Environment, Development and Sustainability
https://doi.org/10.1007/s10668-023-03740-w

Banking on strong rural livelihoods and the sustainable use of natural capital in post-conflict Colombia

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Received: 21 July 2022 / Accepted: 1 August 2023

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 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

Extended author information available on the last page of the article 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., 2021a, 2021b; Lange et al., 2018; Polasky et al., 2015; Stiglitz et al., 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 & Cicowiez, 2019; Banerjee et al., 2016, 2019b, 2019c) with high resolution spatially explicit land use land cover (LULC) change and ecosystem services models (IEEM + ESM; Banerjee et al., 2020a). 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 & Bennett, 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 Materials and methods

2.1 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).

2.2 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 & Cicowiez, 2019; Banerjee et al., 2019b, 2019c). 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 & 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/.

2.3 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 & Verburg, 2004; Verburg & Overmars, 2009; Verburg et al., 2002, 2021) 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.

2.4 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., 2019a). 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; 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 & 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

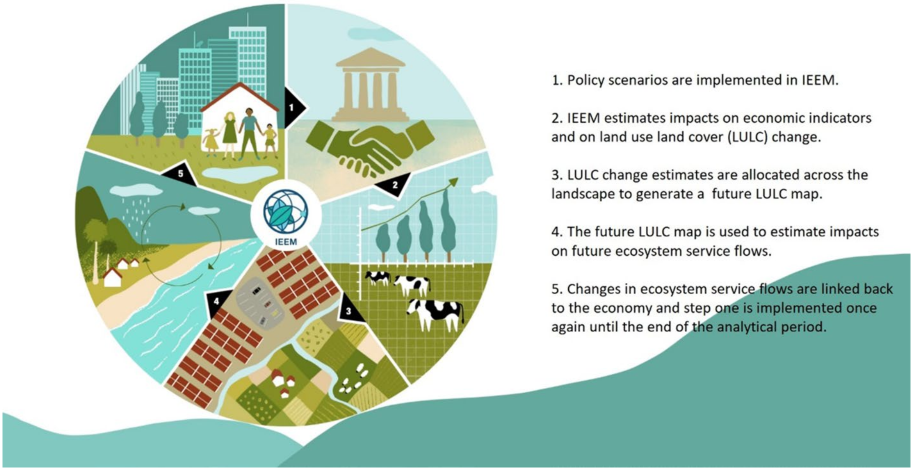

Fig. 1 The Integrated Economic-Environmental Modeling + Ecosystem Services Modeling (IEEM + ESM) workflow with dynamic endogenous feedbacks. Source: Authors' own elaboration

and the economy must be first identified and then operationalized for each specific country context.[1]

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-m 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 (Fig. 1).

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

[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 et al. (2021a).

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 Eq. (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).

$$LPL_d = \frac{SER_d}{TAA_d} \cdot 0.08 \tag{1}$$

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).

2.5 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 Eq. (2) (Banerjee et al., 2020a; Banerjee et al., 2021a, 2021b):

$$GenuineSAV_t = GNSAV_t - DeprCapStock_t - DeplForStock_t - DeplMinStock_t - EmiVal_t \tag{2}$$

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 Eq. (3).

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

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

3 Results

3.1 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

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

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

PES payments for ecosystem services, *SPS* Silvopastoral systems, *COMBI* PES + SPS, *PES + SPSe* PES + endogenized livestock productivity, *HAB* habitat banking

LULC and ecosystem services at a spatial resolution of 300 m 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).

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).

3.2 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.

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.

3.3 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 (Fig. 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

Table 2 Impacts on macroeconomic indicators as difference between business-as-usual in 2040 in millions of (2019) U.S. Dollars

	Including ecosystem services					Excluding ecosystem services				
	PES	SPS	COMBI	PES + SPSe	HAB	PES	SPS	COMBI	PES + SPSe	HAB
GDP	−262	694	549	0	188	−276	747	596	0	111
Genuine savings	−325	125	−22	−216	1607	−330	147	−3	−223	1576
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

On the left, scenario impacts including ecosystem services values, and on the right, not including ecosystem services values

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

GDP Gross Domestic Product, *PES* Payments for ecosystem services, *SPS* Silvopastoral systems, *COMBI* PES + SPS, *PES + SPSe* PES + endogenized livestock productivity, *HAB* Habitat banking

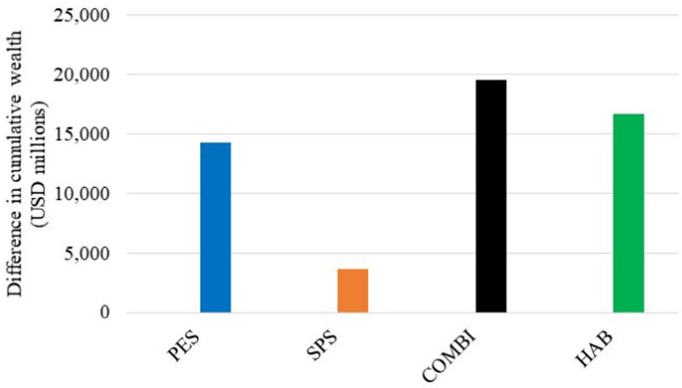

Fig. 2 Cumulative wealth, difference between scenarios and business-as-usual in 2040 in millions of (2019) U.S. Dollars (USD). PES: Payments for ecosystem services, SPS: Silvopastoral systems, COMBI: PES + SPS, PES + SPSe: PES + endogenized livestock productivity, HAB: Habitat banking. Source: Integrated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

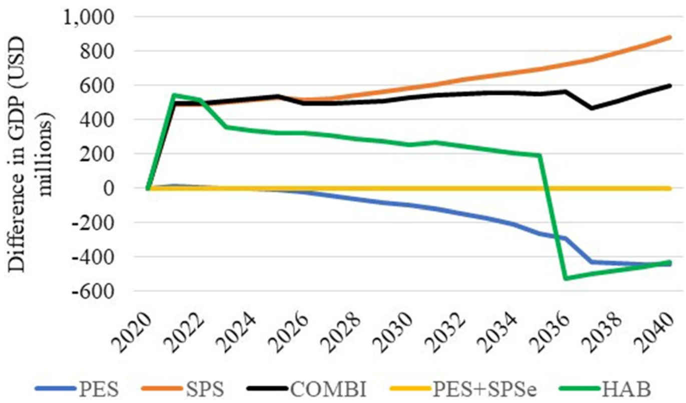

Fig. 3 GDP at factor cost, difference from business-as-usual in millions of (2019) U.S. Dollars (USD). PES: Payments for ecosystem services, SPS: Silvopastoral systems, COMBI: PES + SPS, PES + SPSe: PES + endogenized livestock productivity, HAB: Habitat banking. Source: Integrated Economic-Environmental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

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).

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.

For most scenarios, we can expect the return to business-as-usual levels in wealth once the investments have been fully implemented after 2034 (Fig. 4). Some indicators

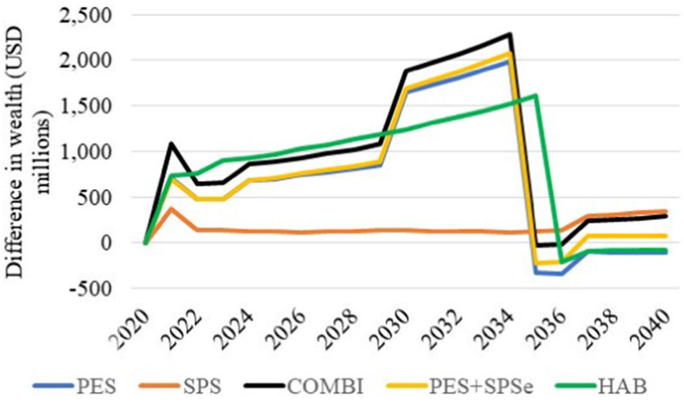

Fig. 4 Wealth, difference from business-as-usual in millions of (2019) U.S. Dollars (USD). PES: Payments for ecosystem services, SPS: Silvopastoral systems, COMBI: PES + SPS, PES + SPSe: PES + endogenized livestock productivity, HAB: Habitat banking. Source: Integrated Economic-Environmental Modeling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

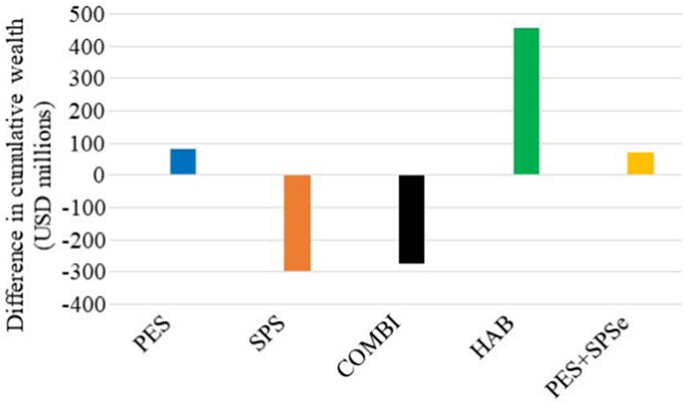

Fig. 5 Difference in cumulative wealth when ecosystem services are valued. Values are expressed as the difference between scenarios and business-as-usual until 2040 in millions of (2019) U.S. Dollars (USD). PES: Payments for ecosystem services, SPS: Silvopastoral systems, COMBI: PES + SPS, PES + SPSe: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

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 (Fig. 2).

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

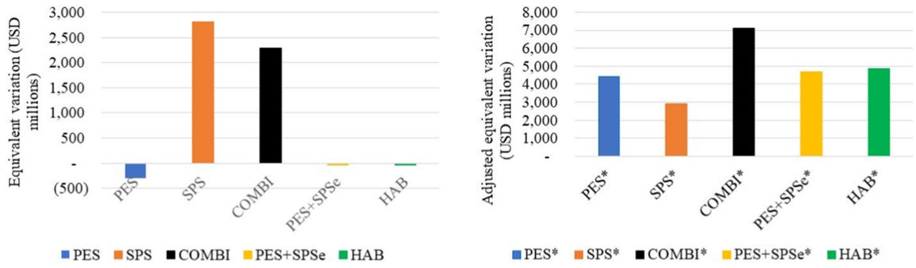

Fig. 6 On the left, Net Present Value (NPV) calculated based on equivalent variation in millions of (2019) U.S. Dollars (USD); on the right, NPV calculated based on equivalent variation and adjusted for changes in natural capital and environmental quality in millions of (2019) USD. PES: Payments for 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

contribute an additional US$80 million in wealth (Fig. 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.

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, 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 (Fig. 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.

4 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 et al., 2020b; 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 et al., 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 et al., 2020b; 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, 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.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s10668-023-03740-w.

Acknowledgements The authors thank Javier Rojas Cala from Colombia's Ministry of the Environment and Andrés Camilo Alvarez-Espinosa, Sioux Melo, Leidy Riveros and Germán Romero from Colombia's National Planning Department for their collaboration in the development of the IEEM database for Colombia and various applications of the framework. Thanks to Robert Marks, Emily McKenzie and Felix Nugee and the Dasgupta Review Team for their constructive review of this paper. The authors thank Mariana Sarmiento and Jose David Taborda from the Terrasos Habitat Bank Team in Colombia for their contribution to the design of the habitat banking scenario. Thanks to Luke Brander for his insightful comments on the paper. The authors thank Annette Kilmer, Allen Blackman, Leandro Gaston Andrian, Gregory Watson, Carlos Salazar and Pedro Martel for their review and comments on the paper.

Funding This study was funded by the Inter-American Development Bank and the Department for Environment, Food and Rural Affairs (UK). Support for Kenneth J. Bagstad's time was provided by the U.S. Geological Survey's Land Change Science Program.

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

Declarations

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

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