while the Government is responsible for other program costs (Figure S6). Livestock producers receive a total payment in the amount of US$5.012 billion between 2021 and 2036 to cover some of the establishment, maintenance and operational costs incurred.

Figure S6. Sustainable Silvopastoral System costs in millions of USD

(iii) COMBI: The COMBI scenario is the joint implementation of the PES and SPS scenarios.

(iv) Payment for Ecosystem Services and endogenous estimation of livestock Total Factor Productivity (PES+SPSe): This scenario implements the establishment of PES as in the PES scenario and endogenizes livestock productivity such that GDP in this scenario tracks GDP in the BASE. This effectively renders program costs GDP neutral.

(v) Habitat Bank Scenario (HAB): This scenario implements the expansion of Colombia’s habitat banking system based on program structure and costs of the existing Terrasos Habitat Bank (Fundepúblico and Terrasos, 2020). The additional area brought under habitat banking is 500,000 ha where 80% of the area will be designated as strict conservation and 20% as restoration. In IEEM and the LULC change modeling, the areas of strict conservation will be unmanaged forest, primarily tropical and tropical dry forests. Target areas will include the Caribbean coast region, the Cauca and lower Magdalena region and the center region on the Tochecito valley. Specifically, areas were distributed in equal parts among the Departments in each of these regions. For the Caribbean Region, areas were established in Departments of Atlántico, Bolivar, Cesar, Laguajira, Magdalena, Sucre. In the Valle Tochecito, areas were established in Tolima and Quindio. In the Andean and Pacific Region, areas were established in Cauca.

The 200,000 ha of restoration areas will require activities including planting of native trees, installation of fences and ongoing monitoring over a period of 30 years. The cost for restoration or preservation is US$3,275/ha with an additional cost of US$1,607/ha for administration and overhead for a total cost of US$4,882.

There are two mechanisms through which the establishment of the habitat bank will affect the economy. The first is through avoided deforestation, which will be equivalent to the amount of the area conserved and restored, which is 500,000 ha. As with the PES scenario, we implement a government reallocation of resources to enhance the effectiveness of the monitoring and enforcement of deforestation legislation. The second is through reduced transaction costs for the mining sector, which is anticipated to be the primary clients of the habitat bank initially. Mining sector firms will engage in habitat banking to offset conservation liabilities for activities that generate environmental impacts.

Habitat banking is an attractive alternative for firms whose activities generate environmental impacts. Conservation and restoration activities are usually not part of mining and other sector firms' competitive advantage. By investing in habitat banking, firms reduce their transaction costs which is modeled as a reduction in factor use to simulate more efficient mining sector operations. The cost of the habitat banking program is covered by an increase in Government expenditure, which is financed through a payment made by the mining sector to the Government. The Government revenues raised by this payment are set to an amount equivalent to the business-as-usual costs of mining sector conservation off-setting. The reduced transaction costs generated through habitat banking are set equivalent to the business-as-usual cost of conservation off-setting.

The initial investment in habitat banking will occur in year 2021. Avoided deforestation will occur linearly between 2021 and 2035. Legal and administrative structuring will take place in years 2021 and 2022. Operations will begin in year 2023, including restoration activities, which will take place over a 13-year period, until year 2035. Preservation activities also begin in year 2023. The habitat bank guarantees conservation of the 500,000 ha over a 30-year period. Biodiversity credit sale will begin in year 2023, progressively increasing until all credits are sold by year 2030. Seventy percent of all required financing will be from domestic private investment and 30% will be from external debt.

For all of the above non-business-as-usual scenarios, we change the macroclosures as follows: (i) for the savings-investment balance, instead of imposing a fixed GDP share for private investment, investment spending (including its GDP share) is endogenous, adjusting to make use of available financing in the context of exogenous household savings rates; (ii) for the government balance, the treatment depends on the simulation design; specifically, the clearing variable is changed as part of the simulation design, and; (iii) for the balance of payments, the treatment is the same as in the business-as-usual scenario with the real exchange rate balancing the account.

Beyond the macrobalances, the policy scenarios also differ from the business-as-usual scenario in that the following payments are fixed at the levels generated in the BASE scenario, instead of as fixed shares of GDP: domestic government financing (fixed in domestic currency, implicitly indexed to the Consumer Price Index, the model numeraire), and; private and government transfers and financing from the rest of the world (fixed in foreign currency).[1] The reason for this is that in the BASE scenario, it is assumed that many variables follow GDP as a constant share. For example, if GDP increases in the BASE scenario, remittances will need to increase to keep the ratio to GDP constant. This is a reasonable assumption to generate a business-as-usual scenario, but not a good assumption for the policy scenarios themselves. For example, if we simulate an agricultural productivity shock that has a positive impact on GDP, there is no reason why remittances should also increase. Therefore, we change how some variables behave in the scenarios, including remittances in this hypothetical example.

Instead of assuming that these variables' proportion to GDP is constant, we assume that in real terms they evolve the same as in the BASE scenario. In other words, the same value of remittances in the above example continues to enter the country, regardless of what happens to GDP as a result of the agricultural productivity shock. This feature is critical for a sensible interpretation of the results. Specifically, scenario impacts therefore are solely attributable to the change in agricultural productivity and not confounded by other features. The same type of reasoning applies to other payments that change their behavioral rule between business-as-usual and the scenarios analyzed.

S3: Methods and detailed results

The linked IEEM and ecosystem services modeling (IEEM+ESM) workflow

The IEEM+ESM workflow is outlined in Figure S7. This workflow is an innovation on previous work (Banerjee et al. 2020) with the integration of dynamic endogenous feedbacks between the economic system, LULC change and ecosystem service flows. The three models, IEEM, the LULC change model and the ecosystem services models are run iteratively in 5-year time steps for the analytical period from 2020 to 2040. In this application, we use a multi-regional version of IEEM for Colombia, which disaggregates Colombia into its 32 Departments. The first step in the IEEM+ESM workflow is to generate a baseline projection for the first time period. IEEM produces results for the first period in terms of impacts on economic indicators, natural capital and demand for land. The projected estimates of demand for land for the first period are allocated spatially with the LULC change model and a LULC map is produced for the beginning of the period t and the end of the period t+5. We model each of Colombia's 32 Departments individually over a 300-meter spatial grid.

Figure S7. The IEEM+ESM workflow with dynamic endogenous feedbacks

The ecosystem service models, in this case, carbon storage, sediment retention, nutrient retention (a proxy for water quality) and water regulation, are parameterized based on the IEEM ecosystem service model datapackets which contain the best available local and

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[1] For the BASE scenario, imposing GDP shares has the advantage of generating a balanced evolution of targeted indicators. However, for non-base scenarios (which will be compared to the base and to each other), it is not reasonable to assume that, for example, in response to changes in the exchange rate or GDP, payments in foreign currency automatically are adjusted sufficiently to stay unchanged as shares of GDP. Fixing these payments in foreign currency has the additional advantage of leveling the playing field across the different simulations – they are to an identical extent able to rely on payments from the rest of the world – and, unless otherwise noted, the level of foreign liabilities is identical at the end of the simulation period.

global data, in this case including (1) spatial datasets and (2) parameter tables adapted for use with Colombian land cover data and nationally specific coefficients (where available) required by the ecosystem service models (Inter-American Development Bank 2021). The ecosystem service models are run for the period t and t+5 based on the LULC maps generated in the previous step. Ecosystem service model results are generated for each of Colombia's 32 Departments. Based on the changes in ecosystem service supply calculated as the difference between each scenario and business-as-usual, an economic shock is estimated to account for the economic impacts of changes in future ecosystem service supply. In the next iteration, this shock is introduced in IEEM in t+6 to t+10, and the iteration cycle begins again. These iterations continue in 5-year steps until 2040.

Changes in ecosystem service supply affect the economy through various mechanisms. Increased soil erosion, for example, reduces agricultural productivity (Borrelli et al. 2017, 2017; Panagos et al. 2018; Panagos, Borrelli, and Robinson 2015; Pimentel 2006; Pimentel et al. 1995). Increased erosion and nutrient run-off affect water quality, which can have implications for water treatment costs, human health and tourism values (Aguilera et al. 2018; O. Banerjee et al. In preparation; Keeler et al. 2012; O'Neil et al. 2012; Paerl and Huisman 2008; STAC 2013). While this workflow could be used to endogenize the impact of changes in a range of ecosystem service supply, in this application we focus on how changes in erosion mitigation ecosystem services interact with the economy through their impact on agricultural productivity.

The impact of soil erosion mitigation ecosystem services on agricultural productivity

We estimate the impact of changes in soil erosion mitigation ecosystem services on agricultural productivity based on a survey of the literature. Severe erosion is considered to occur where erosion is greater than 11 tons per hectare per year. In our business-as-usual projection, we identify the number of pixels exhibiting severe erosion. We estimate the land area subject to severe erosion as the number of pixels with severe erosion multiplied by the spatial resolution of the LULC map. Next, we identify the number of pixels in each scenario that exhibit severe erosion and multiply it by the spatial resolution of the LULC map. If the area of severe erosion is greater in the policy scenario than in the business-as-usual projection, the increase in erosion is attributable to the policy scenario.

Based on a survey of the literature (Panagos et al. 2017), we relate the presence of severe erosion to a reduction in agricultural productivity of 8%. To create a feedback between changes in ecosystem services and the economic system represented by IEEM, we apply equation 1 to the business-as-usual case and to each scenario:

$$LPL_d = \frac{SER_d}{TAA_d} \cdot 0.08 \qquad \text{equation 1}$$

Where:

- LPL_d is the land productivity loss by subscript *d* Department;
- SER_d is the agricultural land area (hectares) subject to severe erosion of >11t/ha/year in each Department as a difference from business-as-usual;
- TAA_d is the total agricultural area, both crop and livestock, by Department, and;.

- 0.08 is the agricultural productivity shock estimated based on the literature (Panagos et al. 2017).

We implement this agricultural productivity shock in IEEM and implement iterative runs of all three models as described above.

Land Use Land Cover Change Modeling Methods and Detailed Results

Land use conversions are expected to take place at locations with the highest suitability for the specific type of land use. Suitability represents the outcome of the interactions between the different actors and decision-making processes that have resulted in a specific spatial land use configuration. The preference of a location is empirically estimated from a set of factors that describe the location characteristics of individual land use and land cover classes. We use the IEEM-enhanced, Dynamic Conversion of Land Use and its Effects (Dyna-CLUE) model (Veldkamp and Verburg 2004; P. H. Verburg et al. 2021; Peter H. Verburg et al. 2002; Peter H. Verburg and Overmars 2009) to spatially allocate LULC change using empirically quantified relationships between land use and location factors, in combination with the dynamic modeling of competition between land use types. In the Dyna-CLUE modeling framework, suitability is calculated by first developing a binomial logit statistical model of two choices: the presence of a particular land use type at a specific location (grid cell) or its absence. The location suitability is the underlying driver of this choice. However, the location suitability cannot be observed or measured directly and therefore has to be calculated as a probability. The function that relates these probabilities with the biophysical and socio-economic location characteristics is defined in a logit model as follows:

$$\log\left(\frac{P_i}{1-P_i}\right) = \beta_0 + \beta_1 X_{1,i} + \beta_2 X_{2,i} \cdots + \beta_n X_{n,i} \qquad \text{equation 2}$$

where P_i is the probability of a land use type occurring on a specific grid cell with location i, and; X's are location factors.

The coefficients (β) are estimated through logistic regression using the observed land use pattern as the dependent variable.

We used a wide variety of location factors to empirically study the occurrence of different LULC types in Colombia (Table S2). Most of them come from relatively recent global datasets, which are coarser than the 200-meter (m) resolution that was applied in this study. Therefore, all data were resampled to 200 m to match the native land cover resolution. We also analyzed how correlated the location factors are to exclude highly correlated variables. The variables of temperature and elevation were highly correlated in the Colombian case, due to the effect of the Andes, however we kept them both, as they are both important driving factors for agricultural activities. Additionally, location specific addition of 'land degradation' was used to guide the allocation of the silvopastoral systems in the SPS, COMBI and PES+SPSe scenarios. These systems were allocated to areas with high erosion to be consistent with the scenario definitions themselves. In these scenarios, we used the same suitability for the silvopastoral system as for pastures but increased the suitability in areas with high erosion by 0.1 and decreased the suitability in pasture systems in the same areas by 0.05. In this way, SPS was spatially targeted in degraded areas.

We performed binary logistic regressions for the individual land use types using forward conditional regressions, where we excluded all insignificant variables ($P<0.05$). First, we prepared balanced random samples of presence and absence of each land use type: we randomly selected 1,000 points where the specific land use type is found, constrained by a 1 km minimum allowed distance between sample points. We then selected 1,000 points where the specific land use type is absent. We used this balanced sample to collect information on the location factors, which we then used to perform binary logistic regression. The same procedure was performed for all land use types, except forest plantations, which were not observe in the landscape to the extent that would allow such a large sample. We therefore selected 350 presence and absence points each for forest plantations. To assess the quality of the regression models, we calculated the Area Under Curve (AUC) of the Receiver Operating Characteristic. In this way, we can also estimate how well our statistical model captures the suitability for a given land use type based on the location factors used.

We can observe the influence of different socio-economic and biophysical characteristics on the spatial distribution of different land use types (Table S3). Cropland is more likely to be present in areas close to markets, lower population density, but higher rural population density. Biophysical factors do not play such a significant role, which can be again explained by the fact that different crops with different requirements in terms of soil and climate are represented in this class. Grazing areas also occur in areas with good market access, but seemingly poorer biophysical conditions (lower organic content, higher pH and lower precipitation). Forest plantations are situated in areas different from natural forests. Forest plantations are generally located closer to markets and on soils that are better drained and have a higher clay content. An overview of LULC in Figure S8 shows Colombia's original 2014 LULC, our projected LULC in the BASE in 2020 and all scenario LULC in 2040. While changes in LULC in Figure S8 are difficult to detect at the scale presented, these changes drive impacts on ES supply.

Figure S8. LULC maps for initial land cover (2014), business-as-usual in 2020, and all 2040 scenarios

In Figure S8, the business-as-usual and five scenarios differ in 2040 primarily in terms of the amount of cropland and grazing land and their spatial distribution. All scenarios project land use change trends that have been observed in Colombia over the past decades.

Figure S9. Scenario impact on land use and land cover, highlighting converted areas by scenario by 2040

In Figure S9 we highlight the areas converted from forest to other uses by scenario by 2040. LULC change is modeled individually (and independently) for each of Colombia's 32 Departments; such detailed LULCC modeling at the national scale is uncommon. This approach enables a detailed analysis of LULC change, which is the main driver of changes in ecosystem service supply, as well as the spatial targeting of the policy scenarios. As an example, Figure S10, presents LULC across scenarios for the Department of Cauca in Colombia's southwest. This figure highlights, for example, how the differences in areas converted to cropland differ across scenarios. Smaller changes in conversion to grazing are detected in PES and HAB, for example, when compared with the business-as-usual scenario.

Figure S10. Detailed scenario impacts on LUCC, Department of Cauca

Figure S8 shows the annual change in deforestation (Panel A), crops (Panel B) and livestock (Panel C) areas. The projection of deforestation over the analytical period is described in S2. In summary, the supply of agricultural land grows by the rate of deforestation, which, for the base-year, varies between 0.02 and 1.8 percent per year across all of Colombia's 32 departments. In all scenarios but SPS, deforestation is reduced. With deforestation generating cleared land, this land is distributed between used based on relative returns to land. Changes in land use fundamentally drive changes in future ecosystem services supply and economic outcomes.

Figure S11. Annual change in deforestation, cropland and livestock for Colombia
Panel A. Annual change in deforestation
Panel B. Annual change in crops in hectares
Panel C. Annual change in livestock in hectares

S4: Biodiversity and Ecosystem Services Modeling Detailed Results

Figure S9 provides a visual overview of the performance of each scenario in terms of the ecosystem service production potential. Scenarios in these charts are compared against each other with total ecosystem service values for all scenarios presented as a normalized index. It is important to note that while some departments showed a loss in ecosystem services, in some cases the reduction in this ecosystem service was attributable to small differences between business-as-usual and the scenarios, though the calculated percent difference can be large. For example, a 10 hectare increase in erosion in the business-as-usual scenario compared with a 14 hectare increase in a scenario translates into a scenario impact of 40%.

Figure S12. Summary of scenario performance in terms of ES (scenarios compared against each other)

Figure S13 summarizes changes in erosion mitigation ecosystem services between all scenarios and the business-as-usual case in 2040. Positive values indicate that the scenario has a positive impact on erosion mitigation ecosystem services (with lower soil loss). Negative values indicate that there was a reduction in erosion mitigation ecosystem services (with higher soil loss). Figure S14 evaluates scenario impacts on carbon storage. Positive values indicate that the carbon storage potential in a scenario is higher than in the business-as-usual scenario. Negative numbers indicate that the scenario has a lower carbon storage potential compared to business-as-usual. All scenarios result in increased carbon storage compared to business-as-usual, with HAB and PES+SPS being the most beneficial.

While the habitat banking scenario map may appear to show that it has generated less benefits than others, this is attributable to the fact that yellow regions were generally on the lower end of the interval band classification, though the overall outcomes were positive.

Figure S13. Changes in erosion mitigation services in 2040 as a difference from base in percent. Numbers next to the scenario name describe the change on a national level for the scenario

Figure S14. Differences in carbon storage in 2040 as a difference from business-as-usual in percent. Numbers below the scenario name describe the change on a national level for the scenario

Figure S15 and Figure S16 display percentage changes in water purification ecosystem services, specifically, nitrogen and phosphorus, comparing all scenarios with business-as-usual in 2040. Positive values indicate an increase in water purification ecosystem services and that less nutrients reach the waterways compared to the business-as-usual case. Negative values indicate a reduction in water purification ecosystem services and that more nutrients are delivered to the waterways in the scenario compared to the business-as-usual case. The results show that overall, all scenarios except SPS increase water purification ecosystem services when compared with business-as-usual; HAB being the most beneficial, both in terms of nitrogen and phosphorus retention.

Figure S15. Differences in nitrogen retention in 2040 as a difference from business-as-usual in percent. Numbers below the scenario name represent the overall change.

Figure S16. Differences in phosphorus retention in 2040 as a difference from business-as-usual in percent. Numbers below the scenario name represent the overall change.

Figure S17 presents the percentage change in the regulation of hydrologic water flows. In the InVEST annual water yield model, water yield is expressed as the annual volume of water in cubic meters (m^3) that is available to flow back into streams and rivers. When deforestation rates are higher and forest cover is lower compared with the business-as-usual case, water yield increases. In this study, we focus on the regulation of water flows. Since the policy scenarios generally result in lower deforestation rates and higher forest cover than business-as-usual, the annual water yield volume calculated by InVEST is lower in the policy scenarios. The regulation of hydrologic water flows on the other hand increases with more water used for ecological functions including evapotranspiration. This increase in regulation of water flows indicates a higher capacity of ecosystems to mitigate floods in the case of extreme rainfall events as well as overall regulation of water quantity. In summary, in the policy scenarios where deforestation rates are reduced and forest cover increases relative to business-as-usual, annual water yield declines but the regulation of hydrologic water flows shown in Figure S17 increases.

Figure S17. Differences in regulation of hydrologic water flows in 2040 as a difference from BASE in percent. Numbers below the scenario name describe the change on a national level for the scenario.

Figure S18 shows the scenario impacts on biodiversity compared to business-as-usual in 2040 expressed as a percent change in the Biodiversity Intactness Index (BII). A positive number indicates that the scenario has a positive impact on biodiversity when compared with business-as-usual. A negative number indicates a reduction in biodiversity compared with business-as-usual. Overall, all scenarios have a positive impact on biodiversity.

Figure S18. Scenario impacts on BII compared to business-as-usual in 2040. Numbers below the scenario names define the difference in BII for scenario on the national level.

S5: Biodiversity Assessment Methods

To analyze how changes to LULC impact biodiversity levels, we calculated the composite BII. The BII presents the average abundance of originally present species across a broad range of species, and is defined as a coefficient for relative to the abundance in an undisturbed habitat (Hudson et al. 2017; Newbold et al. 2016).

We used the PREDICTS database (Trustees of the Natural History Museum, London n.d.), an extensive database collecting case study information on the relationship between land use and biodiversity (Hudson et al. 2017; Newbold et al. 2016). PREDICTS has 32 million observations from over 32,000 locations and covers more than 50,000 species. For Colombia alone, we used data from a collection of 285 locations where the relationship between land use change and biodiversity have been monitored and assessed (Echeverría-Londoño et al. 2016). Using mean BII values from Echeverria-Londoño et al. (2016), presented in Table S4, we were able to assign BII coefficients to different land use types and calculate the composite BII. Calculating a composite BII enabled us to compare different scenarios through time relative to the business-as-usual scenario.

While the BII might seem like a simple and straightforward approach, it is a data-demanding synthesis that has been made possible by the extensive PREDICTS database, which is continuously being updated with new documented observations on the relation between biodiversity and land use. See Table S4.

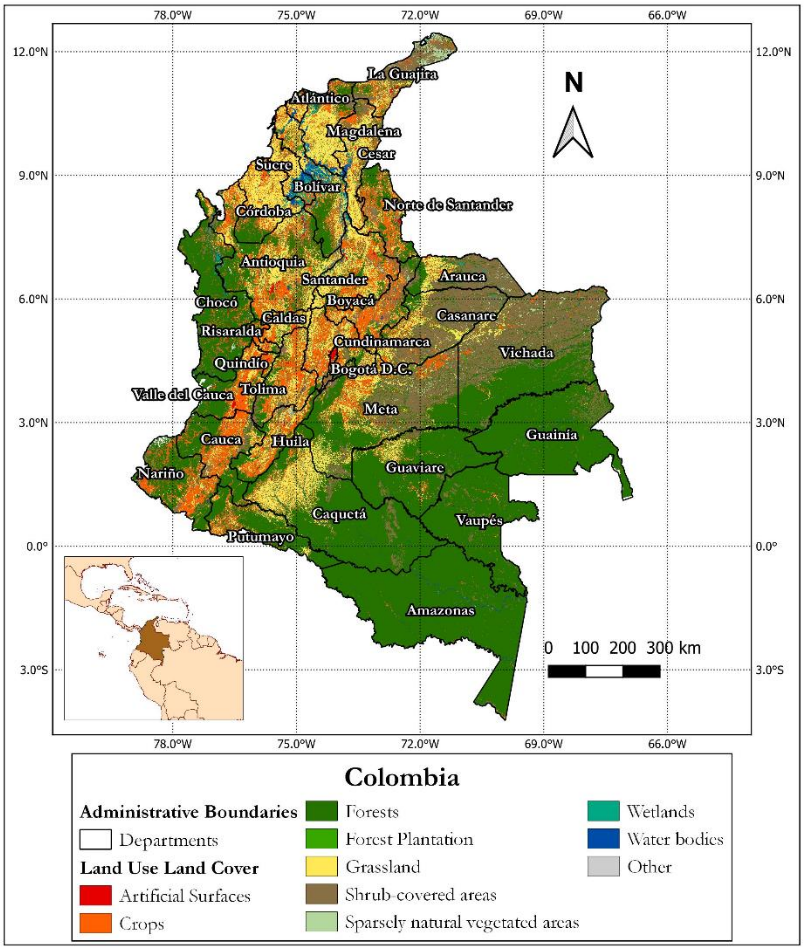


Figure S1. Land use land cover classes (2012). Source: Authors' own elaboration, based on Coordination of Information on the Environment (CORINE) land cover **(IDEAM 2010)**.

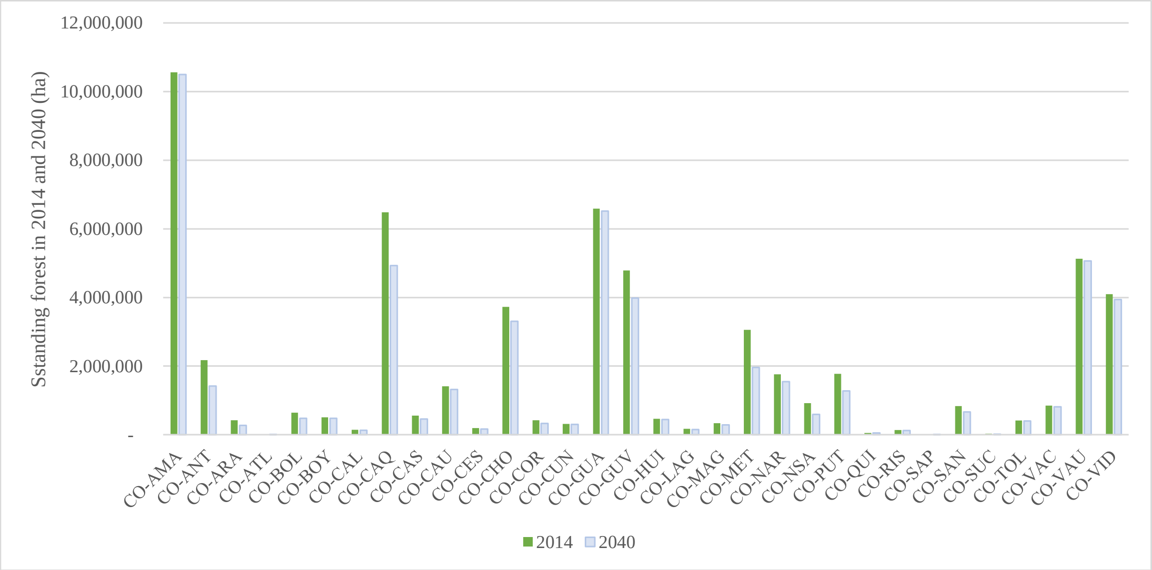


Figure S2. Standing forest in the base year and 2040 in hectares for Colombia’s 32 departments. Source: Authors’ own elaboration based on Instituto de Hidrología, Meteorología y Estudios Ambientales (IDEAM) (2019 and 2020). Department codes: AMA = Amazonas, ANT = Antioquia, ARA = Arauca, ATL = Atlántico, BOL = Bolívar, BOY = Boyacá, CAL = Caldas, CAQ = Caquetá, CAS = Casanare, CAU = Cauca, CES = Cesar, CHO = Chocó, COR = Cordoba, CUN = Cundinamarca, GUA = Guainía, GUV = Guaviare, HUI = Huila, LAG = La Guajira, MAG = Magdalena, MET = Meta, NAR = Nariño, NSA = Norte de Santander, PUT = Putumayo, QUI = Quindío, RIS = Risaralda, SAN = Santander, SAP = San Andrés y Providencia, SUC = Sucre, TOL = Tolima, VAC = Valle del Cauca, VAU = Vaupés, VID = Vichada.

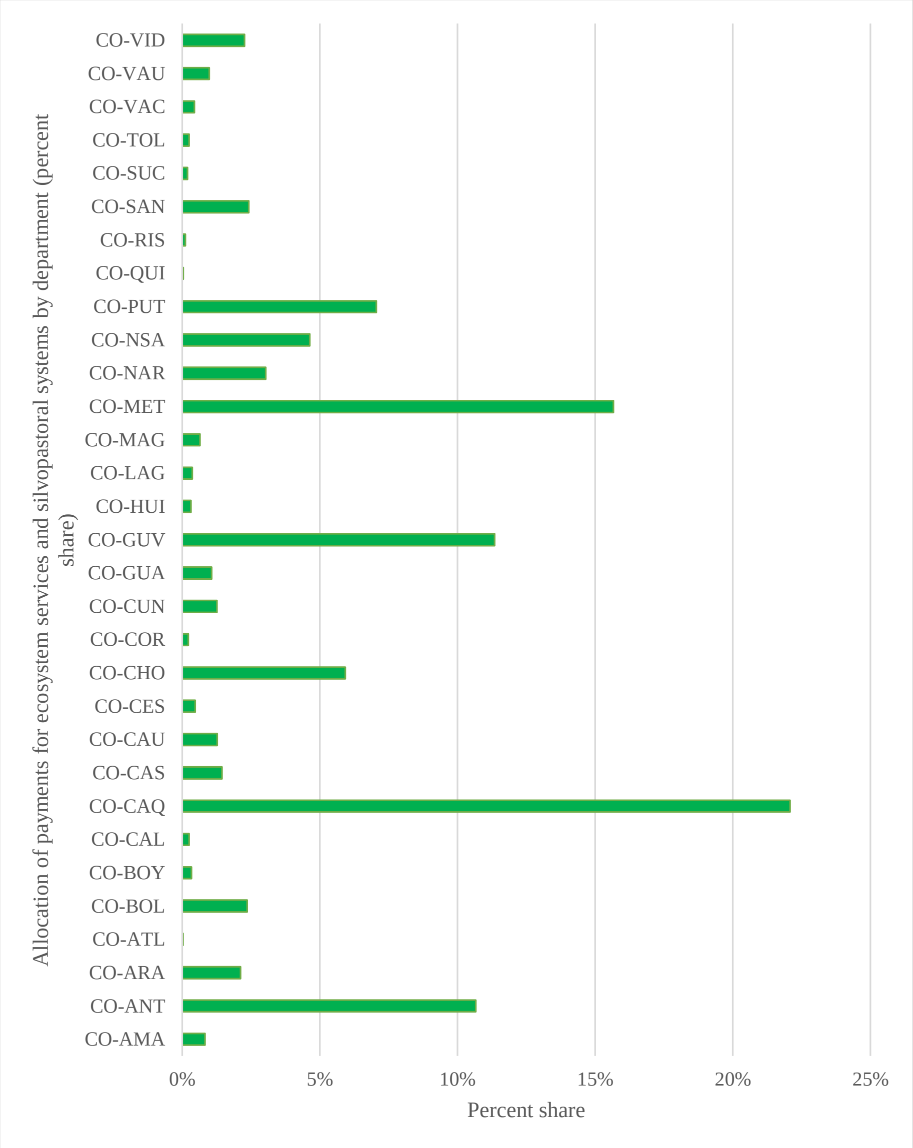


Figure S3. Allocation of payments for ecosystem services (PES) and silvopastoral systems (SPS) by Department in percent share. Source: Authors' own elaboration based on data from Ministry of the Environment and Sustainable Development. Note that Bogota's Federal District is aggregated with Cundinamarca throughout this paper. Department codes: AMA = Amazonas, ANT = Antioquia, ARA = Arauca, ATL = Atlántico, BOL = Bolívar, BOY = Boyacá, CAL = Caldas, CAQ = Caquetá, CAS = Casanare, CAU = Cauca, CES = Cesar, CHO = Chocó, COR = Cordoba, CUN = Cundinamarca, GUA = Guainía, GUV = Guaviare, HUI = Huila, LAG = La Guajira, MAG = Magdalena, MET = Meta, NAR = Nariño, NSA = Norte de Santander, PUT = Putumayo, QUI = Quindío, RIS = Risaralda, SAN = Santander, SAP = San Andrés y Providencia, SUC = Sucre, TOL = Tolima, VAC = Valle del Cauca, VAU = Vaupés, VID = Vichada.

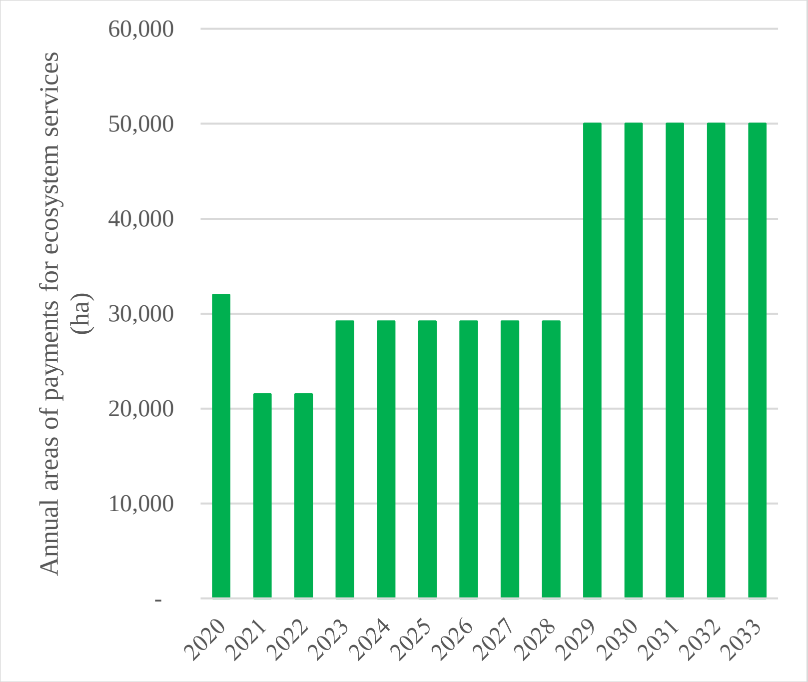


Figure S4. Annual area of payments for ecosystem services (PES) established in hectares. Source: Authors' own elaboration based on National Council for Social and Economic Policy (CONPES), 2017.

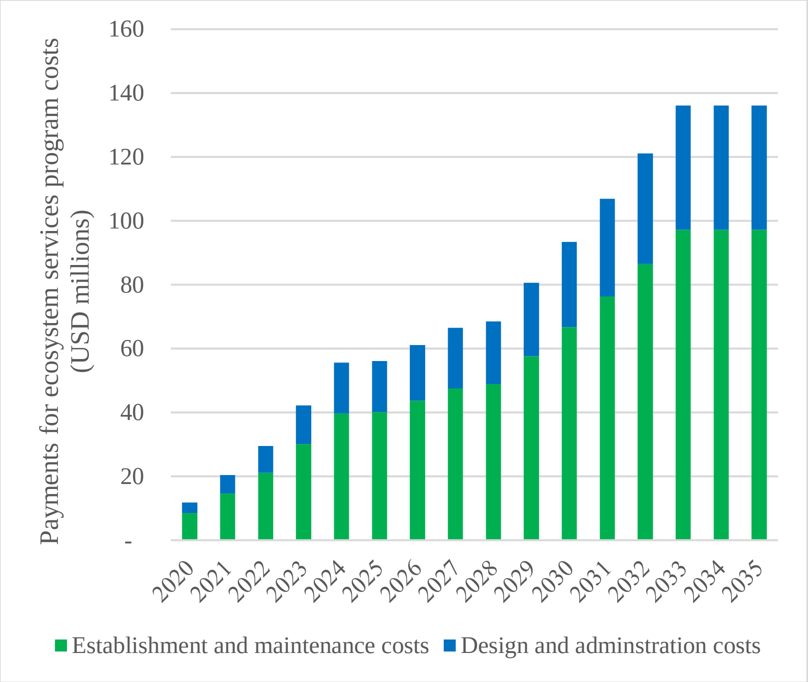


Figure S5. Payments for ecosystem services program costs, millions of U.S. Dollars (USD). Source: Authors' own elaboration based on (CONPES 2017).

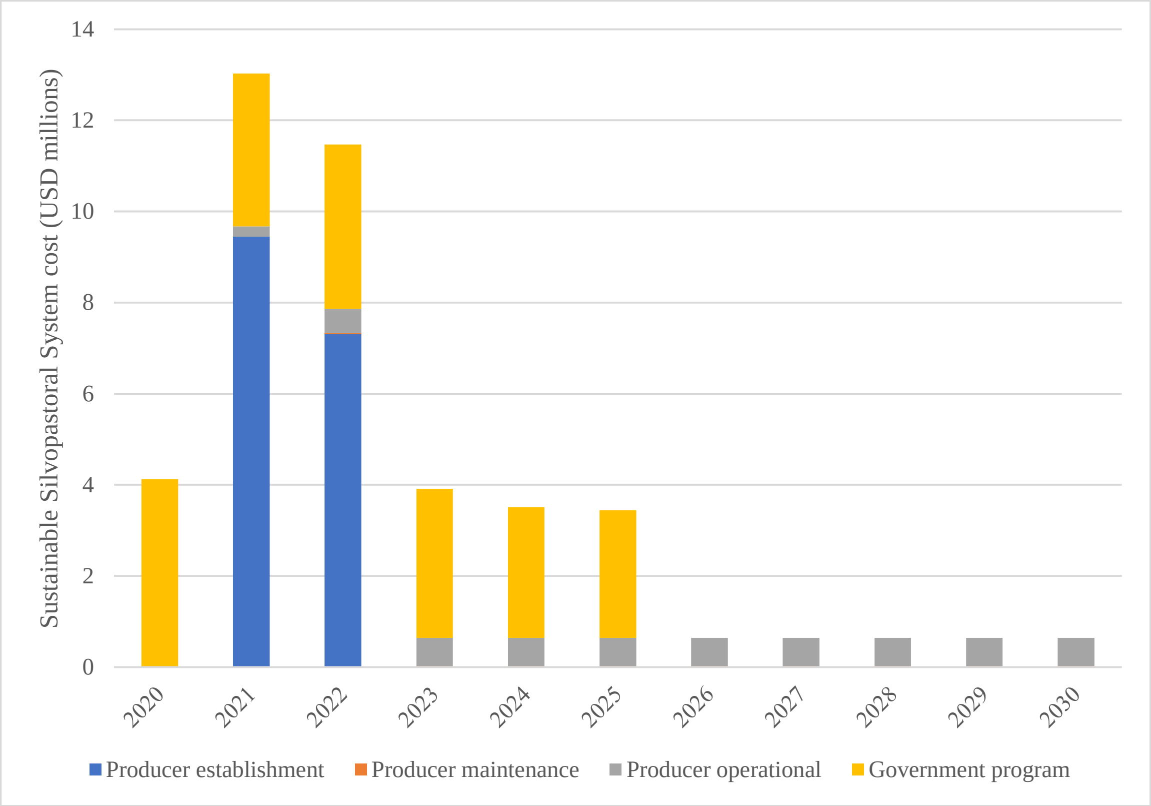
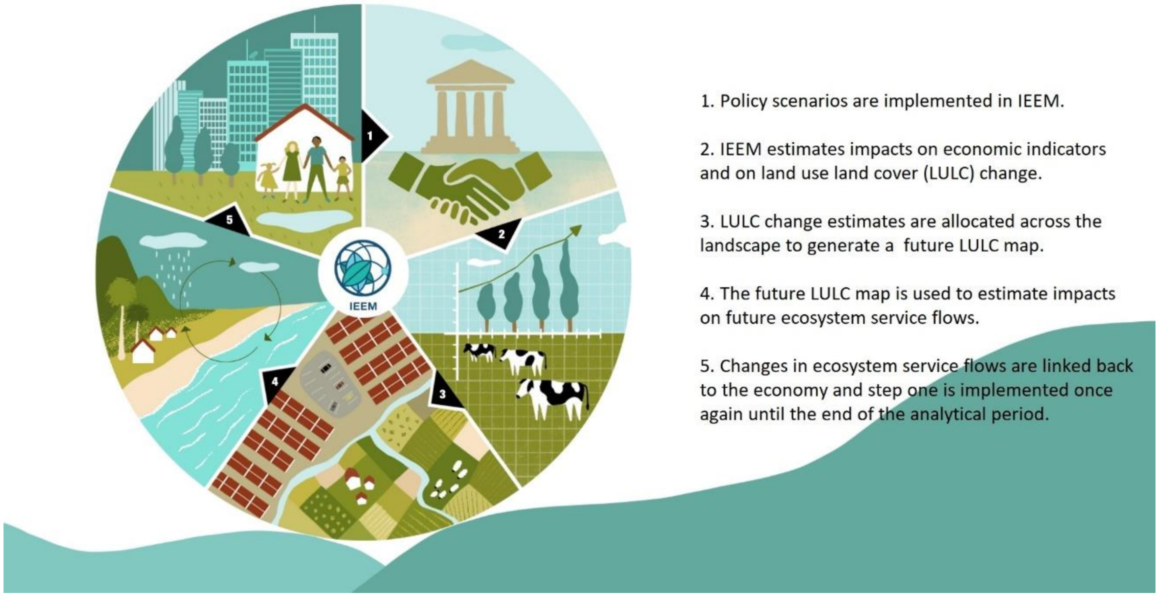


Figure S6. Sustainable Silvopastoral System costs in millions of U.S. Dollars (USD). Source: Authors' own elaboration based on Rodríguez, 2017. Note that costs remain constant at their 2026 values on to 2040.



1. Policy scenarios are implemented in IEEM.

2. IEEM estimates impacts on economic indicators and on land use land cover (LULC) change.

3. LULC change estimates are allocated across the landscape to generate a future LULC map.

4. The future LULC map is used to estimate impacts on future ecosystem service flows.

5. Changes in ecosystem service flows are linked back to the economy and step one is implemented once again until the end of the analytical period.

Figure S7. The Integrated Economic-Environmental Modeling + Ecosystem Services Modeling (IEEM+ESM) workflow with dynamic endogenous feedbacks. Source: Authors' own elaboration.

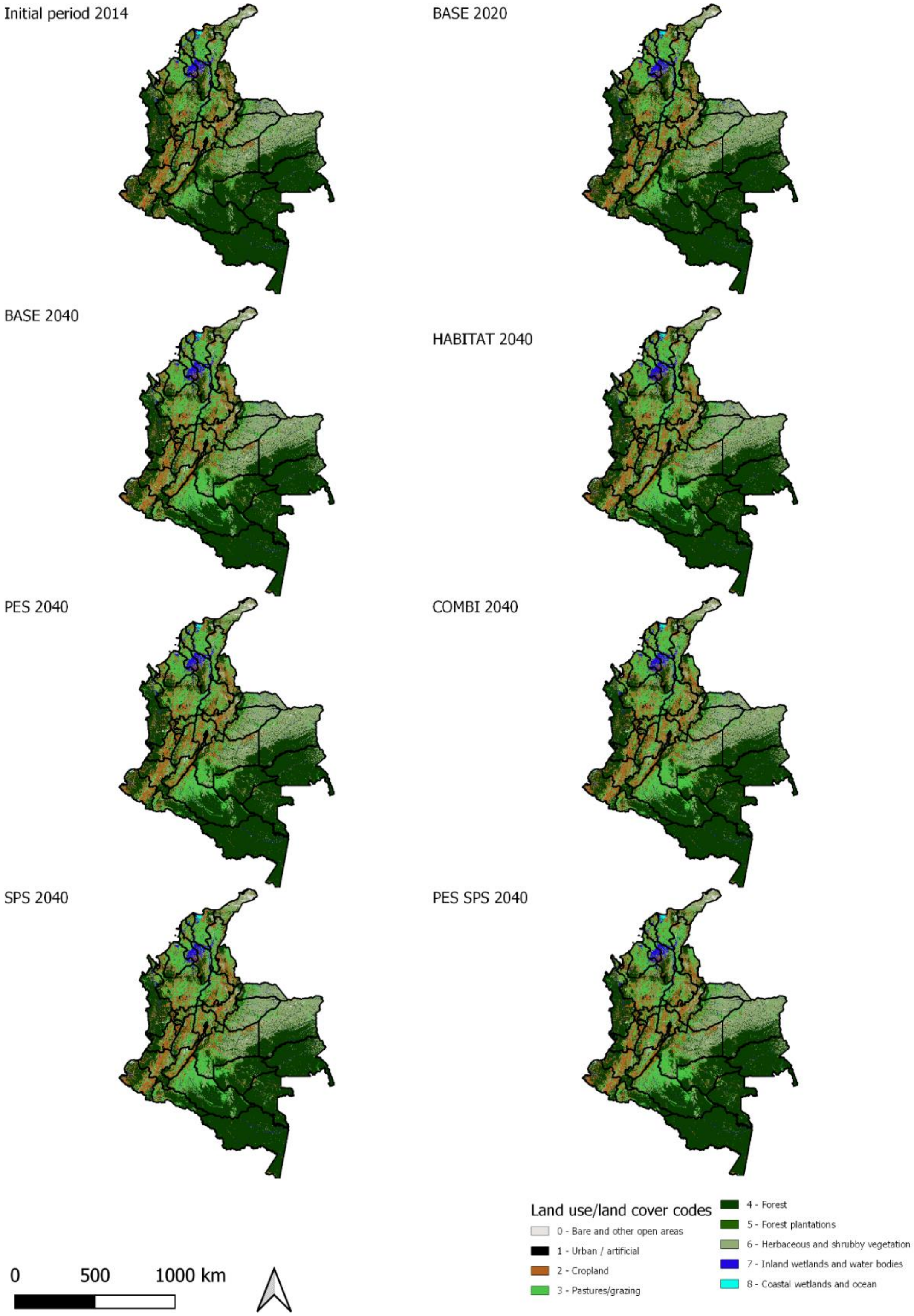


Figure S8. Land Use Land Cover maps for initial land cover (2014), business-as-usual (BASE) in 2020, and all 2040 scenarios (HABITAT: Habitat banking, PES: Payments for ecosystem services, SPS: Silvopastoral systems, COMBI: PES + SPS, PES SPS: PES + endogenized livestock productivity).

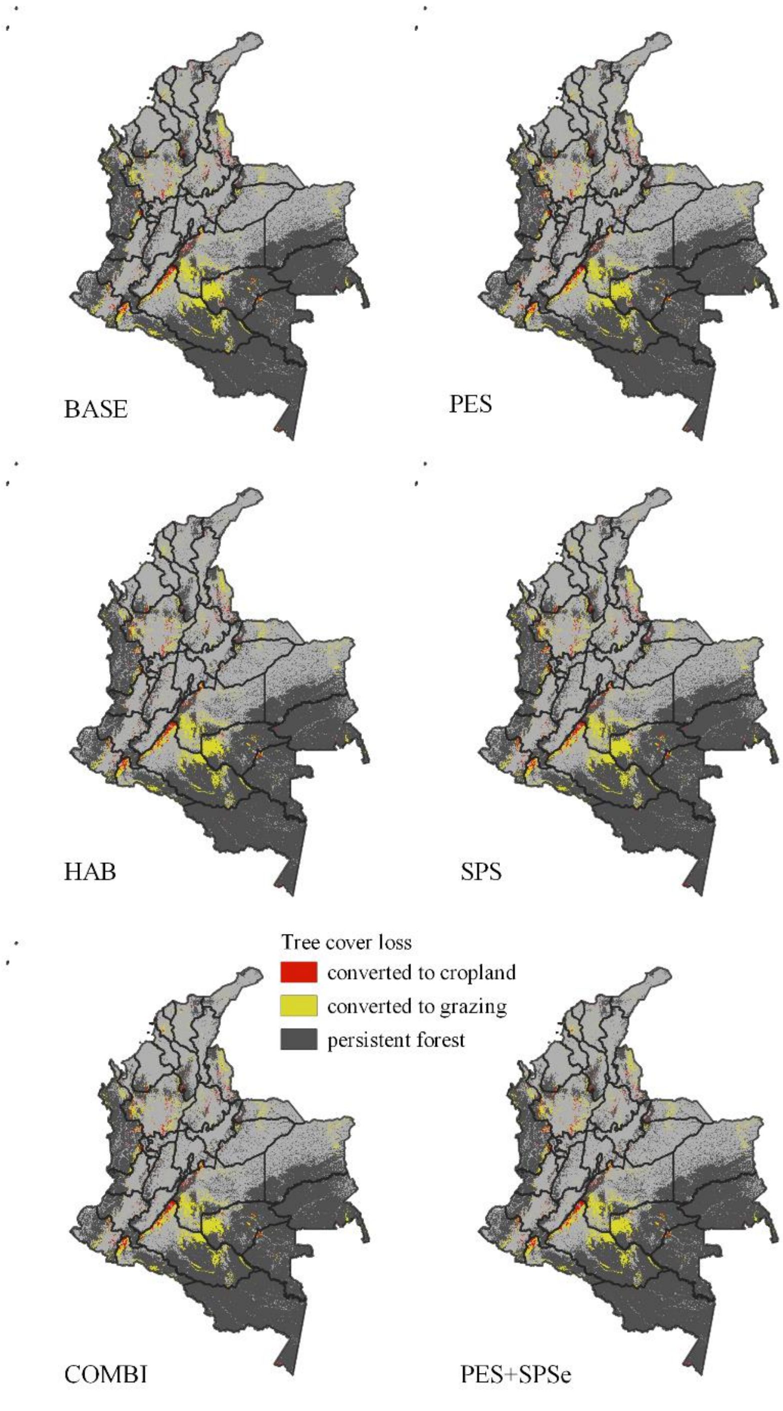


Figure S9. Scenario impact on land use and land cover, highlighting converted areas by scenario by 2040. BASE: Business-as-usual, HAB: Habitat banking, PES: Payments for ecosystem services, SPS: Silvopastoral systems, COMBI: PES + SPS, PES+SPSe: PES + endogenized livestock productivity. Source: Integrated Economic-Environmental Modeling + Ecosystem Services Modeling (IEEM+ESM) results.

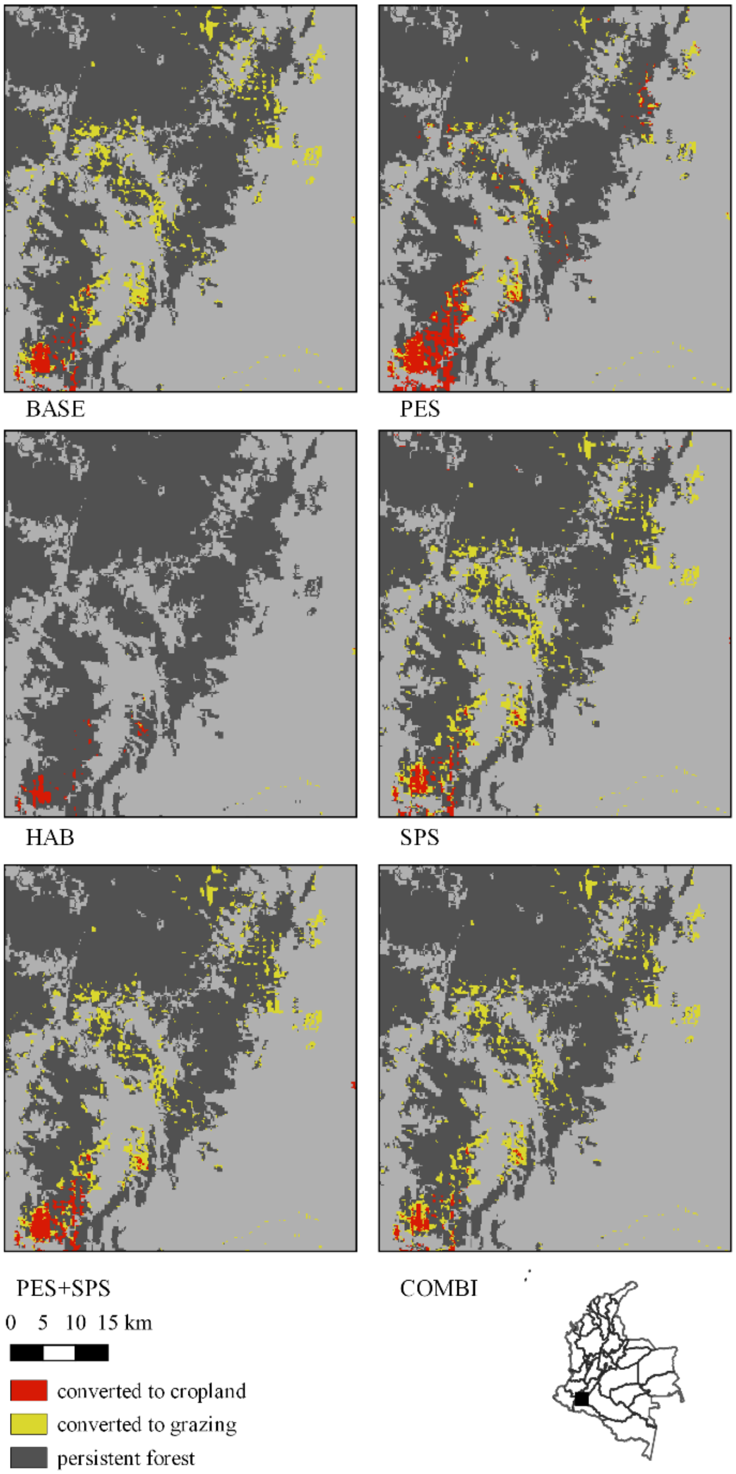
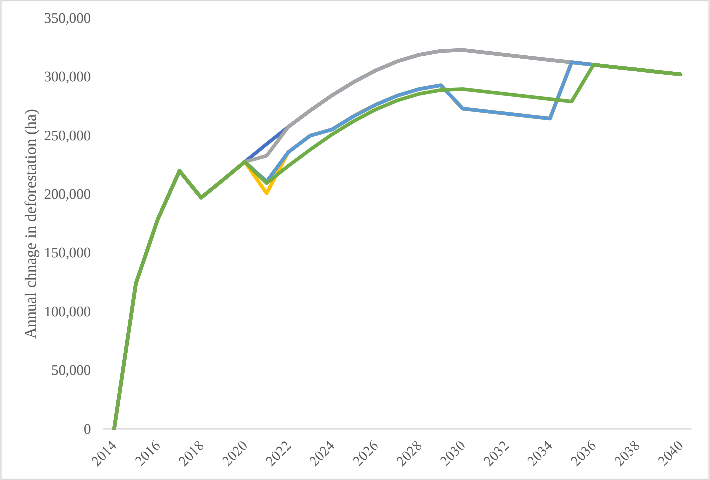
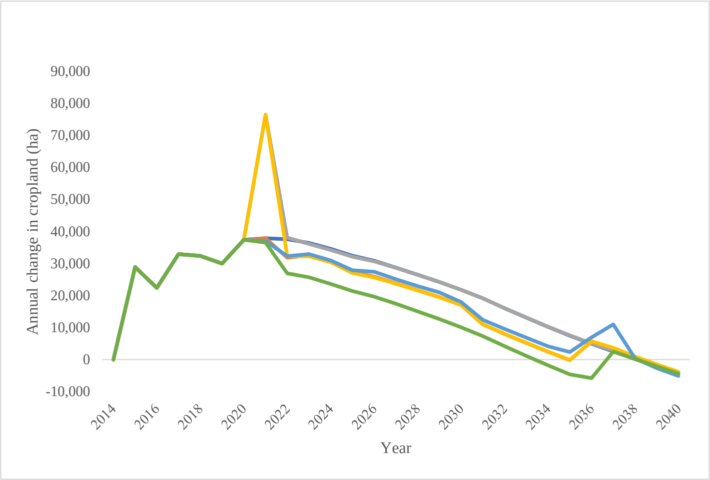


Figure S7. Detailed scenario impacts on Land Use Land Cover, Department of Cauca. BASE: Business-as-usual, HAB: Habitat banking, PES: Payments for ecosystem services, SPS: Silvopastoral systems, COMBI: PES + SPS, PES+SPS: PES + endogenized livestock productivity. Source: Integrated Economic-Environmental Modeling + Ecosystem Services Modeling (IEEM+ESM) results.

Panel A. Annual change in deforestation.

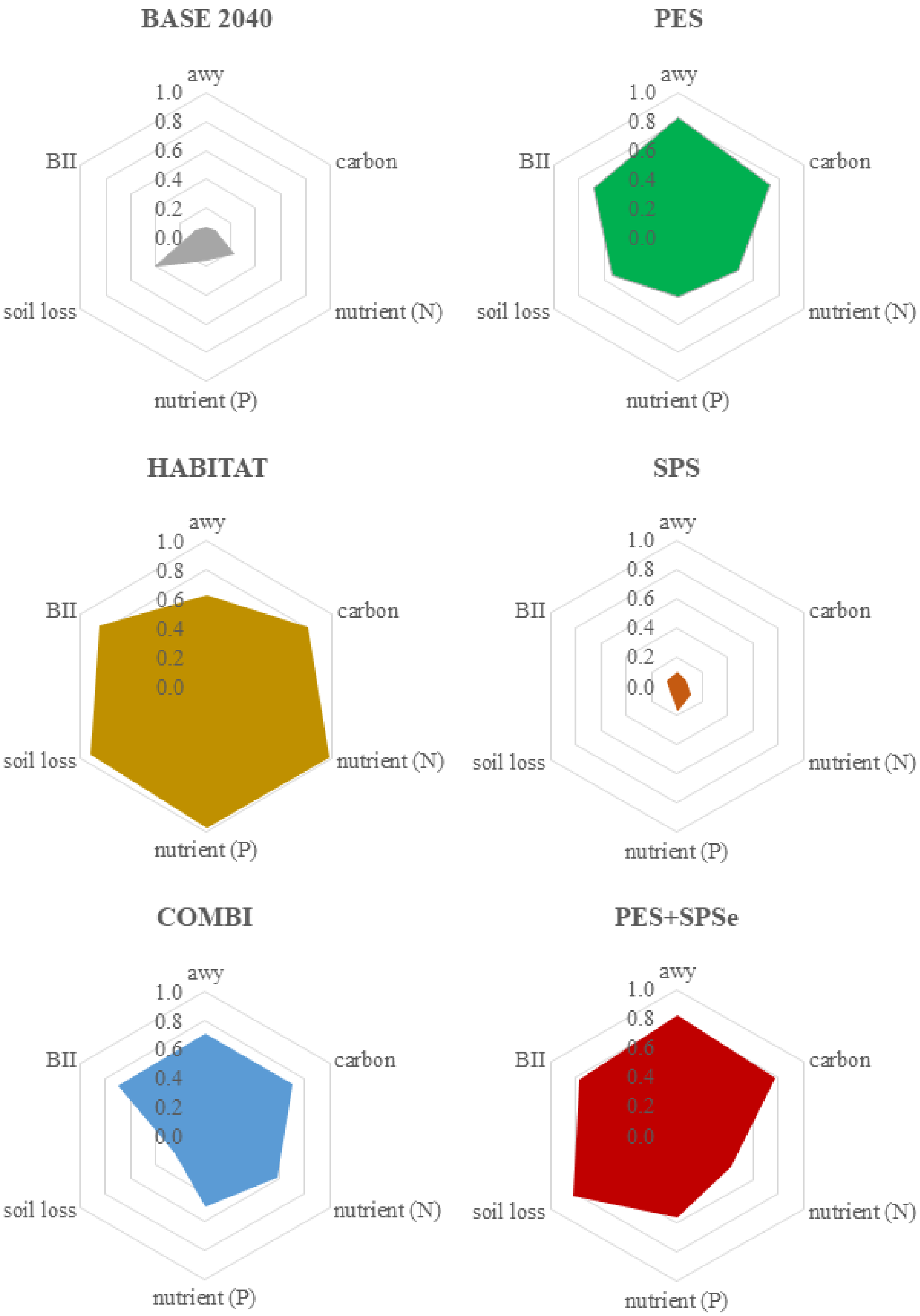


Panel B. Annual change in crops in hectares.



Panel C. Annual change in livestock in hectares.

Figure S8. Annual change in deforestation, cropland and livestock for Colombia. BASE: Business-as-usual, HAB: Habitat banking, PES: Payments for ecosystem services, SPS: Silvopastoral systems, COMBI: PES + SPS, PES+SPSe: PES + endogenized livestock productivity. Source: Integrated Economic-Environmental Modeling + Ecosystem Services Modeling (IEEM+ESM).



BASE 2040

PES

HABITAT

SPS

COMBI

PES+SPSe

Figure S9. Summary of scenario performance in terms of ES (scenarios compared against each other). Total ecosystem service values for all scenarios presented are here all normalized (between 0-1) for illustrative purposes. AWY is annual water yield and BII is Biodiversity Intactness Index. BASE: Business-as-usual, HABITAT: Habitat banking, PES: Payments for ecosystem services, SPS: Silvopastoral systems, COMBI: PES + SPS, PES+SPSe: PES + endogenized livestock productivity. Source: Integrated Economic-

Environmental Modeling + Ecosystem Services Modeling (IEEM+ESM) results.

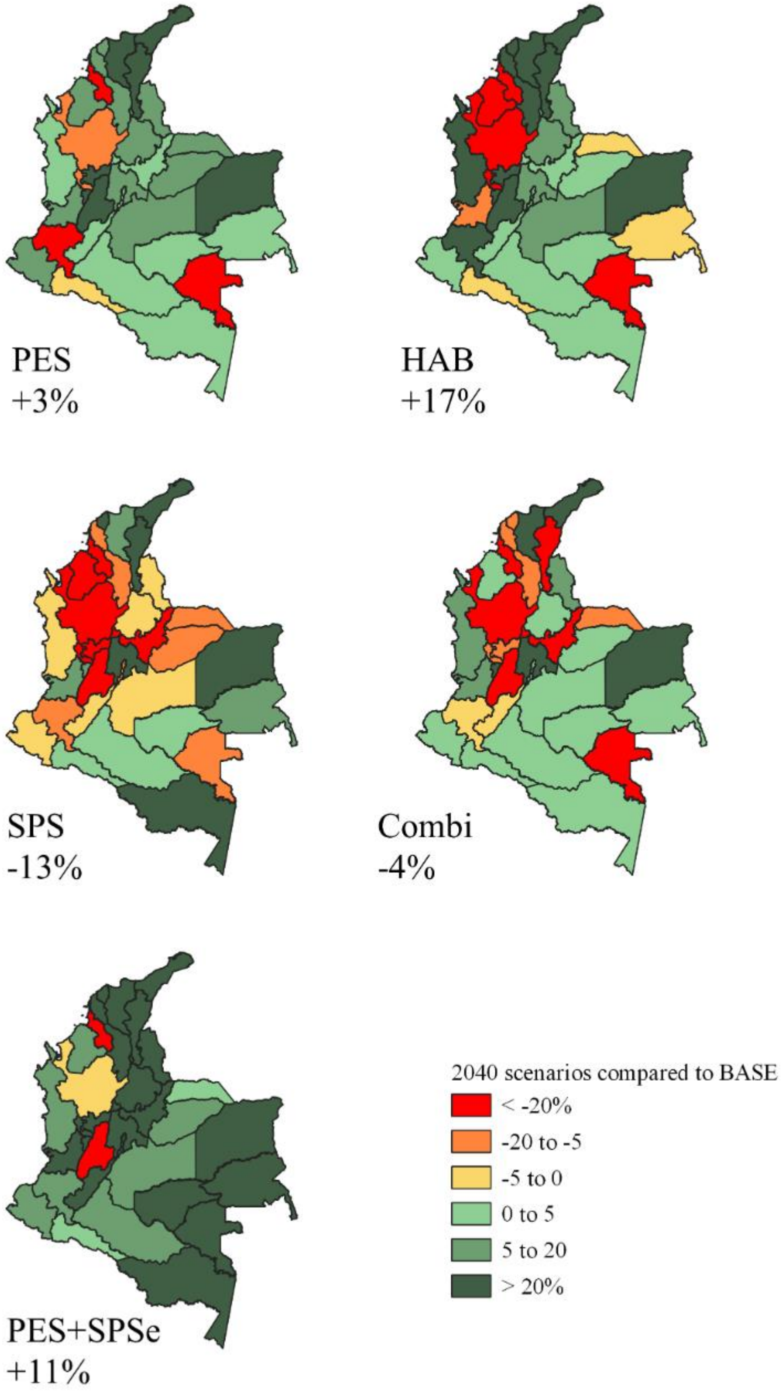


Figure S13. Changes in erosion mitigation services in 2040 as a difference from base in %. Numbers next to the scenario name describe the change on a national level for the scenario. BASE: Business-as-usual, HAB: Habitat banking, PES: Payments for ecosystem services, SPS: Silvopastoral systems, COMBI: PES + SPS, PES+SPSe: PES + endogenized livestock productivity. Source: Integrated Economic-Environmental Modeling + Ecosystem Services Modeling (IEEM+ESM) results.

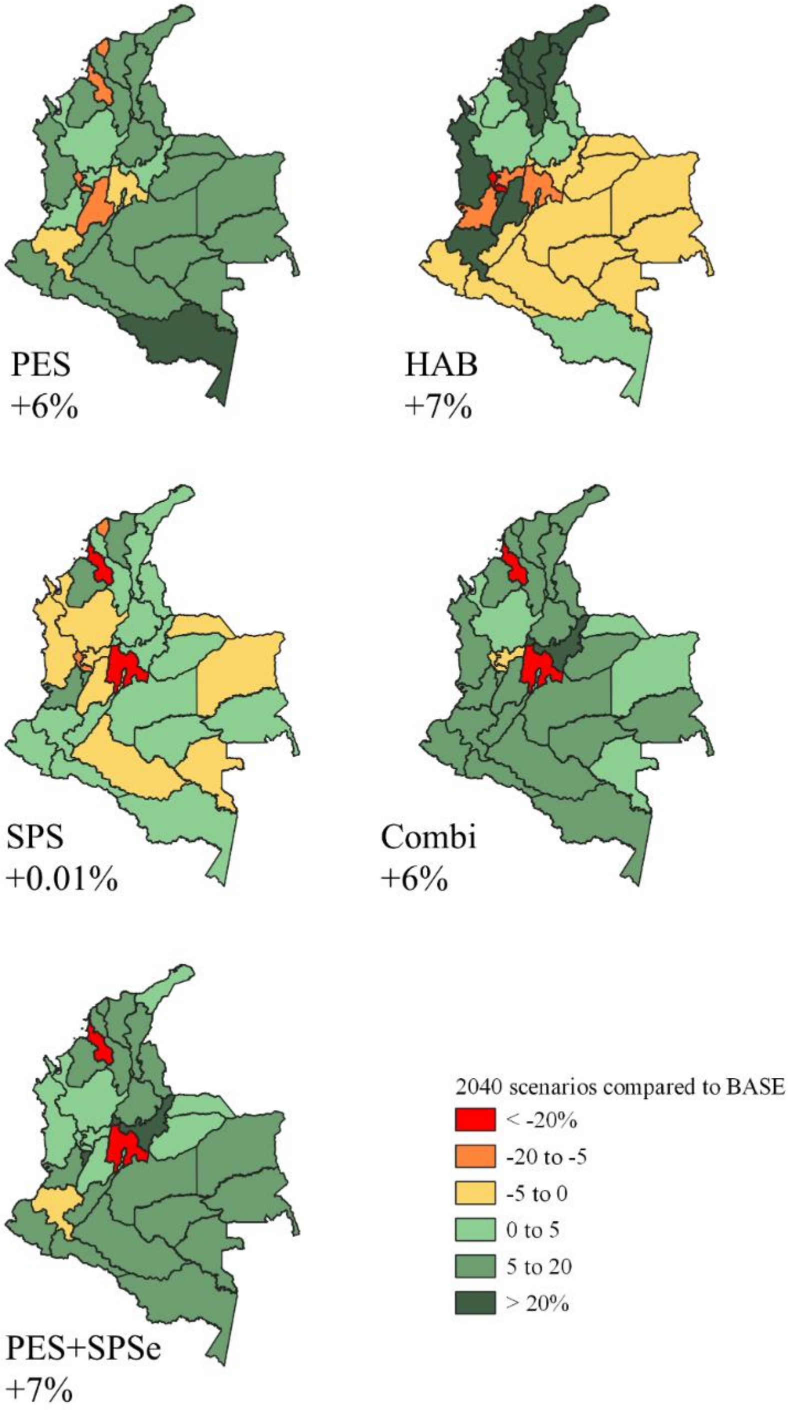


Figure S14. Differences in carbon storage in 2040 as a difference from business-as-usual in percent. Numbers below the scenario name describe the change on a national level for the scenario. BASE: Business-as-usual, HAB: Habitat banking, PES: Payments for ecosystem services, SPS: Silvopastoral systems, COMBI: PES + SPS, PES+SPSe: PES + endogenized livestock productivity. Source: Integrated Economic-Environmental Modeling + Ecosystem Services Modeling (IEEM+ESM) results.

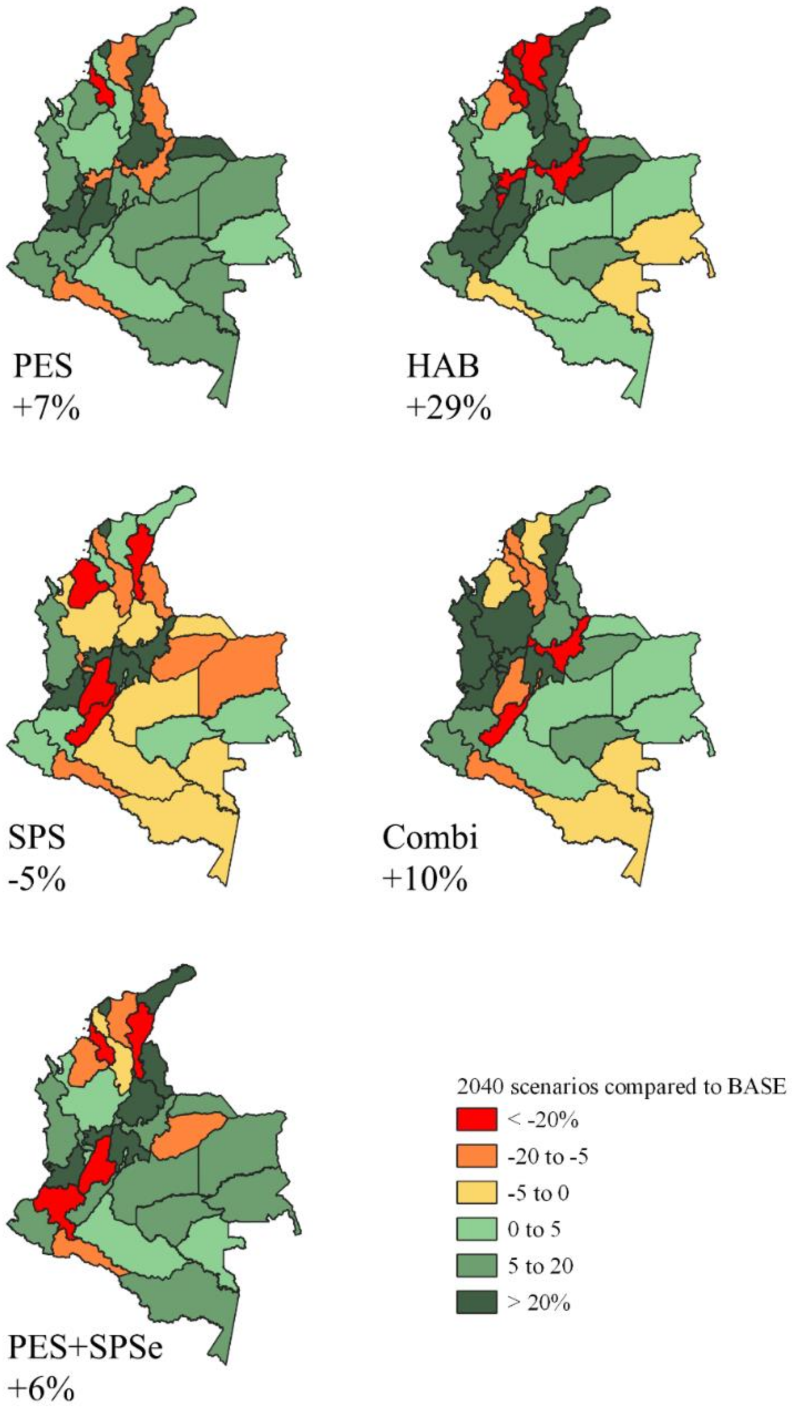


Figure S15. Differences in nitrogen retention in 2040 as a difference from business-as-usual in percent. Numbers below the scenario name represent the overall change. BASE: Business-as-usual, HAB: Habitat banking, PES: Payments for ecosystem services, SPS: Silvopastoral systems, COMBI: PES + SPS, PES+SPSe: PES + endogenized livestock productivity. Source: Integrated Economic-Environmental Modeling + Ecosystem Services Modeling (IEEM+ESM) results.

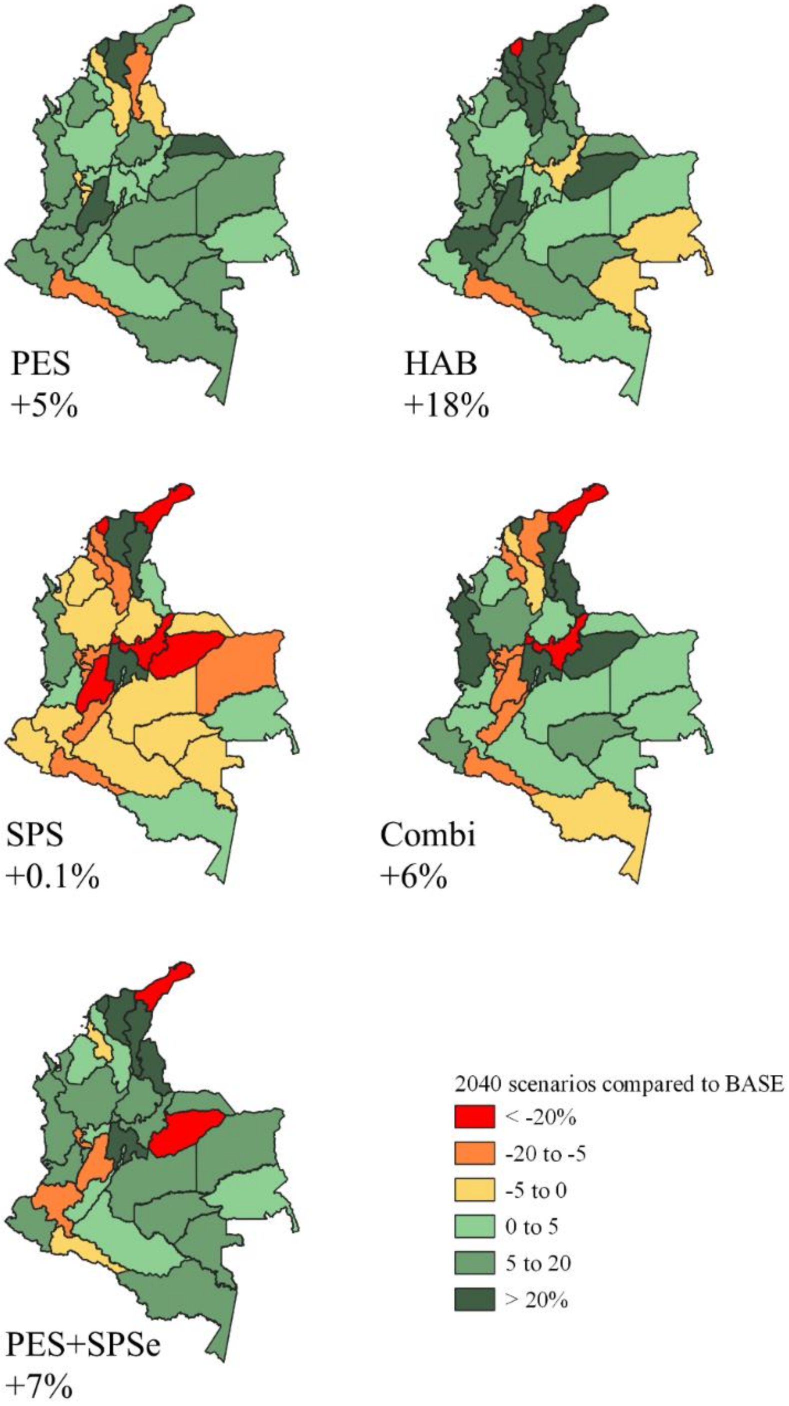


Figure S16. Differences in phosphorus retention in 2040 as a difference from business-as-usual in percent. Numbers below the scenario name represent the overall change. BASE: Business-as-usual, HAB: Habitat banking, PES: Payments for ecosystem services, SPS: Silvopastoral systems, COMBI: PES + SPS, PES+SPSe: PES + endogenized livestock productivity. Source: Integrated Economic-Environmental Modeling + Ecosystem Services Modeling (IEEM+ESM) results.

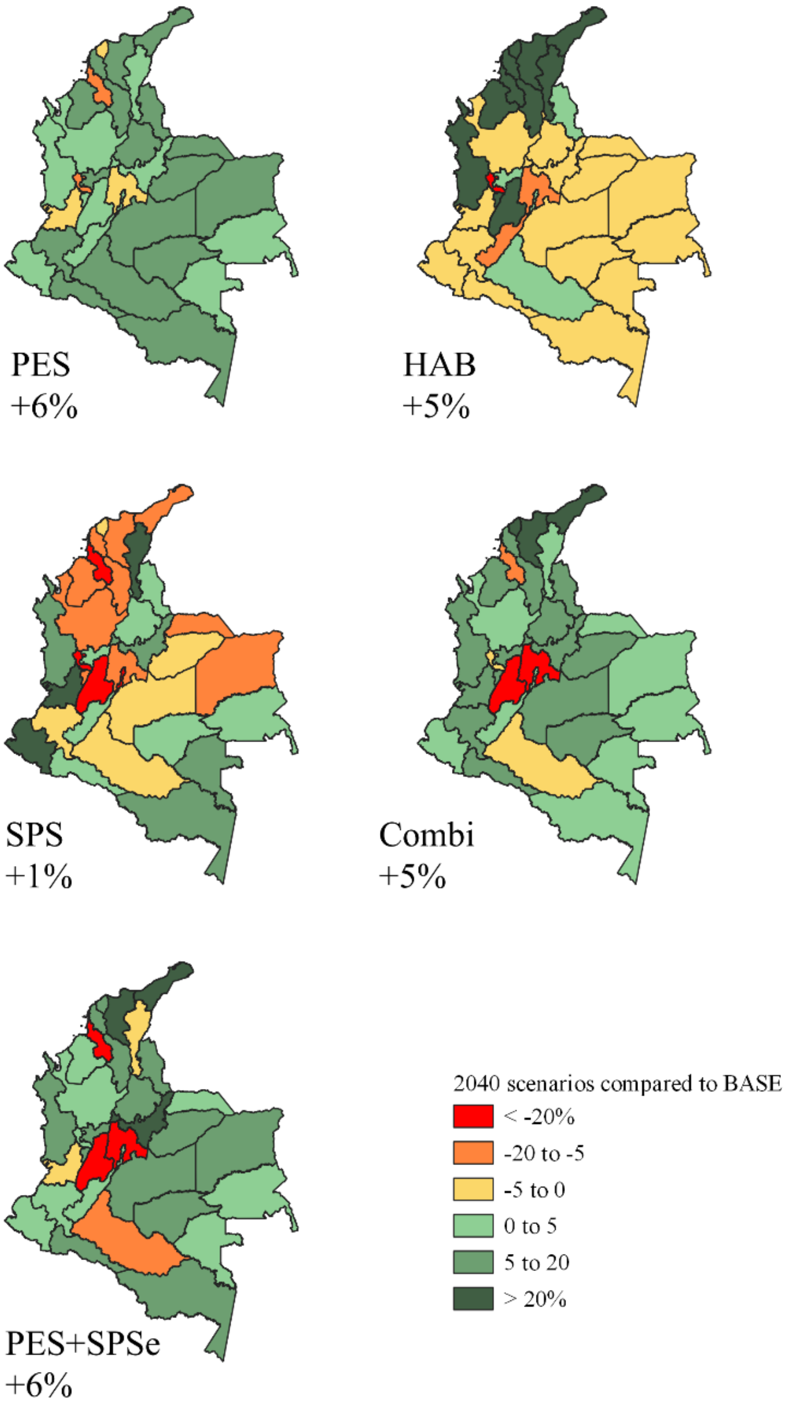


Figure S17. Differences in regulation of hydrologic water flows in 2040 as a difference from BASE in percent. Numbers below the scenario name describe the change on a national level for the scenario. BASE: Business-as-usual, HAB: Habitat banking, PES: Payments for ecosystem services, SPS: Silvopastoral systems, COMBI: PES + SPS, PES+SPSe: PES + endogenized livestock productivity. Source: Integrated Economic-Environmental Modeling + Ecosystem Services Modeling (IEEM+ESM) results.

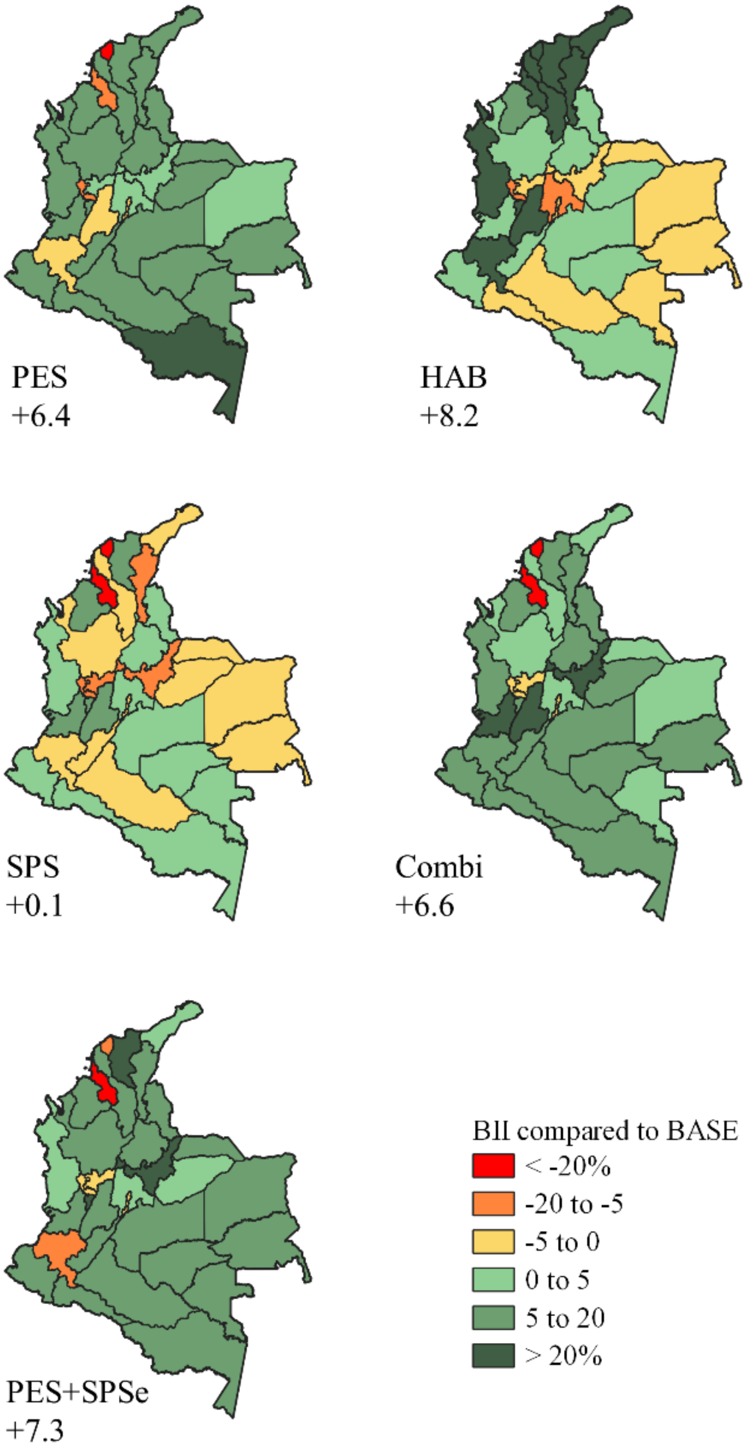


Figure S18. Scenario impacts on the biodiversity intactness index compared to business-as-usual in 2040. Numbers below the scenario names define the difference in BII for scenario on the national level. BASE: Business-as-usual, HAB: Habitat banking, PES: Payments for ecosystem services, SPS: Silvopastoral systems, COMBI: PES + SPS, PES+SPSe: PES + endogenized livestock productivity. Source: Integrated Economic-Environmental Modeling + Ecosystem Services Modeling (IEEM+ESM) results.

Table S1. Land use in the business-as-usual scenario and projected to 2040 in hectares

Land use	Base 2014 (Ha)	Base 2040 (Ha)
Crops	8,476,711	9,038,276
Livestock	34,426,622	40,912,934
Forest Plantation	584,802	608,042
Forest	58,971,012	51,923,135

Source: Authors' own elaboration based on Integrated Economic-Environmental Modeling (IEEM) projections.

Table S2. Location factors used in the analysis

Explanatory factor	Description	Unit	Original resolution	Source
Biophysical				
Temperature	Average temperature (mean of monthly means)	°C	1 km	(Hijmans et al. 2005)
Precipitation	Annual precipitation	Mm	1 km	(Hijmans et al. 2005)
Potential Evapotranspiration (PET)	Annual PET	Mm	1 km	(Trabucco and Zomer 2009)
Altitude	Elevation above sea level	M	100 m	Provided by IADB
Slope	Derived from altitude	Slope degrees	100 m	Derived from altitude
Land degradation areas	Areas defined as moderately (moderada) to very severely (muy severa) eroded by Colombian ministry for Environment (only used to allocate the silvopastoral system)	Units identified with erosion	shapefile	Obtained from http://www.siac.gov.co/catalogo-de-mapas
Soil				
Drainage	Internal drainage of soils	Class	1 km	(ISRIC 2018)
Soil depth	Soil depth	Cm	1 km	(Stoorvogel et al. 2016)
Sand and clay content	Share of sand and clay	%	1 km	(Stoorvogel et al. 2016)
Cation Exchange Capacity (CEC)	Proxy for nutrient retention capacity	cmol/kg	1 km	(ISRIC 2018)
Soil pH	pH index measured in water solution	1-7	1 km	(ISRIC 2018)
Organic content	Organic carbon content in the top 50 cm of soil	g /kg of soil	1 km	(Stoorvogel et al. 2016)
Socio-economic				
Population density	Distribution of human population	People/km^2	1km	(CIESIN and SEDAC 2015)

Rural population density	Distribution of rural population	People/km^2	10 km	(CIESIN, IFPRI, and CIAT 2011)
Market Accessibility	Indicator for the accessibility to markets.	Index	1 km	(Peter H Verburg, Ellis, and Letourneau 2011)

Source: Authors’ own elaboration.

Table S3. Logistic regression models for land use types that are subject to changes in the Colombia study.

	Cropland	**Grazing**	**Forest**	**Planted forest**	**Shrubs and other vegetation**
population density	-0.00033	-0.00055			
rural population	0.00345	0.00323	-0.00596		-0.00163
market access	2.78217	2.299545	-2.63041	4.48505	-0.8484
organic content	-0.00465	-0.01001		-0.01773	0.00703
soil drainage			-0.24954	1.05954	0.67954
clay soil		0.022567	-0.05474	0.01933	0.05312
CECS	0.03884	0.043672	-0.04462	0.04992	
soil depth	-0.01276		0.011885		
sand			-0.03794		0.03613
soil pH		0.041388	-0.07242		-0.04586
elevation			-0.00343	0.00143	
slope		-0.03022	0.044379	-0.11525	
precipitation		-0.00055	0.000593	-0.00029	-0.00099
temperature		-0.28834	-0.51877		
PET		0.00699	-0.00271		
constant	0.21704	-6.8789	25.23958	-6.95029	-1.65359
AUC	0.787	0.812	0.843	0.893	0.741

Values present regression coefficients. For all variables $P<0.05$ is valid. Area under the curve (AUC) values range between 0-1, and values over 0.5 mean that the model's predictive ability is better than random when describing the spatial distribution of the land cover types. CECS: Cation exchange capacity, PET: Potential evapotranspiration.
Source: Authors' own elaboration.

Table S4. Biodiversity Intactness Index (BII) for different land use types, based on 285 observations in Colombia (Echeverría- Londoño et al. 2016).

Land use	Biodiversity Intactness
Bare	0
Urban	0
Cropland	0.49
Pasture	0.59
Forest	1
Planted	0.79
Shrubs	0.8
inland wetlands	0
coastal wetland	0
Silvopastoral	0.75

Source: Authors’ own elaboration. Notes: all values present a coefficient of the BII compared to a reference land use type, in this case forest. Note that bare and urban areas and wetlands do host considerable levels of biodiversity. These types, however, were not subject to change and were therefore not important for this analysis. Additionally, studies on converting these to or from these land use types were not available for Colombia.

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Banking on Strong Rural Livelihoods and the Sustainable Use of Natural Capital in Post-Conflict Colombia

Abstract

In post-conflict Colombia, the government has prioritized resettlement of displaced people through development of strong rural livelihoods and the sustainable use of natural capital. In this paper, we considered government proposals for expanding payment for ecosystem services (PES) and sustainable silvopastoral systems, and private-sector investment in habitat banking. We coupled the Integrated Economic-Environmental Model (IEEM) with spatially explicit land use and land cover change and ecosystem services models to assess the potential impacts of these programs through the lens of wealth and sustainable economic development. This innovative workflow integrates dynamic endogenous feedbacks between natural capital, ecosystem services and the economic system, and can be applied to other country contexts. Results show that PES and habitat banking programs are strong investment propositions (Net Present Value of US$4.4 and $4.9 billion, respectively), but only when moving beyond conventional economic analysis to include non-market ecosystem services. Where a portfolio investment approach is taken and PES is implemented with sustainable silvopastoral systems, investment returns would reach US$7.1 billion. This paper provides a detailed evaluation of the benefits of investing in rural livelihoods and enhancing Colombia's natural capital base, with empirical evidence to inform the spatial targeting of policies to maximize economic, environmental and social outcomes.

Keywords: dynamic computable general equilibrium (CGE) model; ecosystem services modeling; land use land cover modeling; natural capital; payment for ecosystem services; habitat banking; biodiversity.

1.0 Introduction

The government of Colombia signed a Peace Accord with the Revolutionary Armed Forces of Colombia in November of 2016, after over 50 years of civil conflict. Drawing from the experience of other post-conflict countries, the return of displaced people following the resolution of conflict, coupled with ineffective land use planning, often intensifies unsustainable natural capital use and drives deforestation and other environmental degradation (Calderon et al., 2016; Suarez et al., 2017). On signing the Peace Accord, the Colombian government focused public investment on security and social and economic recovery, which may further intensify pressures on natural capital (Bustos & Jaramillo, 2016; Conca & Wallace, 2009; McNeish, 2017).

About 19% of Colombia’s population is rural (World Bank, 2021b) and remains strongly reliant on agriculture. Growth in this sector has been stagnant due to a lack of incentives, land tenure and inappropriate land management practices. Climate change and increased weather-related disasters affect the rural poor disproportionately and the intensity and frequency of these events are only expected to increase (IFAD, 2016). With the Peace Accord, there were renewed hopes for improving the prospects of the rural poor through integrated rural reform including provisions for investing in public services, measures to enhance agricultural productivity and granting land to small farmers. The implementation of these measures, however, has been progressing relatively slowly (Cobb, 2022).

Colombia is home to 10% of the planet’s biodiversity and is the second most biodiverse nation on Earth (CONPES, 2017; Moreno et al., 2019). Over half of the country is forested and it has the greatest abundance of water resources among all countries in Latin America and the Caribbean (World Bank, 2015). In the past 25 years, Colombia lost 5.2 million hectares of forest cover, 3 million hectares of which were deforested in municipalities affected by the armed conflict (DNP, 2017). Colombia’s protected areas have not been spared, with deforestation spiking in the post-conflict period and accounting for 11% of the national total in 2017. Deforestation, land degradation and soil erosion were estimated to cost on average 0.7% of gross domestic product (GDP) annually (Sanchez-Triana et al., 2007).

Clearing land for agriculture and livestock is the main driver of deforestation, accounting for 65% of the deforestation over the previous decade (Etter et al., 2006; Hanauer & Canavire Bacarreza, 2018; Prem et al., 2020; UNODC, 2019). Deforestation is also closely related to illegal activities, which have proliferated due to weak governance. Forests in some areas have been replaced with illicit crops or illegal mining and logging, with access made possible by informal roadbuilding. Since the Peace Accord, Colombia’s coca production has tripled, accounting for 70% of the global harvest (UNODC, 2019). With the onset of peace, vast swaths of tropical forest and other ecosystems and the valuable ecosystem services they provide are now accessible~~, effectively ‘open for business’~~ and in some areas, this accessibility is spawning a frontier mentality (Hanauer & Canavire Bacarreza, 2018; Prem et al., 2020).

More recently, the Colombian government has come to view its natural capital base as an asset and opportunity for developing strong rural livelihoods to generate sustainable economic development opportunities in the countryside and mitigate climate change. Various policies and programs demonstrate this commitment. In 2019, the government established the multi-donor Sustainable Colombia Fund, which includes funding for Payment for Ecosystem Services (PES) to integrate biodiversity conservation with productive projects that will benefit post-conflict zones (CONPES, 2017; DNP, 2019a). PES programs have had positive household welfare impacts in some contexts while PES effectiveness can be enhanced where conservation and equity objectives are pursued simultaneously (Börner et al., 2017). Colombia's Green Growth Strategy is supporting the efficient use of natural capital through the development of strong bioeconomies (CONPES, 2018). The commitment to green growth was reaffirmed in Colombia's National Development Plan, which is aligned and consistent with the Paris Agreement, Colombia's National Climate Change Plan and the Sustainable Development Goals (DNP, 2017, 2019b; Gobierno de Colombia, 2017). Reducing deforestation is a critical element of these national strategies and plans, along with reducing greenhouse gas emissions by up to 30% by 2030 (DNP, 2016).

To measure progress toward sustainable economic development, like that now pursued by Colombia, metrics are required that gauge impacts on its three dimensions, namely social, economic and environmental outcomes. While GDP has been misused for this purpose (Banerjee et al. 2021; Lange, Wodon, and Carey 2018; Polasky et al. 2015; Stiglitz, Sen, and Fitoussi 2009, 2010), better methods and data are now available to measure and track more robust metrics such as wealth (HM Treasury, 2020; UNEP, 2018). Our innovative approach brings the value of biodiversity and ecosystem services into economic decision making by linking the Integrated Economic-Environmental Model (IEEM) (Banerjee et al. 2016, 2019) with high resolution spatially explicit land use land cover (LULC) change and ecosystem services models (IEEM+ESM; Banerjee, Bagstad, et al. 2020). This framework enables estimation of indicators that more accurately measure sustainable economic development, all consistent and compatible with a country's System of National Accounts (European Commission et al., 2009) thus lending a high degree of credibility to the results.

The IEEM+ESM workflow integrates dynamic endogenous feedbacks between natural capital, ecosystem services and the economic system. This approach considers the interdependencies between the economy and natural capital and enables the estimation of ecosystem service values based on their contribution to the economy. This contrasts with welfare-based ecosystem service valuation approaches prevalent in the literature (Boyle, 2017; Hanley & Czajkowski, 2019; Johnston et al., 2017; Rolfe, 2006). While welfare-based stated preference approaches estimate values that individuals may be willing to pay for a change in ecosystem service provision, the use of willingness to pay estimates is not feasible in an economy-wide framework such as IEEM where a transaction must occur such that for every expenditure, there is an equal income.

Instead, the IEEM+ESM approach developed here links these ecosystem services with economic outcomes making it possible to derive their marginal economic contribution to the economy and society. We apply this approach to the analysis of post-conflict strategies for the development of strong rural livelihoods and enhance natural capital, specifically: (i) expansion of Colombia's PES program; (ii) development of more productive and sustainable silvopastoral systems; and (iii) expansion of habitat banking for natural capital restoration and conservation.

2.0 Materials and Methods

Scenarios

We designed five scenarios to assess Colombian government and private sector plans to promote the development of rural livelihood opportunities and enhance natural capital and ecosystem service flows. Specifically, these scenarios simulate the expansion of the PES program, investment in sustainable silvopastoral systems (CONPES, 2017; DNP, 2019a), and private-sector investment in expanding habitat banking for environmental offsetting (Fundepúblico & Terrasos, 2020). We compared these policy scenarios to a business-as-usual scenario defined by current trends. The general features of each scenario follow (see Supplementary Information (S2) for more details).

(i) Business-as-Usual (BASE): In this analysis, all scenarios are compared to a business-as-usual scenario (abbreviated as BASE). In the BASE, Colombia's economy is projected to the year 2040 without the implementation of any new public policies or investments. Economic growth projections are based on the International Monetary Fund's World Economic Outlook (IMF, 2018). Labor force and population growth rates are drawn from the United Nations' Population Prospects projections (UN, 2019; see S2 for additional details on the BASE scenario).

(ii) Payment for Ecosystem Services (PES): This scenario simulates the establishment of 500,000 hectares (ha) of PES for strict preservation, beginning in 2021 and concluding in 2034. This area is equivalent to 0.84% of Colombia's total forested area. We assumed that each hectare preserved avoids the deforestation of one hectare of forest in perpetuity, assuming payments and compliance are maintained, which are prerequisites of a PES program (Börner et al., 2017; Engel et al., 2008; Wunder, 2005; Wunder et al., 2008. See Figures S1-S5 in S2).

(iii) Silvopastoral Systems (SPS): This scenario simulates the restoration of 125,000 ha of degraded pasture areas with more productive silvopastoral systems. This area is equivalent to 0.36% of Colombia's total livestock area. Expanding sustainable silvopastoral systems can reduce demand for agricultural land and reduce deforestation pressures (see Figure S6 in S2). Productivity gains and investment costs are based on previous Colombian studies (Rodríguez, 2017).

(iv) COMBI: The COMBI scenario is the joint implementation of the PES and SPS scenarios.

(v) PES and endogenous estimation of livestock Total Factor Productivity (PES+SPSe): This scenario simulates the establishment of 500,000 ha of PES and endogenizes livestock productivity such that GDP in the scenario tracks the GDP in the business-as-usual scenario. This scenario identifies the increase in the level of livestock productivity that would be required for the investment in PES to be GDP-neutral. Recent assessments of the productivity potential of enhanced silvopastoral systems show a large potential range to the upside (Chará et al. 2019; Mahecha et al. 2011;).

(vi) Habitat Bank Scenario (HAB): This scenario simulates the expansion of 500,000 ha of Colombia's habitat banking system where 80% of this area would be designated as strict preservation of existing intact ecosystems and 20% would involve restoration of degraded ecosystems. Habitat banking has been used in Colombia to enable firms to offset conservation liabilities by undertaking activities that generate positive environmental externalities (Fundepúblico & Terrasos, 2020).

Overview of IEEM

We used IEEM as the basis for this analysis because it allows for the quantification of the effects of public policies on standard indicators such as GDP, income and employment, as well as the impacts on stocks of natural capital, environmental quality, wealth and well-being, which are central to the discussion on post-conflict development prospects for Colombia (see S1 for more details on IEEM). Our measure of wealth is an adjusted form of genuine savings, which considers household savings, natural capital stocks and environmental quality. IEEM integrates natural capital accounts in the System of Environmental-Economic Accounting (SEEA) (United Nations et al., 2014) format, has environmental modeling modules to capture the dynamics of each environmental asset and ecosystem services, and generates indicators that enable assessment of impacts on the three pillars of sustainable development – society, economy and environment.

At the core of IEEM is a dynamic computable general equilibrium (CGE) model. The theory, structure and strengths and limitations of CGE modeling for public policy and investment analysis are discussed in a body of literature that has developed over the last four decades (Burfisher, 2021; Dervis et al., 1982; Dixon & Jorgenson, 2012; Kehoe, 2005; Shoven & Whalley, 1992). The IEEM conceptual framework and natural capital-specific modeling modules are described in Banerjee et al. (2016) while its mathematical structure is documented in Banerjee and Cicowiez (2020). IEEM's database is an environmentally extended Social Accounting Matrix (SAM; Banerjee et al. 2019). The main sources of data used in constructing the extended SAM are Colombia's National Accounts Environmental-Economic Accounts, Integrated Economic Accounts and Agricultural Census data (DANE, 2015, 2016, 2017, 2018). A user guide for a generic version of IEEM, applicable to any country with the corresponding database, is available (Banerjee and Cicowiez 2019). IEEM models for over 20 countries and various other resources are open source and available online on the OPEN IEEM Platform: https://openieem.iadb.org/

Linking IEEM with Spatial LULC and Ecosystem Services Modeling

In this application, we linked IEEM with LULC change and ecosystem services modeling (IEEM+ESM) to represent the economy, natural capital and ecosystem services as one integrated and complex system. To more accurately capture regional LULC dynamics and enable the spatial targeting of policies, we disaggregate IEEM's agriculture, livestock, and forestry sectors according to Colombia's 32 departments. We used the IEEM-Enhanced version of the Dynamic Conversion of Land Use and its Effects (Dyna-CLUE) model (Veldkamp and Verburg 2004; Verburg et al. 2021; Verburg et al. 2002; Verburg and Overmars 2009) to spatially allocate the LULC change projected by IEEM. LULC allocation is implemented based on empirically quantified relationships between land use and location factors (e.g., climate, topography, soil and socioeconomic factors), in combination with the dynamic modeling of competition between land use types (see S3 for more details on the application of Dyna-CLUE).

We modeled changes in future ecosystem service flows using the Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST) suite of models and the IEEM+ESM ecosystem services modeling datapackets (IDB, 2021). Data collection and processing is the most time consuming and resource-intense aspect of ecosystem services modeling. The IEEM+ESM datapackets were developed to enable rapid deployment of ecosystem services models to support real time decision making. Datapackets were developed for these four InVEST ecosystem services models as well as the coastal vulnerability model for all countries of Latin America and the Caribbean, including Colombia. InVEST combines LULC maps and biophysical information to calculate ecosystem service flows. We used four models: the sediment delivery ratio model, used to calculate the Revised Universal Soil Loss Equation and sediment export (as well as soil erosion mitigation – the amount of soil held in place by vegetation); the carbon storage model, used to calculate carbon storage and carbon sequestration potential; the annual water yield model, used to calculate water supply, and; the nutrient delivery ratio model, used as a proxy for the water purification potential of landscapes in absorbing nitrogen and phosphorus (see S3) (Sharp et al., 2020).

In addition to the above-mentioned ecosystem services, the impact of policy scenarios on biodiversity was evaluated by calculating composite Biodiversity Intactness Indices (BII) (Hudson et al., 2017; Newbold et al., 2016). The BII is a coefficient based on the average abundance of species originally present across undisturbed habitats (Newbold et al., 2016). Our estimates are based on the Projecting Responses of Ecological Diversity In Changing Terrestrial Systems (PREDICTS) database, an extensive database collecting case study information on the relationship between land use and biodiversity, with over 32 million observations from 32,000 locations and covering 50,000 species (Trustees of the Natural History Museum, 2020). For Colombia alone, the database had a collection of 285 locations (Echeverría- Londoño et al., 2016) where the relationship between LULC and biodiversity have been monitored and assessed. Using calculated mean BII values, which are based on undisturbed natural habitats, we assigned BII coefficients to the land use types considered in this analysis. For each scenario and year, we then recalculated the composite BII across scenarios and through time based on LULC change.

Integrating Dynamic Endogenous Feedbacks between the Economy and Ecosystem Services

IEEM+ESM can be used directly to estimate economic impacts of changes in the supply of most provisioning ecosystem services (European Environment Agency, 2018; Haines-Young & Potschin, 2012) that have a market price. These provisioning services include benefits to people in the form of food, timber/fiber/biomass, and mineral and non-mineral subsoil extracts. IEEM+ESM can also be used directly to estimate economic impacts of changes in the supply of some cultural ecosystem services such as tourism and recreation (Banerjee et al., 2018). A key contribution of this work is the development of a methodology for integrating LULC-driven changes in regulating and maintenance ecosystem services into IEEM+ESM and CGE models more generally. In contrast to provisioning and some cultural ecosystem services, regulating and maintenance services usually do not have a market price; examples of these services include erosion mitigation, water purification, water regulation, microclimate regulation (temperature, precipitation and humidity) and regulation of extreme events such as floods and landslides. We achieve this integration of regulating and maintenance ecosystem services into IEEM+ESM through the modeling of dynamic endogenous feedbacks between natural capital, ecosystem services and the economic system represented by IEEM+ESM.

Feedbacks from changes in ecosystem service supply affect agent behavior in the economy through various mechanisms. For example, a reduction in soil erosion mitigation ecosystem services reduces agricultural productivity and thus affects prices, returns to factors of production, producer demand for factors of production and the levels and composition of household demand (Borrelli et al., 2017, 2017; Panagos et al., 2015, 2018; Pimentel, 2006; Pimentel et al., 1995). Reduced soil regulation functions that moderate nutrient run-off can affect water quality which in turn can impact water treatment costs, human health and the quality of water-based recreational experiences. The resulting higher water treatment costs, health risks and changes in recreational quality affect agent behavior and demand (Aguilera et al. 2018; Keeler et al. 2012; O'Neil et al. 2012; Paerl and Huisman 2008; STAC 2013).

While it is possible to endogenize the impact of a range of ecosystem services in IEEM+ESM, in this application we focus on soil erosion mitigation services to demonstrate the methodology. This also enables us to isolate effects and identify how changes in erosion mitigation ecosystem services interact with the economy through their impact on agricultural productivity and in turn, producer and household behavior in response to changes in prices. Furthermore, more research is required to enable the integration of other ecosystem services in IEEM and other CGE models; for each regulating and maintenance ecosystem service, the pathway between changes in the supply of that ecosystem service and the economy must be first identified and then operationalized for each specific country context[1].

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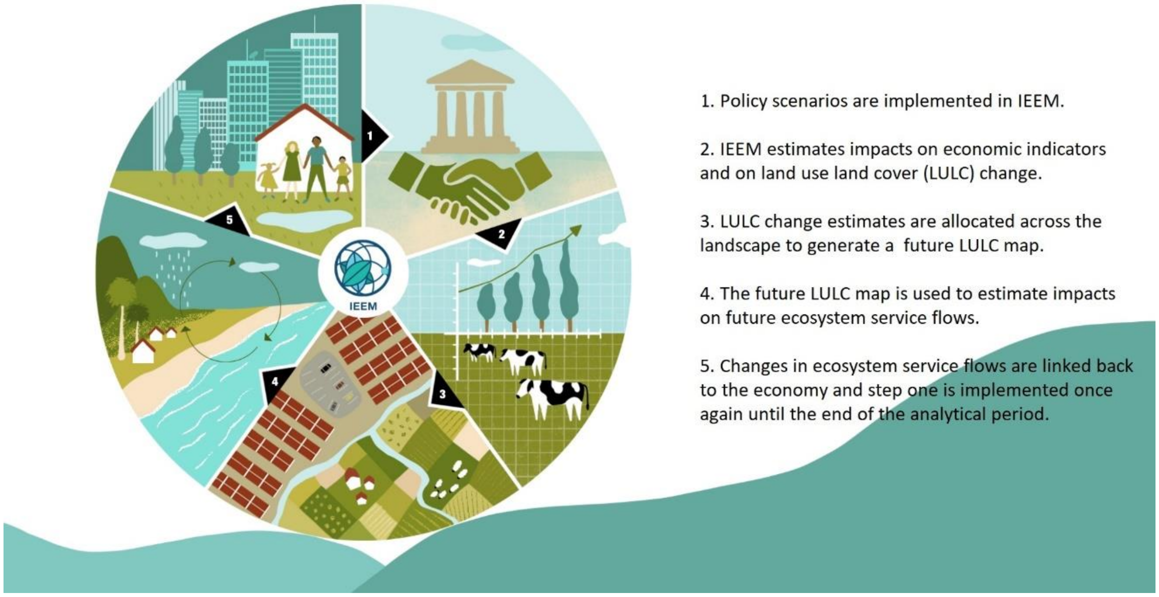
[1] While for some ecosystem services, the pathways to impact can be relatively straightforward to identify, the numerical estimation of the amount by which IEEM model variables should be adjusted poses challenges and in many cases, the science to support such estimations are incipient. For example, consider changes in forest cover that can affect microclimate regulation ecosystem services, including precipitation patterns and transpiration. In terms of identifying the pathway to impact, one pathway could be related to the productivity of rainfed agriculture. The main challenge in operationalizing this integration relates to estimating a quantitative relationship between forest cover and precipitation for a specific study area. Once this relationship is established, then the relationship between changes in precipitation and rainfed agricultural

To endogenize feedbacks between the economy and ecosystem services, we ran the three models (IEEM, Dyna-CLUE and InVEST models) iteratively in 5-year time steps. IEEM produces a projection of demand for land for the first time period which we spatially allocate with Dyna-CLUE to produce a LULC map for the beginning of the period (t) and the end of the period (t+5). We modeled each of Colombia's 32 departments individually over a 300-meter spatial grid. We run the soil erosion mitigation model for the period t and t+5 based on the Dyna-CLUE-generated LULC maps. Based on the changes in ecosystem service supply calculated as the difference between each scenario and business-as-usual, an economic feedback is estimated to account for the impacts of changes in future soil erosion mitigation ecosystem service supply. This feedback is introduced in IEEM in t+6 to t+10 which results in a new projection in demand for land accounting for changes in agent behavior estimated in the previous period. This new IEEM-based projection of demand for land is again spatially attributed with Dyna-CLUE and the iteration cycle begins again continuing in 5-year steps until the end of the analytical period in 2040 (Figure 1).



1. Policy scenarios are implemented in IEEM.

2. IEEM estimates impacts on economic indicators and on land use land cover (LULC) change.

3. LULC change estimates are allocated across the landscape to generate a future LULC map.

4. The future LULC map is used to estimate impacts on future ecosystem service flows.

5. Changes in ecosystem service flows are linked back to the economy and step one is implemented once again until the end of the analytical period.

Fig. 1. The Integrated Economic-Environmental Modeling + Ecosystem Services Modeling (IEEM+ESM) workflow with dynamic endogenous feedbacks.
Source: Authors' own elaboration.

We establish a relationship between changes in soil erosion mitigation ecosystem services and agricultural productivity based on a survey of the literature (Panagos et al., 2018). Severe erosion is considered to occur where erosion is greater than 11 tons per hectare per

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productivity can be estimated. This estimation could follow an approach similar to that described in Banerjee, Cicowiez, Macedo, et al. (2021).

year; we relate the presence of severe erosion to an 8% reduction in agricultural productivity. The feedback introduced in IEEM in the second and subsequent periods to account for changes in soil erosion mitigation services is calculated as described in equation 1, where the area of severe erosion as a difference from business-as-usual is a function of the total area of agricultural land in each department and the relationship between soil erosion mitigation services and agricultural productivity (see S3 for additional details).

$$LPL_d = \frac{SER_d}{TAA_d} \cdot 0.08 \qquad \text{equation 1.}$$

Where:

- LPL_d is the land productivity loss by subscript *d* department;
- SER_d is the agricultural land area (hectares) subject to severe erosion of >11t/ha/year in each department as a difference from business-as-usual;
- TAA_d is the total agricultural area, both crop and livestock, by department, and;
- 0.08 is the agricultural productivity shock estimated based on the literature (Panagos et al., 2018).

Estimating Changes in Colombia's Wealth

The estimation of how the policy alternatives affect wealth is a key element of this work. For this, we used an adjusted form of genuine savings to focus on the economic and environmental impacts on changes in wealth. This is reasonable, since changes in human capital are often measured by changes in investments in education or lifetime earnings (Lange et al., 2018; World Bank, 2021a), which in our study, do not differ across the business-as-usual case and scenarios. Genuine savings is calculated as in equation 2 (Banerjee et al. 2021; Banerjee, Vargas, and Cicowiez 2020):

$$GenuineSAV_t = GNSAV_t - DeprCapStock_t - DeplForStock_t - DeplMinStock_t - EmiVal_t \qquad \text{equation 2.}$$

Where:

- $GNSAV_t$ = Gross National Savings ($GNDI_t - PrvCon_t - GovCon_t$). This term includes the scenario-impact of changes in ecosystem service supply;
- $GNDI_t$ = 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, and;
- $EmiVal_t$ = Cost of damage from CO_2 emissions; US$30 per ton of CO_2.

For natural capital, the value of depletion is defined as in equation 3.

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

Where:
$qdepl_t$ = quantity of the resource extracted;
$unitrent_t$ = unit rent in year t, the value of which is endogenous in IEEM, and;
$intrat_t$ = interest rate (4% as in (Lange et al., 2018)).

3.0 Results

Modeled land use-land cover and ecosystem services changes

Owing to the structure of the IEEM+ESM workflow, changes in LULC are reported first, followed by impacts on ecosystem service flows and economic impacts. We modeled LULC and ecosystem services at a spatial resolution of 300 meters for each of Colombia's 32 departments, enabling detailed analysis of LULC change - the primary determinant of changes in ecosystem service supply - across the landscape (see Figure S8 in the S3 section).

The main LULC change driver in Colombia is the conversion of forest to grazing land to meet growing demand for land, particularly along the Amazon Forest frontier. Although this is the predominant process of forest loss that we observed in our scenarios, we also observed some conversion of forests to grazing land near roads but far from the forest edge, for example, in the department of Amazonas. Encroachment of cropland into forests is more common in the Pacific regions. Other processes, such as conversion from cropland to grazing land and vice versa occurred though at a smaller scale and mostly in departments on the Pacific coast and in the Andes. Forest and shrub cover loss also occurred in the Llanos region in central Colombia towards the border with Venezuela.

At the national level by 2040, PES and HAB enhance soil erosion mitigation ecosystem services by 3.3% and 16.7%, respectively. The SPS and COMBI scenarios *reduce* erosion mitigation services by 12.5% and 4%, respectively, due to different shares of cropland and grassland, despite similar deforestation trends (Table 1).

Table 1 National-level impacts on ecosystem services supply compared with business-as-usual in percent in 2040.

	PES	SPS	COMBI	PES+SPSe	HAB
Soil erosion mitigation	3.3	-12.5	-4.0	11.4	16.7
Carbon storage	6.3	0.01	6.1	6.8	7.2
Nutrient (nitrogen) retention	7.3	4.9	10.3	6.0	29.4
Nutrient (phosphorus) retention	4.9	0.1	6.1	7.2	18.8
Regulation of annual water yield	6.4	0.6	5.4	6.3	4.8
Biodiversity Intactness	6.4	0.1	6.6	7.3	8.2

PES: Payments for ecosystem services, SPS: Silvopastoral systems, COMBI: PES + SPS, PES+SPSe: PES + endogenized livestock productivity, HAB: Habitat banking. Source:

Integrated Economic-Environmental Modeling + Ecosystem Services Modeling (IEEM+ESM) results.

Cropland can have higher rates of erosion than grassland, which is mostly responsible for the reduction of erosion mitigation in the case of SPS and COMBI. Impacts, however, are spatially heterogenous; even in the PES scenario, some departments experienced a reduction in erosion mitigation services.

All scenarios resulted in increased carbon storage, with the HAB and PES+SPSe scenarios showing the greatest increase (Table 1; 7.2% and 6.8%, respectively). Overall, all scenarios except SPS increase water purification ecosystem services with HAB outperforming others in terms of increases in both nitrogen and phosphorus retention (29.4% and 18.8%, respectively). Relative to business-as-usual, all scenarios result in greater evapotranspiration, benefitting Colombia's hydrological systems (see S3). This results in less water runoff, thus reducing the impacts of floods, while maintaining better water quality and more water for dry-season flows and other important biological and ecosystem functions. Compared to business-as-usual, improvements to water regulation in other scenarios range from 0.6% in SPS, to 6.4% in the PES scenario (detailed ecosystem services impacts are shown in S3 and Figures S9-S18).

Economic impacts in 2040: Business-as-usual vs. scenarios

The economic impact of implementing these policies varied with the inclusion of ecosystem service values. When ecosystem service values are not included, the PES scenario would generate competition for crop and livestock land and would result in a US$276 million decline in GDP in 2040 compared with business-as-usual (Table 2). With the importance of agriculture to the incomes of many rural households, household consumption would contract by US$199 million; despite the policy's positive impact on natural capital, the decline in income and savings would push wealth downward by US$330 million. The implementation of SPS on the other hand would have a strong positive impact on GDP (US$694 million) and wealth (US$125 million). These gains are driven by the enhanced productivity of sustainable silvopastoral systems. When comparing the impact of SPS on GDP *when ecosystem services values are included*, positive economic returns to SPS would be over-estimated by US$53 million, due to the uncounted effects of worsening soil erosion.

Table 2 Impacts on macroeconomic indicators as difference between business-as-usual in 2040 in millions of (2019) U.S. Dollars. On the left, scenario impacts including ecosystem services values, and on the right, not including ecosystem services values.

	PES	SPS	COMBI	PES+SPSe	HAB	PES	SPS	COMBI	PES+SPSe	HAB
	Including ecosystem services					Excluding ecosystem services				
GDP	-262	694	549	0	188	-276	747	596	0	111
Genuine Savings	-325	125	-22	-216	1,607	-330	147	-3	-223	1,576
Private consumption	-188	725	444	-27	-237	-199	766	480	40	-299
Private investment	-244	76	-12	-130	134	-247	92	3	-182	114
Exports	-141	115	39	-69	237	-144	127	49	-80	217
Imports	-55	152	97	-1	166	-58	161	104	-3	151

GDP: Gross Domestic Product, PES: Payments for ecosystem services, SPS: Silvopastoral systems, COMBI: PES + SPS, PES+SPSe: PES + endogenized livestock productivity, HAB: Habitat banking. Source: Integrated Economic-Environmental Modeling + Ecosystem Services Modeling (IEEM+ESM) results.

With PES reducing deforestation and thus the supply of land available for crops and livestock, factor availability for agriculture is reduced. This result highlights the importance of investing in agricultural productivity and extension services, which in this case would have compensated for some of the negative economic impacts that arose in implementation of PES+SPSe. In Colombia in particular, there is large scope for enhancing agricultural and livestock factor productivity as it is considered low when compared to factor productivity in neighboring countries (Jiménez et al., 2018).

The joint implementation of PES and SPS in the COMBI scenario would boost GDP by US$549 million with a relatively small negative impact on wealth (US$22 million). In this scenario, double dividends would be achieved with increased income, consumption and savings through heightened economic activity, coupled with increased natural capital stocks and future ecosystem service flows. In PES+SPSe, where baseline GDP is tracked by endogenous adjustment of livestock productivity, the negative impact on wealth is driven by reduced crop and livestock output which negatively impacts household savings, a key component of wealth.

The establishment of habitat banking outperforms other scenarios across most economic indicators and would boost GDP by US$188 million and wealth by US$1.6 billion. The HAB scenario not only would increase natural capital stocks but would also show some additionality for ecosystem services provision. Comparing the HAB scenario's performance with and without the inclusion of ecosystem services values, it is evident that ecosystem services contribute significantly to the economy, by US$77 million and US$31 million to GDP and wealth, respectively.

Cumulative economic impacts in 2040: Business-as-usual vs. scenarios

Examining the cumulative value of wealth as the sum of the annual difference from business-as-usual provides a different perspective from that of Table 2. Where Table 2 shows a decline in wealth from 2020 to 2040 arising from PES (i.e., genuine savings), the cumulative impact on wealth vs. business-as-usual in 2040 is in contrast positive and would generate an additional US$14 billion in wealth (Figure 2). Combined with sustainable silvopastoral systems, wealth would increase by more than US$19.5 billion. Habitat banking again presents clear gains in wealth of over US$16.6 billion. While SPS alone generates important gains when considering the difference between 2020 and 2040, it does not perform as well from the perspective of cumulative wealth (i.e., compared to 2040 business-as-usual).

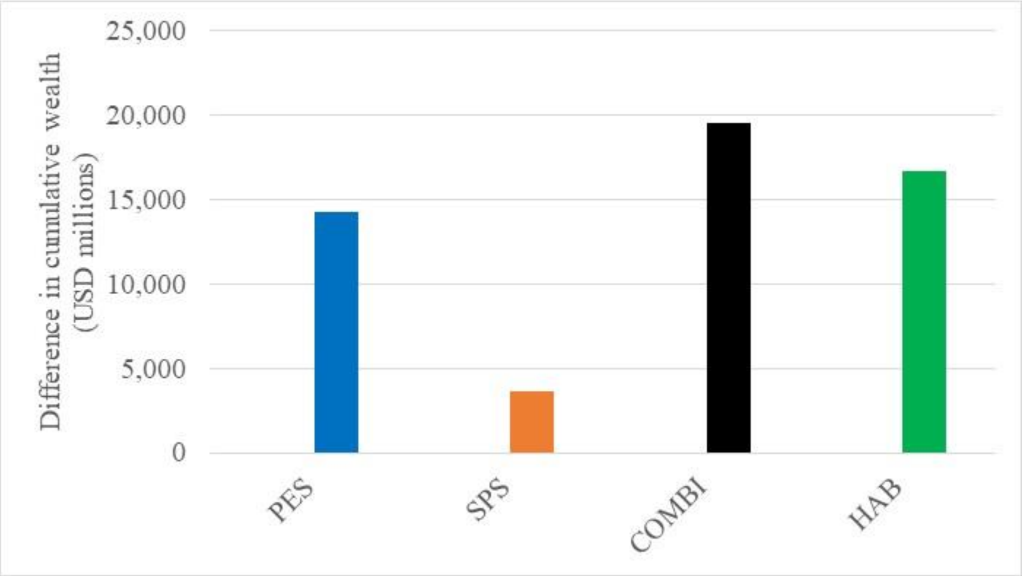

Fig. 2. Cumulative wealth, difference between scenarios and business-as-usual in 2040 in millions of (2019) U.S. Dollars (USD). PES: Payments for ecosystem services, SPS: Silvopastoral systems, COMBI: PES + SPS, PES+SPSe: PES + endogenized livestock productivity, HAB: Habitat banking. Source: Integrated Economic-Environmental Modeling + Ecosystem Services Modeling (IEEM+ESM) results.

Figure 3 shows a smooth trajectory for GDP in the SPS scenario and the offsetting impact of SPS on the downward pull of PES on GDP in COMBI. In the case of HAB, there would be an initial stimulus to the economy, a Keynesian effect from increased government expenditure, in the first two years during which habitat banking is established. This scenario shows gains that extend until 2035, after which there are no additional benefits as the program has achieved its purpose. Specifically, the drop in GDP in the HAB scenario in 2035 is explained by the fact that increases in productivity attributable to habitat banking and the Keynesian effect of increased public expenditure terminate in this year.

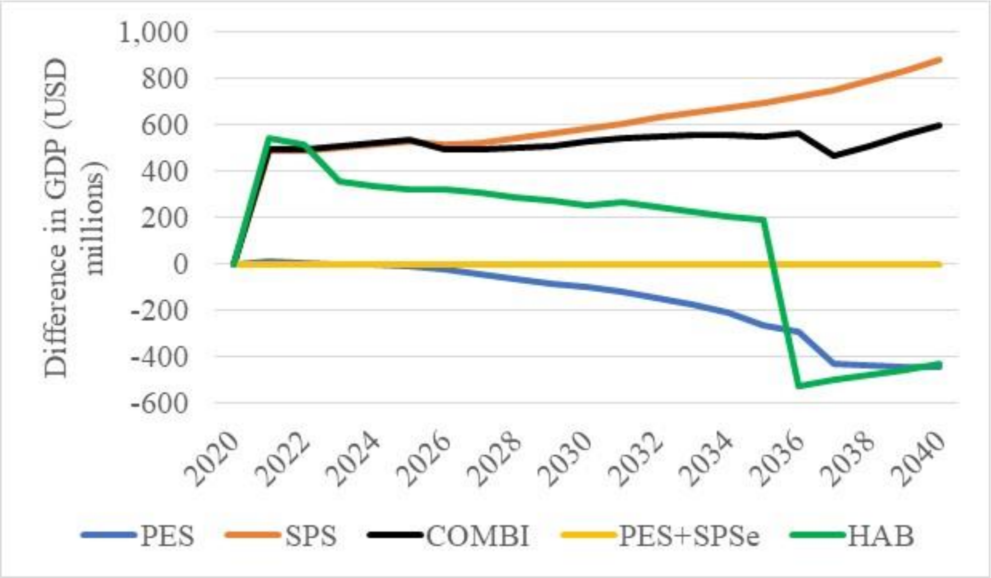

Fig. 3. GDP at factor cost, difference from business-as-usual in millions of (2019) U.S. Dollars (USD). PES: Payments for ecosystem services, SPS: Silvopastoral systems, COMBI: PES + SPS, PES+SPSe: PES + endogenized livestock productivity, HAB: Habitat banking. Source: Integrated Economic-Environmental Modeling + Ecosystem Services Modeling (IEEM+ESM) results.

For most scenarios, we can expect the return to business-as-usual levels in wealth once the investments have been fully implemented after 2034 (Figure 4). Some indicators such as wealth would drop slightly below business-as-usual due to the decrease in output, which in turn translates into a decrease in income, savings and investment. The explanation in terms of decreased investment is directly related to changes in household income. In later years, impacts on wealth tend to gravitate toward business-as-usual levels. That said, it is important to emphasize that over the analytical period, the positive deviations in flows of wealth would outweigh the negative ones and the overall impact of the policy scenarios on cumulative wealth, effectively the stock of Colombia’s wealth, would be positive (Figure 2).

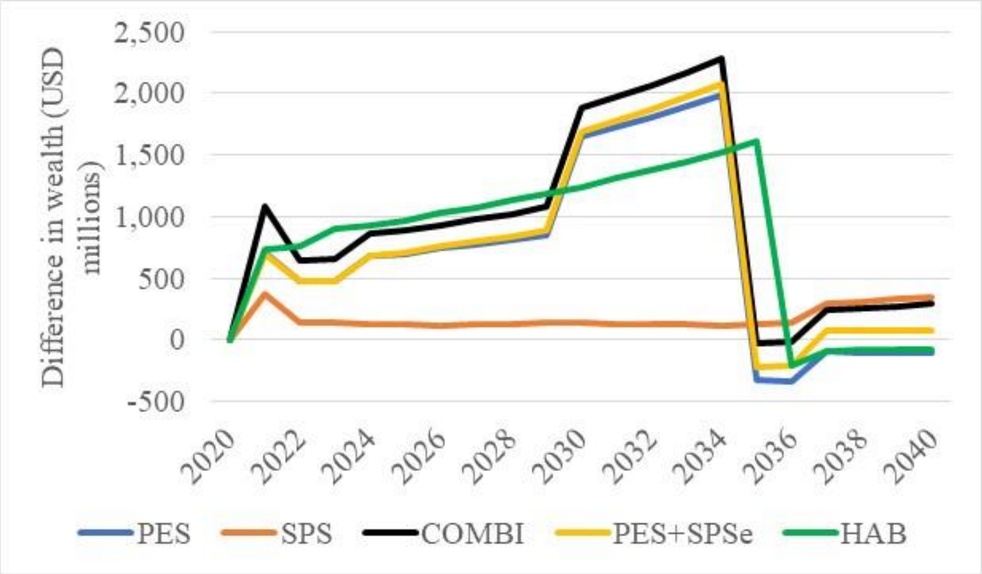

Fig. 4. Wealth, difference from business-as-usual in millions of (2019) U.S. Dollars (USD). PES: Payments for ecosystem services, SPS: Silvopastoral systems, COMBI: PES + SPS, PES+SPSe: PES + endogenized livestock productivity, HAB: Habitat banking. Source: Integrated Economic-Environmental Modeling + Ecosystem Services Modeling (IEEM+ESM) results.

The importance of including natural capital and ecosystem services values in public policy and investment decisions is unambiguous. In the case of PES, ecosystem services contribute an additional US$80 million in wealth (Figure 5). Silvopastoral systems create losses in ecosystem service-based wealth, on the order of US$295 million. Habitat banking outperforms other scenarios with an increase US$457 million in additional ecosystem service-based wealth.

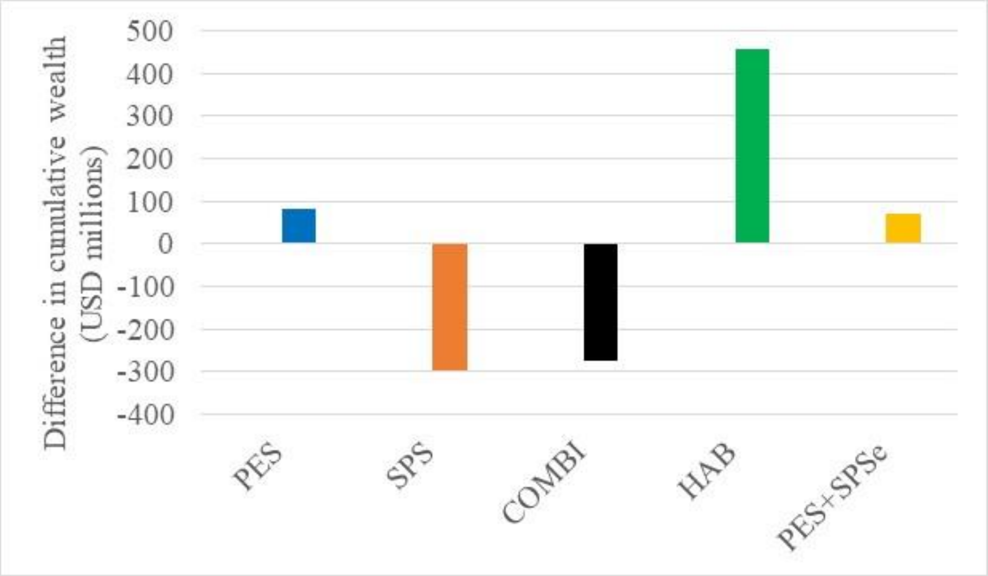

Fig. 5. Difference in cumulative wealth when ecosystem services are valued. Values are expressed as the difference between scenarios and business-as-usual until 2040 in millions of (2019) U.S. Dollars (USD). PES: Payments for ecosystem services, SPS: Silvopastoral systems, COMBI: PES + SPS, PES+SPSe: PES + endogenized livestock productivity, HAB: Habitat banking. Source: Integrated Economic-Environmental Modeling + Ecosystem Services Modeling (IEEM+ESM) results.

Calculating the Net Present Value (NPV) in a benefit-cost framework is a standard approach to assessing the economic viability of public investments. NPV is calculated here using a 12% discount rate, the standard discount rate used by some multilateral investment institutions. NPV is calculated based on equivalent variation, which is the amount of income an individual would need to receive to be as well-off had an investment project not been implemented (Banerjee, Cicowiez, and Moreda 2019). The costs used in the benefit-cost analysis are the investment costs related to the implementation of each of the scenarios as described in S2.

When considering household welfare alone, the implementation of PES results in an economically unviable project with an NPV of negative US$293 million (Figure 6). Coupling PES with silvopastoral systems results in a viable investment with an NPV of US$2.8 billion. The habitat banking scenario is not economically viable when ecosystem service values are not included, with an NPV of negative US$37 million. When the value of natural capital and ecosystem services are included, the outcomes change. The implementation of PES and HAB become strong investment propositions, with an NPV of US$4.4 billion and US$4.9 billion, respectively. The joint implementation of PES with silvopastoral systems results in a NPV of US$7.1 billion, capturing the benefits of both enhanced conservation as well as productivity and rural income opportunities.

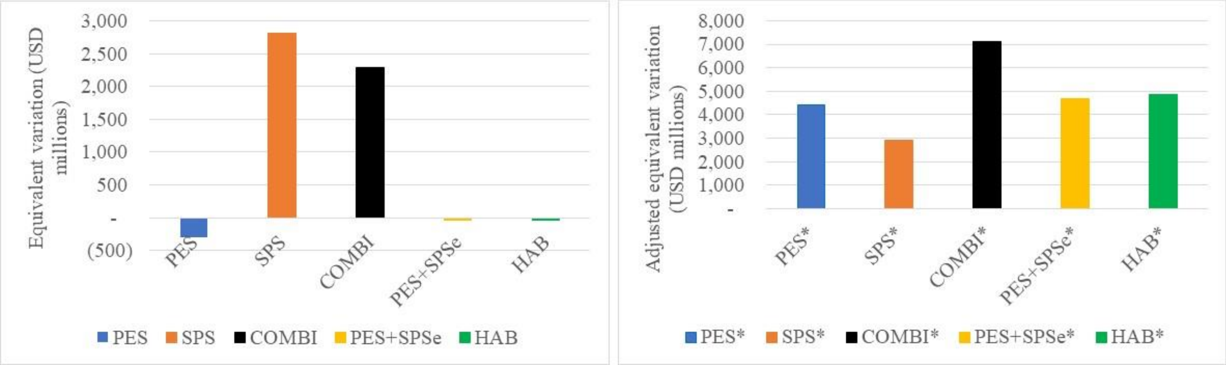

Figure 6. On the left, Net Present Value (NPV) calculated based on equivalent variation in millions of (2019) U.S. Dollars (USD); on the right, NPV calculated based on equivalent variation and adjusted for changes in natural capital and environmental quality in millions of (2019) USD. PES: Payments for ecosystem services, SPS: Silvopastoral systems, COMBI: PES + SPS, PES+SPSe: PES + endogenized livestock productivity, HAB: Habitat banking. Source: Integrated Economic-Environmental Modeling + Ecosystem Services Modeling (IEEM+ESM) results.

4.0 Discussion

We demonstrate the importance of including natural capital and ecosystem service values in public policy and decision making and the benefit-cost analysis used by governments and multilateral institutions around the world. If these values are included they can be expected to improve decision making and long-term socioeconomic outcomes through consideration of the contribution of all forms of capital, namely natural, manufactured and human, to sustainable economic development and wealth. Cumulatively, PES and habitat banking contribute an additional US$14 billion and US$16.6 billion in wealth, respectively, which can help sustain the peace in post-conflict Colombia for current and future generations. These results make the economics of biodiversity explicit and aligned to the assertion that "Economic valuation [of the environment] is always implicit or explicit; it cannot fail to happen at all" (Pearce, 2006).

The IEEM+ESM approach is the first integrated analytical framework to endogenize feedbacks between future changes in land use and ecosystem services and the economy, a research challenge posed in earlier work (Banerjee, Crossman, et al. 2020; Crossman et al. 2018). This approach is critical to account for how flows of ecosystem services have dynamic effects on the economy. It also provides an estimate of the marginal value of ecosystem services, consistent with a country's System of National Accounts, the primary accounting framework used by countries around the world to measure and monitor economic development. Enhanced ecosystem service flows from investing in habitat banking generated an additional US$77 million in GDP; this is effectively the marginal value of ecosystem services. This economic contribution is not trivial since in just one year, it amounts to 69% of the habitat banking scenario impact on GDP. Consistency with the country's System of National Accounts, provides a great deal of credibility to the IEEM+ESM approach compared with welfare-based valuation methods which have been the subject of some criticism.

A handful of earlier studies have explicitly considered the contribution of ecosystem services to economic development in an economy-wide framework. One such study examined how future changes in demand for agriculture would affect the European landscape (Verburg, Eickhout, and van Meijl 2008). A logical extension of this work is to consider how the change in land use would affect future ecosystem service supply. Another example with origins in the WWF's Global Futures project (Banerjee, Crossman, et al. 2020; Crossman et al. 2018; Johnson et al. 2020) linked a global static economy-wide model underpinned by the Global Trade Analysis Project (GTAP) database (Aguiar et al., 2019; Baldos & Corong, 2020; Fischer et al., 2012) with land use land cover and ecosystem services modeling (Chaplin-Kramer et al., 2019; Johnson et al., 2021). Integrating feedbacks between changes in ecosystem service flows and the economy using a dynamic modeling framework as implemented in this study is the next step for global approaches. At the same time, given the complexity of land use dynamics at the local scale, results of the implementation of global approaches require careful country-level validation.

Assessments of opportunities for enhancing natural capital and building strong bioeconomies in post-conflict societies are rare. Analyses are typically ex post and focus on political stability and socioeconomic development while considering the environment and natural capital as independent concerns (Bustos & Jaramillo, 2016; Suarez et al., 2017). This study has shown the importance of considering economy, society and environment as an integrated and inter-dependent system. With a focus on building strong bioeconomies, this assessment considers the contribution of natural capital and ecosystem services to the sustainability of economic development, and in particular, wealth. This emphasis supports a more equitable reconciliation and socioeconomic development process because rural households are the most acutely affected by policies that impact the quantity and quality of natural capital and ecosystem service flows (Fedele et al., 2021).

This study has shown that investment in PES and habitat banking would generate strong benefits in terms of future ecosystem service supply while sustainable silvopastoral systems on average would have a negative impact on ecosystem services. In light of these heterogenous outcomes and with the large rural livelihood development benefits that sustainable silvopastoral systems can provide, a portfolio approach combining these strategies would generate economic gains that are critical to economic stability that sustains the peace while simultaneously mitigating environmental harm and enhancing the productive natural capital base. The evidence presented in this study builds a strong business case for financing such an approach rooted in fostering the development of strong rural bioeconomies.

The IEEM+ESM approach provides critical information for the design of spatially targeted public policy and investment. The spatial distribution of impacts on one ecosystem service are not necessarily the same as those of other ecosystem services. In the case of carbon storage services, overall impacts across scenarios would be positive; however, some departments show a reduction in this service while others compensate with increases. Policy scenario impacts on water quality services would have differentiated spatial impacts, especially in the case of the implementation of sustainable silvopastoral systems.

Biodiversity intactness, while generally increasing across policy scenarios, also reveals spatially differentiated patterns. Knowing where the impacts are the largest and where communities may be most vulnerable can help policymakers target actions to strengthen the natural capital base and mitigate ecosystem service loss. As this study has demonstrated, stocks of natural capital and future ecosystem service flows are inextricably linked to economic outcomes and wealth.

Both PES and habitat banking aim to conserve half a million hectares. PES program distribution across the landscape was conducted based on the relative importance of deforestation in each of Colombia's 32 departments. In contrast, the HAB scenario targeted specific regions of Colombia with high conservation value forests, such as the Tropical Dry Forest, and regions with high ecosystem service supply potential. The results presented demonstrate that there are important advantages to spatial targeting for maximizing economic and ecosystem service outcomes. These increases in ecosystem service flows translate into hard currency when evaluated from an economic standpoint (i.e., in terms of increased farm revenue resulting from reduced soil erosion) and provide compelling evidence for increasing the importance of spatial targeting in PES design where the scientific underpinning of many programs is lacking (Naeem et al., 2015).

Net Present Value calculations represent the 'bottom-line' for public policy and investment evaluated by governments and multilateral institutions around the world. Public investments financed by multilateral development institutions need to generate returns on investment greater than the standard 12% discount rate used by some institutions such as the Inter-American Development Bank (Banerjee, Cicowiez, and Moreda 2019). With the relatively high discount rate used here, results in terms of returns on investment are conservative. A lower discount rate, such as the 3.5% proposed in the UK's Green Book, would result in a much greater contribution of ecosystem services and natural capital to investment returns and a yet more compelling investment case.

Results show just how fundamental the inclusion of the value of natural capital and ecosystem services is in benefit-cost analysis. Future research to understand linkages between additional ecosystem services and the economy in the form of modeled economic feedbacks (see Materials and Methods) will enable a fuller understanding of the economy's dependence on nature and more comprehensive valuation of natural capital. Investment in conservation through PES and habitat banking is not considered economically viable until the value of natural capital and ecosystem service is included. This is the difference between funding and not funding a project. Including the value of ecosystem services, PES and HAB become strong investment propositions with an NPV of US$4.4 billion and US$4.9 billion, respectively. The consequences of valuing ecosystem services and biodiversity in economic decision making are far reaching.

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Data Availability Statement

The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

Dear Dr. Hens,

We have responded to all the constructive comments provided by the reviewer and indicated where changes in the manuscript were made.

We sincerely thank you for your consideration.

We are very pleased that we will soon see this manuscript in print.

All best wishes.