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The economics of decarbonizing Costa Rica's agriculture, forestry and other land uses sectors

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ABSTRACT

In 2018, Costa Rica demonstrated its commitment to the Paris Agreement and published its Decarbonization Plan for achieving zero net emissions by the year 2050. We evaluate the impacts of the country's strategy for decarbonizing its Agriculture, Forestry and Other Land Uses (AFOLU) sectors by coupling the Integrated Economic-Environmental Modeling framework with high-resolution spatial land use-land cover change and ecosystem services modeling (IEEM+ESM). Our results show that decarbonization of AFOLU would simultaneously enhance carbon storage, water purification, water regulation and erosion mitigation ecosystem services. Moreover, the positive cumulative wealth impact of decarbonization would be approximately US$7.27 billion by 2050 while lifting an additional 3810 individuals out of poverty. From a public investment perspective, decarbonization would have a fiscally neutral impact with the economic benefits sufficient in magnitude to off-set policy implementation costs and generate economic returns of over US$852 million when changes in natural capital stocks and environmental quality are considered. This application to Costa Rica is the first integrated economy-wide analysis of a growing number of decarbonization plans globally. The IEEM+ESM approach provides an integrated framework for analyzing decarbonization plans and can be used to refine AFOLU mitigation strategies to capitalize on synergies and minimize negative trade-offs across the three dimensions of wealth and sustainable economic development, namely economy, society and the environment.

1. Introduction

The Agriculture, Forestry and Other Land Use (AFOLU) sector is responsible for 23% of net global greenhouse gas emissions (OECD, 2020) which is fourth in terms of greenhouse gas emitting sectors with transport, industry and waste management as the top three. To reach the Paris Agreement limit of global temperature increases to below 2 °C, leveraging the emissions reduction potential of AFOLU is critical. The Intergovernmental Panel on Climate Change identifies three main supply-side strategies for mitigation of greenhouse gas emissions within AFOLU: (i) reduction and prevention of emissions by conserving existing carbon pools in vegetation and soils or by reducing methane and nitrous oxide emissions; (ii) sequestration of carbon dioxide (CO_2) through greater uptake of carbon in terrestrial carbon pools; and (iii) reducing CO_2 emission by substituting biofuels for fossil fuels (Smith et al., 2014). The AFOLU sector is central to climate regulation and is one nature's most critical contributions to human well-being (Daily, 1997; Pascual et al., 2017). In addition, emissions reductions through implementing enhanced AFOLU management strategies can generate many ecosystem service (ES) co-benefits, such as improved air and water quality, greater erosion mitigation and enriching biodiversity (Díaz et al., 2015).

The role of AFOLU in country strategies for reducing emissions and meeting Paris Agreement commitments varies between countries and in many cases the targets are not aligned with AFOLU's potential for

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reducing emissions. Henderson et al. (2020) reviewed AFOLU targets for 20 countries accounting for half of global AFOLU emissions and found that only two countries had legally binding targets. One of these countries was Costa Rica, which has proven itself a leader in designing strategies to meet decarbonization targets. Indeed, the country's hydropower generation system supplies 99.5% of all electricity used. Demonstrating its commitment to the Paris Agreement, Costa Rica developed one of the first Decarbonization Plans, which describes its strategy for achieving zero net emissions by the year 2050 (Government of Costa Rica, 2018). On the path to reach this goal, the 2030 target for maximum net emissions is 9.11 million tons of carbon dioxide equivalent (CO_2e), with a maximum net emissions budget for 2021 to 2030 of 106.53 million tons of CO_2e (Government of Costa Rica, 2018; Government of Costa Rica and MINAE, 2015; Groves et al., 2020).

Despite its small size, covering roughly 0.03% of the global terrestrial surface, Costa Rica is a biodiversity hotspot hosting a disproportionate share of global biodiversity (Myers et al., 2000). To reduce environmental degradation and biodiversity loss, Costa Rica has expanded its protected areas network and its globally renowned Payment for Environmental Services (PES) program (Broadbent et al., 2012; Locatelli et al., 2014). Both measures were not only effective in enhancing forest cover but also contributed to climate regulation ES (Tafoya et al., 2020). With the implementation of these and other progressive, well-enforced forest policies, Costa Rica has increased its forest cover from 20% to over 50% from 1980 to 2010 (Porras et al., 2013).

Costa Rica's expansion of forest cover has tapped into the emissions reduction potential of AFOLU, which includes agroforestry and sustainable silvopastoral systems, while additional opportunities exist for expanding forest cover and increasing the agricultural sector's contribution to reducing emissions. Despite the increases in forest cover, the AFOLU sector is responsible for 38% of Costa Rica's net CO_2 emissions (Government of Costa Rica, 2018). The main sources of CO_2 as well as nitrous oxide and methane emissions from the AFOLU sector are livestock grazing, rice cultivation and commodity production (coffee, sugarcane and banana). Consequently, AFOLU emissions reductions are critical for the country to reach its overall target of net-zero emissions by 2050.

To inform government policy and decision making and the allocation of scarce public resources, understanding the benefits, costs, synergies and trade-offs of emissions reduction strategies is critical. Emissions reduction strategies for AFOLU and other sectors will have impacts across the economy (Köberle et al., 2021) as well as employment, poverty and wealth effects. This study offers quantitative analytics that can be used to refine the decarbonization of AFOLU strategies by shedding light on their impacts on the economy, society and the environment in an integrated way. We applied the Integrated Economic-Environmental Modeling (IEEM) framework (Banerjee et al., 2016; Banerjee et al., 2019) coupled with high-resolution spatial land use-land cover (LULC) change and ES modeling to investigate the sectorally, temporally and spatially variable impacts of AFOLU emissions reductions strategies. Where policies have broad multi-sectoral impacts, there are no real alternatives to an economy-wide Computable General Equilibrium (CGE) approach (Arrow, 2005) such as IEEM.

2. Materials and methods

2.1. Overview of the IEEM model and database for Costa Rica

Almost all economic sectors consume energy, which includes substantial amounts of fossil fuels. The development of strategies to reduce emissions requires an analytical approach that simultaneously considers all economic sectors, economic actors, institutions and their interactions. The input-output relationships between economic sectors and final demand addresses such multi-sectoral linkages (Arrow, 2005). For example, an expansion of the forestry sector requires a concomitant increase in transportation services to deliver forest products to markets and ports. A CGE model is effective in capturing these multi-sectoral linkages and identifying the synergies and trade-offs of different strategies for reducing emissions.

This study advances the IEEM framework constructed for Costa Rica in collaboration with the Central Bank of Costa Rica and previous applications of the framework to, for example, decarbonization of the transport sector (Banerjee and Cicowiez, 2021). While IEEM integrates rich natural capital accounting data, we link IEEM with high resolution LULC change and ES modeling (i.e., IEEM+ESM) to include ES that do not currently have a market price. While there is a growing body of literature that investigates LULC change impacts on ES (Bagstad et al., 2020; Chaplin-Kramer et al., 2017; Fang et al., 2022; Gomes et al., 2020; Vallet et al., 2016; Verburg et al., 2008; Yi et al., 2018; Zhao et al., 2004), the IEEM+ESM approach is the first of its kind to link a detailed CGE model with high resolution LULC and ES models (Banerjee et al., 2020a, 2020b, 2022a, 2023). IEEM on its own may be applied to estimate scenario impacts on economic indicators, emissions, natural capital and most provisioning ES such as food, fiber and fuel (European Environment Agency, 2018; Haines-Young and Potschin-Young, 2018). The linkage of IEEM with LULC change and ES modeling enables estimation of impacts on non-market regulating ES including carbon storage, water purification, water regulation and erosion mitigation (Banerjee et al., 2023; Banerjee et al., 2022b; Banerjee et al., 2022a).

IEEM models have been developed for 30 countries around the world and applied to hundreds of questions of public policy and investment. IEEM is based on a recursive dynamic CGE model that integrates natural capital accounting data organized under the System of Environmental-Economic Accounting (European Commission, United Nations, Food and Agriculture Organization, International Monetary Fund, Organisation for Economic Cooperation and Development, The World Bank, 2014). CGE modeling has a broad literature spanning decades (Burfisher, 2021; Dervis et al., 1982; Dixon and Jorgenson, 2012; Kehoe, 2005; Shoven and Whalley, 1992). IEEM is well documented with its natural resources modeling modules described in Banerjee et al. (2016), its mathematical structure in Banerjee and Cicowiez (2020) and its environmentally extended Social Accounting Matrix (SAM) in Banerjee et al. (2021). Many IEEM models and training resources are open source and currently available at the OPEN IEEM Platform https://openieem.iadb.org/

IEEM's core database, an environmentally extended SAM for Costa Rica, is comprised of 136 economic activities and 183 products at its highest level of disaggregation and is based on Supply and Use Tables and other data from Costa Rica's System of National Accounts. For this application, economic sectors and products have both been aggregated to 48 sectors/commodities. The environmentally extended SAM includes base year emissions from all economic sectors. With regards to LULC, the SAM shows that emissions from the crop and livestock sectors were responsible for 75.1% and 24.9% of emissions from AFOLU, respectively (which includes agroforestry and silvopastoral systems), with AFOLU responsible for 23% of Costa Rica's net GHG emissions (see Supplementary Information section 1, Table SI 1). As for emissions from energy consumption, households, through their consumption of fuel for automobiles, were responsible for 36% of emissions, while the freight transport sector was responsible for 16% of emissions from the consumption of fuel.

Our methods enable the calculation of 2 robust measures of sustainable economic development and returns on investment, namely wealth and environmentally enhanced Net Present Value (NPV). We use an adjusted form of genuine savings as an indicator of wealth as presented in Banerjee et al. (2023), which focuses on the economic and environmental impacts on changes in wealth (eq. 1). Eq. 1 omits changes in human capital since this is measured by changes in investments in education or lifetime earnings (Lange et al., 2018; World Bank, 2021a); investments in these areas do not change across our scenarios.

$$GenuineSAV_t = GNSAV_t - DeprCapStock_t - DeplForStock_t - DeplMinStock_t - EmiVal_t \tag{1}$$

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.

The value of depletion of natural capital is defined as in eq. 2.

$$\sum_{i=t}^{t+T-1} \frac{qdepl_t \cdot unitrent_t}{(1 + intrat)^{i-t}} \tag{2}$$

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)).

We calculated NPV using a benefit-cost analytical framework which is a standard approach to assessing the economic viability of projects and is used by governments and multi-lateral institutions around the world. NPV in this study is calculated with a 12% discount rate, which is used by some multi-lateral investment banks (Banerjee et al., 2019; Banerjee and Alavalapati, 2012; Banerjee and Moreda, 2015).[1]

$$NPV = \sum_{t=2020}^{2050} \frac{EV + \Delta EmiVal + \Delta DeplForStock}{(1 + intrat)^{t-2020}} \tag{3}$$

where:

EV = equivalent variation; $\Delta EmiVal$ = change in value of emissions between base and non-base scenarios; $\Delta DeplForStock$ = change in value of forest stock between base and non-base scenarios, and; $intrat_t$ = discount rate (12%).

The NPV calculation is presented in eq. 3 and is 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. The environmental dimension of IEEM enables us to calculate an adjusted form of NPV, which takes into account changes in the standing stock of forests and CO_2e emissions damage (World Bank, 2021a, 2021b) much in the same way as our calculation of wealth.

2.2. Linking IEEM with land use-land cover change and ecosystem services modeling

The bridge between IEEM and changes in future ES supply is established through LULC change modeling. IEEM projections of demand for land are spatially allocated with a LULC change model and used to generate business-as-usual and scenario-based LULC maps from the base year until 2050. The LULC changes depicted in these maps are the variable of change in the ES modeling, with all other model variables held constant through time. We use the Dynamic Conversion of Land Use and its Effects (Dyna-CLUE) modeling framework 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 (Veldkamp and Verburg, 2004; Verburg et al., 2021, Verburg et al., 2002; Verburg and Overmars, 2009; see Supplementary Information section 2 for more details on Dyna-CLUE and its implementation). Dyna-CLUE is among the most widely used spatial LULC change models and has been applied on different scales across the globe in more than 150 studies (Rakotoarinia et al., 2023).

The Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST) suite of models is used to calculate spatially explicit changes in ES supply (Sharp et al., 2020). InVEST combines LULC maps and biophysical information to calculate spatial and temporal dynamics of ES. InVEST is one of the most widely used open source ES modeling tools available globally (Posner et al., 2016), is well documented and has a large and active user community. We applied four InVEST models to calculate changes in ES supply across the baseline projection and all scenarios: (i) the sediment delivery ratio model to calculate the Revised Universal Soil Loss Equation and sediment export (erosion mitigation ES); (ii) the carbon storage model to calculate above and below ground carbon storage and carbon sequestration potential (carbon storage ES); (iii) the annual water yield model to calculate water supply (water regulation ES) and; (iv) the nutrient delivery ratio model used as a proxy for calculating the water purification potential of landscapes through nitrogen and phosphorus absorption (water purification ES). In addition, climate regulation ES were estimated with IEEM as net emissions from energy consumption across economic sectors and changes in the carbon stored in LULC types.

One of the main challenges of applying InVEST and other ES models in ES assessments is the time and expertise required to assemble the best-available spatial and biophysical data and parameters. This study used the ES modeling datapackets developed by the authors of the present study, which render four InVEST ES models "plug and play" (IDB, 2021). These datapackets contain all the processed spatial data and lookup tables required to run the InVEST sediment delivery ratio, carbon storage, water yield and nutrient delivery ratio models for all countries in Latin America and the Caribbean as well as a rapidly growing number of countries outside of the region (see the OPEN IEEM Platform Model & Data Repository to view and download the datapackets for Costa Rica: https://openieem.iadb.org/#/model-data).

3. Scenario design

3.1. Costa Rica's intended nationally determined contributions

Nationally Determined Contributions (NDCs) reflect a country's commitment to keeping average global temperature increases below 2 °C and potentially below 1.5 °C, based on each country's emissions reduction capacity. For Costa Rica, this commitment involves reducing emissions by 25% with respect to 2012 emissions, effectively 170,500 tons of CO_2 per year until 2030 (Government of Costa Rica and MINAE, 2015).

The Network for Greening the Financial System, a group of Central Banks partnering with climate change research institutions, developed six scenarios to understand climate change physical risks and their interaction with transition risk (Boushey et al., 2021) under different emissions reduction futures globally. The scenarios are: Net Zero 2050; Below 2 °C; Divergent Net Zero; Delayed Transition; NDC; and Current Policies. In what follows, we focus on the NDC scenario, which assumes the unconditional NDCs are fully implemented with moderate climate ambition beginning in 2021 through 2100 (Bertram et al., 2021). In this scenario, global emissions decline, though warming reaches 2.5 °C with moderate to severe physical risks accompanied by relatively low transition risks.

Three primary Integrated Assessment Models (IAMs) were used in generating emissions projections for these scenarios, each with different levels of spatial aggregation. They are the Model for Energy Supply Systems And their General Environmental impact-Global Biosphere Management Model (MESSAGEix-GLOBIOM), which has 11 model regions, the REgional Model of Investment and Development- *Model* of Agricultural Production and its Impact on the *Environment* (REMIND-MAgPIE) with 12 model regions and the Global Change Assessment Model (GCAM) with 32 model regions (Bertram et al., 2021). The key

[1] We include in Supplementary Information 4 a sensitivity analysis to model the effects on NPV of varying the discount rate for the six scenarios, applying discount rates of 3, 6, 9, 12, and 15%.

economic, energy and emissions variables in these models were downscaled using a consistent methodology for about 132 countries, including Costa Rica. In country-level downscaling, each country was assumed to begin in its current state, gradually converging to the regionally projected emissions pathway determined by the IAM. The speed of convergence was based on country-specific factors related to emissions and emissions reduction potential. The downscaling of these key variables was undertaken by applying a standardized methodology across countries and therefore does not account for the implementation of country-specific policies (Bertram et al., 2021).

The policy assumption beyond current NDC target periods (2025 and 2030) is that the climate policy ambition remains comparable to the levels implied by the NDC. Beyond 2030, the extrapolation of policy ambition is subject to large uncertainties, which are implemented differently across the three IAMs and therefore there are relatively large differences between the results of the three models. Our study fills an important gap in knowledge by bridging the emissions transition pathways modeled at the global level with IAMs and downscaled to the country level with country-specific policies that can be implemented to achieve the NDCs or other emissions targets. With a standardized methodology applied across all countries in the downscaling of key variables, this is a critical step in harmonizing global estimates with country-specific feasibility and opportunities. The results from our analysis will show the emissions reduction potential that Costa Rica's strategies for decarbonization of AFOLU sectors have and how closely our modeled emissions reduction pathway follows that of the downscaled emissions pathways modeled with the IAMs through the Network for Greening the Financial System. With MESSAGE and REMIND IAMs more aligned with the expectations of AFOLU emissions for Costa Rica, we compare the emissions pathways of these two models with the results of our analysis of AFOLU strategies in section 4.

3.2. Business-as-usual scenario

We develop a business-as-usual (BASE) scenario and three policy scenarios, which we implement individually and in combination. The BASE scenario projects the Costa Rican economy from 2016 to 2021 based on observed economic data and from 2022 to 2050 based on economic growth projections from the International Monetary Fund's Economic Outlook (IMF, 2019). Population was projected based on the World Population Prospects report (UN, 2019). Public and private capital stocks grow according to public and private investment, respectively.

For the business-as-usual LULC projection, we use Costa Rica's Ministry of the Environment and Energy (MINAE, 2019a; MINAE, 2019b) projection, which is based on the forest reference emissions levels submitted by the government to the Secretariat of the United Nations Framework Convention on Climate Change. The methodology applied to develop the projection is described in Pedroni (2015) and Sierra (2016). To estimate the emissions associated with this LULC projection, we apply the approach outlined in Supplementary Information section 3, which is essentially the sum of changes in carbon stocks for each LULC class converted to units of CO_2e following IPCC (2006) guidelines.

3.3. Crop and livestock AFOLU emissions reduction strategies

Following Costa Rica's Decarbonization Plan and Strategies for the AFOLU sectors in particular, the policy scenarios were designed to target emissions reductions, enhance agricultural productivity and reduce emissions from deforestation and forest degradation. In IEEM, as well as in reality, all investments require the source of financing to be identified. While various alternatives are possible, all scenario investments were modeled to be funded by an increase in the direct tax rate and foreign debt. Future analysis could consider market-based mechanisms and other funding sources including domestic debt or grant financing, repurposing of existing subsidies a more efficient allocation of Government resources, among others.[2] The following three scenarios simulate emissions reduction strategies for the crop and livestock sectors.

3.3.1. EMI

The emissions reduction scenario (EMI) simulates changes in the amount of CO_2e produced per unit of agricultural crop and livestock output. First, we focus on the four extensively grown crops for which emissions reductions targets are identified in Costa Rica's Decarbonization Plan, namely, sugarcane, coffee, banana and rice. Collectively, these crops represented 36.0% of agricultural value-added, 39.7% of agricultural employment, 43.5% of agricultural exports and 245,000 ha of land use in 2016.

The emissions reduction potential for these crops was estimated by first comparing their carbon intensity to the known crop carbon intensity frontier internationally (Clune et al., 2017; SI Section 3, Table SI 5). Based on these data, we assumed a convex downward convergence towards 80% of the frontier (Fig. 1, Panel A) representing the Government's emissions reduction targets in the Decarbonization Plan. To achieve these targets, the Plan describes that the most advanced technologies will be applied (MINAE, 2019b) in improving soil management practices (Vignola et al., 2010). The specific improved practices include substituting mineral fertilizer with organic fertilizer, new crop rotations, cover cropping and integrated cropping systems. The cost of these strategies follows Gillingham and Stock (2018) estimations of the unit cost of reducing emissions by improved soil management and is equivalent to US$57 per ton of CO_2e at 2017 prices.

Next, we focus on emissions reduction from improved livestock management practices for beef, pork and chicken (SI Section 3, Table SI 5). The largest share of livestock CO_2e emissions are produced by ruminant livestock enteric fermentation and waste management. Possible mitigation options include: (i) increasing the energy content and digestibility of feed; (ii) the use of enhanced animal growth and lactation supplements; (iii) feed supplementation to combat nutrient deficiencies; (iv) implementation of more intensive grazing systems and; (v) the use of anaerobic digesters for methane emissions capture (Beach et al., 2008; Gillingham and Stock, 2018). The emissions reduction potential was estimated by first comparing the baseline carbon intensity of each livestock type against the known carbon intensity frontier internationally (Clune et al., 2017). In our estimation, convex downward convergence towards the frontier was assumed (Fig. 1, Panel C). The total cost of this strategy for each of the emissions trajectories was calculated based on the unit cost estimate for each strategy, equivalent to US$71 per ton of CO_2e reduced at 2017 prices (Gillingham and Stock, 2018).

3.3.2. YIELD

The YIELD scenario simulates the Decarbonization Plan's strategy for enhancing yields of key crops (Government of Costa Rica, 2018). The agricultural practices to be implemented include precision agriculture and the expansion of more productive and climate resilient crop varieties. While the implementation of more efficient practices could also contribute to reducing emissions, we do not explicitly consider these spillover effects and instead treat emissions reductions separately in the EMI scenario. This approach sheds light on the individual contribution of each strategy and is consistent with the framing of the Decarbonization Plan.

The yield enhancement trajectories were estimated by comparing baseline productivity of sugarcane, coffee, banana and rice in Costa Rica with countries producing at the productivity frontier (SI Section 3, Table SI 5, Fig. 1, Panel B). This frontier was estimated based on UN Food and Agriculture Organization (FAO) productivity data and

[2] We include in Supplementary Information 4 a sensitivity analysis to model the effects on NPV of using domestic debt financing on the COMBI scenario.

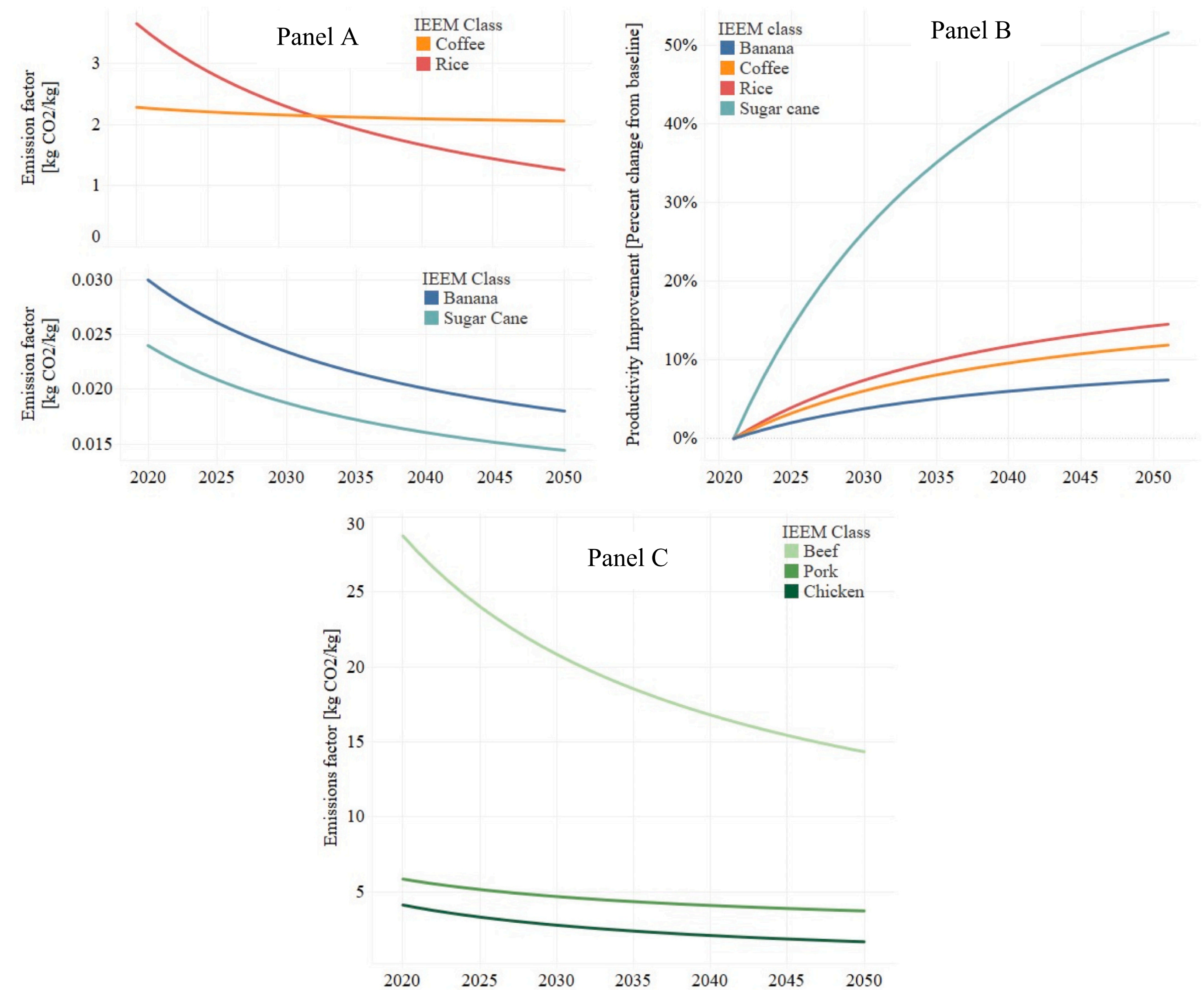

Fig. 1. Panel A: Emissions factor reductions for crops in kilograms (kg) of carbon dioxide equivalent (CO_2e) per kg of crop output. Panel B: Productivity improvement for the yield improvement scenario. Panel C: Emissions factor baseline and target for livestock in kg of CO_2e per kg of meat output.

included only countries with: (i) significant levels of output of the target crops compared to total crop output and (ii) similar climatic and economic conditions to Costa Rica (Sayre et al., 2020). To be conservative, we assumed that the simulated strategies for increasing yields improved productivity up to half of the known frontier (Fig. 1, Panel B). The costs for achieving these productivity gains were based on net capital stocks for the crop sector in Costa Rica compared with those at the frontier (SI Section 3, Table SI 6).

3.3.3. YIELD + EMI

This scenario is the simultaneous implementation of the EMI and YIELD strategies.

3.4. Forestry AFOLU emissions reductions strategies

Costa Rica is expanding its Reduced Emissions from Deforestation and Forest Degradation (REDD+) strategy for forests to play a key role in climate change mitigation. The Government is in the process of strengthening its REDD+ program in such a way that is consistent with the National Plan for Forest Development (FONAFIFO, 2019) and the National Strategy for Biodiversity (MINAE, CONAGEBIO, SINAC, 2016) to catalyze new investment in forests and maximize ES benefits. Between 2011 and 2015, Costa Rica expanded its original REDD strategy and created the more comprehensive REDD+ strategy, which includes sustainable forest management and increasing forest carbon stocks (MINAE, MAG, 2015).

Costa Rica's revised REDD+ strategy is comprised of six main policies: (i) promotion of low carbon emissions agricultural systems including agroforestry and silvopastoral activities; (ii) improved control of LULC change and fire; (iii) incentives for conservation and sustainable forest management; (iv) landscape and forest restoration; (v) enhanced participatory processes, especially with Indigenous Peoples and (vi) implementing the required conditions for successful implementation. We developed the following 2 scenarios to simulate the REDD+ strategy, drawing directly from the targets and implementation costs established in the strategy documents (MINAE, 2017; MINAE, MAG, 2015).

3.4.1. REDD1

The first REDD+ scenario simulates an expansion of the current REDD+ strategy as outlined by MINAE (2017), which will convert 122,241 ha of livestock areas into silvopastoral systems and 121,093 ha of agricultural areas into agroforestry systems between 2021 and 2027.

Based on MINAE (2017), the total cost is US$39,463,967 above existing investment levels, which equates to US$6,577,328/year from 2021 to 2027. The Government aims to create disincentives for deforestation through improved land management and complementary policies. Specifically, the Government will support a Guarantee Program as part of the Low Carbon Livestock Strategy (Estrategia para la Ganadería Baja en Carbono, (MINAE, MAG, 2015)) in the context of Nationally Appropriate Mitigation Action for the livestock sector. The Forest Plantations Program (Programa de Plantaciones de Aprovechamiento Forestal, PPAF) will provide farmers with funding to establish trees in agroforestry and silvopastoral systems (MINAE, 2017).

3.4.2. REDD2

The second REDD+ scenario simulates the establishment of a total of 19,900 ha of new mixed species forest plantations on unproductive and degraded shrubland between 2021 and 2027.[3] While the Costa Rican Government aims to establish 400,000 ha of forest plantations by 2050 as part of its Decarbonization Plan, we simulate only a fraction of this, for which more reliable data (LULC projections and cost data) exist. The annual cost of this strategy is US$666,331 from 2021 to 2027. Following MINAE (2017), 3200 ha will be established in both 2021 and 2022 and 2700 ha annually for the rest of the period.

3.4.3. COMBI

This final scenario is the simultaneous implementation of the YIELD, EMI, REDD1 and REDD2 strategies and represents the implementation of Costa Rica's full AFOLU decarbonation strategy. Table 1 summarizes all scenarios previously described.

4. Results

Results are presented first for LULC change, then ES impacts, followed by economic impacts. In terms of LULC change, the agricultural productivity enhancement (YIELD) and YIELD plus reduced emissions (YIELD+EMI) scenarios show that some crop area would be converted to livestock production (Table 2). In REDD1, areas with tree cover would increase by 48,667 ha while livestock and crop area would decrease by 30,352 ha and 18,314 ha, respectively. Livestock areas would decline more, since crop returns per unit of area are higher than livestock returns. The REDD2 scenario would increase forest plantations by 19,900 ha. Full decarbonization of AFOLU sectors (COMBI) would increase forest plantations by 68,567 ha and livestock and crop areas would decline by 7873 ha and 40,794 ha, respectively.

LULC in the business-as-usual scenario in the base year of 2013 is shown in Fig. 2. Spatial changes in LULC are presented in Fig. 3. This figure shows areas of change in terms of crop, livestock, forest plantation and forest as a comparison of the BASE between the first year and in 2050, and a comparison between the BASE and COMBI in 2050. Areas that do not change in the modeling exercise are identified as persistent areas.

Table 1
Scenario overview.

Scenario	Description
BASE	Business as usual
EMI	Emissions reduction with climate smart agriculture
YIELD	Enhanced agricultural productivity
YIELD+EMI	Joint implementation of EMI and YIELD
REDD1	Establishing agroforestry and silvopastoral systems
REDD2	Establishing forest plantations
COMBI	Joint implementation of YIELD+EMI + REDD1 + REDD2

[3] Throughout the paper, our usage of the term 'forest plantations' refers to mixed species forest plantations.

With regard to ES impacts (Table 2 and Figs. 4, 5 and 6), full implementation of the decarbonization strategy for AFOLU would result in a 0.43% increase in carbon storage, with more than half coming from the REDD1 (0.30%) component of the strategy. Erosion mitigation ES would improve across scenarios with the exception of EMI where it would be unaffected. With the full implementation of the AFOLU strategy, erosion mitigation ES would be enhanced by 2.28% with about half of this improvement driven by the REDD1 scenario. Water purification ES, proxied for by nitrogen exports to streams, would improve by 5.25% with full implementation of the AFOLU strategy. The YIELD and REDD1 scenarios would drive this improvement by 2.70% and 2.54%, respectively. Water regulation ES would be most positively affected by the REDD1 and REDD2 scenarios with the full implementation of the AFOLU strategy improving water regulation ES by 0.10%.

Climate regulation ES is reported as the net change in emissions in thousands of metric tons of CO2e accounting for changes in emissions from the consumption of fossil fuels in economic activities including public, private and freight transport services and any additional carbon stored or lost from changes in LULC. The EMI scenario would reduce emissions by 4180 thousand tons of CO2e. The YIELD scenario would increase net emissions by 950 thousand tons while the YIELD+EMI scenario would reduce net emissions by 4919 thousand tons CO_2e. The REDD1 scenario would reduce net emissions by 103 thousand tons. The REDD2 scenario would increase net emissions by 36 thousand tons. The full implementation of the AFOLU strategy would result in a 4263-thousand-ton reduction in CO_2e.

Considering impacts on economic indicators, the YIELD scenario would generate strong positive impacts with a US$439 million and US $135 million impact on GDP and wealth, respectively (Table 2). The EMI scenario impact would be comparatively small except for a US$151 million increase in wealth due to reduced emissions. The joint effect of the productivity enhancement and the emissions reduction scenarios (YIELD+EMI) would result in GDP and wealth impacts of US$432 million and US$292 million, respectively. With increased areas allocated to agroforestry and silvopastoral systems, REDD1 would generate an additional US$170 million in GDP and US$42 million in wealth in 2050. Full decarbonization of AFOLU would have a large positive impact across indicators with a US$609 million boost to GDP and a US$335 million increase in wealth. The sensitivity analysis presented in Supplementary Information section 4 shows that when an alternative financing is considered, specifically, domestic debt financing, GDP impacts would be less than one-third (US$178 million) of that reported for the full decarbonization of AFOLU.

GDP and wealth trajectories would trend up across scenarios with the exception of the EMI and REDD2 scenarios (Fig. 7). In YIELD and YIELD+EMI scenarios, there would be an abrupt increase in wealth, which is also prominent in the COMBI scenario with the full implementation of the decarbonization of AFOLU. EMI would have a small impact on GDP due to the investments required by the new agricultural practices while the relatively small impact of the REDD2 scenario is a result of the small area of new forest plantations. Across scenarios, government savings would increase due to greater economic activity and increased tax revenues. The increase in Gross National Savings would be the main determinant of the growth in wealth. Crop yields and investment would grow at a decreasing rate, which helps explain GDP and wealth trajectories.

With regards to poverty impacts, the YIELD scenario would increase poverty in the first few years with 2744 more poor than in the BASE in 2021 (Fig. 7, Panel C). Poverty then would trend downward, falling to 3430 less poor individuals compared with business-as-usual. The full decarbonization of AFOLU would reduce poverty by 3810 individuals by 2050 or 1.3% lower in 2050 than in the business-as-usual case.

The trajectory of emissions reduction in the case of EMI would follow the implementation of measures to reduce emissions from the crop and livestock subsectors throughout the analytical period (Fig. 7, Panel D).

Table 2
All impacts as difference from business-as-usual (BASE) in 2050. Economic and land use impacts are reported in millions of US Dollars (2019 USD) and hectares, respectively. Carbon storage, erosion mitigation, water purification and water regulation ecosystem services (ES) are reported in percentage points. Climate regulation ES are reported in thousands of tons of CO_2e. Net Present Value (NPV) is reported with the inclusion of the value of changes in natural capital and environmental quality (*) and without, both in millions of 2019 USD using a 12% discount rate. GDP: gross domestic product; YIELD: enhanced agricultural productivity; EMI: emissions reductions from climate-smart agriculture; REDD1: agroforestry and silvopastoral systems; REDD2: forest plantations; COMBI: joint implementation of YIELD, EMI, REDD1, REDD2.

	YIELD	EMI	YIELD+EMI	REDD1	REDD2	COMBI
Economic impacts (millions of 2019 US Dollars)						
GDP	439	-7	432	170	3	609
Wealth	135	151	292	42	-1	335
Private consumption	421	-8	413	124	2	542
Private investment	135	-1	133	33	1	167
Exports	209	-5	204	69	1	256
Imports	197	-2	195	66	0	247
Land use impacts (hectares)						
Forest plantations	0	0	0	48,667	19,900	68,567
Livestock	26,468	-6	26,459	-30,352	0	-4,717
Crops	-26,468	6	-26,459	-18,314	0	-43,949
Ecosystem service impacts (% change; thousands of metric tons of CO_2e for climate regulation ES)						
Carbon storage ES	0.02	0.00	0.02	0.30	0.12	0.43
Erosion mitigation ES	0.55	0.00	0.54	1.14	0.21	2.28
Water purification ES	2.70	0.01	2.69	2.54	0.16	5.25
Water regulation ES	-0.01	0.00	-0.01	0.08	0.03	0.10
Climate regulation ES	950	-4,180	-4,919	-103	36	-4,263
NPV with(*) and without change in natural capital and environmental quality (millions of 2019 USD)						
NPV	27	-44	-17	178	3	172
NPV*	86	187	276	366	208	852

REDD1 and REDD2 emissions trajectories would be influenced by the establishment schedule for agroforestry, silvopastoral and forest plantations as well as by accompanying increases in economic activity. The YIELD scenario would result in an upward trajectory for emissions due to enhanced economic activity. The full implementation of AFOLU measures would combine all these elements and after some variability in the early years caused by the implementation of REDD1 and REDD2, the trend would extend downward more gradually reaching a maximum reduction in the year 2050.

Cumulative impacts on wealth would be largely driven by improvements in environmental quality and increased household savings generated by increased agricultural productivity (Fig. 7, Panel E). Emissions reductions alone would boost wealth by US$2.345 billion. The increase in planted trees through agroforestry and silvopastoral systems would generate an additional US$1.163 billion when compared with business-as-usual in 2050. Establishing forest plantations would increase wealth by US$462 million. The full strategy for decarbonization of AFOLU would enhance wealth in Costa Rica by over US$7.267 billion.

Table 2 reports the NPV calculation with and without the inclusion of the change in natural capital stocks and environmental quality. When considering household welfare alone, the YIELD scenario would generate an NPV of US$27 million (Table 2 and Fig. 7, Panel F). Considering changes in environmental quality and natural capital stocks, the returns would be higher reaching approximately US$86 million. The EMI scenario would generate a negative economic return (US$44 million), however when natural capital and environmental quality are integrated in the analysis, this scenario would generate a strong positive return of US$187 million. The productivity enhancement scenario coupled with reduced emissions (YIELD+EMI) would yield a negative return of US$17 million without natural capital and environmental quality considerations and a positive return of US$276 million when these variables are considered. The expansion of agroforestry and silvopastoral activities would generate strong returns of US$178 million from the conventional perspective and even greater returns of US$366 million when environmental variables are considered. Forest plantations would generate positive returns, amounting to US$208 million considering environmental variables. The full implementation of the decarbonization of AFOLU would generate US$852 million in returns on investment when environmental variables are considered and US$172 million when they are not. The sensitivity analysis presented in Supplementary Information section 4 shows that returns would be higher when lower discount rates are used, for example, returns of over US$4.2 billion when a 3% discount rate is used.

Fig. 8 presents the annual deviation in emissions as projected in the COMBI scenario and compared with the MESSAGE and REMIND IAM results, which were plotted based on data from Gidden and Huppmann (2019) and Huppmann et al. (2021). The figure shows that by 2050, total emissions were estimated at 13.6 megatons (Mt) of CO_2 while emissions from AFOLU were − 2.3 Mt. according to MESSAGE. Based on REMIND results, total emissions and AFOLU emissions were estimated for 2050 as 10.3 Mt. and − 1.6 Mt. of CO_2, respectively.

In terms of the pronounced trough and peak evident in the COMBI emissions annual change, the former is explained by the fact that the AFOLU strategies were implemented beginning in the year 2021 resulting in a sharp decline in emissions. The peak that is evident in 2028 is explained by the conclusion of the investment in the REDD1 and REDD2 programs. Following 2028, there are no additional scenario-driven changes in forest cover and with the investment concluded in that same year, resource reallocation would result in an increase in private consumption, which also would drive emissions upward temporarily. Overall, the emissions pathway in the COMBI scenario compared with the MESSAGE and REMIND NDC emissions pathways are similar with respect to the annual deviation. This is indicative of consistency between the national-level implementation of AFOLU strategies embodied in the COMBI scenario and the downscaled IAM results.

5. Discussion

We present an innovative economy-wide approach to linking economic, LULC and ES models to quantify how human activities can lead

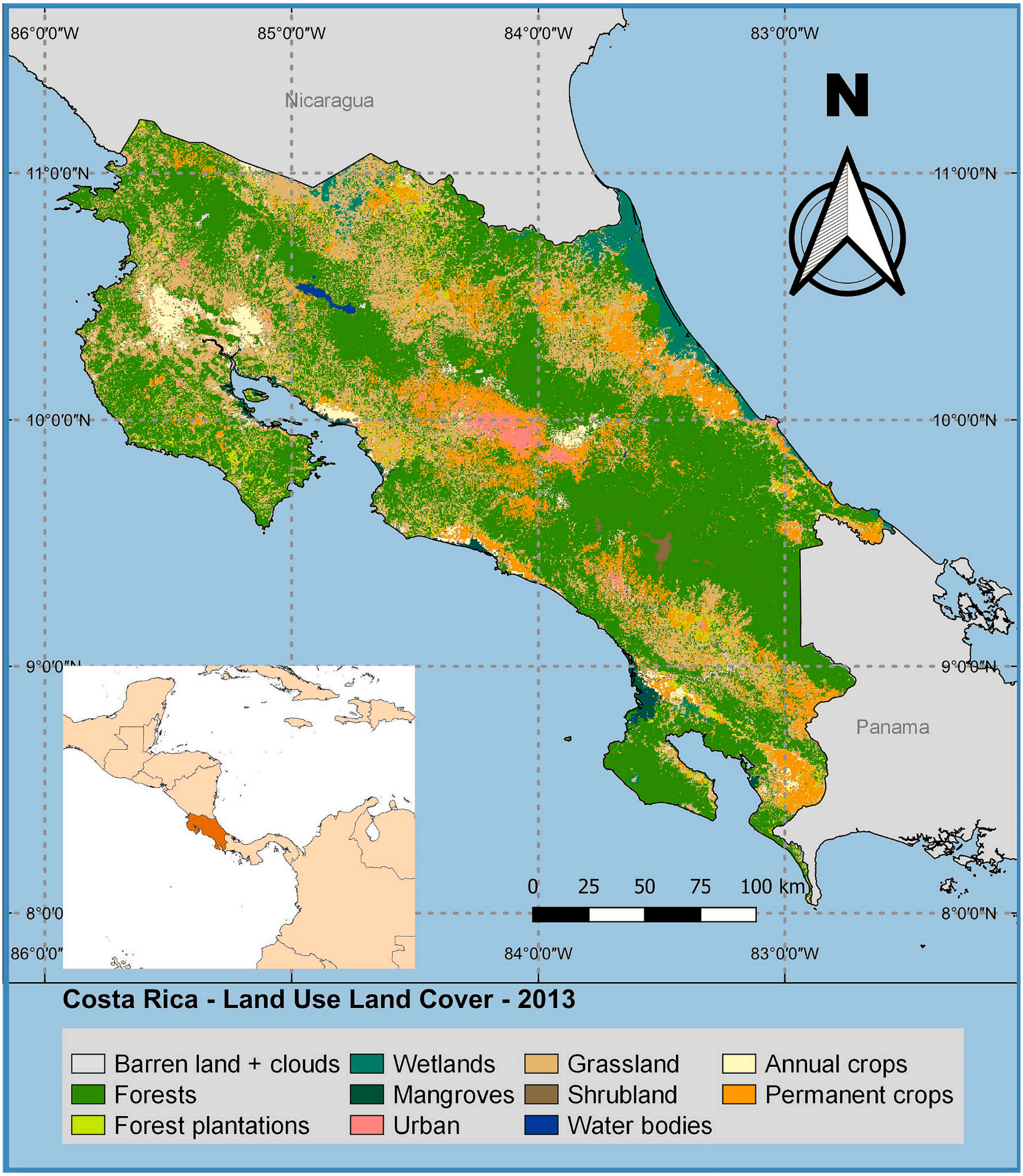

Fig. 2. Base Land Use-Land Cover of Costa Rica in 2013.
Source: Developed based on data from Fernández-Landa et al. (2016).

to environmental change and how these impacts can be mitigated. This is the first forward looking study for Costa Rica that considers how the economy may evolve with the implementation of climate change mitigation strategies for AFOLU as well as its interaction with LULC change and changes in future flows of ES.

This study revealed several important trade-offs. For example, while the EMI scenario would reduce net emissions substantially, both the YIELD and REDD2 scenarios would increase emissions. This increase is due to the scenario-driven acceleration of overall economic growth. With faster economic growth, in the absence of complementary mitigating measures for non-AFOLU sectors, emissions would grow more quickly. In the COMBI scenario, emissions initially drop as EMI emissions reduction measures are implemented and trees are planted in the REDD2 scenarios and in the new agroforestry and silvopastoral systems. Once the trees are planted and approach maturity, new carbon capture slows and eventually new carbon capture becomes similar to baseline levels (i.e., a steady state).

An economy-wide approach is essential for understanding policy impacts across sectors and economic indicators. For example, the YIELD scenario would have a strong positive impact on Costa Rica's economy and across various environmental indicators (erosion mitigation, water quality and carbon storage); the agricultural productivity gains would

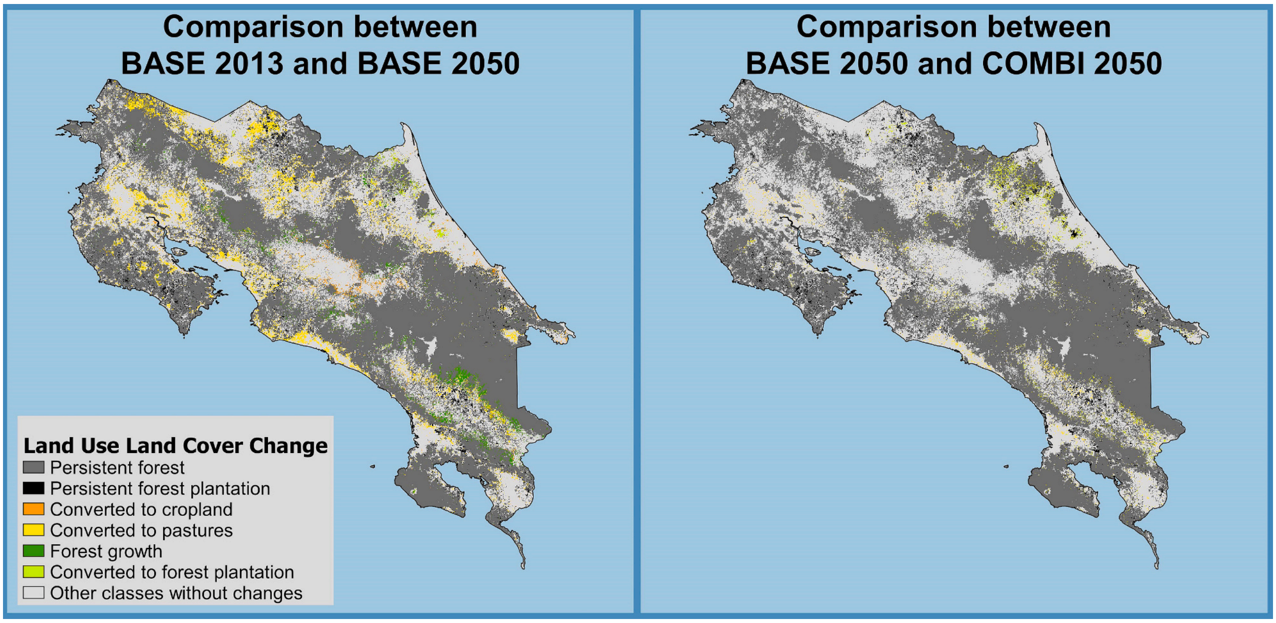

Fig. 3. Land Use-Land Cover Difference between business-as-usual (BASE) in 2013 and 2050 (left) and between BASE and Full Agriculture, Forestry and Other Land Use decarbonization strategy impacts (COMBI) in 2050 (right).

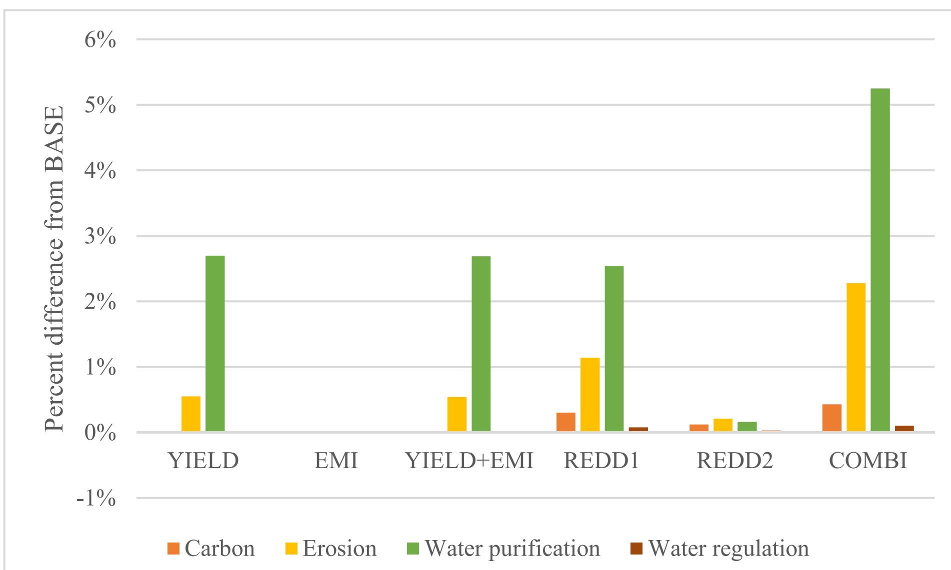

Fig. 4. Scenario impacts on Ecosystem Service (ES) supply as percent difference from business-as-usual in 2050. YIELD: enhanced agricultural productivity; EMI: emissions reductions from climate-smart agriculture; REDD1: agroforestry and silvopastoral systems; REDD2: forest plantations; COMBI: joint implementation of YIELD, EMI, REDD1, REDD2.

boost agricultural output, reduce agricultural prices and release factors of production (labor and capital) for use in other sectors. Together, these impacts would result in an overall positive effect on wages, employment and household welfare. In addition, faster agricultural growth and factor availability would stimulate more rapid growth in non-agricultural sectors by increasing final demand for non-agricultural products, lowering input prices and fostering upstream processing. For instance, in the YIELD scenario, output for the food-processing sector would grow 0.7 percentage points more quickly than in the business-as-usual case.

The way in which investments in reducing emissions are financed can have important implications for societal well-being. With regard to poverty, for example, we found that there would be 2744 more poor with the implementation of the full AFOLU strategy than in the business-as-usual case in the first few years of investment. This initial increase in poverty is the consequence of the increase in taxes that would be required to finance the decarbonization strategy. Once the investment concluded and tax rates can return to their original levels, poverty would fall steadily thereafter and the net effect at the end of the period would be a reduction in poverty on the order of 3810 individuals. In the IEEM+ESM framework, it is possible to explore alternative financing arrangements, considering the repurposing of subsidies, domestic or foreign debt financing as well as non-reimbursable grants. Each of these financing mechanisms would have a different impact across the indicators reported here.

The full implementation of the decarbonization strategy for AFOLU would have a positive impact on wealth. There is an initial abrupt

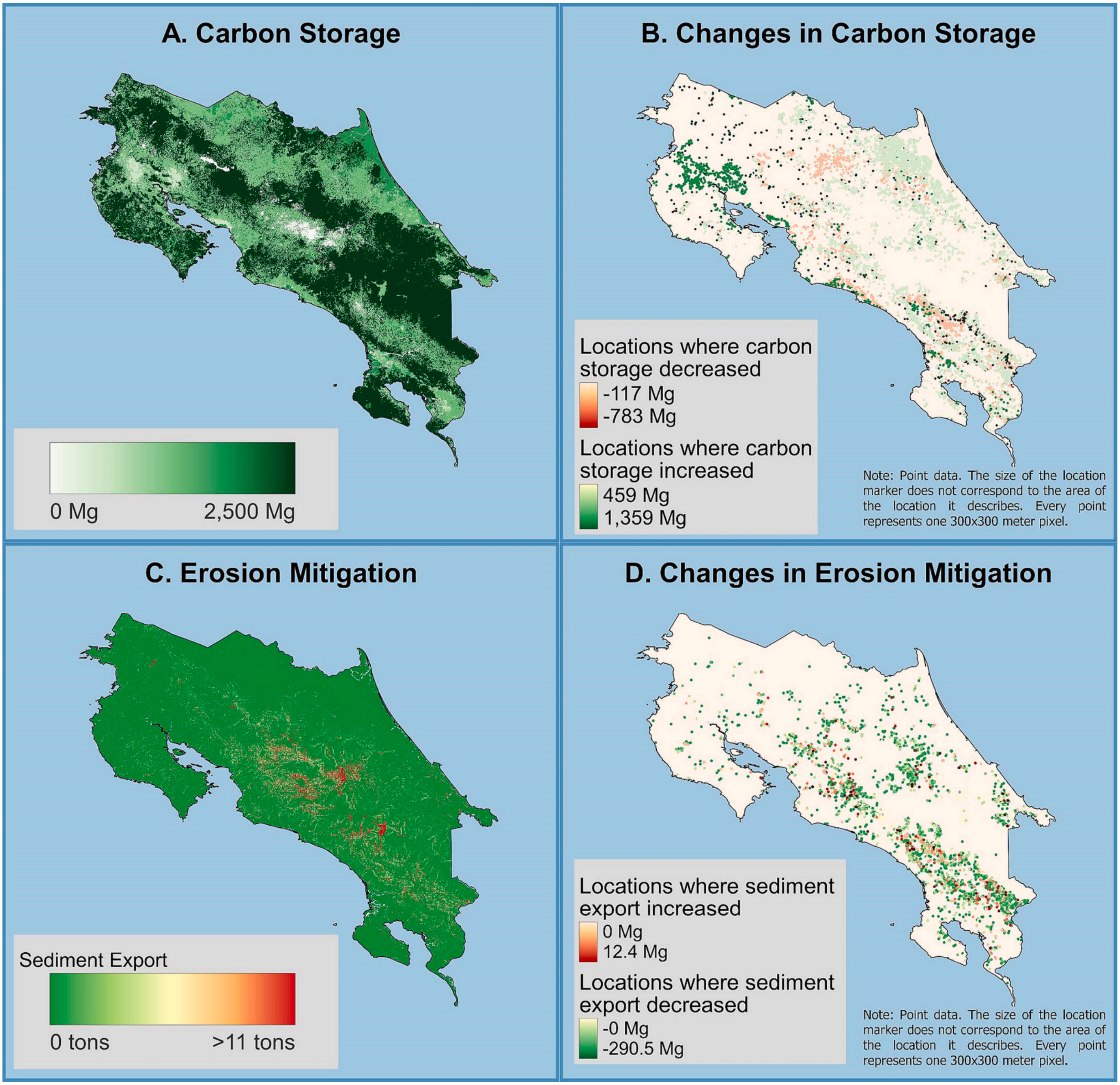

Fig. 5. Full implementation of the AFOLU decarbonization strategy (COMBI scenario) in 2050. Panel A: Level of carbon storage. Panel B. Changes in carbon storage. Panel C. Level of erosion mitigation. Panel D. Changes in erosion mitigation.

increase in wealth arising from the new investments, as Fig. 7 (Panel B) shows, which begins to taper off after 2028 once policy implementation has concluded. The main drivers of the changes in wealth are as follows. In the EMI scenario, emissions reductions and consequent reduction in emissions damages would drive increases in wealth. In the YIELD scenario, increases in Gross National Savings would drive positive wealth impacts. In the case of expanding forest plantations, both Gross National Savings and emissions reductions would push wealth upward. The combined cumulative impact would be an increase of US$7.267 billion in wealth.

When comparing the emissions pathway in the COMBI scenario with the MESSAGE and REMIND NDC emissions pathways, Fig. 8 shows that they are similar with respect to the annual deviation. This indicates a degree of consistency between the AFOLU decarbonization strategies considered here and the downscaled IAM results. Analysis of the data underpinning the IAM plot revealed two noteworthy points that explain differences in the absolute values of the IAMs compared with IEEM projections. The first is that the economy-wide and AFOLU emissions in IEEM and the IAMs differed in magnitude in the starting year due to different data sources, which makes comparison of absolute values not very meaningful. Second, the treatment of removals of carbon from forests differed between IEEM and the IAMs. In IEEM, carbon is recovered through the establishment of new forests while there is no additional recovery of carbon from already established forests. This assumes that carbon in existing forests has achieved a steady state. Carbon removals from forests in the IAMs on the other hand are continuous and do not reach a steady state. Both the base year emissions and treatment of carbon removals from established forests in IEEM could be adjusted for

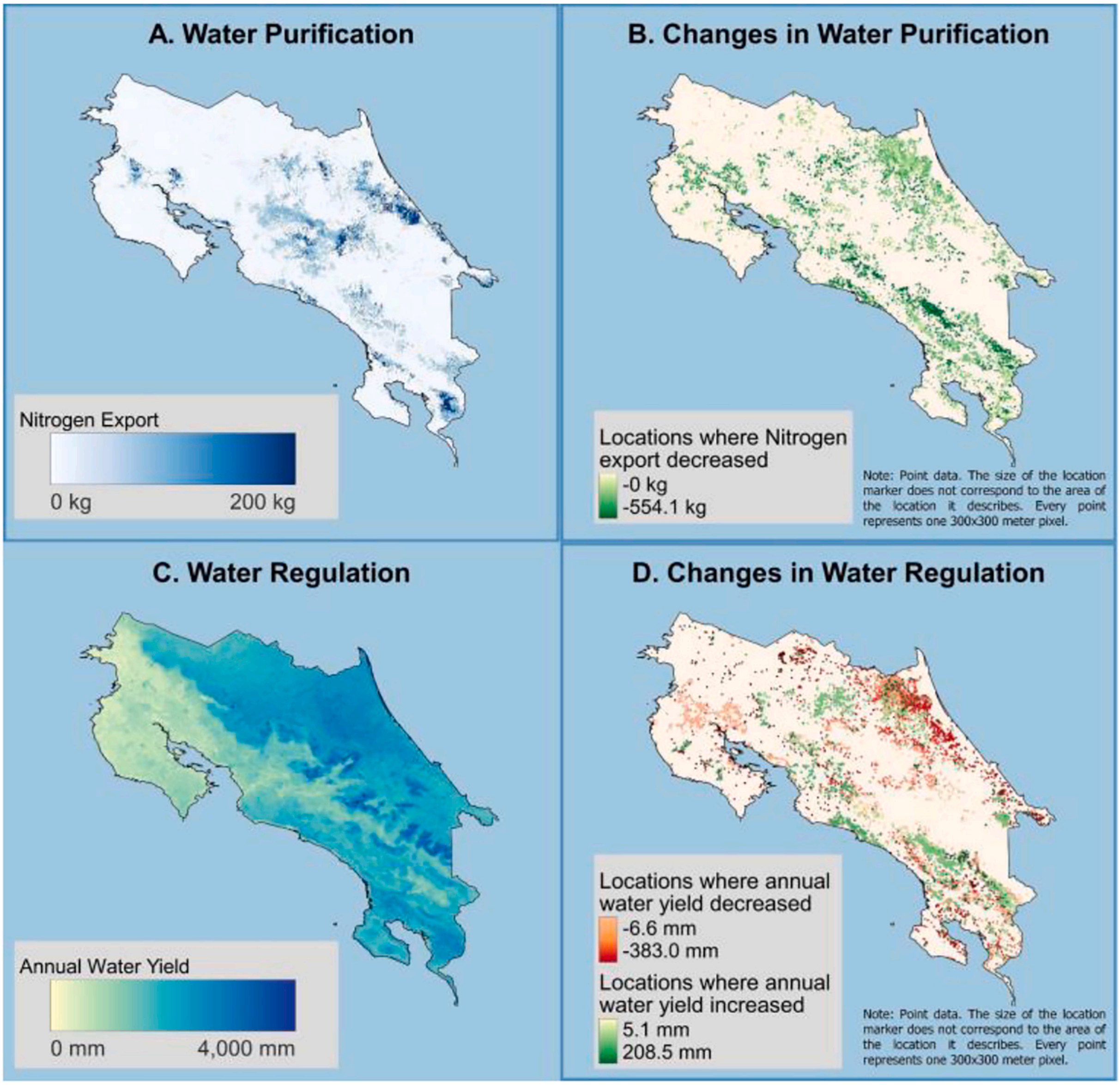

Fig. 6. Full implementation of the AFOLU decarbonization strategy (COMBI scenario) in 2050. Panel A: Level of water purification. Panel B. Changes in water purification. Panel C. Level of water regulation. Panel D. Changes in water regulation.

consistency with the IAMs, however, additional research would be required to motivate these adjustments, particularly with regard to base year emissions from AFOLU.

Our environmentally adjusted calculation of NPV demonstrates the importance of considering changes in natural capital and environmental damage in benefit-cost investment analysis. For example, the emissions reduction (EMI) scenario would generate a negative economic return of US$44 million, however when natural capital and environmental quality are integrated in the analysis, this scenario would generate a strong positive return of US$187 million. Similarly, the productivity enhancement scenario coupled with reduced emissions (YIELD+EMI) would yield a negative return of US$17 million without natural capital and environmental quality considerations and a return of positive US $276 million when these variables are considered. Thus, without natural capital and environmental considerations, both of these benefits would have been considered unfinanceable from a conventional economic lens.

Finally, it is worth noting that Costa Rica's top emitting sectors are transport, industry and waste management with AFOLU as the fourth. While we account for emissions from the combustion of fossil fuels from these and all other economic sectors, we do not consider the Decarbonization Plan emissions reduction strategies for those sectors. An important next step in this analysis would be to consider Decarbonization Plan emissions reduction strategies for all economic sectors simultaneously, including transport as investigated in Banerjee and Cicowiez (2021), industry and waste. It is highly probable that interventions in one sector will imply trade-offs for other non-target sectors, which the IEEM+ESM approach is designed to capture (Banerjee et al., 2019; Banerjee and Cicowiez, 2021; Turner et al., 2000).

6. Conclusions

With 38% of Costa Rica's CO_2 emissions arising from AFOLU, its decarbonization is critical for achieving the country's Paris Agreement commitment and the targets set in the Decarbonization Plan. This study has generated four key insights that can help the Government of Costa Rica refine its strategies for decarbonizing AFOLU sectors. First, strategies to reduce emissions alone would have a small negative impact on GDP growth and income in the short run. When coupled with investments in enhanced agricultural productivity, which also serve to reduce incentives for deforestation and land use change, the impact on

Fig. 7. Impact on Gross Domestic Product (panel A; millions of 2019 US Dollars, USD) and wealth (panel B; millions of USD) as the difference from business-as-usual (BASE). Impact on number of individuals below the poverty line (panel C; number of individuals) and emissions (panel D; tons CO_2e) as the difference from BASE. Impact on cumulative wealth as difference from BASE in 2050 (panel E; millions of USD). Net Present Value (panel F; millions of USD, presented using both a 4% and 12% discount rate with (*) and without the inclusion of changes in natural capital and emissions damages). YIELD: enhanced agricultural productivity; EMI: emissions reductions from climate-smart agriculture; REDD1: agroforestry and silvopastoral systems; REDD2: forest plantations; COMBI: joint implementation of YIELD, EMI, REDD1, REDD2.

GDP growth would be positive (US$432 million). More importantly from a sustainable economic development perspective, these investments would be wealth enhancing, on the order of US$7.267 billion. Additional benefits would arise from the increase in future ES flows (carbon storage, erosion mitigation, water regulation and water purification ES), which, while not valued in this study, provide tangible benefits and make our overall economic analysis of benefits a conservative one.

Second, trade-offs became apparent across the AFOLU strategies considered. Emissions would grow faster in the YIELD scenario due to the increased rates of economic growth across most sectors. On the other hand, the joint impact of investments in enhanced productivity and emissions reductions would tend to reduce emissions overall by approximately 4.919 million tons CO_2e by 2050. Increasing agroforestry and silvopastoral systems, and increasing forest plantations, would have modest impacts on emissions, while the overall impact of the full decarbonization of AFOLU sectors would reduce emissions by 4.263 million tons CO_2e, when compared with business-as-usual in 2050.

How does this relate to Costa Rica's emissions targets for AFOLU? While we recognize that IEEM and the IAMs use a different base level of emissions and treatment of carbon recovery, our analysis shows that it is probable that Costa Rica's strategy for the decarbonization of AFOLU would have to be more ambitious in order to meet the NDC target. Our results for the full implementation of Costa Rica's AFOLU strategy would still result in positive emissions by 2050, on the order of 15 million tons of CO_2e. This contrasts with the negative emissions for AFOLU projected by the IAMs, which is a result of the different data sources used and absence of country specific policies modeled by the IAMs.

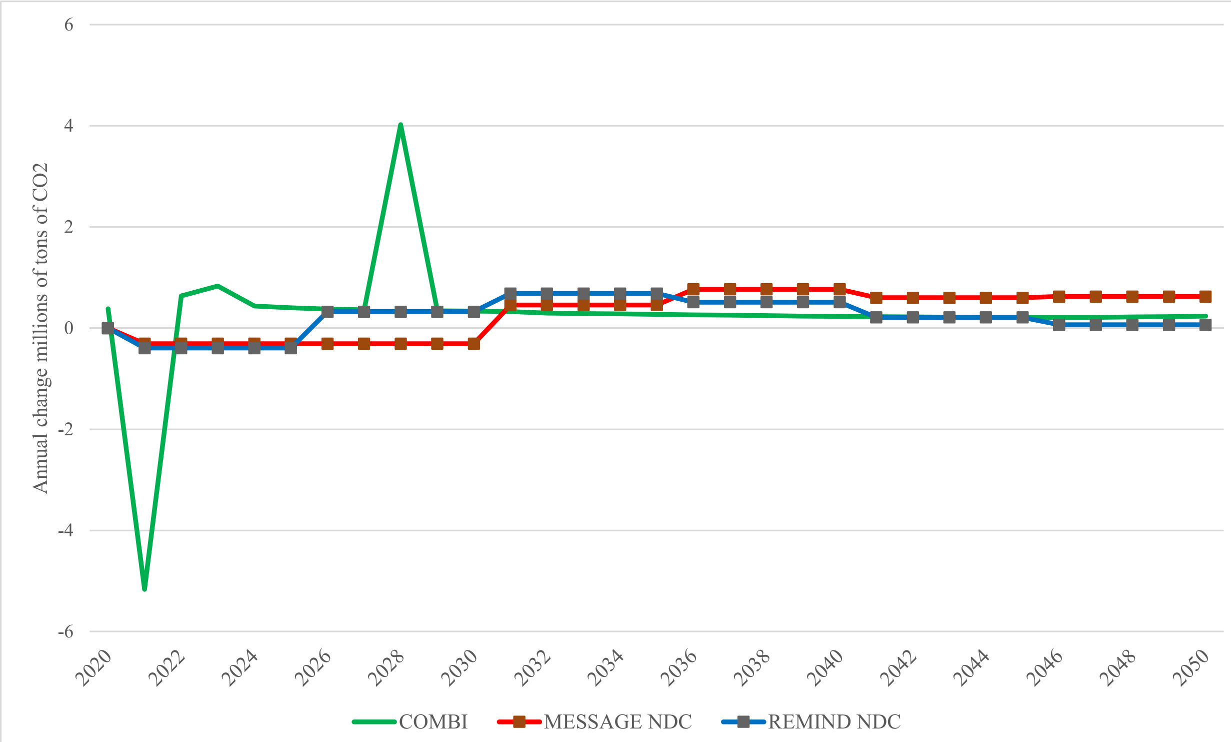

Fig. 8. Integrated Economic-Environmental Model COMBI (joint implementation of all Agriculture, Forestry, and Other Land Uses scenarios) and Integrated Assessment Model Nationally Determined Contributions (NDC) scenarios projected annual change in millions of tons of CO_2e for the Agriculture, Forestry and Other Land Uses sectors.
Source: COMBI scenario based on Integrated Economic-Environmental Modeling + Ecosystem Services Modeling (IEEM+ESM) results, and; Model for Energy Supply Systems And their General Environmental impact (MESSAGE) and REgional Model of Investment and Development (REMIND) NDC based on Gidden and Huppmann (2019) and Huppmann et al. (2021).

Third, in terms of poverty impacts, the decarbonization strategy for AFOLU sectors taken as a whole would be poverty reducing, with 3810 less poor people in 2050. This may not be the case with some other lines of action in Costa Rica's Decarbonization Plan (e.g., electrification of transportation fleets), where there may be important trade-offs to consider, as well as how adjustment costs to a low-emissions future are distributed across society.

Fourth, analysis with IEEM requires that the source of investment financing be made explicit in scenario design and implementation. The AFOLU investments considered here were funded half through an adjustment in the direct tax rate and the other half through an increase in domestic debt. Understanding the fiscal impacts of investing in decarbonization strategies is critical to enable effective government planning. As a share of GDP, we found that while initially, investments would amount to almost 0.3% of GDP, the investments would begin to generate positive returns for the government by around the year 2040. Thus, while initially the government would need to allocate a small share of its budget towards investment in decarbonization of AFOLU, these investments would be more than compensated by future returns on the strategies implemented. Overall, the full implementation of the decarbonization of AFOLU would generate US$852 million in returns on government investment.

The methods presented in this paper link economy-wide modeling to LULC change and ES modeling to understand the economic, environmental and social impacts of decarbonization plans and synergies and trade-offs that may exist across strategies. Results from this study can be used to refine Costa Rica's strategies for decarbonization of AFOLU sectors. These methods can be applied to other countries that are in the process of developing or refining their NDCs. All of the tools used in this analysis have been made available through the OPEN IEEM Platform. The data underpinning these tools are derived from a country's own economic reporting system, the System of National Accounts and thus are consistent with other national development planning and policy frameworks.

CRediT authorship contribution statement

Onil Banerjee: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Supervision, Writing – original draft, Writing – review & editing. **Martín Cicowiez:** Conceptualization, Formal analysis, Methodology, Writing – original draft, Writing – review & editing. **Renato Vargas:** Data curation, Methodology, Writing – original draft, Writing – review & editing. **Edmundo Molina-Pérez:** Data curation, Formal analysis, Investigation, Methodology. **Kenneth J. Bagstad:** Conceptualization, Data curation, Formal analysis, Methodology, Writing – original draft, Writing – review & editing. **Žiga Malek:** Formal analysis, Methodology, Writing – original draft, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

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