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Abstract

This paper evaluates the economic and environmental impacts of implementing Costa Rica's Decarbonization Plan, focusing specifically on the Agriculture, Forestry and Other Land Uses (AFOLU) sectors. To do so, we apply the Integrated Economic-Environmental Modeling (IEEM) framework for Costa Rica, linked with high resolution spatial land use land cover and ecosystem services modeling (IEEM+ESM). This is the first economy-wide analysis of Costa Rica's Decarbonization Plan that integrates both economic and ecosystem services impacts. Such an integrated approach is critical for understanding cross-sectoral implications of decarbonization despite the sector-specific focus of AFOLU, while considering the impacts on future ecosystem services flows and wealth. Our results indicate that the positive cumulative wealth impacts of the full decarbonization of Costa Rica's AFOLU sectors are on the order of US$8,747 million by 2050 and generally enhances the future flow of ecosystem services. Decarbonization of AFOLU is pro-poor, lifting 4,530 out of poverty by 2050. From a public investment perspective, decarbonization generates economic returns of US$1,114 million when natural capital and environmental quality are considered. The IEEM+ESM Platform developed in this paper provides a strong foundation for future analysis and refinement of proposed decarbonization strategies for the country, while weighing the relative costs and benefits of the economic, environmental and social dimensions in an integrated way.

1.0. Introduction

In the context of the Paris Agreement, Costa Rica assumed a commitment to reduce greenhouse gas emissions (GHGs) across economic sectors. Reinforcing and operationalizing this commitment, Costa Rica published its Decarbonization Plan which details strategic areas of action for achieving zero net emissions by the year 2050. In 2016, 38% of net carbon dioxide (CO_2) emissions were linked to Agriculture, Forestry and Other Land Uses (AFOLU). Consequently, the decarbonization of activities related to AFOLU are essential to achieve the domestic and international commitments assumed by the country. The design of specific strategies for reducing emissions from AFOLU in Costa Rica are incipient, though key agricultural subsectors have been targeted including the coffee, rice and livestock sectors. Reduced emissions from forestry through enhanced conservation of primary forests and increasing agroforestry, silvopastoral and forest plantation systems are also being targeted through expansion of Costa Rica's Reduced Emissions from Deforestation and Degradation (REDD+) and its globally renowned Payment for Ecosystem Services (PES) Programs.

Understanding the benefits, costs and trade-offs inherent in emissions reductions strategies is important for informing government policy and decision making and the allocation of scarce public resources. Polices for emissions reductions in AFOLU and other economic sectors will have broad impacts across the economy, as well as poverty and intergenerational equity and wealth impacts. This paper contributes to policy discourse on the design of strategies for reducing emissions from AFOLU through estimation of their impacts on the economy, society and the environment. Given the multi-sectoral nature of emissions reductions strategies for AFOLU and their potentially wide-spread impacts, sectorally, spatially and temporally, the Integrated Economic-Environmental Modeling (IEEM) Platform (Banerjee et al., 2016; Banerjee et al., 2019a, 2019b) linked with high resolution spatial land use land cover (LULC) change and ecosystem services modeling (ESM) is a applied to shed light on all these different dimensions of impacts (Banerjee et al., 2019a; Banerjee et al., 2020). The linked IEEM+ESM approach represents the state-of-the-art in integrated economic environmental analysis and is increasingly being applied across Latin America and beyond (Banerjee et al., 2019a).

This paper is organized as follows. The next section describes the IEEM+ESM methodology, beginning with the IEEM model for Costa Rica (IEEM-CRI; (Banerjee et al., 2019d)), followed by the LULC change modeling and ESM approach. Also in this section, the baseline trajectory is developed for the Costa Rican economy, including the business-as-usual projection of CO_2 emissions. Next, we define the scenarios to be evaluated with IEEM+ESM which is followed by a presentation of the economic, LULC and ecosystem services impacts of the strategies. These

results are then used in a cost benefit analysis. The paper concludes with a discussion of the key findings and policy implications as Costa Rica refines its strategies for achieving zero net emissions from the AFOLU and other critical sectors to the country's economy.

2.0. Methods

2.1. The Integrated Economic-Environmental Model for Costa Rica

To design and evaluate emissions reductions strategies for a country, the analytical approach must enable consideration of all economic sectors and economic agents and their interactions in a consistent and simultaneous way. In particular, both the input-output relationships between productive sectors, and the different components of final demand, especially that of households, must be considered. For example, an expansion of the agricultural sector cannot be achieved without a simultaneous increase in the provision of transport services to deliver agricultural output to domestic and international markets.

For this reason, a whole of economy, computable general equilibrium (CGE) modeling approach is the ideal methodology to capture the multisectoral impacts and trade-offs of different emissions reductions strategies. For emissions reductions of AFOLU sectors, the IEEM+ESM framework is particularly well-suited with its integration of rich natural capital accounting data under the System of Environmental-Economic Accounting (SEEA; United Nations et al., 2014). The IEEM model for Costa Rica applied in this study has been developed in collaboration with the Central Bank of Costa Rica and has been applied to evaluate numerous policy and investment questions including decarbonization of the transport sector, fiscal reform, tourism policy and investment, and the economic impacts of COVID-19.

This study builds on and advances previous IEEM applications in Costa Rica by linking IEEM with LULC change and ecosystem services modeling. While the IEEM model for Costa Rica by itself can be used to estimate scenario impacts on economic indicators, natural capital, most provisioning ecosystem services and emissions, the linkage with LULC change and ecosystem services modeling enables estimation of impacts on non-market and non-provisioning ecosystem services. The IEEM+ESM approach is spatially explicit through the spatial allocation of scenario-based demand for land across a high-resolution spatial grid. Based on these spatial projections of LULC change, we then model the scenario impacts on non-market ecosystem services, specifically, carbon storage, water quality, water supply and erosion mitigation ecosystem services. Thus, results from IEEM+ESM analysis shed light on policy impacts on economic, wealth, natural capital, LULC change and ecosystem services indicators in an integrated, consistent, and spatially and temporally specific way. This level of detail and spatial dimension is

highly advantageous for refining and spatially targeting the Costa Rican government's strategies for the decarbonization of the AFOLU sectors.

At the core of IEEM is a recursive dynamic 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 4 decades (Burfisher, 2017; Dervis et al., 1982; Dixon and Jorgenson, 2012; Kehoe, 2005; Shoven and Whalley, 1992). The IEEM Platform is publicly available[1]. IEEM's mathematical structure is documented in Banerjee and Cicowiez (2020). IEEM's database is an environmentally-extended Social Accounting Matrix (SAM). The construction of the IEEM database is described in Banerjee et al. (2019). A user guide for a generic version of IEEM, applicable to any country with the corresponding database, is available in Banerjee and Cicowiez (2019).

Figure 1 summarizes the main economic flows captured by IEEM in any given period with the arrows representing income flows. CGE-based models including IEEM consider only the real side of the economy, excluding monetary aspects. Consequently, they do not consider phenomena such as inflation. Instead, they focus on capturing changes in the way that real economic resources are allocated across the economy, both temporally and in the case of IEEM+ESM, spatially as well.

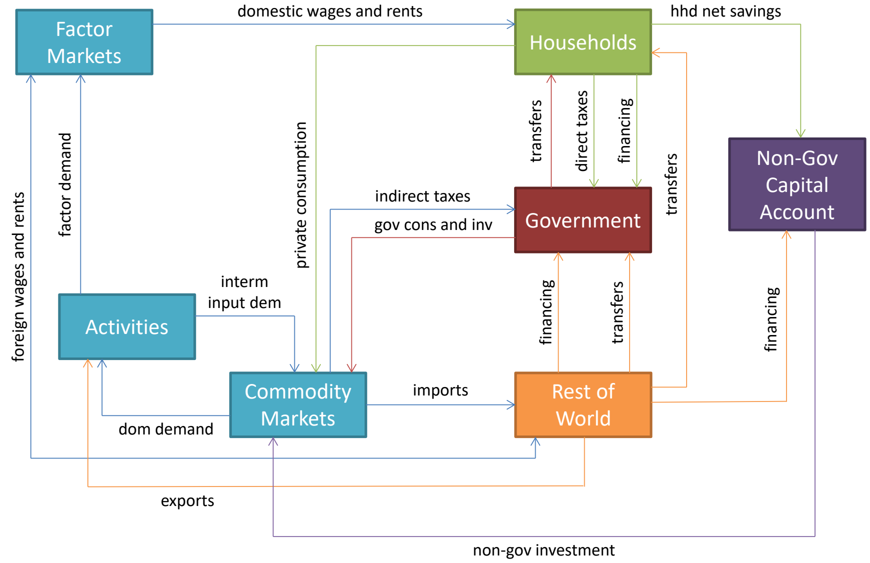
The productive economic sectors are represented by activities that maximize benefits in competitive markets. The production technology used in each economic sector, in its simplest version, is summarized in Figure 2. This figure shows that first, value-added and intermediate inputs are combined in fixed proportions. The value-added, in turn, is generated by combining primary factors of production, namely labor capital and for some economic sectors, natural capital. Intermediate inputs can come from domestic supply or from the rest of the world as imports.

Economic sectors can produce one or more products in fixed proportions. In turn, each product can be produced by more than one economic sector. The total production of each good or service can be destined for the domestic market or exported to the rest of the world. IEEM's production function allows economic sectors to endogenously determine the energy sources they use in production. More advanced nested specifications are possible with IEEM depending on the specific policy question, for example, the substitution of energy sources, inclusion of water as a

[1] All IEEM models, databases and documentation will be available here: https://www.iadb.org/en/topics/environment/biodiversity-platform/the-idbs-biodiversity-platform%2C6825.html

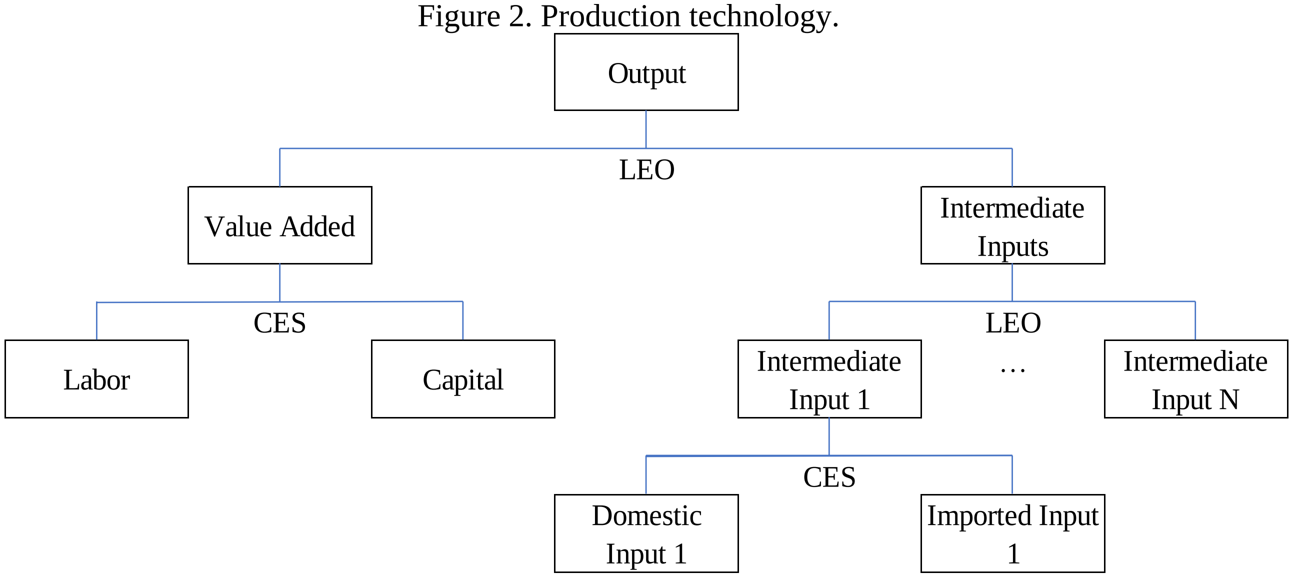
factor of production, the use of fertilizers and feed as substitutes for land in agricultural production, among others.

Figure 1. The circular flow of income in IEEM.



Source: authors' elaboration.

Figure 2. Production technology.



Note: CES = constant elasticity of substitution and LEO = Leontief. Source: authors' elaboration.

Institutions in IEEM are comprised of households, firms, government, and the rest of the world. Households obtain their income from ownership of productive assets and from the transfers they receive from other institutions. Households spend their income buying the goods and services they consume, by saving, paying taxes, and by making transfers to other institutions. The government receives income through tax collection, provides goods and services, makes transfers to

households, and saves or takes on debt, both domestic and foreign. The rest of the world demands exports and supplies imports. The IEEM model for Costa Rica enables the consideration of eight types of taxes, namely taxes on household income, economic activities, consumption, value added, exports, imports, factor income, and the use of factors of production by economic activities. Trade and transport margins are explicitly modeled, assuming that the corresponding services are required in fixed proportions to move a good from the producer to the consumer.

In terms of foreign trade, goods and services are assumed to differ according to their country of origin following the Armington assumption (Armington, 1969). Thus, two-way trade can be modeled, that is, the same good or service is imported and exported simultaneously. The combination of domestic and imported products is made at the border of the modeled country. Imperfect substitution between imports and domestic purchases is implemented with a Constant Elasticity of Substitution (CES) function. On the production side, a symmetrical assumption is made where exports are an imperfect substitute for sales to the domestic market. This imperfect transformation is implemented using a Constant Elasticity of Transformation (CET) function. In addition, Costa Rica is modeled as a small country, so it takes as given the world prices of the products it trades with the rest of the world.

In the labor market, it is assumed that there is unemployment that is represented by a wage curve. The wage curve establishes a negative relationship between the level of wages and the unemployment rate (Blanchflower and Oswald, 1994). In the scenarios considered herein, labor is perfectly mobile between economic sectors while capital once installed, is immobile between sectors.

IEEM is a recursive dynamic model where economic agents are myopic, and their expectations are stationary. In other words, economic agents expect future prices to be identical to those in the current period. There are four sources of dynamics in IEEM: capital accumulation and growth in the labor force, factor productivity and natural capital supply. At the beginning of each period, the sectoral capital stocks are adjusted based on levels of previous period investment. The endowments of the other productive factors grow exogenously. The investment and capital stocks of each period are differentiated between public and private investment.

Conventional CGE analysis does not have sufficient household level detail to consider distributional impacts. We address this limitation in IEEM through its linkage with a microsimulation model for estimation of the policy impacts on moderate and extreme poverty rates and income inequality measured by the Gini coefficient (Banerjee et al., 2018). Results obtained from IEEM on per capita income for the representative households identified in the IEEM database

are used to modify the per capita household income of each of the households recorded in the most recent national income and expenditure survey (INEC, 2018). In addition, changes in the prices of goods and services are considered to determine the change in real per capita consumption expenditure of households.

2.2. The IEEM database

At the core of the IEEM database is a Social Accounting Matrix (SAM). Our 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 (European Commission et al., 2009). The most recent Supply and Use Tables available are for the year 2016, which is the base year of our IEEM model for Costa Rica. For this application, economic sectors and products have both been aggregated to 48 sectors and products. Economic sectors associated with the AFOLU sectors are maintained at the highest possible level of disaggregation. For this application, there is one representative household in the SAM, though should future analysis demand it, we have a more detailed household sector representation where households are disaggregated into 16 categories according to their location (i.e. urban/rural) and their main source of income, according to employment qualification, capital, remittances, or transfers.

The IEEM database contains base year emissions from all economic sectors. Table 1 shows emissions flows from energy consumption and LULC change in the base year (2016) of IEEM. With regards to the AFOLU sectors, emissions from crops and livestock sectors are responsible for 75.1% and 24.9% of emissions from AFOLU, respectively. Households, through their consumption of refined petroleum products, largely in the form of fuel for automobiles, are responsible for 36% of emissions, while the transportation sector is responsible for 16% of emissions from the consumption of fuel.

Table 1. Emissions flows from energy consumption and land use land cover change in percent share.

		Energy consumption						
Emissions source	AFOLU	Forestry	Mining	Food	Refined pet	Chemicals	Other mnfc	Total
Households	0.0	41.6	0.0	0.0	36.1	100.0	0.0	14.4
Crops	75.1	0.0	0.0	2.8	4.3	0.0	0.0	41.8
Livestock	24.9	0.0	0.0	0.0	1.2	0.0	0.0	13.8
Forestry	0.0	1.3	0.0	0.0	0.0	0.0	0.0	0.1
Other agr	0.0	0.0	0.0	0.0	1.5	0.0	0.0	0.5
Mining	0.0	0.0	0.0	0.0	1.4	0.0	0.0	0.5
Food	0.0	3.2	0.0	56.1	7.2	0.0	100.0	8.9
Other mnfc	0.0	42.9	100.0	41.2	10.4	0.0	0.0	6.6
Elect, gas, wat	0.0	0.0	0.0	0.0	4.4	0.0	0.0	1.5
Construction	0.0	0.0	0.0	0.0	4.1	0.0	0.0	1.4
Trade	0.0	0.0	0.0	0.0	1.8	0.0	0.0	0.6
Hotels and rest	0.0	11.0	0.0	0.0	1.2	0.0	0.0	1.0
Transport	0.0	0.0	0.0	0.0	16.5	0.0	0.0	5.6
Other ser	0.0	0.0	0.0	0.0	10.1	0.0	0.0	3.4
Total	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0

Source: Authors' own elaboration.

In addition to the Social Accounting Matrix, supply and demand elasticities are required for model calibration and are the best available estimates obtained through a comprehensive literature review. The elasticity of substitution between primary factors of production varies from 0.2 for the natural capital extractive sectors to 0.95 for services such as construction, trade and transport (Aguiar et al., 2019). This implies that agricultural and extractive sectors, those that are intensive in their use of natural capital, cannot easily increase production without concurrent increases in the endowment of land and natural capital. Based on the literature available for developing countries (Sadoulet and de Janvry, 1995), the elasticities of substitution between imports and domestic purchases are set at 2.0 for primary goods, 1.5 for manufacturing, and 0.8 for other industries and services. In this case of substitution between imports and domestic goods, a value of less than one implies that there is some complementarity between domestic and imported goods. The transformation elasticities between exports and national sales are assumed to be equal to the elasticities of substitution between imports and domestic purchases.

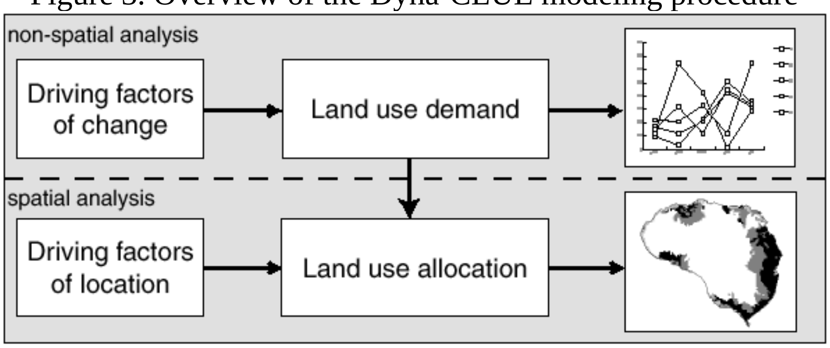
On the consumption side, IEEM assumes that consumer preferences are of the Stone-Geary type, from which a linear expenditure system (LES) is derived. The income elasticities for Costa Rica were obtained from the econometric work of Sanchez (2004), with relatively low income elasticity estimates for food and textile goods. The Frisch parameter (Dervis et al., 1982) was estimated in the range -3.6 to -1.8 depending on the level of per capita income of the representative household. The elasticity of wages with respect to the unemployment rate of the wage curve was

set at -0.1 for the three employment qualifications categories considered, which is consistent with the estimates reported in Blanchflower and Oswald, 2005 for many countries.

2.3. Linking IEEM with land use land cover modeling

The bridge between IEEM and changes in future ecosystem services supply is established through LULC change modeling. IEEM projections of demand for land are spatially allocated with the LULC change model and used to generate business-as-usual and scenario-based LULC maps from the base year until 2050. These maps are the variable of change in the ecosystem services modeling, while all other model variables are held constant through time. We use the CLUE (Conversion of Land Use and its Effects) modelling framework to spatially allocate LULC change using empirically quantified relationships between land use and location factors, in combination with the dynamic modelling of competition between land use types. CLUE is among the most widely used spatial LULC change models and has been applied on different scales across the globe. The version of the CLUE model family we use is the Dynamic CLUE (Dyna-CLUE) model which is appropriate for smaller regional extents compared with global LULCC modeling (Veldkamp and Verburg, 2004; Verburg et al., 2002; Verburg and Overmars, 2009).

Figure 3. Overview of the Dyna-CLUE modeling procedure

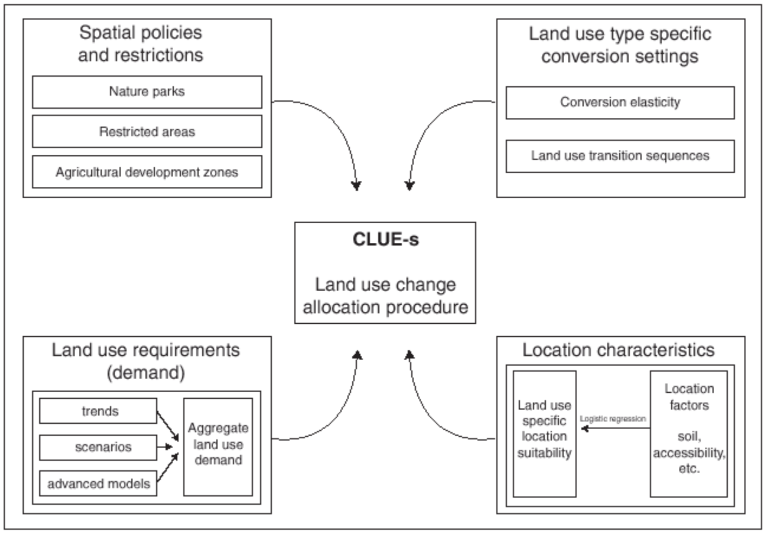


Source: (Verburg et al., 2002).

The Dyna-CLUE model is sub-divided into two distinct modules: a non-spatial demand module and a spatially explicit allocation module (Figure 3). The non-spatial module calculates the change in area for all land use types at the aggregate level, which in this case is an input derived from IEEM. Within the allocation module, these demands are translated into land use changes at different locations within the study region using a raster-based system.

Figure 4 provides an overview of the information required to run Dyna-CLUE. This information is subdivided into four categories that together create a set of conditions and possibilities for which the model calculates the best solution in an iterative process. Detailed information on the suitability analysis and all Dyna-CLUE model parameters and procedures is provided in the Supplementary Information section 2.

Figure 4. Overview of the information flow in the Dyna-CLUE model.

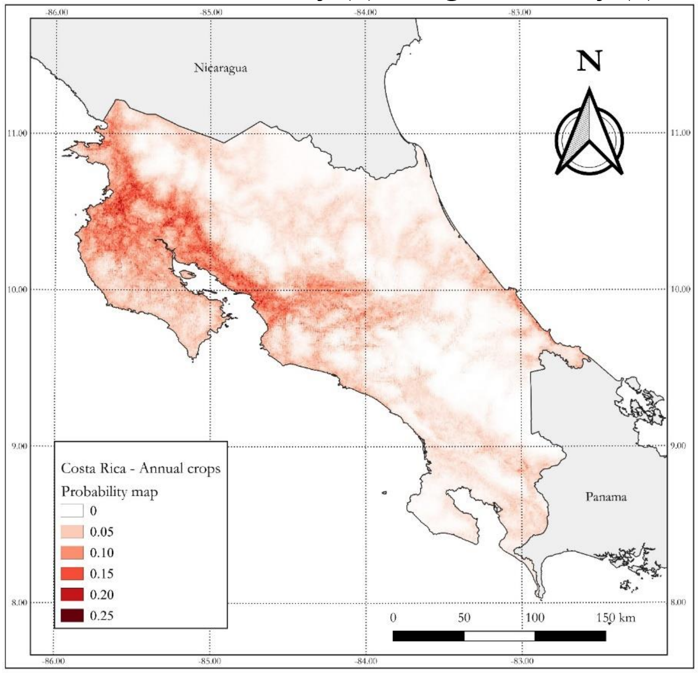


Source: (Verburg et al., 2002).

For the land use demand module in

Figure 4, different model specifications are possible ranging from simple trend extrapolations to complex economic models, such as in this case with the linkage of Dyna-CLUE with IEEM. The results from the demand module need to specify, on an annual basis, the area occupied by the different land use types, which is a direct input to the allocation module. In this study, annual demands for forest, forest plantation, cropland and grazing areas were estimated by IEEM according to producer demand for land. This demand is allocated based on a combination of empirical estimations, spatial analyses and dynamic modelling. In an intermediate step to the allocation of demand for land, Dyna-CLUE calculates suitability maps for each land use type based on the independent suitability rasters used in the logistic econometric estimation procedure. Figure 5 presents one such suitability map for crops in this study.

Figure 5. Spatial suitability for cropland based on the logistic regression. The scale low to high refers to low suitability (0) to high suitability (1).



Source: IEEM+ESM results.

2.4. Ecosystem Services Modeling

The Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST) suite of models is used to calculate spatially explicit changes in ecosystem services supply (Sharp et al., 2020). InVEST combines LULC maps and biophysical information to calculate ecosystem services, with the option to add additional parameters to assist in ecosystem services valuation where desirable. InVEST is one of the most widely used open-source ecosystem services modeling tools (Posner et al., 2016) and is well documented with a large user community.

A wide variety of ecosystem services can be calculated through the InVEST suite, whether biophysical or socio-cultural in nature. In this paper we parameterize and apply four InVEST ecosystem services models to calculate changes in ecosystem services supply across the baseline projection and all scenarios. The models we use are: (i) the sediment delivery ratio model used to calculated the Revised Universal Soil Loss Equation and sediment export; (ii) the carbon storage model used to calculate carbon storage and carbon sequestration potential; (iii) the annual water

yield model to calculate water supply, and; (iv) the nutrient delivery ratio model which is used as a proxy for the water purification potential of landscapes in absorbing nitrogen and phosphorus.

One of the primary limitations of InVEST and other ecosystem services models is the time and expertise required to assemble the best-available spatial data and biophysical lookup tables for their application. This study is the first application of the ecosystem services modeling data packets developed by the IDB and described in (Bagstad et al., In press). These data packets are essentially "plug and play" in that they contain all the processed spatial data and lookup tables needed to run the InVEST carbon storage, annual water yield, sediment delivery ratio, and nutrient delivery ratio models for 21 countries in Latin America and the Caribbean region, including Costa Rica.

3.0. Scenario design

3.1. IEEM Baseline reference scenario

The reference for all policy scenarios is the BASE business-as-usual scenario where we project Costa Rica's economy first from the base year of 2016 to 2019 based on observed economic data, and then from 2020 to 2050. The business-as-usual scenario assumes no new policies or interventions are implemented during the period. Economic growth for 2021 to 2050 is based on estimates from the International Monetary Fund (IMF, 2019). On average, Costa Rica's GDP grows to 3.5 percent for the period 2020 to 2050. In the business-as-usual scenario, total factor productivity adjusts endogenously to meet GDP growth. In the policy scenarios that follow, the (calibrated) exogenous component of total factor productivity remains constant based on business-as-usual total factor productivity. Population projections were obtained from the World Population Prospects report prepared by the United Nations (United Nations et al., 2019). The economically active population grows at the same rate as the working age population.

The supply of agricultural land evolves according to the projections described in section 3.3.1 of this paper, while the supply of extractive natural capital resources follows the GDP growth rate. The evolution of the capital stock is a function of public and private investment. We assume that government demand for government services, transfers from government to households, and domestic and foreign government net financing are all maintained as fixed shares of GDP at their

base-year values. Taxes are fixed at their base-year rates, which means that they will grow at a similar pace to the overall economy.

At the macro level, IEEM, like any other CGE model, requires the specification of equilibrating mechanisms known as model closures for three macroeconomic balances, namely the: (i) government closure; (ii) savings-investment closure, and; (iii) balance of payments closure. For the business-as-usual scenario, the following closures are used: (i) the government's accounts are balanced through adjustments in the direct tax rate; (ii) the savings-investment balance is achieved with private domestic investment equal to household savings as a fixed share of GDP at the base-year value. Private foreign investment is financed through the balance of payments. Government investment is a fixed share of the government budget which in turn is a fixed share of GDP at its base-year value, and; (iii) the real exchange rate equilibrates the balance of payments by influencing export and import quantities and values. The non-trade-related payments in the balance of payments, specifically, transfers and non-government net foreign financing and foreign direct investment, are non-clearing and kept fixed as shares of GDP[2].

3.2. Baseline emissions projections

In addition to the economic component of generating a business-as-usual scenario in IEEM, described in the preceding section, we also require a business-as-usual emissions projection to serve as a reference scenario to assess scenario impacts on business-as-usual emissions. This emissions baseline estimation is comprised of emissions from crop and livestock production and from current LULC (carbon stocks) as well as LULC change (flows). Sectoral crop and livestock emissions are estimated by equations 1 and 1.1:

$$E_t = \sum_s A_{s,t} \times F_{s,t} \times Y_{s,t} \tag{1}$$

and

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

$$\mathrm{Y_s = P_s/A_s} \tag{1.1}$$

Where:
E = emissions
P = production for crop or livestock type
A = crop area or livestock head count
F = emissions factor
Y = yield factor
s = crop or livestock type
t = time period

The Supplementary Information section Table SI 1 presents the business-as-usual emissions estimated with equation 1 and the data sources used. Columns A and P indicate estimated values for each type of crop in IEEM based on the FAO's database. It is important to note that while for some classes, there is a 1:1 correspondence between IEEM and FAO classes, but for other classes, it was necessary to aggregate different items in the FAO database to match the class in IEEM. Columns E1 and E2 list the estimated emission factors for IEEM classes and the data sources used (Clune et al., 2017, De Figueiredo et al., 2010, Basset-Mens et al., 2016).

For changes in carbon stocks arising from changes in LULC, following the IPCC (2006, p. 2.6) guidelines, we estimate the CO_2 released from negative differences in carbon stocks multiplied by a factor that considers the molecular weight of carbon and oxygen in CO_2 particles. Based on our ecosystem services modeling results, we first estimate annual carbon stock changes for AFOLU sectors between our business-as-usual scenarios and all other scenarios' final year values according to equation 2.

$$\Delta C_{AFOLU} = \Delta C_{FL} + \Delta C_{CL} + \Delta C_{GL} + \Delta C_{WL} + \Delta C_{SL} + \Delta C_{OL} \tag{2}$$

Where:

ΔC = change in carbon stock, and; the indices used denote the following: Agriculture, Forestry and Other Land Use (AFOLU), Forest Land (FL), Cropland (CL), Grassland (GL), Wetlands (WL), Settlements (SL), Other Land (OL). For conversion of LULC from one use or cover to another, we apply the IPCC conventions (2006, p. 2.7) to our data configuration and estimated changes in carbon stocks from above-ground biomass, below-ground biomass, deadwood and soil

using equation 3:

$$\Delta C_{LU} = \Delta A_{LU} \times (F_{AB} + F_{BB} + F_{DW} + F_{SO}) \quad (3)$$

Where:

ΔC = carbon stock change

ΔA = change in area in hectares

F = carbon storage factor, and; the indices used denote the following: Land Use Category (LU), carbon pools for above-ground biomass (AB), below-ground biomass (BB), deadwood (DW) and soils (SO).

Finally, also following IPCC (2006, p. 2.11), we approximate emissions from the ratio of molecular weights of carbon and oxygen in CO_2 (-44/12), with a change in sign denoting that increases in carbon stocks represent "negative emissions" from the atmosphere, while decreases in carbon stocks represent positive emissions to the atmosphere, using equation 4:

$$Emission = \Delta C_{AFOLU} \times (-{}^{44}/_{12}) \quad (4)$$

Where:

Emission = Net CO_2 emissions from land use changes

ΔC = carbon stock change

AFOLU = Agriculture, Forestry and Other Land Use

It is worth noting that biomass associated with annual and perennial plants is relatively ephemeral, in that it decays and regenerates annually or every few years. Emissions from this decay are balanced by removals due to re-growth making overall net C stocks in biomass stable in the long term (IPCC, 2006). For that reason, our estimations include only the CO_2 emissions that arise from changes in LULC which are fully described by equations 1 through 4 above.

3.3. Policy scenarios

We define three groups of policy scenarios to represent the different lines of action that comprise Costa Rica's strategy for emissions reduction from AFOLU sectors as described in the

Decarbonization Plan.

3.3.1. Emissions reduction scenarios

EMI: This is an emissions reduction scenario, abbreviated as EMI for ease of presentation of results, that simulates changes in the amount of carbon dioxide equivalent (CO_2e) produced per unit of agricultural crop and livestock output. For agricultural crops, we consider the four crops for which emissions reductions targets are identified in Costa Rica' Decarbonization Plan, namely, sugar cane, coffee, banana and rice. In 2016, the base year for IEEM, these crops represented 36.0% of agricultural value-added, 39.7% of agricultural employment, and 43.5% of agricultural exports.

In addition to their economic importance, these crops are also relevant for Costa Rica because of the land used in their cultivation, which was approximately 245,000 hectares in the base year. To estimate the emission reduction potential for these crops, we first compare the baseline carbon intensity of these crops in Costa Rica against the known crop carbon intensity frontier internationally (Table 2), based on the literature review described in the Supplementary Information section (Table SI 1). Based on this information, we assume a convex downward convergence towards the frontier as in Figure 6. This figure describes for each crop how the carbon intensity changes, assuming an exponential rate of decay towards 80% of the frontier.

The use of this emissions reduction potential aims to embody, in a conservative way, the actions the Costa Rican government plans to implement to meet its emissions reduction targets in the Decarbonization Plan. In particular, the Plan states that the coffee, sugar cane, rice, banana, and livestock sectors will adopt emission reduction technologies both at the farm level and at the processing stage level. Furthermore, it states that by 2050, the most advanced methods and technologies will be applied to achieve sustainable, competitive, low carbon emissions agriculture that is both resilient and generates the lowest levels of pollution possible (MINAE, 2019a). Emissions reductions from these sectors will be achieved through the implementation of improved soil management practices that reduce emissions arising from fertilizer use. These practices include crop rotation, cover cropping, application of manures and compost, liming, and the

implementation of integrated cropping systems.[3]

Table 2. Emissions factor baseline and target for crops in kilograms of CO_2e per kilogram of crop output.

IEEM Class	Baseline factor (kg CO2e/kg)	Frontier target (kg CO2e/kg)	Data source
Sugar cane	0.024	0.012	IMN, 2020, page 6
Coffee	2.28	2	IMN, 2016 & Rahn 2013, Table 4.
Banana	0.03	0.15	IMN, 2020, page 6.
Rice	3.65	0.66	IMN, 2016 & Clune 2016, Table 4.

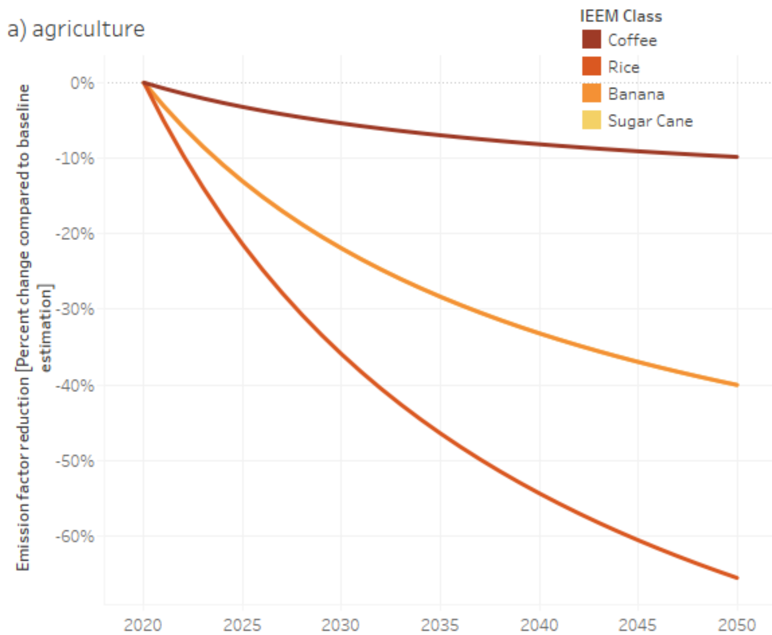
Source: author's own elaboration based on cited literature.

To estimate the cost of implementing improved soil management practices, we follow estimates provided by Gillingham and Stock, 2018 on the unit cost of emissions reduction through soil management which is equivalent to US$57 per ton of CO_2e at 2017 prices. To estimate the total cost of this strategy for each of the emissions factor curves presented in Figure 6, we calculate the annual reduction in CO_2e emissions and multiply this marginal reduction by the unit cost of reduction.

For livestock, we focus on beef, pork and chicken meat production where emissions reductions are achieved through the implementation of improved livestock management practices. To estimate the emissions reduction potential of from the livestock sector, we first compare the baseline carbon intensity of each livestock type against the known carbon intensity frontier internationally based on Clune et al. (2017). Table 3 presents the baseline carbon intensity factors for beef, pork and chicken in Costa Rica compared with the known carbon intensity frontier internationally, based on the literature review described in Supplementary Information Table SI 1.

[3] It is possible that not all of these practices will be applied to all of the crops considered. The level of aggregation of our model for these scenarios is such that the marginal effect and cost of each of these practices cannot be considered in isolation. As a result, each scenario modelled represents the average effect and cost of the combined use of these practices, and not the individual effect.

Figure 6. Emissions factor reductions for crops in kilograms of CO2e per kilogram of crop output.



Source: author's own elaboration.

Table 3. Emission factor improvement scenario for livestock in kilograms of CO2e per kilogram of crop output.

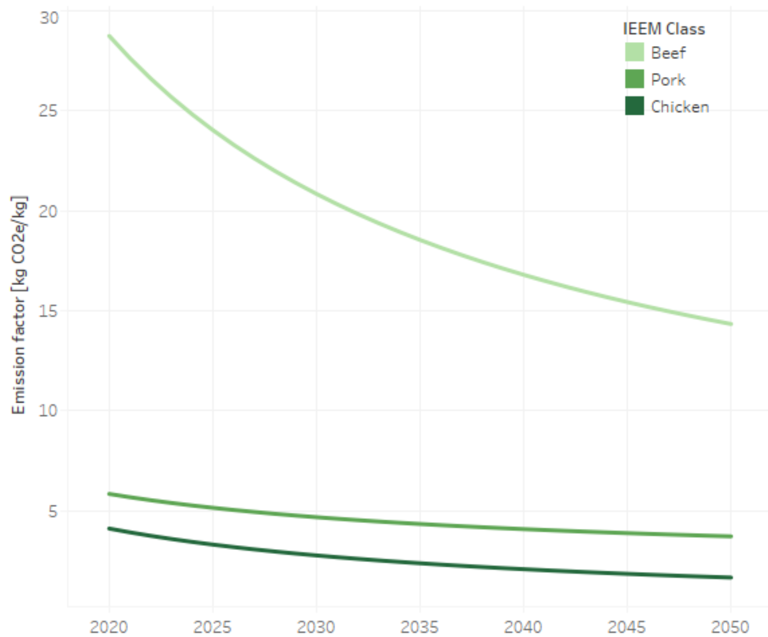
IEEM commodity	Baseline factor (kg CO2e/kg)	Frontier target (kg CO2e/kg)	Source for comparison
Beef	28.73	10.74	Clune et al. (2017), Table 6
Pork	5.85	3.20	Clune et al. (2017), Table 7.
Chicken	4.12	1.06	Clune et al. (2017), Table 7.

Source: Author's own elaboration based on Clune et al. (2017).

We assume a convex downward convergence towards the frontier as shown in Figure 7. Since the majority of livestock CO_2e emissions are produced by ruminant livestock enteric fermentation and manure management, the mitigation options we considered 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 CH_4 emissions capture (Beach et al., 2008; Gillingham and Stock, 2018). We estimate the total cost of this strategy for each of the emissions trajectories presented in Figure 7 following the same approach described for crop emissions. Our cost unit cost estimate for these mitigation strategies is based on Gillingham and

Stock (2018) and is equivalent to US$71 per ton of CO_2e reduced at 2017 prices.

Figure 7. Emissions factor baseline and target for livestock in kilograms of CO_2e per kilogram of meat output.



Source: Authors' estimations.

3.3.2. Enhanced productivity scenarios

YIELD: This scenario, abbreviated as YIELD, captures the Decarbonization Plan's strategic line of action aimed at improving the productivity of key crops. The agricultural practices that lead to the productivity improvements outlined here include precision agriculture and more productive and climate resilient crop varieties. While the implementation of more efficient practices could also reduce the emissions from crop production, we do not explicitly consider spillover effects, and instead treat emissions reductions strategies independently in the EMI scenario in order to isolate and understand the impacts of the measures individually. This is consistent with the framing of the AFOLU strategies in the Decarbonization Plan.

To estimate the productivity improvement trajectories, we compare the estimated baseline productivity of sugarcane, coffee, banana and rice in Costa Rica with countries located at the

productivity frontier, as shown in **Error! Reference source not found.**[4]. We estimate this frontier by using FAO data on productivity at the national level, considering only countries with: (i) significant production levels of the targeted crop, compared to total production, and; (ii) similar economic and climatic conditions to those of Costa Rica as shown in Sayre et al. (2020).

Table 4. Parameters used in the productivity improvement scenarios.

IEEM crop class	Baseline productivity (ton/ha)	Frontier Productivity (ton/ha)	Frontier country	FAO crop class
Sugar cane	63.5	129	Guatemala	Sugar cane
Coffee	1.22	1.51	Brazil	Coffee, green
Banana	52.22	60	Indonesia	Bananas
Rice	4.23	5.46	Brazil	Rice, paddy

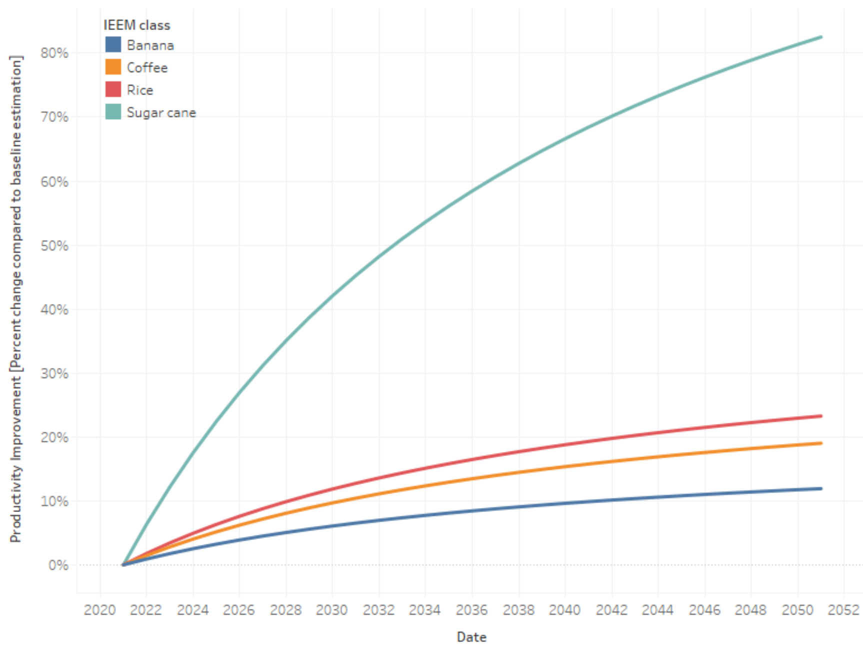
Source: Authors' estimations based on FAO (2020a).

Taking these parameters as a reference, we model future productivity trajectories for these crops. We take a conservative approach and assume that the Decarbonization Plan strategies for increasing yields improve crop productivity by 50% of the known frontier. The modeled yield trajectories for these crops are displayed in Figure 8.

To estimate the investment costs required to attain these productivity improvements, we follow two steps[5]. First, we estimate the difference in net capital stocks, proportional to the level of crop output between Costa Rica and the productivity frontier country (Table 5). Second, we project this until 2050, assuming that differences in capital stocks amount to the investment required to reach the productivity frontier. Net capital stocks in the System of National Accounts measure past flows of capital formation, correcting for depreciation. We take into account that each annual investment is an addition to the capital stock, while each retirement or deterioration of capital enters as a deduction (OECD, 2014).

[4] Note that this modeling assumption does not account for the biophysical processes associated with these yield improvement scenarios which could vary significantly across countries. More detailed modeling of these causal links could contribute to account in more detail for the effect of different climates and local resources on the marginal effect on productivity of implementing precision agriculture and crop selection practices.
[5] Our cost estimates represent the investments required to attain a certain level of productivity for particular crops and do not consider other institutional factors such as patterns of ownership and market structures, as well as operational costs. Future research is proposed for developing more robust estimates of costs as Costa Rica refines its strategies for emissions reduction

Figure 8. Productivity improvement scenario.



Source: Authors' own estimations.

Although this is an aggregate estimate, it provides a reasonable preliminary estimate of the investment required to move closer towards the productivity frontier. The proportion of the value of the crop subsector when compared with the overall agricultural sector is multiplied by the agricultural sector capital stock at the frontier. The total investment required in Costa Rica to bridge this productivity gap is the difference between the crop subsector capital stock at the frontier and Costa Rica's crop subsector capital stock.

Table 5. Productivity investment cost parameters.

Crop (frontier country)	Agriculture capital stock frontier (millions of USD, 2016 prices)	Crop as percent of total agricultural production (frontier)	Capital stock in Costa Rica, proportional to total production (millions of USD, 2016 prices)	Total cumulative investment required to 2050 (millions of USD, 2016 prices)
Rice (Egypt)	$27,525	6%	$114	$781
Sugar Cane (Guatemala)	$11,307	71%	$2321	$2,833
Banana (Indonesia)	$169,024	2%	$1,373	$947
Coffee (Vietnam)	$24,124	1%	$57	$135

Source: Authors' own estimations based on (FAO, 2020b).

3.3.3. Reducing Emissions from Deforestation and forest Degradation (REDD+) scenarios

With the implementation of strong and progressive forest policies, Costa Rica has increased its forest cover from 20% of total land area in the 1980s to over 50% in the 2010's (Porras et al., 2013). Costa Rica has developed its Reducing Emissions from Deforestation and forest Degradation (REDD+) strategy for forests to play a key role in the climate change solution. The country's Protected Areas System and PES program provide coverage for 35% of the country and 70% of its forests. The Government has proposed further strengthening of the REDD+ program, consistent with the National Plan for Forest Development and the National Climate Change and Biodiversity Strategy, as a means of catalyzing investment in forests to maximize co-benefits. Between 2011 and 2015, Costa Rica reconfigured its original REDD strategy into a more expansive strategy, known as REDD+ which includes the sustainable management of forests as well as the conservation and enhancement of forest carbon stocks.

Costa Rica's revised REDD+ strategy has 5 main policies, namely: (i) promotion of low carbon emissions productive systems through agroforestry and silvopastoral activities; (ii) strengthening programs for the prevention and control of land use change and forest fires; (iii) incentives for conservation and sustainable forest management; (iv) restoration of landscapes and forested ecosystems; (v) encouraging the participation of indigenous peoples, and; (vi) facilitating conditions.

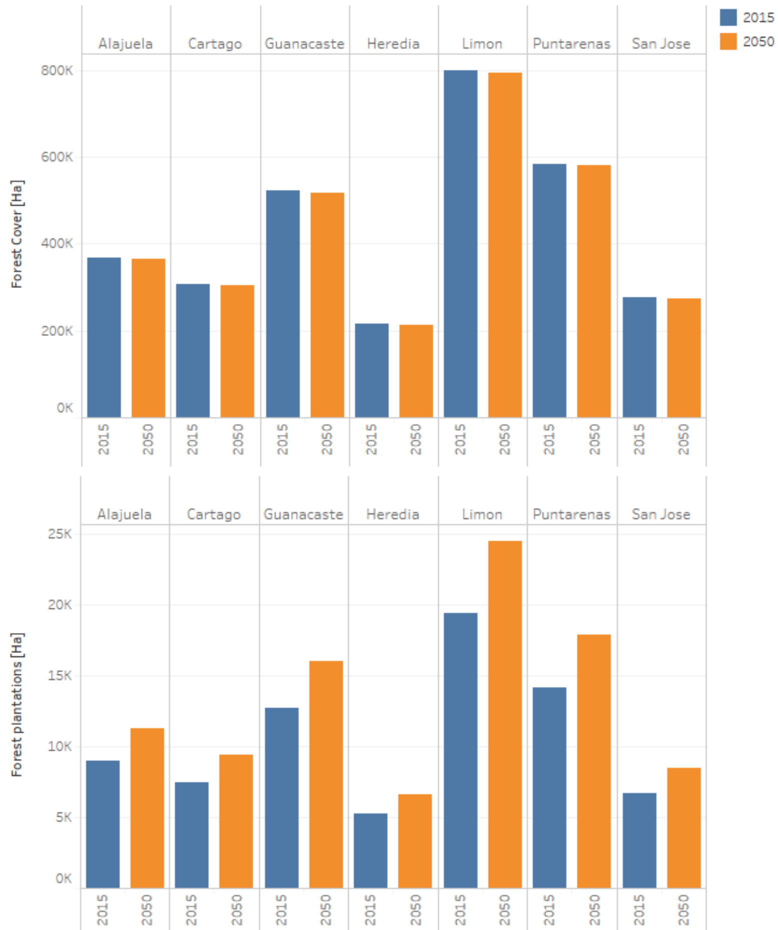
In the following sections we develop a LULC business-as-usual projection and two policy scenarios to simulate key policies comprising Costa Rica's REDD+ strategy. Specifically, of the 5 policies outlined above, we implement policy (i) promotion of low carbon emissions productive systems through agroforestry and silvopastoral activities and policy (iv) for the restoration of landscapes and forested ecosystems through the establishment of forest plantations. These scenarios draw directly from the targets and implementation costs established in Costa Rica's REDD+ strategy (MINAE, 2017, 2015).

3.3.1. Baseline LULC projection

Our business-as-usual LULC projection for Costa Rica is based on the projection prepared in the development of the country's REDD+ strategy, which it is the most recent dataset available that describes land use changes induced by Costa Rica's reforestation program throughout 2050 (MINAE, 2019b). This business-as-usual projection was supplied to the authors by Costa Rica's Ministry of the Environment and Energy (MINAE). This LULC projection is based on the estimated forest reference emissions levels submitted by Costa Rica to the Secretariat of the United Nations Framework Convention on Climate Change. The methodological details of the business-as-usual estimate and the transition matrix used for elaborating this projection are described in Sierra (2016) and Pedroni (2015).

To regionalize this national REDD projection to the provincial level, we assume that the current distribution of forest cover across Costa Rica's provinces remains constant throughout the simulation. Figure 9 shows the corresponding downscaled projection of forest cover. Note that primary natural forest cover changes very little, while forest plantations expand over the period presented in Figure 9.

Figure 9. Primary natural forest and forest plantation area by Province in 2015 and 2050.



Source: Authors' own elaboration based on REDD+ projection.

For modeling the emissions impacts of the projection of land use change, we multiply the area of land use change by the emission factors estimated in the business-as-usual exercise, as outlined in equation 2.

3.3.2. Implementing the expanded REDD+ strategy

We implement two key policies of the expanded REDD+ strategy as follows.

REDD1: The first REDD+ policy we simulate is the introduction of agroforestry and silvopastoral systems. These systems will be implemented on current agricultural areas and will involve the planting of trees in these areas. It is anticipated that through better land management and more sustainable agricultural productivity, the incentives for new deforestation and land clearing will be

reduced. To achieve this end, the Government will support a new Guarantee Program as part of the Estratégia para la Ganadería Baja en Carbono (EDGBC) in the context of Nationally Appropriate Mitigation Action (NAMA) Ganadería. Another mechanism for putting the right incentives in place is through the strengthening of the Programa de Plantaciones de Aprovechamiento Forestal (PPAF) managed by Fondo Nacional de Financiamiento Forestal (FONAFIFO) which finances farmers to plant trees in agroforestry and silvopastoral systems to produce wood and mitigate climate change (MINAE, 2017).

MINAE, (2017) states that in addition to the current REDD+ strategy which is already being implemented, the expanded REDD+ strategy would convert 122,241 ha of livestock areas into silvopastoral systems and 121,093 ha of agricultural areas into agroforestry systems over a 7-year period. This additionality to the current REDD+ strategy is what we simulate in this scenario. To do so, we establish these areas equally, equivalent to 17,463 ha and 17,299 ha for silvopastoral and agroforestry systems, respectively, between 2021 and 2027. Following MINAE (2017), the total implementation cost is US$39,463,967 in addition to what the current strategy demands in terms of investment. This implies an annual cost of US$6,577,328 from 2021 to 2027. In IEEM, we approximate the positive productivity impact of well-managed agroforestry and silvopastoral systems by increasing crops and livestock productivity in the newly established areas by 10% and 6%, respectively (Jiménez et al., 2018; Rodríguez, 2017).

REDD2: The second REDD+ policy we simulate is the establishment of forest plantations. This policy aims to establish a total of 19,900 ha between 2021 and 2027[6]. The annual cost of this strategy is US$666,331 from 2021 to 2027. We implement these new forest plantation areas with 3,200 ha in the first two years and with 2,700 ha per year for the remaining five years (MINAE, 2017).

3.3.2. Additional scenarios and overview

Two additional scenarios are implemented, which are combinations of previously defined scenarios. They are:

[6] 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 exists.

YIELD+EMI: this is the simultaneous implementation of the EMI and the YIELD scenarios.

COMBI: This is the simultaneous implementation of the YIELD, EMI, REDD1 and REDD2 strategies.

Table 6 provides an overview summary of all scenarios and their abbreviations to facilitate the interpretation of the results.

Table 6. 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

Source: Authors' own elaboration.

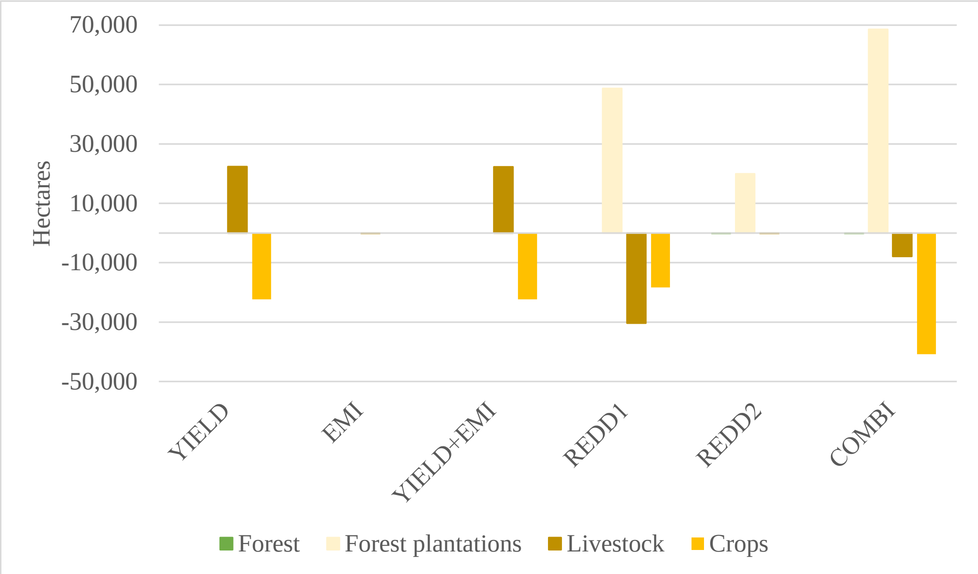
4.0 Results

Figure 10 shows scenario impacts on land use in IEEM. The agricultural productivity enhancement (YIELD) and reduced emissions (EMI) scenarios show that there would be a movement of some crop area toward livestock production. In the case of increasing agroforestry and silvopastoral systems (REDD1), we find an increase in 48,667 hectares in areas with tree cover and a decrease in livestock and crops of 30,352 hectares and 18,314 hectares, respectively. The decrease in livestock is larger because crop returns per unit area are higher when compared with livestock returns.

Our scenario for expanding forest plantations (REDD2) would increase the area planted with trees by 19,900 hectares. Finally, full decarbonization of the AFOLU sectors (COMBI) would result in a 68,567 hectare increase in forest plantations, a 7,873 hectare reduction in livestock and a 40,794 hectare reduction in crop area. These results show that with the implementation of AFOLU

strategies, land would be used more efficiently to meet growing future demand as the cultivated area falls with respect to the business-as-usual projection.

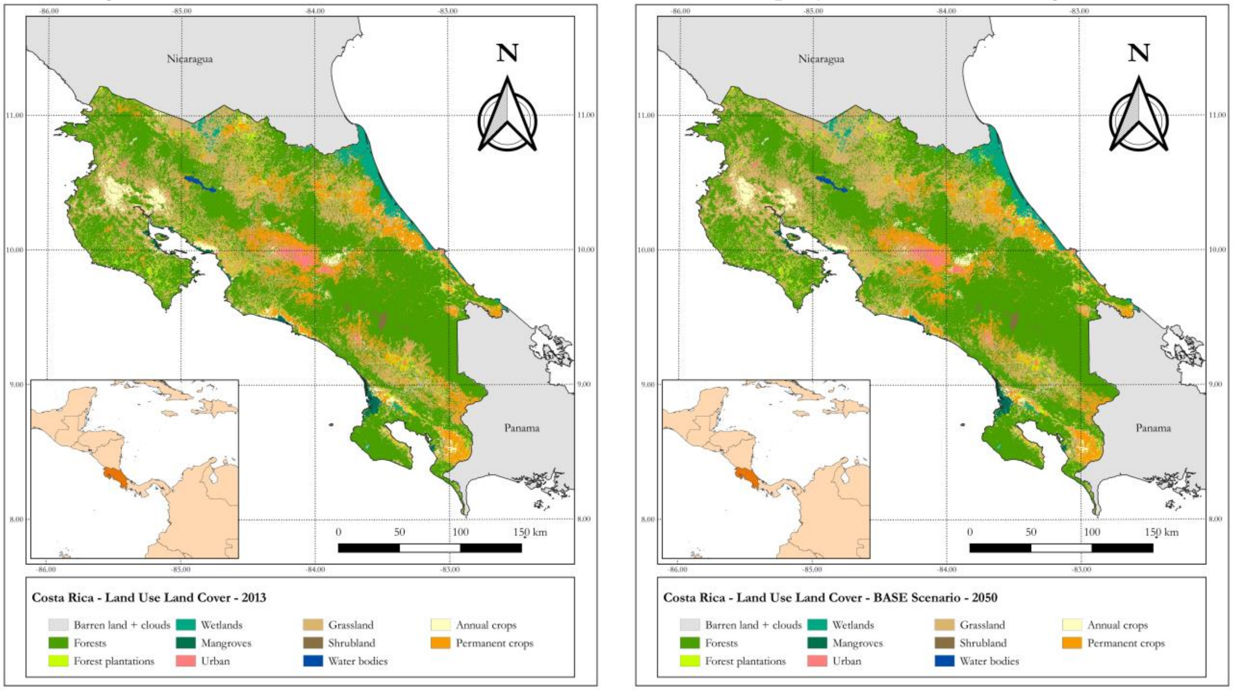
Figure 10. Scenario impacts on IEEM land use classes as difference from business-as-usual in 2050 in hectares.



Source: IEEM+ESM results.

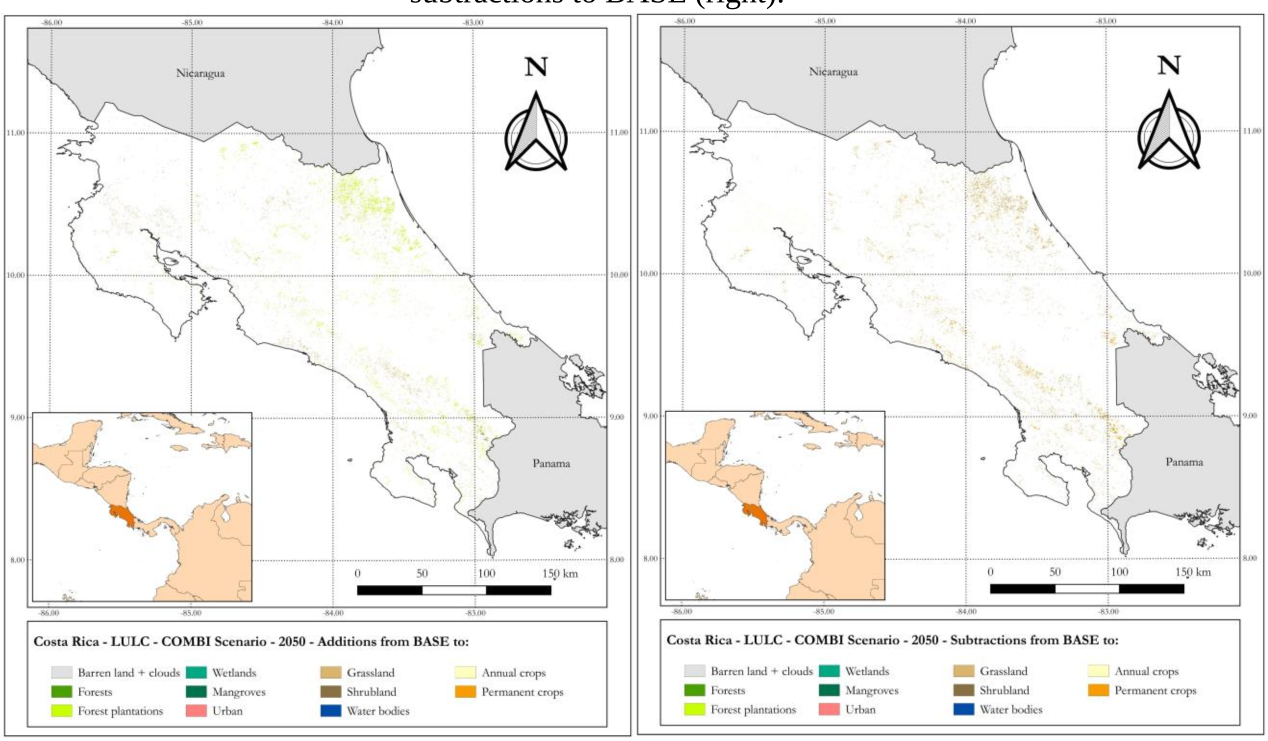
The spatial distribution of LULC in the business-as-usual scenario is shown in Figure 11. The map on the left shows the base year of 2013 while the map on the right shows how LULC could evolve by 2050 in the absence of any new public policy or investment intervention. Figure 12 helps discern the changes in LULC and identifies the specific areas where crop, livestock and forest plantations land uses have increased (left) or decreased (right) across the country with full implementation of the AFOLU strategy by 2050.

Figure 11. Business-as-usual LULC in 2013 (left) and projection to 2050 (right).



Source: IEEM+ESM results.

Figure 12. Full decarbonization strategy impacts on LULC as additions to BASE (left) and subtractions to BASE (right).



Source IEEM+ESM results.

Table 7 shows impacts on macroeconomic indicators as the difference from business-as-usual in the final year of 2050. The YIELD scenario would be strongly positive across all indicators with a US$439 million and US$135 million impact on GDP and wealth, respectively. The productivity gain would boost agricultural production, reduce agricultural prices and release factors of production for use in other sectors. All of these impacts together would result in an overall positive effect on wages, employment, and household welfare. In addition, faster agricultural growth would stimulate faster growth in the non-agricultural sectors, both by increasing final demand for non-agricultural products and by lowering input prices and fostering upstream processing. For instance, in the YIELD+EMI scenario, output for the food-processing sector would grow 0.7 percentage points more quickly than business-as-usual. On a sector-by-sector basis, the export to output ratio is relevant in interpreting sectoral impacts.

Table 7. Scenario impacts on macroeconomic indicators as difference from business-as-usual in 2050 in millions of USD.

	YIELD	EMI	YIELD+EMI	REDD1	REDD2	COMBI
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

Source: IEEM+ESM results.

The impacts of the EMI scenario would be comparatively small with the exception of an important US$151 million increase in wealth which is driven by the reduction in the costs associated with emissions in the calculation of wealth. The combined impact of the productivity enhancement and the emissions reduction scenarios would capture the best of both individual scenarios and would be strongly positive across indicators with a GDP and wealth impact of US$432 million and US$292 million, respectively. Both expanding agroforestry and silvopastoral systems and increasing forest plantations would be positive for the economy as the REDD1 scenario would generate an additional US$170 million in GDP and US$124 million in wealth in 2050. The wealth impact would be smaller than the GDP impact with wealth capturing changes in savings and forest

stock. Implementing additional forest plantation areas in REDD2 would have a small though generally positive impact given the size of the new forest plantations established.

The combined AFOLU decarbonization strategy impact on all indicators would be positive with a US$609 million boost to GDP and a US$335 million increase in wealth. Any downside pressure exerted by the emissions reduction scenario alone would be outweighed by the other measures implemented as part of the overall AFOLU decarbonization strategy. The main drivers of the changes in wealth are as follows. In the emissions reduction scenario, emissions reductions drive increases in wealth. In the enhanced productivity 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.

Table 8 describes how the scenarios would affect ecosystem services supply as a percent difference from business-as-usual. In the case of erosion mitigation services, full implementation of the decarbonization strategy for AFOLU would increase ecosystem service provision. The establishment of agroforestry and silvopastoral systems, as well as forest plantations would contribute strongly to these impacts while increasing agricultural productivity would strongly reduce nutrient exports and thus enhances water quality. In terms of carbon storage, full implementation of the decarbonization strategy would result in a 0.43% increase in carbon storage. With very limited changes in land use in the EMI scenario alone, it would also have a very small impact on future ecosystem service flows[7]. Of course, the impact of the strategy on reducing greenhouse gas emissions flows would be significant and discussed further on.

Overall, the full implementation of the AFOLU decarbonization strategy would result in a reduction in nutrient exports, by 5.25% for nitrogen and by 6.86% for phosphorus which indicates an improvement in water quality accompanying decarbonization of AFOLU. Finally, impacts on water yield would be rather small. Figure 13 provides a visual representation of the results

[7] Note that while the EMI scenario in IEEM includes the implementation of agricultural practices to reduce emissions, due to a lack of information, the management factor parameter in the four InVEST models was not modified. As a result, the implementation of these practices is not reflected in the results presented in this table. The implementation of these practices does, however, affect the estimation of wealth as well as net present value.

presented in Table 8, displaying scenario impacts on ecosystem service supply as percent difference from business-as-usual in 2050.

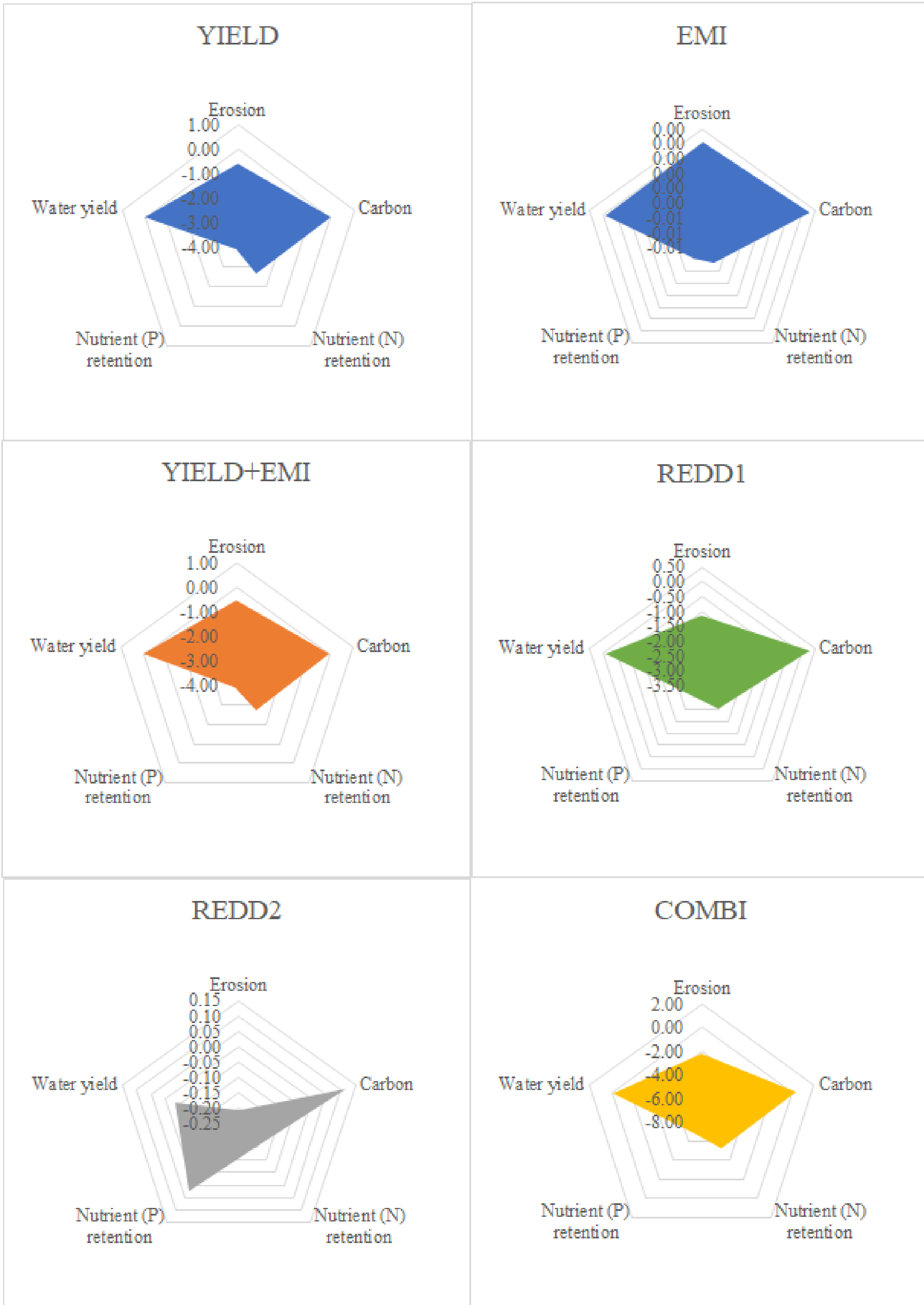
Table 8. Scenario impacts on ecosystem service supply as percent difference from business-as-usual in 2050.

	YIELD	YIELD +EMI	EMI	REDD1	REDD2	COMBI
Soil erosion	-0.54	-0.54	0.00	-1.14	-0.21	-2.28
Carbon storage	0.02	0.02	0.00	0.30	0.12	0.43
Nitrogen export	-2.70	-2.69	-0.01	-2.54	-0.16	-5.25
Phosphorous export	-3.88	-3.88	-0.01	-3.01	0.02	-6.86
Annual water yield	0.01	0.01	0.00	-0.08	-0.03	-0.10

Source: IEEM+ESM results.

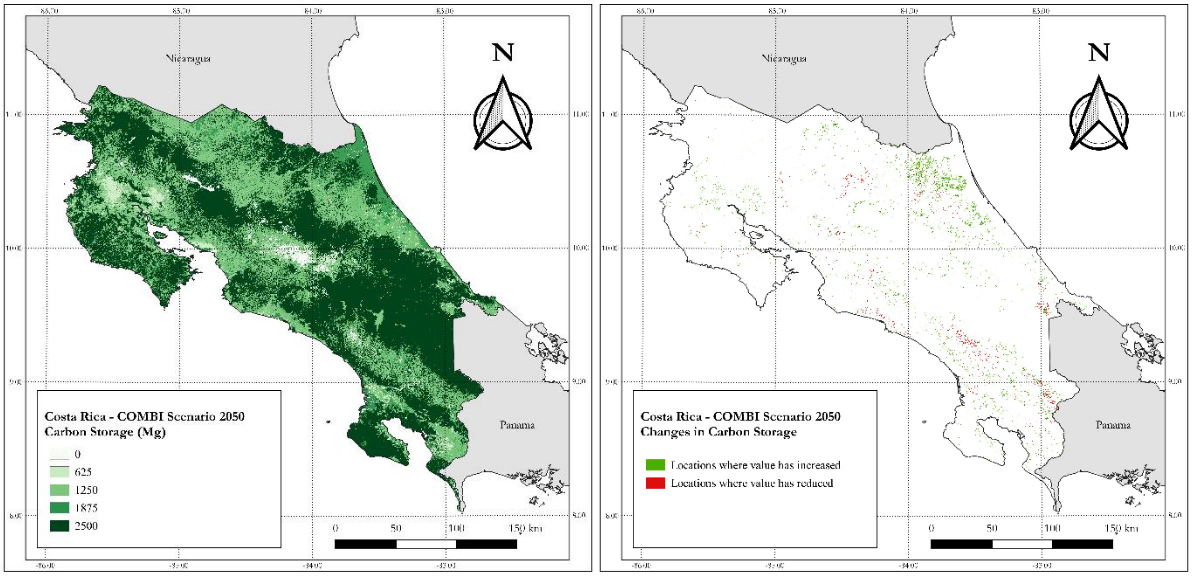
Figure 14 shows projected carbon storage with the full implementation of the AFOLU decarbonization strategy. The spatial distribution of changes in carbon storage follow the changes in land use land cover presented in Figure 12. Figure 15 presents the potential impacts of the full AFOLU decarbonization strategy on water purification ecosystem services. These services are proxied for by the levels of phosphorus (map on the left; note that this map shows nutrient exports in the COMBI scenario and not as a difference from BASE) and nitrogen exports (map on the right).

Figure 13. Scenario impacts on ecosystem services supply as percent difference from business-as-usual in 2050.



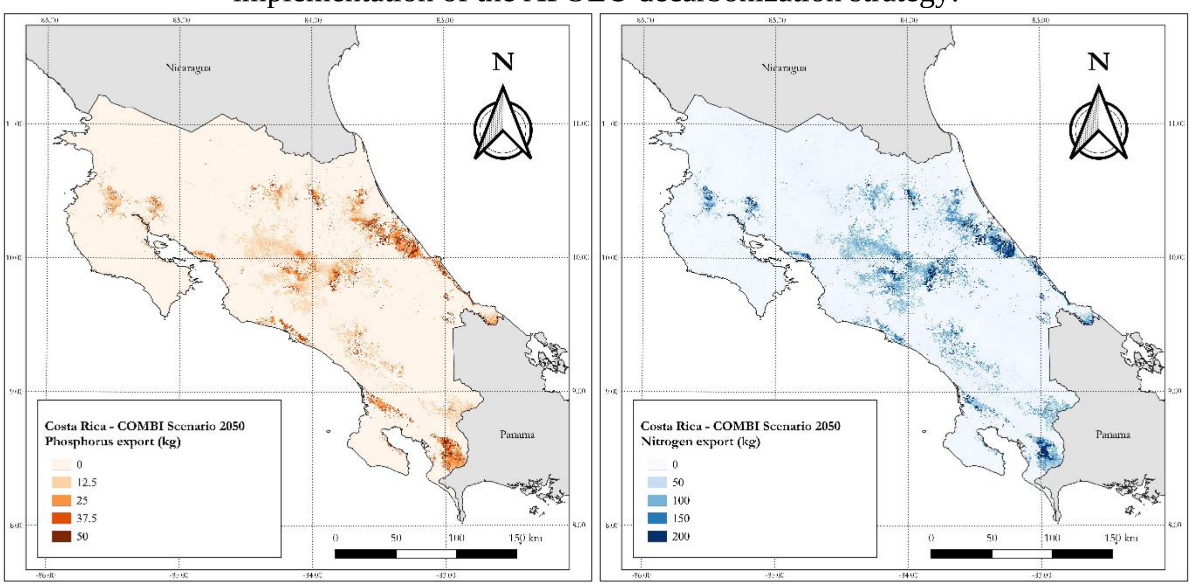
Source: IEEM+ESM results.

Figure 14. Carbon storage with full implementation of the AFOLU decarbonization strategy (left) and changes in carbon storage with full implementation of the decarbonization strategy with respect to business-as-usual (right) in 2050.



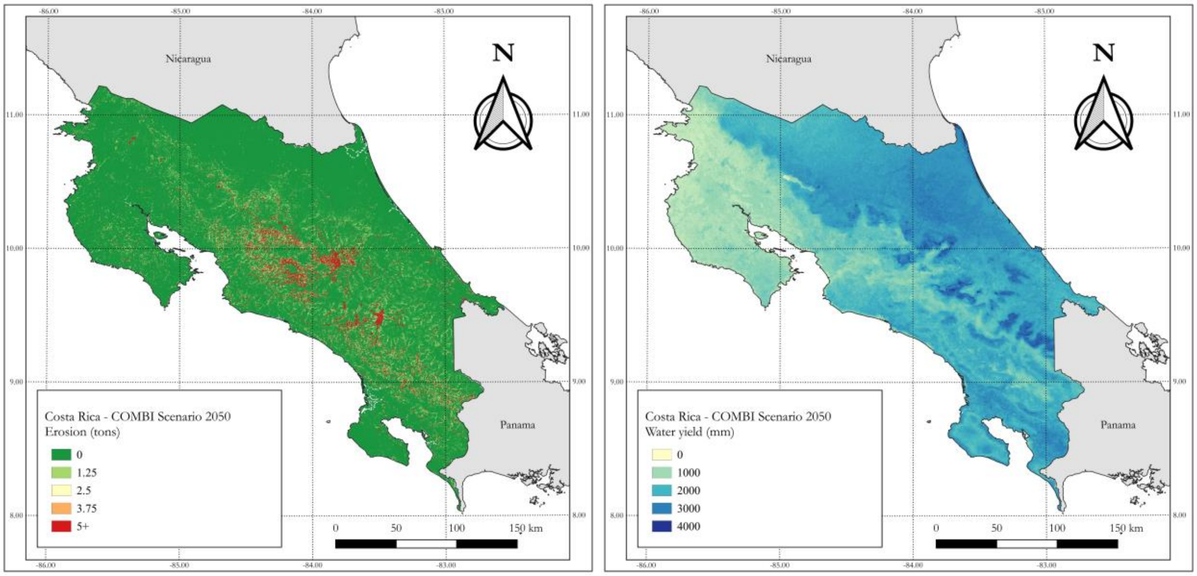
Source: IEEM+ESM results.

Figure 15. Nutrient export for phosphorous (left) and nitrogen (right) in 2050 with the full implementation of the AFOLU decarbonization strategy.



Source: IEEM+ESM results.

Figure 16. The impact of the full AFOLU decarbonization strategy on erosion mitigation (left) and water yield (right) in 2050.

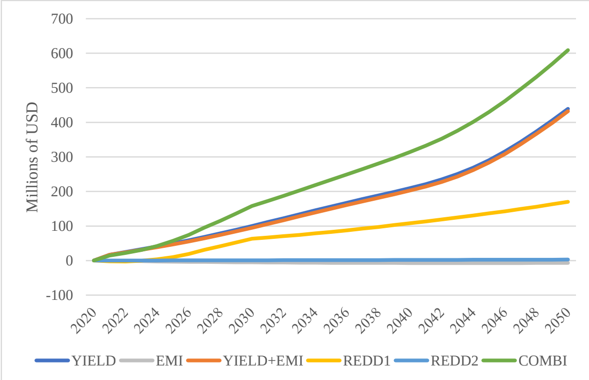


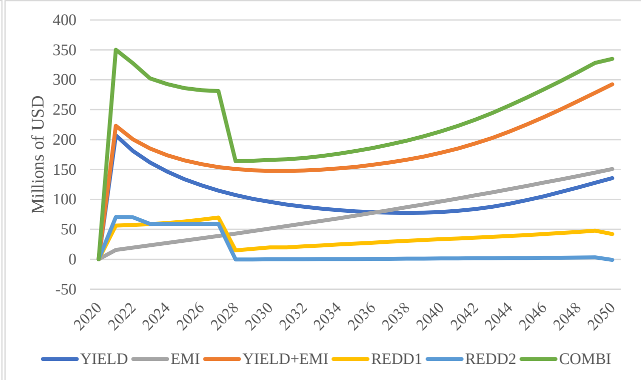
Source: IEEM+ESM results.

The potential spatial distribution of erosion mitigation ecosystem services with the full implementation of the AFOLU decarbonization strategy is shown in Figure 16 (left; note the map shows erosion in the COMBI scenario and not as a difference from BASE), where as noted in table 8, erosion mitigation ecosystem services would be enhanced across the Costa Rican territory, while there would be small changes in water yield (Figure 16, right).

Figure 17 presents the scenario impacts on the trajectory of GDP and wealth, which would be generally smooth and increasing with the exception of the EMI and REDD2 scenarios. There would be a somewhat abrupt increase in wealth in the YIELD scenario and in the YIELD+EMI scenario, which also carries over into the full implementation of the decarbonization of AFOLU. The emissions reduction scenario has a small impact on GDP and is related to the costs of the agricultural practices implemented while the small impact of the REDD2 scenario is a function of the small size of forest plantations established. With Gross National Savings as the main component of wealth, government savings would increase in these scenarios with the investment financed through an increase in domestic debt and the direct tax rate. Note that the increases in crop yields (Figure 8) and investment would increase at a decreasing rate which contributes to explaining the trajectory of GDP and wealth.

Figure 17. Scenario impacts on GDP (left) and wealth (right) as difference from business-as-usual in millions of USD.

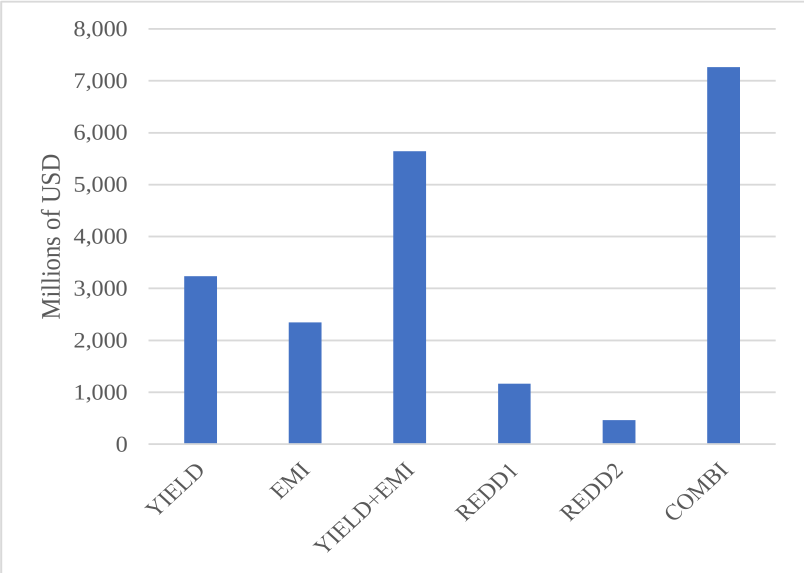




Source: IEEM+ESM results.

Cumulative impacts on wealth would be largely driven by improvements in environmental quality and increased household savings generated by increased agricultural productivity (Figure 18). Emissions reductions alone would boost wealth by US$2,345 million. The increase in planted trees through agroforestry and silvopastoral systems would generate an additional US$1,163 million 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 US$7,267 million.

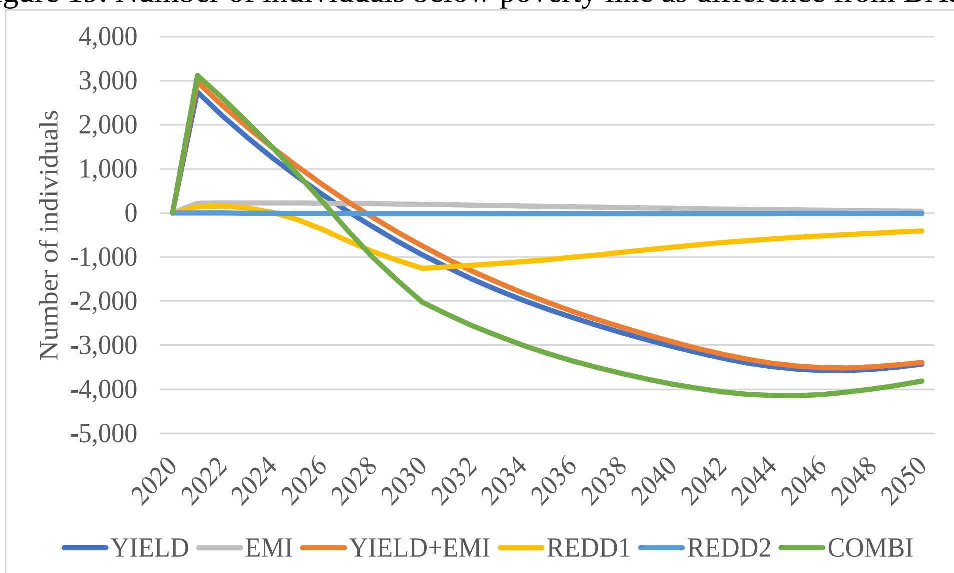
Figure 18. Cumulative wealth as difference from business-as-usual in 2050 in millions of USD.



Source: IEEM+ESM results.

In terms of poverty impacts, the YIELD scenario would generate an initial increase in the first few years with 2,744 more poor than in the business-as-usual case in 2021. This initial spike in poverty in 2021 is the consequence of the increase in direct household taxation that would be required to finance the investment, which affects the poor disproportionately since the same average tax rate is applied across household income classes. Poverty then would tend to fall steadily thereafter, by 3,430 compared with business-as-usual. The full strategy for the decarbonization of AFOLU sectors would have the largest poverty-reducing effect, reducing poverty by 3,810 individuals in 2050.

Figure 19. Number of individuals below poverty line as difference from BASE.



Source: IEEM+ESM results.

Table 9 shows scenario impacts on average growth rates of aggregate economic sectors over the 2020 to 2050 period, compared with business-as-usual growth. Impacts on growth rates would be small given the size of the shocks themselves. Focusing on the improved productivity scenario, crop and livestock output would grow faster than in the business-as-usual case, by 0.39% and 0.05%, respectively, on average over the period of analysis. There would be slightly slower growth in forestry and manufacturing, with the remaining sectors slightly stimulated, growing more quickly than they would in the busines-as-usual-case.

With the implementation of agroforestry and silvopastoral systems, there would be slightly slower

growth in crop and livestock activity (0.05% and 0.02%, respectively), as well as processed food (0.01%). Through increasing forest plantations, forestry activities would grow quicker than in the business-as-usual case as would be expected with the establishment of new forest plantations (0.07%). The full implementation of the AFOLU decarbonization strategy would result in more rapid growth across economic sectors in the country with the exception of slightly slower growth in manufacturing (0.04%). Slower growth of some sectors is due to factor reallocation arising from the implementation of the scenarios. The crops and livestock sectors would grow more quickly over the period on average at 0.29% and 0.04%, respectively Other sectors that would grow more rapidly include forestry (0.15%) other agriculture and fisheries (0.04%) and processed food (0.06%), all with respect to the business-as-usual case.

Table 9. Scenario impacts on average sector growth rate, as different from BASE in percent.

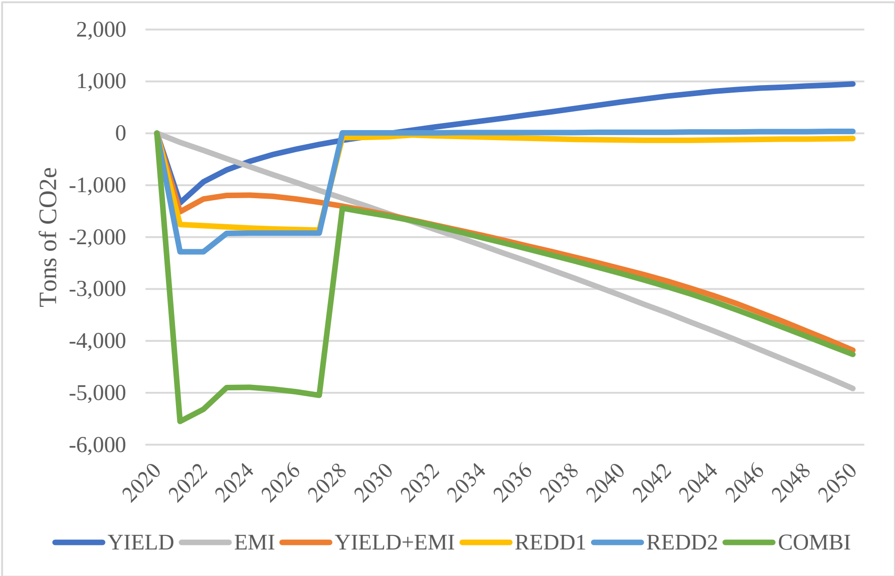
	YIELD	EMI	YIELD+EMI	REDD1	REDD2	COMBI
Crops	0.39	0.00	0.39	-0.05	0.00	0.29
Livestock	0.05	0.00	0.05	-0.02	0.00	0.04
Other agri+fish	0.04	0.00	0.04	-0.01	0.00	0.04
Forestry	-0.04	0.00	-0.04	0.15	0.07	0.15
Mining	0.01	0.00	0.01	0.01	0.00	0.02
Food	0.07	0.00	0.07	-0.01	0.00	0.06
Manufacturing	-0.06	0.00	-0.06	0.02	0.00	-0.04
Utilities	0.01	0.00	0.00	0.00	0.00	0.01
Construction	0.02	0.00	0.02	0.00	0.00	0.02
Trade	0.02	0.00	0.02	0.00	0.00	0.02
Hotel + restaurants	0.01	0.00	0.01	0.00	0.00	0.02
Transportation	0.00	0.00	0.00	0.01	0.00	0.01
Other services	0.00	0.00	0.00	0.00	0.00	0.00

Source: IEEM+ESM results.

Figure 20 shows the scenario impacts on CO_2 equivalent as a difference from business-as-usual. Emissions would grow faster in the enhanced productivity scenario due to the increased rates of economic growth across most sectors (Table 9), by 950 tons CO_2e in 2050. Note that these emissions include emissions from energy consumption as well as LULC change. By 2050, emissions would fall by 4,9194 tons in the emission reduction scenario, while the joint impact of enhanced productivity and emissions reductions is 4,180 tons CO_2e by 2050. Increasing agroforestry and silvopastoral systems, and increasing forest plantations, would have modest impacts on the order of a 103 ton decrease and 36 ton increase by 2050, respectively. The overall

impact of the full decarbonization of AFOLU would reduce emissions by 4,263 tons CO_2e, when compared with business-as-usual in 2050.

Figure 20. Scenario impacts on annual CO_2 emissions equivalent as difference from BASE in tons.



Source: IEEM+ESM results.

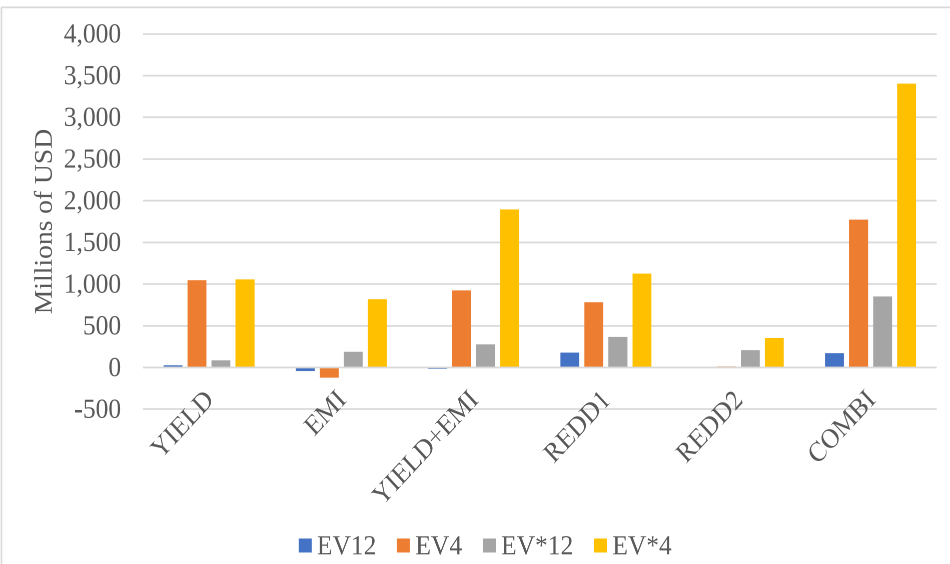
Calculating the Net Present Value (NPV) in a cost-benefit analytical framework is a standard approach to assessing the economic viability of projects and is used by governments around the world. NPV is calculated here with a 12% discount rate which is used by some multi-lateral investment banks. A 4% discount rate is also applied and can be considered more appropriate for investments in sustainable economic development that require longer periods to generate market and non-market returns. 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 et al., 2019c).

Figure 21 shows that when we consider household welfare alone and a discount rate of 12%, the productivity enhancement scenario would generate an NPV of US$27 million. Considering changes in environmental quality and natural capital stocks, the returns would be higher, approximately US$86 million. The emissions reduction scenario would generate a negative

economic return (US$44 million), however when the environment and natural capital stocks are integrated in the analysis, it would generate a strong positive return of US$187 million.

The productivity enhancement scenario coupled with reduced emissions would yield a negative return of US$17 million when based on standard measures of well-being. On the other hand, when environmental impacts are considered, the returns would be positive and on the order of US$276 million. The expansion of agroforestry and silvopastoral activities would generate strong returns of US$178 million from the conventional perspective and even greater returns on the order 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 to the investment when environmental variables are considered, and US$172 million when they are not.

Figure 21. NPV calculated based on equivalent variation (EV below) and equivalent variation adjusted (EV adjusted) for changes in natural capital stocks and environmental quality in millions of USD.



Source: IEEM+ESM results.

5.0. Discussion and conclusions

In 2016, 38% of net CO_2 emissions were linked to AFOLU and thus decarbonization of AFOLU sectors is critical to Costa Rica's ambitions of reaching zero net emissions by 2050. In this paper,

we applied the IEEM+ESM approach to evaluating decarbonization strategies for AFOLU, specifically, investments in: enhancing agricultural productivity to increase output; implementing agricultural practices to reduce emissions; expanding agroforestry and silvopastoral systems to improve productivity and increase carbon stocks, and; establishing new forest plantations for the production of fiber and carbon storage.

Results show that strategies to reduce emissions alone would have a small negative impact on GDP growth and thus 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 GDP growth would be positive (US$432 million). Agricultural technologies that improve environmental quality and reduce emissions generate gains in wealth. Expanding agroforestry and silvopastoral systems in Costa Rica would be positive in terms of both the income growth reflected by GDP, but also in terms of wealth.

Indeed, full implementation of the decarbonization strategy for AFOLU would be strongly positive. GDP in 2050 as a difference from business-as-usual would reach US$609 million while wealth would be enhanced by US$335 million. The wealth gains of decarbonization would be driven by improvements in environmental quality and increased household savings. Emissions reductions alone would boost cumulative wealth by US$2,345 million by 2050. Implementation of forest plantations, and agroforestry and silvopastoral systems, all would affect wealth positively, though in a modest way compared with the increase in wealth that would be attributable to emissions reductions. The full strategy for decarbonization of AFOLU would enhance cumulative wealth in Costa Rica by US$87,267 million by 2050.

Investment in agricultural productivity alone, and coupled with emissions reducing agricultural practices, would have positive impacts across ecosystem services provision. Increasing implementation of agroforestry and silvopastoral systems would tend to enhance soil erosion mitigation services and improve water quality. The full implementation of the AFOLU decarbonization strategy overall would enhance ecosystem services across those services considered in this analysis.

The decarbonization strategy for AFOLU sectors taken as a whole would be poverty reducing, with 3,810 less poor people in 2050. This may not be the case with some other lines of action of Costa Rica's Decarbonization Plan where there may be important trade-offs to consider, as well as the burden of the costs of adjustment to a low emissions future.

Impacts on emissions are affected differently across scenarios. Emissions would grow faster in the enhanced productivity scenario due to the increased rates of economic growth across most sectors. The good news is that the joint impact of investments in enhanced productivity and emissions reductions would tend to reduce emissions overall, and on the order of 4,919 tons CO2e 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 tons CO2e, when compared with business-as-usual in 2050.

Decarbonization of the AFOLU sectors requires strong political will as well as both public and private investment. Our analysis is explicit about the investment costs involved in achieving decarbonization targets. We have also considered different ways in which the public investment component may be financed. Most governments implement cost benefit analysis in assessing the economic viability of policy proposals. Cost benefit analysis is also standard practice of multi-lateral investment banks in assessing whether a loan makes sense from the perspective of the responsible allocation of investment resources.

Our investment analysis goes beyond the conventional by integrating natural capital and environmental quality benefits in a way that is consistent with economic reporting implemented by most countries in the world through the System of National Accounts. We find that investment in agricultural productivity alone is not economically viable when considering trade-offs in environmental quality. Allocation of resources towards emissions reductions is a sound investment, however, when considering both economic and environmental variables. The full implementation of the decarbonization of AFOLU sectors generates US$852 million in returns to the investment when environmental variables are considered and US$3,405 million when a lower discount rate of 4% is considered.

This analysis has shown quantitatively the economic, natural capital and ecosystem service benefits and costs of implementing various lines of action of Costa Rica's 2050 Decarbonization Plan. The analysis has highlighted that there are some trade-offs involved when considering specific lines of action independently. Taken as a whole, the full decarbonization strategy for AFOLU sectors proposed by Costa Rica enhances economic growth and wealth, reduces poverty, and enhances natural capital and ecosystem services supply. The cost benefit investment analysis makes an unequivocal business case for investing in the decarbonization of AFOLU sectors. These findings should contribute to rallying additional political will and public and private sector investment for moving boldly and quickly toward decarbonization and set Costa Rica as an example worldwide of how economic, environmental and social objectives can be reconciled in achieving a more sustainable future.

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Supplementary Information 1

Table SI 1. Baseline emissions (E) for IEEM classes.

IEEM Class	Total Emissions [Ton CO2e]	P Production [Ton]	A Area harvested [ha]	Sources for A &P	E1 Emissions factor [kg CO2e/kg]	E2 Emissions factor [ton CO2e/ha]	Sources for E	Year
Frijol	7,999	16,899	22,020	FAO (2020)	0.47333		(Clune et al., 2017) Table 5	2016
Maíz	6,011	9,542	4,910	FAO (2020)	0.63000		Ibid., Table 5	2016
Legumbres y otras semillas oleaginosas	40,459	61,301	5,860	FAO (2020)	0.66000		Ibid., Table 4	2016
Arroz	745,834	204,338	48,214	FAO (2020)	3.65		Ibid., Table 4	2016
Sandía	32,939	102,934	2,448	FAO (2020)	0.32000		Ibid., Table 5	2016
Melón	169,044	150,261	5,163	FAO (2020)	1.12500		Ibid., Table 5	2016
Cebolla	6,350	35,277	1,294	FAO (2020)	0.18000		Ibid., Table 5	2016
Chayote	675	1,607	177	FAO (2020)	0.42000		Ibid., Table 5	2016
Papa	19,596	97,979	3,967	FAO (2020)	0.20000		Ibid., Table 5	2016
Raíces y tubérculos n.c.p.	2,940	13,999	1,257	FAO (2020)	0.21000		Ibid., Table 6	2016
Hortalizas n.c.p.	21,338	45,401	2,963	FAO (2020)	0.47000		Ibid., Table 6	2016

IEEM Class	Total Emissions [Ton CO2e]	P Production [Ton]	A Area harvested [ha]	Sources for A &P	E1 Emissions factor [kg CO2e/kg]	E2 Emissions factor [ton CO2e/ha]	Sources for E	Year
Caña de azúcar	99,801	4,158,370	65,485	FAO (2020)	0.024		IMN, 2020, page 6and (Yuttitham et al., 2011), Table 1	2016
Flores	23,100	110,000	10,000	FAO (2020)	0.21000		(Clune et al., 2017), Table 6	2016
Follajes	464	1,222	1,060	FAO (2020)	0.38000		Ibid., Table 6	2016
Plátano	73,814	2,460,470	47,110	FAO (2020)	0.03		IMN, 2020, page 6	2016
Piña	2,104,674	2,923,158	43,000	FAO (2020)	0.72000		Ibid., Table 5	2016
Palma aceitera	1,547,016	1,089,448	72,456	FAO (2020)	1.42000		Ibid., Table 6	2016
Café en fruta	234,085	102,669	84,133	FAO (2020)	2.28		IMN, 2020. Page 6	2016
Mango	6,939	49,920	6,240	FAO (2020)	0.13900		(Basset-Mens et al., 2016) Table 2.	2016
Naranja	80,799	230,855	23,000	FAO (2020)	0.35000		(Clune et al., 2017), Table 5	2016
Otros productos de plantas no perennes y perennes n.c.p.	94,267	197,073	12,937	FAO (2020)	0.47833		Ibid., Table 6	2016
Otras frutas, nueces y otros frutos oleaginosos	268,054	507,892	52,055	FAO (2020)	0.52778		Ibid., Table 6	2016
Plantas y raíces vivas	12,971	61,769	5,242	FAO (2020)	0.21000		Ibid., Table 6	2016

IEEM Class	Total Emissions [Ton CO2e]	P Production [Ton]	A Area harvested [ha]	Sources for A &P	E1 Emissions factor [kg CO2e/kg]	E2 Emissions factor [ton CO2e/ha]	Sources for E	Year
Ganado bovino	2,096,572	72,975		FAO (2020)	28.73000		Ibid., Table 4	2016
Ganado porcino	353,112	60,361		FAO (2020)	5.85000		Ibid., Table 7	2016
Pollo en pie	528,456	128,266		FAO (2020)	4.12000		Ibid., Table 7	2016
Otros animales vivos	419	15		FAO (2020)	27.91000		Ibid., Table 7	2016
Mandioca	20	93		FAO (2020)	0.21000		Ibid., Table 6	2016
Plantaciones forestales y bosques secundarios	- 1,843,708		918,483	FAO (2020)		- 2.00734	(Solera et al., no date), pages 35-37.	2016
Bosques primarios	- 160,030		2,215,543	FAO (2020)		- 0.07223	Ibid, pages 35-37.	2016

Supplementary Information 2
Land Use Land Cover Change Modeling

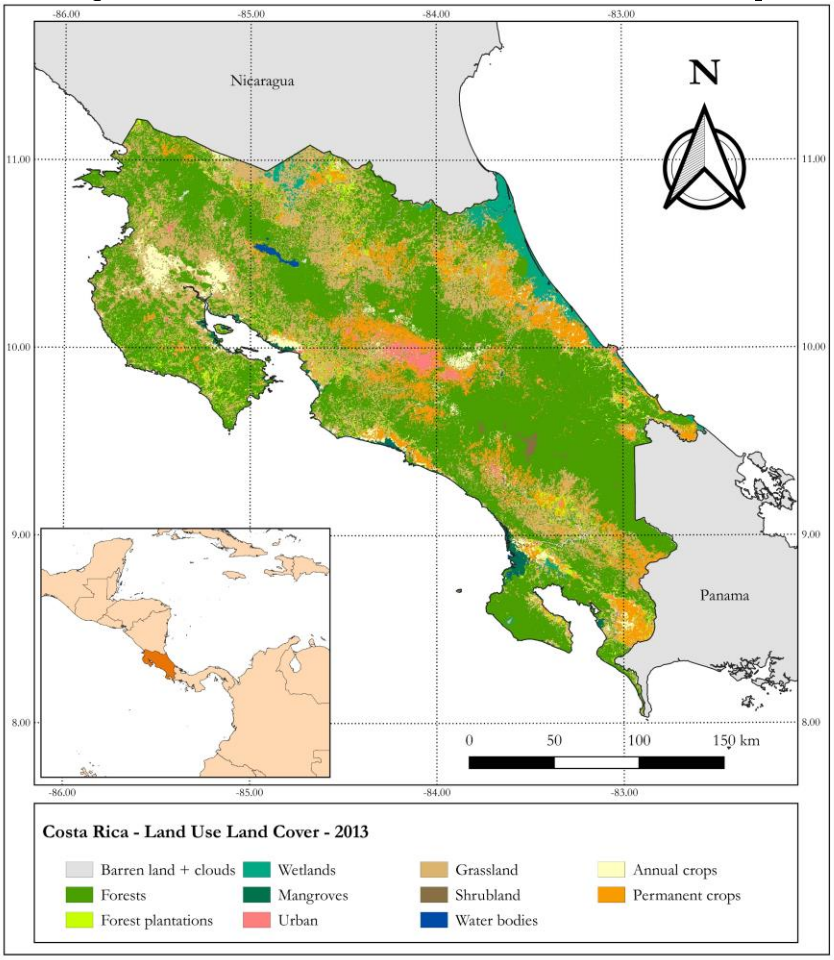
A. Steps for organizing data for implementation in Dyna-CLUE.

1. The basic data for the land modelling implementation is found in the form of raster maps which come from different sources and need a harmonization process that ensures consistency between layers. Setting up an analysis region begins with a LULC map which details different categories of land cover within a country/region. Since there is a tradeoff between resolution and computation times, a reprojection needs to be made so that the grid size is smaller than 1200 x 1200 cells (regardless of the area that those cells represent). In practice, for a small-to-medium country that means cell sizes of between 300m and 500m per side. The reprojection tool must be setup carefully so that cell size is enforced over map extent to prevent differences between sides of the cell (i.e. cells have to be perfectly squared)[8]. A projected coordinate reference system (CRS) in meters must be selected as a target projection (preferably equal area). This basic LULC map has to be checked for unintentional missing values that come from computation omissions at the source. These holes can be filled using different methods[9]. For the regression that we need to perform later in the analysis, each cell represents an observation that can be described by many factors. These factors come in the form of other raster maps that have to be perfectly aligned with the underlying LULC cells to eliminate any ambiguity that can result from having different cell sizes between layers.
2. National LULC maps can contain hundreds of land cover categories, according to the planning needs of a country. To focus the computation resources on those land changes that are of interest, a reclassification is conducted to aggregate categories. For example, a country might have a detailed disaggregation of types of forest, but for the study we might

[8] QGIS users can use the "Warp (Reproject)" tool and make sure to set the optional parameter "Output file resolution in target georeferenced units" to the selected cell size (e.g. 300m) and making sure that the target CRS parameter is set to a projected coordinate reference system in meters (i.e. not in degrees). As a cautionary note, we don't recommend reprojecting by simply exporting to a different file and choosing a target resolution, because that will result in a file with pixels with uneven sized cells. This happens because the method used by that tool enforces the extent over the resolution making slight adjustments of a few decimals per cell. This will cause problems when exporting to the ASCII files required by CLUE.
[9] QGIS users can use GDAL (Fill nodata) or r.fillnuls from the Processing Toolbox, making sure not to extend the boundaries of the country/region beyond the shorelines and its borders. The serval plugin can help make small changes by hand using satellite imagery from an online service underneath as visual reference.

be interested only on knowing if *any* type of forest will be converted to cropland so all types of forest are aggregated into two classes: forest or forest plantation. This aggregation will depend on the objectives of the analysis[10] and is shown in Table 10.

Figure 22. Costa Rica Base Land Use Land Cover Map



Source: IEEM+ESM results.

[10] QGIS users can select the "r.reclass" tool from the Processing Toolbox.

Table 10. Aggregated LULC categories for Costa Rica and number of hectares by category;

Label	Hectares
Barren land + clouds	35,163
Forest	2,756,961
Forest Plantation	167,724
Wetlands	136,656
Mangroves	49,311
Urban	89,676
Grassland	1,169,028
Shrubland	10,449
Water	25,992
Annual crops	164,673
Perennial crops	509,004
Total	5,114,637

Source: IEEM+ESM results.

3. A computational region in CLUE is created by turning a LULC map into a binary map that has a value of 1 in those cells that have a land use value and "NULL" elsewhere. In practice, this map is created using a raster calculator tool and dividing the processed LULC map by itself. This is also known as a MASK.
4. As explained before, all characteristics that will describe each cell need to be aligned to the LULC map perfectly. This is accomplished by multiplying the MASK by each raster map that holds any these factors, while having the resulting map in the MASK's extent and cell size[11].
5. The multiplication of the previous step can result in "jagged" edges along shorelines and borders where the inner reprojection conducted by the raster calculator on the factor map drops those pixels that cannot be allocated to a single cell of the MASK layer. Since the regression explained below will drop any row where any factor is missing information, an additional step has to be conducted to fill those gaps and multiply back the resulting expanded map by the MASK once more. This is done by using any fill method of the GIS software.

[11] QGIS users must select the MASK layer within the raster calculator and choose the "Selected Layer Extent" parameter, making sure that the number of columns and rows is the same than that of the LULC map.

6. The previous step will also take care of gaps in layers different from the LULC raster that are product of omissions. However, researchers that might have reasons not to use the fill method, have to make sure that cells that are not NULL in the MASK or region file, are also not NULL in any given layer because otherwise CLUE will not run and display an error message. Note that NULL is the absence of data and does not equal zero. One workaround without using the fill method is setting all NULL cells from the data layer (e.g. preciptitation) to zero and then multiplying it with the MASK[12].
7. Land cover categories are viewed by CLUE as binary maps where, for each category, a single map is created with cells that have that category in the LULC map display the integer 1, cells that have other categories in the LULC map display 0 and all NULL cells from the LULC map display -9999. This is performed by creating each individual map with the raster calculator set to the value of that category[13]. These files are named as Cov1_*.0.tif where * stands for the number of land cover category in the original LULC map.
8. In the case of CLUE, all maps must be converted to the ASCII format. It is important that in this step, all NULL values are reclassified as the integer -9999[14] and named according to CLUE convention using the format Sc1gr*.fil.tif where * stands for the number of factor according to the analyst prescribed order.
9. The resulting maps can be understood as essentially different spreadsheet tabs of one workbook. The first tab will have the LULC map and each cell will have a number associated with the land cover category. The second tab will represent the values of a factor (for example, precipitation, elevation, distance of that cell to a market or to a road, etc.) and so on for each additional tab. For each cell of those spreadsheets we know the sizes of the cell sides and where in the world they are located (given the projection information).

[12] QGIS users can create a temporary layer to replace the holes in the raster with omissions with the tool r.null, setting to 0 the parameter "The value to replace the null value by [optional]" and then using the raster calculator to multiply the MASK by that temporary layer to remove the zeros outside the area of interest, but keep the zeros where the omissions were in the original raster. ArcGIS users can use the mosaic tool to combine a copy of the MASK file with the offending layer, setting the "Mosaic Operator" function to "Maximum".

[13] For example, if the forest category is identified with the integer 4, then QGIS users can create a map with the raster calculator, setting the formula to <LULC map> = 4 and saving the result as a TIFF file whose NULL values must be set to -9999 and the result saved to the ASCII format.

[14] QGIS users can conduct both of these actions using the r.null tool, and setting the optional parameter "The value to replace the null value by" to -9999, while selecting the "Save to file" option of the NullRaster parameter, choosing .asc as the target file format.

10. After all layers have been produced, they have to be converted to ASCII format, making sure that all layers have the same region data, -9999 as nodata (or NULL), the same origin X and Y values, the same cell size and the same number of NULL cells[15].
11. The next step is converting those maps into a format suitable to conduct a regression. In a regression file, the different explained and explanatory factors or variables are columns and each row represents an observation (a cell's geographic location and area). In our analogy each row would represent a spreadsheet position (for example C:12) and each column would represent the value of that same position in each tab (LULC category number for the first one, precipitation for the second one, elevation for the third one, etc.)[16].

C. Determining land suitability; regression analysis.

1. Through the regression we want to predict, using statistical estimation techniques, the land cover of a cell given certain characteristics (or factors). The selection of explanatory variables of the land cover of interest have to be supported by sound theoretical principles.
2. Biophysical factors dictate the ability and probability of some types of vegetation, plants, animal life and even artificial structures to be present in a given area. Socioeconomic factors increase or decrease the pressure to change from one land cover class to another.
3. In this case, explanatory factors are given by the values of the maps presented in the previous section and the explained variable value comes from the land cover category given by the LULC map. They are identified with the naming convention Sc1gr*.fil.
4. The estimation follows the specification $R_{ki} = a_k X_{1i} + b_k X_{2i} + \ldots + R$ where R is the presence or absence of a land cover class k (1 or 0) in a location i. X_1 and X_2 represent factors or explanatory characteristics. a and b are coefficients describing those factors. Because of the binary nature of the explained variable, a binomial logit form of this model is used.

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[15] QGIS users can use the "Translate (Convert Format)" tool from the raster menu and set it to .asc and the appropriate projection. R users can use the "raster" package to read TIF files (raster function) and write them as ASCII files (writeRaster function).

[16] CLUE has a tool to reformat ASCII map information into this column and row arrangement. This can also be perfomed using the "raster" package of the R software by turning each map into a vector column and then joining those vectors into a dataframe. This is particularly useful if the regression is conducted within R.

5. In practice, the file created with columns as factors or land cover dummy variables and rows as cell positions in space is used as the input file for the regression. The name of the variables follows the naming conventions of the file, and so columns will be named Cov1_1.0, Cov1_2.0, Cov1_3.0… for the explained variables (land cover categories) and Sc1gr0.fil, Sc1gr1.fil, Sc1gr2.fil… for the explanatory factors as shown in Table 11.

Table 11. Sample data extract for regression

cov1_8.0	cov1_9.0	region1.fil	sc1gr0.fil	sc1gr1.fil	sc1gr10.fil	sc1gr11.fil	sc1gr12.fil	…
0	0	0	115	1911	0.17	180.00	526.28	…
0	0	0	154	1860	0.17	180.00	756.01	…
0	0	0	154	1860	0.17	223.15	1011.36	…
0	0	0	140	2120	0.17	163.30	482.70	…
0	0	0	151	2076	0.17	180.00	773.69	…
0	0	0	151	2076	0.17	255.07	1067.05	…
0	0	0	151	2076	0.17	263.91	1361.32	…
0	0	0	198	2161	0.17	268.22	1657.38	…
0	0	0	198	2161	0.17	270.00	1953.18	…
0	0	0	198	2161	0.17	270.00	2249.00	…
0	0	0	140	2120	0.17	171.04	160.00	…
0	0	0	140	2120	0.17	90.00	130.38	…
0	0	0	140	2120	0.17	90.00	425.79	…
...	...	...	...	...	...	...	...	

Source: author’s own elaboration using R and RStudio (R Core Team, 2020).

6. The factors chosen for the exercise, based on sound principles, will dictate the possible variables that can be included as explanatory factors. The possible explained variables will be determined by the LULC categories to predict. Practitioners can aid this process by creating a double-entry matrix with the explained variables as rows and explanatory variables as columns and then identifying those combination of variables that will be chosen for each regression with 1’s as shown in Table 12.

Table 12. Sample selection of variables chosen to predict selected LULC categories

		Sc1gr0.fil	Sc1gr1.fil	Sc1gr2.fil	Sc1gr3.fil	Sc1gr4.fil
Code	LULC category	Accessibility in minutes	Annual precipitation	Clay percentage	Elevation	Organic carbon content percentage
Cov1_0.0	Barren land					
Cov1_1.0	Forest	1	1		1	1
Cov1_2.0	Forest Plantation	1	1	1	1	1
Cov1_3.0	Wetlands			1	1	1
Cov1_4.0	Mangroves		1			1

Source: author’s own elaboration.

7. From this, individual regressions are created for each LULC category. The specific construction of the regression will be dictated by the software used[17], but it will be in the general format Cov1_$*_1$.0 = Sc1gr$*_1$.fil + Sc1gr$*_2$.fil + Sc1gr$*_3$.fil …, using a logarithmic binomial regression with as many explanatory factors as selected in the complete version of Table 12. Statistically significant coefficients are transferred to the file “alloc1.reg” within the CLUE region with a specific format as shown in Figure 23, panel b). This is repeated for all LULC categories of relevance to the analysis.

[17] R users can use the function “**reg1** <- glm(formula = cov1_1.0 ~ Sc1gr0.fil + Sc1gr1.fil + Sc1gr3.fil + …, family = "binomial")”, making sure to load the stats package with the function “library(stats)”, attaching the regression file “attach(name_of_dataframe)” and then calling “summary(**reg1**)” to gauge the significance of variables. This will be followed with the display of results to be copied over to CLUE using the function “as.matrix(format(coef(**reg1**), scientific=F))” where reg1 is the object that will hold the regression information and can be named whatever is most descriptive to the researcher, for example reg1 for land use 1, reg2 for 2, etc.

Figure 23. Sample regression results from R and translation into CLUE format.

a) Regression results displayed in R for LULC category 4

```
Call:
glm(formula = cov1_4.0 ~ Sc1gr1.fil + Sc1gr4.fil + Sc1gr8.fil,
    family = "binomial")

Deviance Residuals:
    Min       1Q   Median       3Q      Max
-0.4382  -0.1566  -0.1302  -0.1096   8.4904

Coefficients:
              Estimate Std. Error z value Pr(>|z|)
(Intercept) -3.099e+00  6.025e-02 -51.428   <2e-16 ***
Sc1gr1.fil  -7.503e-04  2.344e-05 -32.004   <2e-16 ***
Sc1gr4.fil   6.753e-02  2.549e-03  26.493   <2e-16 ***
Sc1gr8.fil   5.728e-02  3.024e-02   1.894   0.0582 .
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

(Dispersion parameter for binomial family taken to be 1)

    Null deviance: 61769  on 568292  degrees of freedom
Residual deviance: 59299  on 568289  degrees of freedom
  (1514529 observations deleted due to missingness)
AIC: 59307
```

b) The same results transferred to CLUE format within the file “alloc1.reg”

```
4                            <-- Explained LULC category
     -3.0987419607           <-- Regression intercept
2                            <--No. of significant factors
     -0.0007503164 1         <--Factor coefficient / factor 1
      0.0675298470 4         <--Factor coefficient / factor 4
                                etc.
-
```

Source: author’s own elaboration.

D. Dyna-CLUE model set-up

1. To setup the model, the following questions must be answered:
    a. What is the extent of the study area to address?
    b. What are the land use types of interest (including only those for which information is available)?
    c. Which location factors affect each LULC category (regression)?
    d. Establish a method to determine change in area by category (for example, a CGE model that output changes to the land factor).
    e. Are spatial policies to be considered (for example, an enforced restriction to deforest protected areas)?
2. Once these questions are answered, they can be fed into CLUE through a demand file. This is simply a text file in the form of a tab delimited data frame that has the different LULC categories as columns and the modeled demand for land of that type for each year of the modelling period, according to the instrument used to answer question d. in the previous paragraph using the naming convention demand.in* where * is a number identifying the scenario number.

Figure 24. Example of a demand scenario text file demand1.fil

```
25
35163	2756961 167724	136656	49311	89676	1169028 10449	25992	164673	509004
35163	2760801 168704	136656	49311	89676	1167097 10449	25992	163967	506821
35163	2764641 169685	136656	49311	89676	1165166 10449	25992	163260	504638
35163	2768481 170665	136656	49311	89676	1163235 10449	25992	162554	502454
35163	2772321 171646	136656	49311	89676	1161304 10449	25992	161848	500271
35163	2775746 172588	136656	49311	89676	1159909 10449	25992	161121	498026
35163	2778773 173492	136656	49311	89676	1158894 10449	25992	160409	495823
35163	2781416 174360	136656	49311	89676	1158123 10449	25992	159739	493752
35163	2783692 175193	136656	49311	89676	1157616 10449	25992	159103	491786
35163	2785616 175993	136656	49311	89676	1157395 10449	25992	158491	489896
35163	2787202 176761	136656	49311	89676	1157466 10449	25992	157898	488062
35163	2788466 177498	136656	49311	89676	1157843 10449	25992	157317	486265
35163	2789421 178206	136656	49311	89676	1158568 10449	25992	156733	484462
35163	2790080 178885	136656	49311	89676	1159656 10449	25992	156140	482628
35163	2790457 179537	136656	49311	89676	1161121 10449	25992	155530	480744
35163	2790563 180163	136656	49311	89676	1162978 10449	25992	154898	478788
35163	2790412 180764	136656	49311	89676	1165240 10449	25992	154235	476739
35163	2790013 181341	136656	49311	89676	1167923 10449	25992	153535	474577
35163	2789380 181895	136656	49311	89676	1171035 10449	25992	152794	472286
35163	2788521 182426	136656	49311	89676	1174581 10449	25992	152007	469855
35163	2787448 182936	136656	49311	89676	1178562 10449	25992	151172	467272
35163	2786169 183426	136656	49311	89676	1182973 10449	25992	150286	464535
35163	2784696 183897	136656	49311	89676	1187804 10449	25992	149351	461643
35163	2783036 184348	136656	49311	89676	1193033 10449	25992	148368	458605
35163	2781198 184782	136656	49311	89676	1198628 10449	25992	147344	455439
```

Source: Open-IEEM + ESM data formatted according to Verburg et al. (2002).

3. In order to restrict LULC changes to those of interest, a transition matrix can be fed into CLUE through an allow.txt file, which is a text delimited square matrix with LULC categories on both axes. The integer 1 in any cell of the matrix represents the possibility of change from the LULC category in the rows to a LULC category in the columns. Zeros represent changes that are not possible. The rows and columns must have the categories ordered in the same sequence as the Cov1_*.0 binary map files explained before. Special care has to be taken to ensure that those demands that will change in the modelled scenario have ones in this matrix. Otherwise CLUE will not run.

E. Dyna-CLUE model implementation

1. With all these files within the Dyna-CLUE analysis region folder, CLUE can be run from its graphical user interface or its command line form.

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