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Strategies for Green Growth: An Application of the IEEM+ESM Platform to Rwanda

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Integrated Economic-Environmental Modeling

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An Application of the IEEM+ESM Platform to Rwanda

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PREAMBLE: Development of an Integrated Economic-Environmental Modeling and Ecosystem Services (IEEM+ESM) Platform and its application to policy analysis is an intra-disciplinary pursuit. Beginning in 2016, the IEEM Team participated in a Science for Nature and People Partnership (SNAPP) which funds the creation of enabling conditions for multidisciplinary teams to convene around a specific global challenge at the intersection of conservation and human well-being. This Policy Brief describes one of the key outputs of a SNAPP-funded collaboration: the development of an IEEM Platform for Rwanda and its application to green growth strategies to enhance economic development and well-being.

1. Introduction

In the last decade, Rwanda has made important advances in reducing poverty (from 58.9% to 38.2% between 2000 to 2017) and inequality while enhancing productivity and economic growth [1, 2]. Nonetheless, with the highest population density in Africa and its population projected to double by 2050, the challenge of sustainable development with increasing pressures on Rwanda's natural capital base poses formidable challenges. For instance, ecosystem services such as erosion mitigation, climate change mitigation and water provisioning services declined substantially from 1990 to 2015, with the largest declines occurring from 1990 to 2000 and 2010 to 2015 [3, 4]. To address these challenges, Rwanda has made a strong commitment to green growth, which is embodied in its Green Growth Strategy [5].

Green growth operationalizes the concept of sustainable development and is defined as growth that is efficient, clean and resilient; to address social dimensions of sustainable development, it should be inclusive [6]. By 2035, Rwanda aims to move from a subsistence agricultural economy to a knowledge-based economy and achieve middle-income status. Various planning tools guide this transformation including its Green Growth Strategy, Vision 2020 (with a transition toward the new Vision 2050), the Economic Development and Poverty Reduction Strategy, The National Strategy for Transformation, and Rwanda's commitment to the Sustainable Development Goals. The forestry and agricultural sectors are critical to this transformation for their role in supplying ecosystem services in the form of food, fuel and fiber, as well as through climate change mitigation.

With Rwanda's limited land base of 26,338 km^2 and increasing population pressure, the spatial configuration and dynamics of ecosystem services supply with respect to the location of beneficiaries requires careful consideration in the planning and implementation of economic development strategies [4]. Frequently, this spatial planning occurs either in a top-down manner or through participatory scenario development and analysis [7]. These approaches suffer from three main limitations: (i) scenario design and land allocation decisions typically lack a theoretical (e.g. economic) foundation; (ii) while these methods enable estimation of changes in ecosystem service supply, the economic consequences of these decisions elude these approaches, and; (iii) scenarios are usually based around notions of sustainability versus unchecked development that lack the specificity required for real policy and decision making. These economic considerations are critical to Ministries of Economics, Finance and Planning to inform allocation of scarce government budgets and revenue projections. This policy brief addresses this critical gap and develops an innovative methodology for development planning by integrating economic, environmental and ecosystem service models to inform decisions on the allocation of scarce resources to achieve complex development goals.

We develop an Integrated Economic-Environmental Modeling (IEEM) Platform for Rwanda [8-10] calibrated with the country's recently published natural capital accounts [4, 11, 12] and ecosystem service models (ESM) to explore the economic and environmental impacts of specific actions toward achieving green growth.

2. Fuel, Timber and Food Provisioning Ecosystem Services

2.1 Fuel and Timber

The forestry sector is critical to Rwandan livelihoods for the ecosystem services it provides and as the country's primary energy source (86% of total energy consumption). Landsat-derived land cover for 2015 estimated that 17.1% of Rwanda was forested [11]. This, however, contrasts with data from the Rwanda Ministry of Natural Resources (MINIRENA), which estimated forest cover at 28.8% of Rwanda, just over a third of which is natural forest with the remainder as forest plantations [13]. Forest plantations supply most of the fuelwood and timber used in the country and help offset pressures on natural forests [14]. With 29.5% of households connected to the electrical grid in 2017 [15], Rwanda's dependency on biomass for energy is not surprising. In 2016/2017, 97% of Rwandan homes used biomass as their main cooking fuel, with 79.9% using firewood and 17.4% using charcoal [16]. Fuelwood and charcoal demand is the main driver of deforestation in Rwanda [17]. In a business-as-usual scenario, fuelwood demand in 2020 is projected to reach 5.7 million tons [18].

To reduce pressure on natural forests and emissions from fuelwood and charcoal consumption, it is necessary to both expand forest plantations while increasing the use efficiency of fuelwood and charcoal. Rwanda's Green Growth and Climate Resilience Strategy and Economic Development and Poverty Reduction Strategy II (Republic of Rwanda, 2011) target the enhancement of fuelwood and charcoal consumption efficiency through more efficient cookstoves and charcoal kilns, while at the same time expanding forest plantations, renewing older plantations, and promoting agroforestry for the provision of multiple ecosystem services.

We focus on two specific measures of Rwanda's Green Growth Strategy aimed at achieving timber and fuel security, which are to: (i) increase forest cover to 30% of the total land area with forest plantations and increase agroforestry to 85% of all cultivated areas, and; (ii) support the adoption of more efficient cookstoves and charcoal kilns. Specifically, we simulate an increase in forest plantations by 110,400 ha by 2035 above the forest plantation coverage of 193,406 ha in 2014. In addition, agroforestry is implemented on 975,084 ha. Regarding energy efficiency, more efficient cookstoves and charcoal kilns are estimated to result in a 25% efficiency gain plus substantial health benefits from reduced fuelwood emissions within households [10, 17, 19, 20]. The total cost of achieving these targets is US$285,581,699 over a 14-year period [14].

2.2 Food and Food Security

Agriculture is the second largest component of Rwanda's economy, averaging around 32% of GDP over the last two decades [21]. Rainfed, small-scale farming is responsible for most agricultural output, and the sector as a whole provides 80% of total employment. Vision 2020 has set a number of targets for the agricultural sector, including 8.5% growth in total output while increasing efficiency and reducing employment in agriculture to 50% nationally, thereby freeing up workers for employment in other sectors of the economy.

In parallel, a key goal for the Government of Rwanda is to become food secure; in the next 5 years, it aims to achieve food security for 90% of the Rwandan population. To do so, the Government is focusing on increasing the productivity of staple crops by up to 28% through improved agricultural practices [22]. These practices include increasing soil conservation infrastructure with progressive and bench terraces, expanding irrigated agriculture from the current 28,796 ha to 94,269 ha (including 42,500 of irrigation in marshlands), and rehabilitating 20,000 ha of irrigation infrastructure. Irrigation opens up the possibility of planting more than one crop in the same year, increases resilience to weather variability and climate change, and can improve crop quality, timing and thus profitability.

Another line of action for meeting the food security target is to increase levels of organic and inorganic fertilizer application. In the short run, the Government plans to provide incentives for doubling inorganic fertilizer use from 20 to 45 kg/ha/yr [22, 23]. Fertilizer application is on the rise in Rwanda with application rates in the country's Crop Intensification Programme reaching 29 kg/ha/year in 2011/12, compared to an average of 4.2 kg/ha/year from 1998 to 2005. This has increased crop yields, especially for maize and wheat. Maize yields have more than tripled while wheat yields have increased by 2.5 times during the same period [23].

We focus on two specific measures of Rwanda's Green Growth Strategy aimed at achieving food security: to rehabilitate and expand irrigation areas and increase fertilizer use to 45 kg/ha/yr. The investment cost for achieving these targets is estimated at US$972.5 million.

3. Methodology: The IEEM+ESM Approach

The Integrated Economic-Environmental Modelling (IEEM) Platform was developed to fill an important gap in the economic development literature and practitioner's toolbox. At the core of IEEM is a future-looking computable general equilibrium (CGE) framework that enables the analysis of public policies and investments on standard economic indicators such as GDP, income and employment, but also on wealth and natural capital stocks, all in a quantitative, comprehensive and consistent framework. Indeed, IEEM generates indicators that enable countries to quantitatively assess alternative strategies to achieving green growth targets and sustainable economic development.

The IEEM Platform's main innovations include: (i) integration of rich environmental data based on the System of Environmental-Economic Accounting Central Framework [24] into an economy-wide model; (ii) IEEM's environmental modeling modules that capture the specific dynamics of each environmental asset. For example, the forest sector behaves very differently from a conventional manufacturing sector, where forests grow, and can be harvested, deforested, degraded or improved, all legally or illegally; and (iii) IEEM indicators that go beyond measures of income flows such as GDP to reflect impacts on the three dimensions of sustainable development, namely the economy, society and the environment, which are embodied in the concept of wealth [25-27].

We advance the IEEM Platform by integrating it with spatially explicit ecosystem service modeling (IEEM+ESM) to capture impacts on ecosystem services for which in many cases, markets do not yet exist. Many regulating ecosystem services (e.g., soil erosion and nutrient regulation, flood regulation, and natural pest control) provide benefits to people, though due to missing markets they lack a market price [28]. Where these services are not quantified or valued, they are most often not taken into account in decision making.

The incorporation of ecosystem services in IEEM+ESM responds to strong demand from policy and decision makers who are concerned with understanding the impacts of policy on these increasingly scarce nonmarket ecosystem services [29], many of which make critical contributions toward green growth. Furthermore, it is critical to understand the spatial dynamics of policy making on ecosystem services to enable development planning, particularly when land constraints are significant.

In the IEEM+ESM workflow (figure 1), a baseline (policy status quo) and set of policy scenarios are implemented in IEEM and results are generated in terms of economic impacts as well as LULC change for each scenario and period of analysis. LULC changes are the result of policy impacts on demand for different types of land, including agriculture, rangeland, managed natural forests and forest plantations. Based on IEEM results, new LULC maps for each scenario and period are developed.

Next, ecosystem service models are parameterized and run using various data sources, including LULC maps for current conditions and subsequent scenarios and periods for which IEEM was run. In this policy brief, our ESM focuses on climate change mitigation through carbon storage, water provisioning services quantified as annual

FIGURE 1. Integrated Economic-Environmental Modelling + Ecosystem Service Modeling (IEEM+ESM) workflow. ES: Ecosystem services; LULC: Land use-land cover.

Source: Authors' own elaboration.

water yield, quick flow and local recharge, erosion mitigation in terms of sediment retention and export, and soil fertility maintenance quantified as nitrogen and phosphorus load, export, and retention.

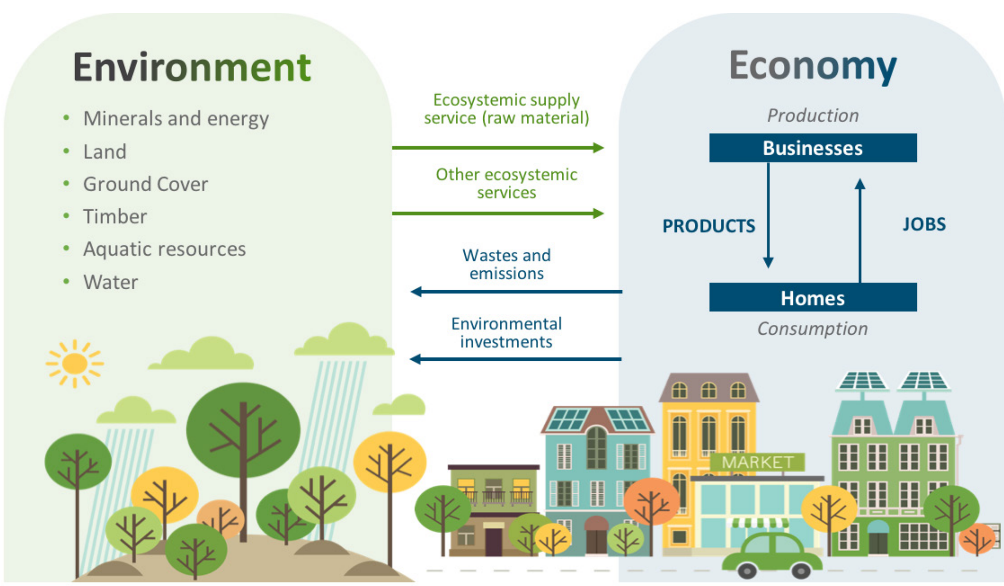
3.1 An IEEM Platform for Rwanda

The IEEM Platform's core is a dynamic CGE model, calibrated with data based on national data from the System of National Accounts [30] and the System of Environmental-Economic Accounts Central Framework (SEEA) [24]. CGE models are considered the 'work horse' of policy analysis [31] and indeed offer the only robust means of exploring policies that can have a wide reaching impact on multiple sectors of the economy [32-35]. With its integration of rich environmental data organized under the SEEA, IEEM lessens the need to make strong assumptions in reconciling environmental and economic data, reduces analytical start-up costs and increases the timeliness of evidence-based policy advice [9].

Figure 2 shows how environment-economy interactions are modeled within IEEM. On the left side of the figure, the environment is quantified using the SEEA, namely mineral and energy, land, soil, timber, fisheries and water accounts. On the right side of the figure is the economy, represented by firms that use labor, capital and other factors of production, and intermediate inputs to produce goods and services that are consumed by households, the government and exports markets. IEEM captures the two-way interactions between the economy and the environment, with the environment serving as an input for productive processes in the form of provisioning ecosystem services. Through economic activity and household consumption of goods and services, emissions and waste are generated and returned to the environment.

To calibrate IEEM, we constructed a Social Accounting Matrix (SAM) for Rwanda with a base year of 2014 [36-39]. IEEM has a modular structure whereby it can be calibrated with one or more natural capital accounts as they become available; we calibrated IEEM with Rwanda's

FIGURE 2. Environment-economy interactions embodied in IEEM.



Source: Authors' own elaboration.

new land and water accounts [11, 12]. Once IEEM has been calibrated, scenarios are designed and described quantitatively to evaluate public policy and investment alternatives. We developed a baseline (BASE) and five groups of policy scenarios simulating the expansion of forest plantations (FOR1 and FOR2), enhanced fuelwood efficiency (FUEL), irrigated agricultural expansion (IRRIG), crop fertilization (FERT), and the combined impacts of forest plantations, irrigated agricultural expansion and fertilization (COMBI1 and COMBI2).

3.2 Description of IEEM Scenarios

We implemented the following scenarios in IEEM:

BASE: The 'BASE' scenario is the baseline, business-as-usual scenario that projects current trends in the Rwandan economy forward from 2014 to 2035. BASE is the reference scenario to which all other scenarios are compared.

FOR1: The FOR1 scenario simulates an increase in the area of forest plantations of 110,400 ha above the BASE in 2035. Competition between land uses is accounted for.

FOR2: As in FOR1, the area of forest plantations in FOR2 is 110,400 ha greater than in BASE in 2035, with the difference being there is no competition between land uses.

FUEL: This scenario simulates the introduction of more efficient household cookstoves and charcoal kilns, which reduce fuelwood demand and improve household health by reducing exposure to smoke and particulates. Gains are modeled through a 25% increase in household fuelwood consumption efficiency [14] and a rural labor productivity increase [40-42] arising from better health.

IRRIG: In IRRIG, 85,473 ha of farmland currently cultivated without irrigation or with irrigation infrastructure in disrepair are brought into irrigated agricultural production. Irrigation will increase yields and crop values given quality improvements and seasonality of irrigated crops.

FERT: This scenario increases the area and quantity of fertilizer applied to all cropland to 45 kg/ha/yr.

COMBI1: This scenario is the joint implementation of FOR1, FUEL, IRRIG and FERT.

COMBI2: This final scenario is the same as COMBI1 but does not account for urban expansion.

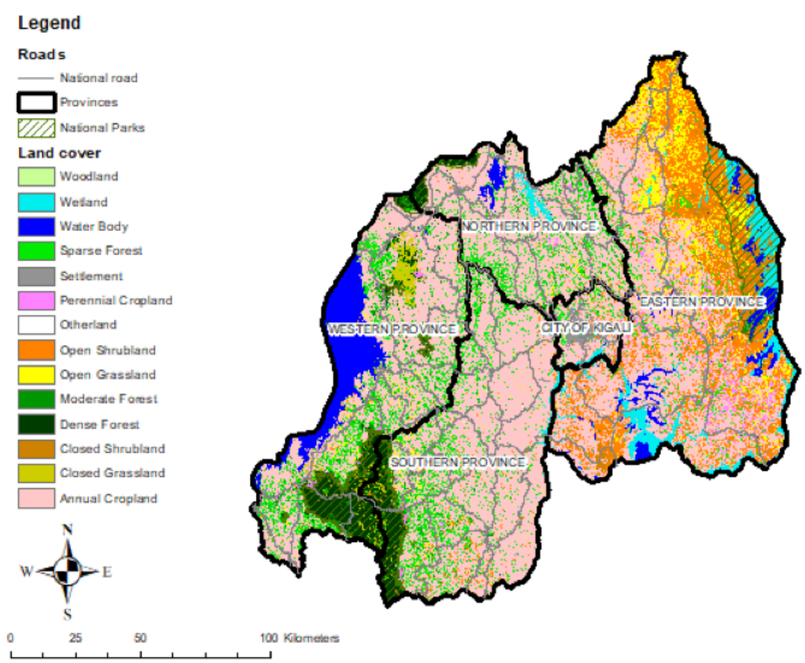
3.3 Land Use-Land Cover Change Model

The LULC Change Model provides the linkage between IEEM and ESM. It is used to spatially allocate LULC change numerically estimated by IEEM for each scenario and time step across the landscape. The third step therefore in the IEEM+ESM workflow (figure 1) is to develop a national LULC Change Model. The LULC Change Model was developed using the ArcGIS Model Builder and has three overall stages: (i) development of a geographic information system (GIS) for Rwanda; (ii) preparation of the initial LULC data layer based on IEEM scenarios, and; (iii) distribution of LULC change based on IEEM outputs according to predefined decision criteria. At the core of our LULC Change Model are decision criteria or land use allocation rules for spatially assigning IEEM LULC change across the LULC data layer. In doing so, our approach follows similar principles as other LULC change models, for example the Conversion of Land Use and its Effects (CLUE) model [43-46].

The spatial data we used in developing the GIS for Rwanda includes the 2015 LULC map, a digital elevation model, hydrography, Rwanda's Land Use Master Plan [47, 48], protected areas, political/provincial boundaries, and road access. The 2015 LULC map is the starting point for allocating scenario-based LULC change (figure 3). This map was developed through the SERVIR initiative using Landsat 7/8 imagery with 30-meter resolution through supervised classification.

Once the LULC Change Model is developed, the first step is to generate the baseline LULC projection to the year 2035, in 5-year increments (2020, 2025, 2030, 2035). Decision criteria for allocating LULC change in the BASE and in the scenarios were developed through expert

FIGURE 3. Land use-land cover map for Rwanda, 2015.



Source: Regional Centre for Mapping of Resources for Development (RCMRD), Rwanda Land Cover 2015 Scheme II

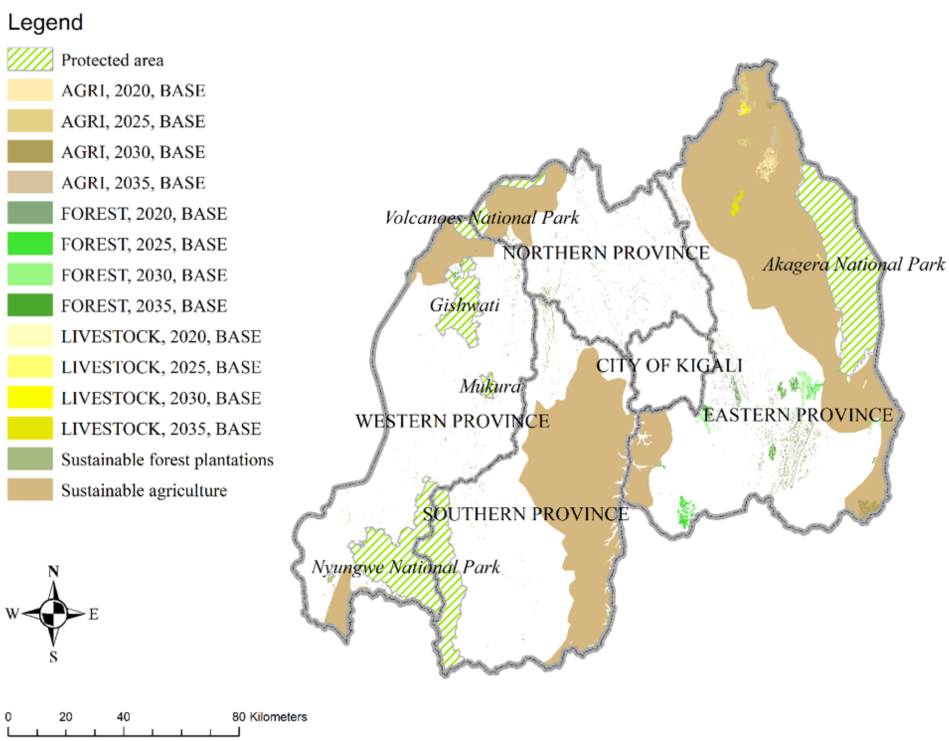
elicitation, including experts involved in implementing Rwanda's Land Use Master Plan.

Figure 4 shows the designated areas for sustainable agriculture and forestry activities in the Land Use Master Plan. Areas eligible for sustainable forest plantations are generally sparsely distributed throughout the country. Much of the areas eligible for sustainable agriculture are located adjacent to Akagera National Park in the Eastern Province, in the Southern Province and adjacent to Volcanoes National Park in the Northern and Western Provinces. Figure 4 also shows the baseline LULC projections in 5-year increments to 2035.

3.4 Ecosystem Service Modeling

We used the Integrated Valuation of Ecosystem Services Tradeoffs (InVEST) 3.3.3 modeling software [49] to quantify carbon storage, sediment regulation (sediment delivery ratio (SDR) model), nutrient regulation (nutrient delivery ratio (NDR) model), and annual and seasonal water yield in Rwanda for the year 2015 and in 5-year increments for BASE and the other seven scenarios. The scenarios substituted the following model inputs: (i) LULC data for the appropriate scenario and year; (ii) updated fertilizer application rates for the FERT and COMBI1/COMBI2 scenarios for the NDR model, and; (iii) updated estimates of the effects of terracing on soil erosion for the SDR model. Because of the uncertainty surrounding investment in terracing, which plays a key role in reducing soil erosion, we modeled SDR for all scenarios using two different assumptions: an aggressive terracing program proposed by Vision 2020, and a business-as-usual terracing program, which carried the observed terracing trends from 2010 to 2015 forward into future years. We used current precipitation and evapotranspiration data for

FIGURE 4. Rwanda Land Use Master Plan areas and conversion to agriculture and livestock in the baseline 5-year increments from 2020 to 2035.



Source: IEEM+ESM Platform results.

all scenarios, i.e., we did not include the potential effects of climate change in our ecosystem service models.

To enhance modeling efficiency, we used Mapping Ecosystem Services to Human well-being (MESH) 0.9.0, a graphical user interface-based tool to batch process InVEST models [50]. We used MESH to model carbon storage, SDR, NDR, and annual water yield (a MESH-compatible model for seasonal water yield was not available). We conducted our analysis at a 30-meter spatial resolution.

The InVEST annual water yield model uses the Budyko curve method to estimate actual evapotranspiration (AET), then subtracts AET from precipitation to estimate annual water yield. Its carbon storage model matches land cover to estimated carbon pools data using a look-up table. The seasonal water yield model quantifies two metrics: quick flow (runoff during and immediately after storm events), estimated using the Curve Number method, and; local recharge, calculated by subtracting AET and quick flow from precipitation. The SDR model calculates sediment retention and export with the universal soil loss equation, which is paired with a connectivity index to estimate sediment export. Finally, the NDR model uses estimates of nitrogen and phosphorus loading and potential nutrient uptake by land cover type, combined with the same connectivity index used in the SDR model to quantify actual nutrient uptake and export [49].

We summarized final results for all ecosystem service models at the national scale and for Rwanda's five provinces using ArcGIS.

4. Results

4.1 Economic Impacts

Table 1 presents scenario impacts on macroindicators for the Rwandan economy expressed as the difference from the BASE in 2035. FOR1 has a relatively small impact on GDP (US$28 million) when compared with the other scenarios while FERT makes the greatest individual contribution to all indicators. FOR1 also shows a small negative impact on private consumption, fixed investment as well as genuine savings. Increasing fertilization boosts GDP and genuine savings by US$2,781 and US$713 million, respectively. The joint impact of all scenarios represented by COMBI generates the largest gains with a US$3,591 million boost to GDP and a US$763 million increase in genuine savings.

Evaluating time trends through to 2035, the FERT and COMBI scenarios show considerably greater GDP (Figure 5, Panel A) and genuine savings impacts (Panel B) and a strong reduction in poverty (Panel C). FOR1 shows a small (0.1%) increase in poverty by 2035.

Table 2 summarizes results in terms percent difference from the BASE in 2035. All scenarios result in faster export growth, from 0.8% in IRRIG, to 16.4% in COMBI1, which is heavily driven by the FERT component. Imports are less responsive with changes ranging from 0.1% in IRRIG to 5.7% in COMBI1. Scenarios result in faster private investment growth, up to 6.77% in COMBI1, and greater indirect government tax revenues across scenarios (9.8% in COMBI1). FERT causes a 7.0% appreciation of the real exchange rate. Wages grow in the case of IRRIG and most markedly in FERT (11.0%). Unemployment increases by 2.2% in FOR1, by 1.3% in FUEL and less in FOR1 (0.3%). The FERT scenario is strongly poverty reducing, by 17.5% in FERT.

Table 2 also reports sector activity, showing Agricultural activity growing across scenarios with the exception of FOR1, but growing by 23.6% in FERT. Livestock activity is stimulated with the exception of FOR1, growing by 8.7% in FERT and 7.7% in COMBI1. Forestry activity registers positively in FOR1 and FOR2 increasing by 2.6% and 2.2%, respectively, though declining in FUEL by 3.3%. On balance, the Forestry sector grows faster, by 2.2% in COMBI1. Manufacturing is positively impacted, up to 9.4% in FERT, as is the Services sector with an increase of 6.4% in COMBI1.

4.2. Natural Capital Impacts

Rwanda's natural capital accounts provide data on forest cover, land and water [11, 12]. In FOR1, agricultural and livestock land use decline by 25,377 ha and 2,284 ha, respectively while forest land use increases by 110,400 ha to meet the forest cover target, all in relation to BASE. FUEL land use changes little in relation to the BASE while in IRRIG, agricultural land use falls by 803 ha while livestock use increases by 828 ha. FERT land-use changes are

TABLE 1. Difference in macroeconomic indicators for baseline versus scenarios for 2035; millions of 2014 USD.

	FOR1	FOR2	FUEL	IRRIG	FERT	COMBI
Absorption	(25)	92	490	185	2,653	3,312
Private consumption	(5)	79	479	141	2,121	2,744
Fixed investment	(20)	12	11	44	532	567
Exports	72	47	165	43	596	886
Imports	19	22	94	13	467	607
GDP	28	116	561	215	2,781	3,591
Genuine savings	(34)	11	27	73	713	763

Source: IEEM+ESM Platform results.

FIGURE 5. Panel A: GDP impact; Panel B: Genuine savings. Difference from baseline in millions of USD (2014). Panel C: Poverty impact. Percent deviation from baseline.

Source: IEEM+ESM Platform results.

more pronounced, with a 10,039 ha decline in agricultural land use in relation to BASE while livestock land use increases by 10,376 ha (with no difference in forest land use). Finally, the COMBI scenarios result in a 35,836 ha decline in agricultural land use, a 8,593 ha increase in livestock and the target 110,400 ha increase in forest cover with respect to BASE. Table 2 reports these changes in land use as the percent difference from the BASE in 2035.

Water consumption increases markedly in the FERT and COMBI scenarios by over 7.23 and 7.20 million m3, respectively. There was reduced water consumption in FOR1 and FUEL (197,252 and 216,860 m3, respectively) and slightly increased water consumption in FOR2 and IRRIG (250,663 and 503,455 m3, respectively). Table 2 reports these changes in water consumption as the percent difference from the BASE in 2035.

4.3 Ecosystem Services Impacts

For carbon storage and water yield models that are driven by LULC change only, two groups of scenario results for 2015 to 2035 emerged–the FOR and COMBI scenarios that lead to increased carbon storage and slightly reduced water yield, and BASE, FERT, FUEL, and IRRIG, which had opposite trends (Figure 6 and 8). In the FOR and COMBI scenarios, quick flow was reduced, which typically benefits water quality, while local recharge, which is critical for maintaining dry-season flows, was increasing to stable (Figure 6 and 9).

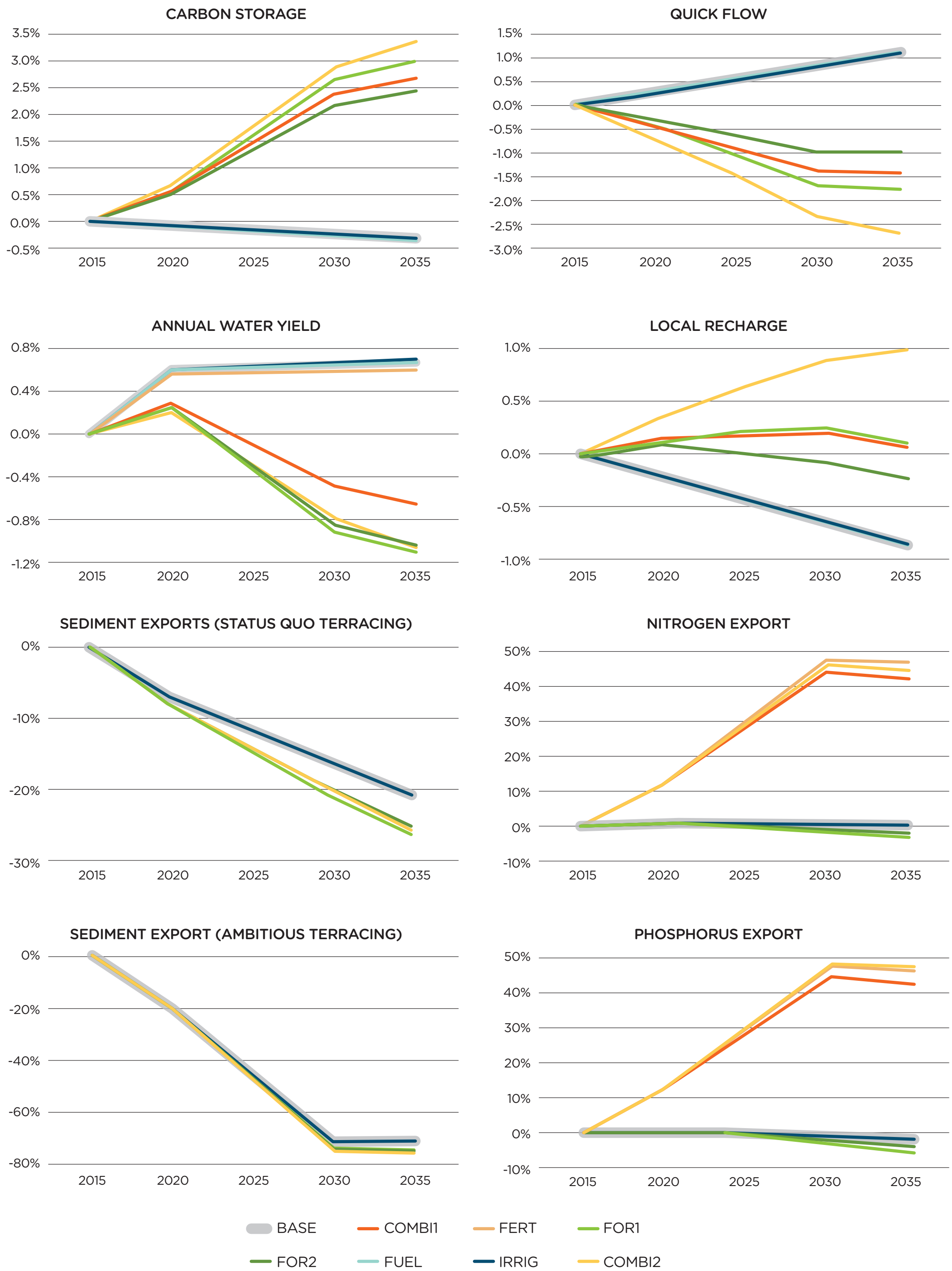
TABLE 2. Macroeconomic, SEEA and ecosystem services impacts expressed as average growth rates from 2015 to 2035.

			AVERAGE GROWTH						
		BASE	FOR1	FOR2	FUEL	IRRIG	FERT	COMBI1	COMBI2
Macroeconomic indicators (IEEM)	Absorption	7.18%	7.18%	7.20%	7.25%	7.21%	7.52%	7.60%	7.60%
	Private consumption	6.97%	6.97%	6.99%	7.07%	7.00%	7.38%	7.49%	7.49%
	Fixed investment	7.43%	7.42%	7.44%	7.44%	7.46%	7.75%	7.77%	7.77%
	Exports	8.24%	8.31%	8.28%	8.39%	8.28%	8.78%	9.02%	9.02%
	Imports	7.55%	7.56%	7.56%	7.60%	7.56%	7.77%	7.84%	7.84%
	GDP	7.23%	7.23%	7.24%	7.31%	7.26%	7.62%	7.74%	7.74%
	Genuine savings	7.59%	7.59%	7.63%	7.62%	7.66%	8.12%	8.20%	8.20%
	Indirect tax income	7.04%	7.04%	7.05%	7.10%	7.06%	7.42%	7.51%	7.51%
	Real exchange rate	-0.06%	-0.06%	-0.04%	-0.02%	0.00%	0.26%	0.34%	0.34%
	Wages	3.69%	3.61%	3.68%	3.65%	3.71%	4.20%	4.13%	4.13%
	Unemployment	7.70%	7.87%	7.73%	7.80%	7.67%	7.02%	7.23%	7.23%
	Poverty	-0.08%	-0.08%	-0.08%	-0.08%	-0.08%	-0.09%	-0.09%	-0.09%
	Sectoral activity-Agriculture	5.00%	4.92%	5.00%	5.01%	5.08%	6.07%	6.06%	6.06%
	Sectoral activity-Livestock	4.77%	4.69%	4.77%	4.78%	4.81%	5.19%	5.14%	5.14%
	Sectoral activity-Forestry	7.91%	8.05%	8.02%	7.74%	7.92%	8.06%	8.03%	8.03%
	Sectoral activity-Manufacturing	7.47%	7.49%	7.49%	7.55%	7.49%	7.93%	8.05%	8.05%
	Sectoral activity-Services	7.98%	7.99%	7.99%	8.01%	8.00%	8.22%	8.29%	8.29%
SEEA Central Framework: Land & water-use change	Agricultural land use	0.04%	-0.05%	0.04%	0.04%	0.04%	0.01%	-0.09%	-0.09%
	Livestock land use	0.10%	0.01%	0.10%	0.10%	0.13%	0.49%	0.43%	0.43%
	Forestry land use	0.35%	2.42%	2.42%	0.35%	0.35%	0.35%	2.42%	2.42%
	Water use	5.75%	5.73%	5.78%	5.73%	5.81%	6.49%	6.49%	6.49%
Ecosystem services	Carbon storage	-0.3%	3.3%	2.8%	-0.0%	0.0%	-0.0%	3.0%	3.7%
	Annual water yield	0.7%	-1.8%	-1.7%	-0.0%	0.0%	-0.1%	-1.3%	-1.7%
	Quick flow	1.1%	-2.9%	-2.1%	0.0%	-0.0%	0.0%	-2.5%	-3.8%
	Local recharge	-0.8%	0.9%	0.6%	0.0%	0.0%	0.0%	0.9%	1.8%
	Sediment export*	-20.9%	0.2%	0.1%	-0.0%	-0.0%	0.0%	0.2%	0.2%
	Nitrogen export*	-0.0%	-3.4%	-2.5%	-0.0%	-0.0%	47.1%	42.4%	44.9%
	Phosphorus export*	-2.1%	-3.1%	-2.2%	-0.0%	-0.0%	49.7%	45.2%	50.1%

*Negative values (i.e., reductions) are beneficial for these indicators

Source: IEEM+ESM results.

FIGURE 6. Scenario land use. Difference from BASE in hectares.



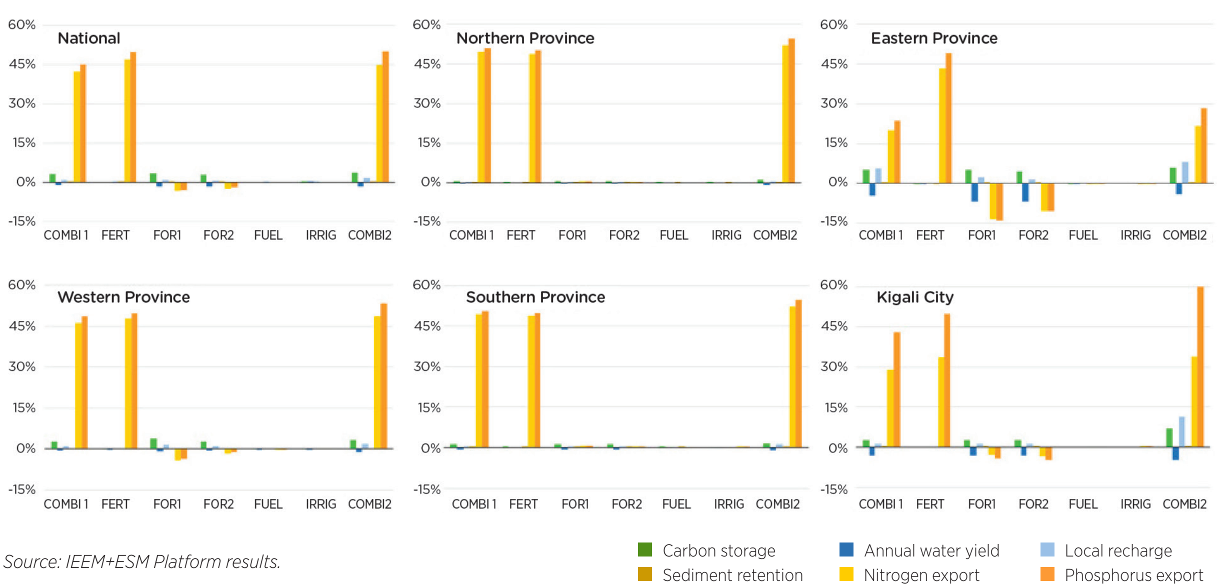
Source: IEEM+ESM Platform results.

The FOR and COMBI scenarios also led to larger reductions in sediment export, though improvements in terracing yielded large reductions in erosion across all scenarios. These reductions varied depending on the assumptions about future rates of terracing. Nitrogen and phosphorus export by 2035 increased by about 47% in the FERT scenario, 45-47% in COMBI2, and 42% in COMBI1. Very slight decreases for nitrogen and phosphorus export (up to 2%) were observed in BASE, FUEL, and IRRIG. Both FOR scenarios had reductions of nitrogen export of about 3% and phosphorus export of 4-5%.

In evaluating ecosystem service changes relative to BASE (which produces declines in carbon storage, local recharge, sediment and nutrient export), differences for the FUEL and IRRIG scenarios are negligible (Figure 7). Differences between BASE and FERT are notable for increasing nitrogen and phosphorus export but have minimal differences between other ecosystem services. The FOR scenarios provide various improvements in ecosystem services relative to BASE, including carbon storage, local recharge, and reduced nutrient export, which are most pronounced in the Eastern Province (where greater reforestation takes place) and to a lesser degree in the Western Province and Kigali City.

At the provincial scale, results for the Western Province are quite similar to the national level; the Northern and Southern provinces have relatively little change except for increases in nutrient export under FERT and COMBI scenarios. Different patterns emerge for Kigali City and the Eastern Province, however. For Kigali City, COMBI2 had the greatest phosphorus export, and relatively large gains in local recharge and carbon storage. This result is largely due to less cropland loss and the increase in impervious urban areas than scenarios with urban growth. For the Eastern Province, nutrient export was substantially greater under the FERT scenario than the COMBI scenarios. While both substantially increased the application of nutrients to croplands, forest expansion in the COMBI scenarios was enough to retain about 83% of the additional nitrogen and phosphorus. Similarly, both FOR scenarios substantially reduced nutrient export. The COMBI and FOR scenarios also lead to increased carbon storage and local recharge in the Eastern Province relative to BASE.

FIGURE 7. Percent changes in ecosystem services relative to BASE at the national and provincial scale for 2035.



Source: IEEM+ESM Platform results.

FIGURE 8. Carbon storage (T); dashed circle/ellipse indicate areas of greatest change between years and across scenarios.

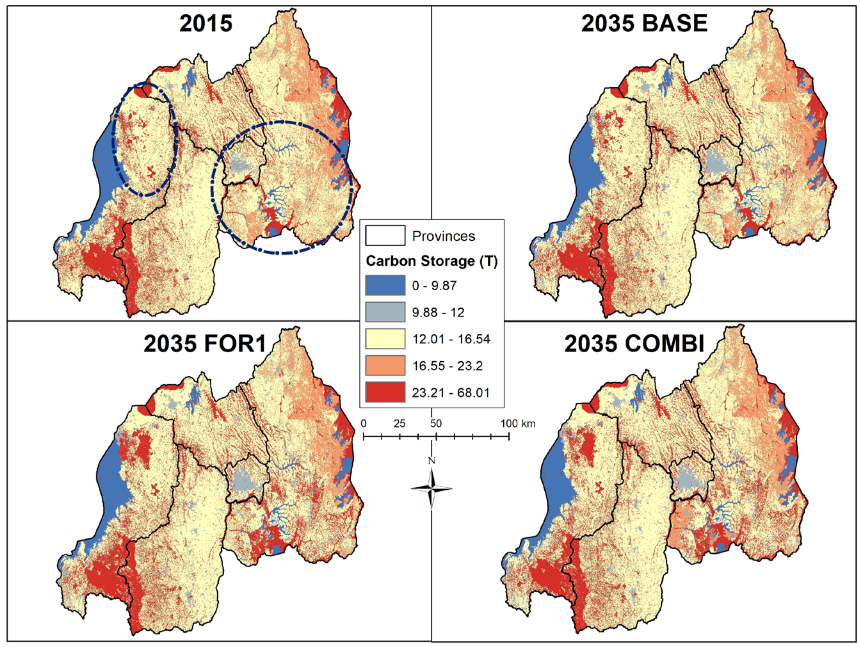
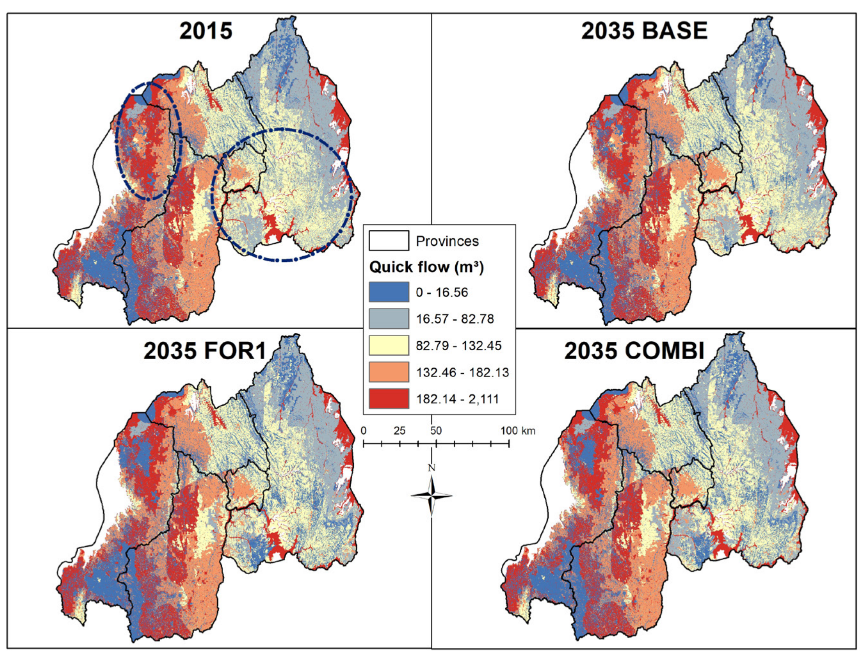


FIGURE 9. Quick flow (m³); dashed circle/ellipse indicate areas of greatest change between years and across scenarios.



5. Discussion

5.1 Development scenarios and green growth for Rwanda

FOR1 impacts on macroeconomic indicators are modest and negative in terms of absorption, private consumption, fixed investment and genuine savings. The GDP impact is small but positive while exports and imports grow faster. The key driving these perhaps surprising results is the increased competition for land arising from new forest plantations. In FOR1, for each new hectare of forest plantation there is a 0.25 ha reduction in land available for both agriculture and livestock. As a result, the agriculture and livestock sectors grow more slowly, also resulting in slower growth in income, savings, private consumption and investment.

In contrast, FOR2 lifts the constraint of competition between forest plantations, agriculture and livestock land uses and the impacts of forest plantation expansion are positive across macroeconomic indicators. As for the composition of genuine savings, the FOR scenarios have a positive impact on the natural capital stock component of genuine savings due to expanded forest plantations. Both FOR1 and FOR2 result in some of the largest gains in ecosystem services over BASE – with increased carbon storage and local recharge and reduced nitrogen and phosphorus exports; the gains in FOR1 are slightly larger.

Sector activity across scenarios generally increases over BASE activity levels, with the exception of the agriculture and livestock sectors in FOR1 and the forestry sector in the FUEL scenario. Slower forest sector growth in FUEL is explained by the reduction in fuelwood demand resulting from greater fuelwood use efficiency. Sectoral activity is heavily stimulated in the FERT and COMBI scenarios, especially for the agricultural sector but also notably for the manufacturing sector.

It is interesting to compare the impacts of expanding forest plantations with those of increasing natural forest management, an area of investigation pursued in earlier work [51]. Increasing natural forest management often involves bringing previously unproductive, public forestland into production. This is equivalent to bringing to the economy a previously untapped resource that can be used to generate new income. The increased availability of this factor of production can have very large impacts on GDP and other macroeconomic indicators, compared with more modest gains from increasing forest plantations.

FUEL scenario results are positive across indicators, including private consumption, exports, imports and GDP. These impacts are greater than those in the FOR scenarios, and compared to IRRIG, with the exception of fixed investment and genuine savings where IRRIG has a more pronounced effect. There are two main transmission pathways that explain FUEL scenario results. First, with the increase in household fuelwood use efficiency, the same amount of cooking energy is obtained with 25% less fuelwood. This results in a decline in fuelwood prices, which benefits households by leaving them with greater disposable income for consumption of other goods and services including education and health services. The second transmission pathway is related to the positive health benefits arising from reduced exposure to fuelwood emissions and particulates in the household. These positive health benefits enhance rural agricultural labor productivity, reduce unemployment and increase agricultural sector output, wages, income and household consumption and savings possibilities. Ecosystem services in FUEL are essentially unchanged from BASE due to little change in land use and land cover.

The IRRIG scenario results in positive macroeconomic indicators with impacts larger than in the FOR scenarios. The productivity gain from irrigating crops boosts crop production, reduces crop prices, and frees up factors of production for use in other sectors of the economy. The overall effect is positive for wages, employment, household welfare, and genuine savings. However, in the short run and due to the inflow of foreign exchange required to finance the investment in irrigation, there is an appreciation of the real exchange rate, which has a negative impact on exports. In the longer run, once the investment is complete, the real exchange rate returns to BASE levels and exports once again grow faster.

In the case of the IRRIG and FERT scenarios, there is a reduction in forest natural capital stocks which has a negative impact on genuine savings. On the other hand, the foreign investment financing in these scenarios contributes positively to genuine savings by enhancing output and incomes. Overall, land-use impacts in IRRIG are small while in FERT, the large increase in agricultural productivity frees up land to be reallocated to livestock. Ecosystem services in IRRIG are essentially unchanged from BASE, though water use is somewhat greater (ca. 0.5 million m3/yr).

As the FERT scenario shows, there are very large gains to be had with increasing fertilization in Rwanda. Increasing fertilization boosts GDP and genuine savings by US$2,781 million and US$713 million, respectively. The joint impact of all scenarios represented by COMBI1 generates the largest gains with a US$3,591 million boost to GDP and a US$763 million increase in genuine savings. While agricultural product prices may fall as a result of the increase in total factor agricultural productivity and the large increase in output, the volume of this output compensates by generating additional household income, which is used for consumption, savings and investment. A portion of this increase in output is also exported, while we also see an increase in imports due to increased demand for all goods and services. Unsurprisingly given its emphasis on increasing fertilizer inputs, FERT results in the largest increases in nitrogen and phosphorus export relative to BASE (47% and 50%, respectively), along with substantially greater water use (7.2 million m3/yr).

The COMBI1 scenario, which is the joint impact of FOR1, FUEL, IRRIG and FERT, shows strong positive effects on the economy. The reduced agricultural land availability arising from FOR1 is more than compensated for through the fuelwood efficiency enhancement as well as the productivity implications of increases in irrigation and fertilizer. The poverty-reducing impact (1.57% less poverty in 2035) is also strong. Enhanced productivity of the agricultural sector is largely attributable to the contribution of fertilization and results in less land used by agriculture and more land reallocated for livestock use. Ecosystem services in COMBI1 show mixed results, with increased carbon storage and local recharge, reflecting the additional forest plantations, but also increases in nitrogen and phosphorus export (42% and 45%, respectively), along with substantially greater water use (7.2 million m3/yr). Nutrient exports are somewhat lower than in FERT, because additional forest plantations provides greater nutrient uptake.

The transmission pathways for the IRRIG, FERT and COMBI scenarios are similar. Both IRRIG and FERT scenarios result in an increase in agricultural total factor productivity, which in turn increases agricultural output while reducing agricultural factor use. This reduction in agricultural factor use frees up capital, labor and land for use in other sectors of the economy, enabling them to increase their output. The overall net effect is an increase in wages, a reduction in unemployment and an increase in household income, consumption and savings.

In terms of evaluating green growth, the FERT and COMBI scenarios are the greatest "winners" for Rwanda from the perspective of economic growth. However, from an ecosystem services perspective, the FOR and COMBI scenarios, which help reverse a 25-year trend of forest loss in Rwanda [3, 4], provide the greatest gains in ecosystem services (Figure 6). Of these, the FOR scenarios yield reductions in nutrient export while when combined with fertilization in the COMBI scenarios, the net effect is an increase in nutrient export, though to a lesser degree than the FERT scenario. Increases in nutrient inputs to surface waters matter because localized problems already exist with water quality and availability in Rwanda, particularly in the dry season [52-54]. Increases in nutrient inputs of over 40% would likely make these problems more pervasive. Increasing water demand (i.e., in the FERT and COMBI scenarios) may further exacerbate water-quality problems by reducing streamflow that dilute nutrients and other water pollutants. Water demand and water quality are thus the two most notable ecosystem service tradeoffs that emerge from our analysis.

Better water-quality outcomes may also be possible if reforestation can be carefully targeted to intercept sediment and nutrients before they reach major waterways [55]. A COMBI-type outcome that produces both positive economic and ecosystem service outcomes may thus be possible with very careful targeting of reforestation,

including along water courses, to protect water quality. Achieving these multiple benefits may require a payments for ecosystem services-like incentive system informed by ecosystem service models. However, green growth scenarios that reduce nutrient inputs into Rwanda's agricultural system, i.e., the FOR scenarios, could best ensure greater water-quality protection, economic considerations aside. Economic arguments generated with the IEEM+ESM Platform such as those presented here can provide the basis for the development of such incentive systems.

All scenarios but COMBI2 account for urban expansion. COMBI2 preserves more farmland, but also more forests, grasslands, and shrublands that are lost to urban development in COMBI1. COMBI2 thus has both greater (detrimental) nutrient export and (beneficial) carbon storage and local recharge. Given Rwanda's limited land base and high population density, urbanization is being implemented as a needed strategy to reduce population pressure on natural resources in rural areas and diversify the urban economy [56, 57], but it comes with its own impacts to local ecosystems and ecosystem service supply.

As our provincial-scale analysis indicates, changes in ecosystem service, and their contributions to human well-being, are not equally distributed across Rwanda. Changes in the Northern, Western, and Southern provinces generally mirrored national-scale trends, while those in Kigali City are influenced by urbanization and those in the Eastern Province by reallocations of LULC, which differed between scenarios. The Eastern Province is the flattest and driest region of Rwanda, where the most substantial changes took place as allocated by the LULC Change Model. Eastern Province ecosystem service trends differ more by scenario than the nation as a whole; notably the COMBI scenarios provide greater nutrient uptake from forest plantation expansion than in the FERT scenario, somewhat mitigating the effects of water-quality changes. Multi-jurisdictional effects may also be felt related to water quality and quantity, such as in neighboring Tanzania and Uganda, who share the Akagera watershed with Rwanda.

Despite the key tradeoffs identified related to fertilizer and water use, water quality and quantity are far more difficult to value monetarily than our economic analysis. To address this limitation, concurrent efforts are focused on introducing feedbacks between IEEM and ESM, where changes in ecosystem service supply have a direct and quantified effect on the economy, which in turn generates new expectations for LULC change and therefore ecosystem service supply. Thus while IEEM can make these "hidden costs" more visible, feedbacks between ecosystem service supply and the economy must be considered if the full cost of alternative policies and investments to achieve green growth are to be taken into account.

Finally, while our water yield models are calibrated, the sediment and nutrient models are not, though our study's emphasis on relative change in these metrics makes this limitation less serious than for other applications. Water-quality data needed to calibrate soil erosion and nutrient models are scarce in Rwanda [58, 59]. Doing so would require a national water-quality monitoring program with adequate spatiotemporal coverage that is co-located with stream gauges to enable estimation of nutrient and sediment loads. Water-quality monitoring initiated in 2017 by the Ministry of Natural Resources may assist in future model calibration efforts for Rwanda [60].

5.2 Next steps for the IEEM+ESM Platform

We present an innovative integration of dynamic CGE, LULC change, and ecosystem service models that more fully characterize linked environmental-economic trade-offs for development planning. At the regional scale there is some experience with linking CGE models with LULC change [44], and recent efforts are working to link these with ecosystem services models at the global scale [61, 62]. These approaches differ in two important ways: (i) the scenarios do not consider specific policy measures, rather they tend to consider broad potential trajectories such as sustainable development versus widespread land-use change, and; (ii) regional and global models require a great number of homogenizing assumptions, where particularly for LULC change and ecosystem services supply, critical country context-specific detail is lost. Thus while these approaches may be useful for advocacy work, they

have limited potential for informing national policy and decision making. In our engagement with government clients and collaborators, there is a clear demand for finer resolution analysis that generates policy insights at the national to subnational level to support public investment and decision making.

Currently in the IEEM+ESM approach, each of the three modeling steps–IEEM, LULC change, and ESM–required a hand-off between models. This process required detailed discussions about the results and their transmission pathways for each scenario implemented in the models. Logistical questions were also tackled, such as those related to data formats, consistency and compatibility of model assumptions, and consistency in the reporting of results [63]. Economic-environmental analysis is fundamentally an interdisciplinary pursuit and these initial discussions are necessary from a technical standpoint, but equally important to bring a richness and depth to the approach and analysis that one discipline alone cannot provide. Once these discussions have been had and logistical questions addressed, however, future application of the IEEM+ESM Platform across policy domains is greatly simplified.

In the case of the IEEM+ESM Platform for Rwanda, the team benefited from very recent ecosystem service modeling studies where collaborators were able to share models, data and parameters [3, 4, 10]. To apply IEEM+ESM in other countries, wider adoption of methods to reuse economic, LULC and ecosystem service models and data would reduce start-up resource requirements dramatically [64]. This is the approach we are taking in the development of an OPEN IEEM+ESM Platform for the Latin American and Caribbean region [65].

6. Conclusions

The IEEM+ESM Platform can be applied to complex policy goals such as those embodied by green growth, and more broadly to the Sustainable Development Goals and Paris Agreement commitments, by quantitatively identifying the economic, social and environmental impacts of alternative strategies for reaching specific targets. By quantifying policy impacts, the IEEM+ESM Platform generates evidence-based policy advice along these three fundamental dimensions of sustainable development, which is fundamental in the context of analyzing synergies and trade-offs between strategies. The metrics generated by the IEEM+ESM Platform go beyond measures of income flow represented by GDP, and capture the sustainability of income growth as indicated by impacts on genuine savings, natural capital stocks and ecosystem service supply. Policy analysis that produces and reports these more robust metrics is made possible with many countries around the globe, including Rwanda, implementing the System of Environmental-Economic Accounting [24].

The analysis presented here shows clear trade-offs and synergies when considering multiple strategies for achieving green growth. Many of these would have gone undetected through the conventional application of stand-alone economic, LULC change and ecosystem service modeling and analysis. Here we show for example that increasing fertilization has very strong positive economic impacts for Rwanda, however, the intensity of environmental resource use, water for example, increases markedly. There are also important impacts on increased nutrient export, which has implications for water quality, potential eutrophication of watercourses and undesirable impacts to downstream water users.

On the other hand, our analysis shows that expanding forest cover has the potential to mitigate some of the impact of increased water consumption as well as enhancing erosion mitigation and nutrient uptake. This analysis thus provides strong economic and environmental arguments for a portfolio approach to achieving green growth targets where fertilization, irrigation and improving fuelwood use efficiency deliver important economic benefits. Forest cover expansion provides fuelwood and other raw material, reduces nutrient and sediment exports, reduces quickflow and enhances water recharge, all while increasing above and below-ground carbon stocks for climate change mitigation.

Our analysis is spatially explicit and at a scale that is relevant for policy and decision makers to take action. Impacts on LULC and ecosystem service changes are not homogenous across the landscape and knowing the location and magnitude of change is critical for targeting action; while we summarized LULC and ecosystem service changes by province, impacts could similarly be estimated by districts, watersheds, or other subnational units. In our engagement with Rwandan policy makers, highlighting the concentration of potential changes in LULC in the Eastern Province, for example, generated important discussion on trade-offs and synergies between economic, environmental and social objectives for that region. In Africa's most densely populated country with a very limited land endowment, our analysis for Rwanda elucidates the importance of reconciling government plans and targets with the realities of current natural capital availability, threats and vulnerabilities.

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References

1. **World Bank, World Development Indicators.** 2017, World Bank: Washington DC.
2. **NISR, The Fifth Integrated Household Living Survey** (EICV5): 2016/2017 Poverty Profile Report. 2018, National Institute of Statistics of Rwanda: Kigali.
3. **Rukundo, E., et al., Spatio-temporal dynamics of critical ecosystem services in response to agricultural expansion in Rwanda, East Africa. Ecological Indicators,** 2018. 89: p. 696-705.
4. **Bagstad, K.J., et al., Toward ecosystem accounts for Rwanda: Tracking 25 years of change in ecosystem service potential and flows. Proceedings of the National Academy of Science**s, In Review.
5. **Republic of Rwanda, Green Growth and Climate Resiliience: National Strategy for Climate Change and Low Carbon Development**. 2011, Republic of Rwanda: Kigali.
6. **World Bank, Inclusive Green Growth: The Pathway to Sustainable Development.** 2012, World Bank: Washington DC.
7. **McKenzie, E., et al., Developing Scenarios to Assess Ecosystem Service Tradeoffs: Guidance and Case Studies for InVEST Users.** 2012, World Wildlife Fund: Washington DC.
8. **Banerjee, O., et al., The SEEA-Based Integrated Economic-Environmental Modelling Framework: An Illustration with Guatemala's Forest and Fuelwood Sector. Environmental and Resource Economics,** 2019. 72: p. 539–558.
9. **Banerjee, O., et al., A Conceptual Framework for Integrated Economic–Environmental Modeling. The Journal of Environment & Development,** 2016. 25(3): p. 276-305.
10. **Banerjee, O., et al., Evaluating synergies and trade-offs in achieving the SDGs of zero hunger and clean water and sanitation: An application of the IEEM Platform to Guatemala. Ecological Economics**, 2019. 161: p. 280-291.
11. **Government of Rwanda, Natural Capital Accounts for Land.** 2018, NISR, Ministry of Environment and Ministry of Lands and Forestry: Kigali.
12. **Government of Rwanda, Natural Capital Accounts for Water.** 2019, National Institute of Statistics Rwanda and Ministry of Environment: Kigali.
13. **MINIRENA, Forest Landscape Restoration Opportunity Assessment for Rwanda.** 2014, Ministry of Natural Resources: Kigali.
14. **Isaac, A.O., M. Willy, and N. Jean, Costing of Sutainable Forestry, Agroforestry and Biomass Energy in Rwanda.** 2016, The UN Food and Agriculture Organization, Rwanda Country Office: Kigali.
15. **RDB. Status of Energy Generation.** 2019 [cited 2019; Available from: http://rdb.rw/demo2/investment-opportunities/energy/.
16. **NISR, Rwanda Statistical YearBook 2018.** 2018, National Institute of Statistics of Rwanda: Kigali.
17. **Nahayo, A., I. Ekise, and A. Mukarugwiza, Comparative Study on Charcoal Yield Produced by Traditional and Improved Kilns: A Case Study of Nyaruguru and Nyamababe Districts in Southern Province of Rwanda. Energy and Environment Research**, 2013. 3(1).
18. **Drigo, R., et al., Update and Upgrade of WISDOM Rwanda and Woodfuels Value Chain Analysis as a Basis for a Rwanda Supply Master Plan for Fuelwood and Charcoal.** 2013, Agriconsulting: Kigali.
19. **Bill, S., Improved Wood Waste and Charcoal Burning Stoves: A Practioners Manual. Improved Wood Waste and Charcoal Burning Stoves.** 1987, Warwickshire: Practical Action Publishing.
20. **Pennise, D.M., et al., Emissions of greenhouse gases and other airborne pollutants from charcoal making in Kenya and Brazil. Journal of Geophysical Research: Atmospheres,** 2001. 106(D20): p. 24143-24155.
21. **NISR, GDP National Accounts, 2018.** 2019, National Institute of Statistics of Rwanda: Kigali.
22. **Kaindaneh, P.M. and I. Ntabana, Towards Inclusive Green Growth in Rwanda: Costing of Investments in Agriculture and Natural Resources.** 2014, Authors: Kigali.
23. **Ministry of Agriculture and Animal Resources, Strategic Plan for the Transformation of Agriculture in Rwanda Phase III.** 2013, Ministry of Agriculture and Animal Resources: Kigali.
24. **United Nations, et al., System of Environmental Economic Accounting 2012- Central Framework.** 2014, UN: New York.
25. **Stiglitz, J.E., A. Sen, and J. Fitoussi, Report by the Commission on the Measurement of Economic Performance and Social Progress.** 2009.
26. **Lange, G.-M., Q. Wodon, and K. Carey, eds. The Changing Wealth of Nations 2018: Building a Sustainable Future.** 2018, World Bank: Washingon DC.
27. **Polasky, S., et al., Inclusive Wealth as a Metric of Sustainable Development. Annual Review of Environment & Resources**, 2015. 40: p. 445-466.
28. **Millenium Ecosystems Assessment, Ecosystems and Human Well-being: Synthesis.** 2005, Washington, D.C.: Island Press.
29. **Guerry, A.D., et al., Natural capital and ecosystem services informing decisions: From promise to practice. Proceedings of the National Academy of Sciences,** 2015. 112(24): p. 7348-7355.
30. **European Commission, et al., System of National Accounts 2008.** 2009, EC, IMF, OECD, UN, WB.
31. **Jones, R.W., The Structure of Simple General Equilibrium Models. The Journal of Political Economy,** 1965. 73(6).
32. **Arrow, K.J., Personal Reflections on Applied General Equilibrium Models, in Frontiers in Applied General Equilibrium Modeling: In Honor of Herbert Scarf, T.J. Kehoe, T.N. Srinivasan, and J. Whalley, Editors.** 2005, Cambridge University Press: Cambridge.
33. **Dixon, P.B. and M.T. Rimmer, Dynamic general equilibrium modelling for forecasting and policy: A practical guide and documentation of MONASH.** 2002, Bingley: Emerald Group Publishing. xiv.
34. **Dixon, P.B., et al., ORANI: A Multisectoral Model of the Australian Economy.** 1982, Amsterdam: North Holland.
35. **Shoven, J. and J. Whalley, Applying general equilibrium.** 1992, Cambridge: Cambridge University Press.
36. **Pyatt, G. and J.I. Round, eds. Social Accounting Matrrices: A Basis for Planning.** 1985, The World Bank: Washington DC.
37. **King, B., What is a SAM? A Layman's Guide to Social Accounting Matrices, in Staff Working Paper No. SWP 463.** 1981, The World Bank: Washington DC.

38. **Breisinger, C., M. Thomas, and J. Thurlow, Social Accounting Matrices and Multiplier Analysis: An Introduction with Exercises, in Food Security in Practice Techincal Guide Series, IFPRI, Editor.** 2009, International Food Policy Research Institute: Washington D.C.

39. **Banerjee, O., M. Cicowiez, and J. Cotta, Economics of tourism investment in data scarce countries. Annals of Tourism Research,** 2016. 60: p. 115-138.

40. **Duflo, E., M. Greenstone, and R. Hanna, Indoor Air Pollution, Health and Economic Well-Being. Surveys and Perspectives Integrating Environment and Society,** 2008. 1(1): p. 1-9.

41. **Lambe, F. and C. Ochieng, Improved Cookstoves in Central America: Health Impacts and Uptake.** 2015, Stockholm Environment Institute.: Stockholm.

42. **McCracken, J.P. and K.R. Smith, Emissions and Efficiency of Improved Woodburning Cookstoves in Highland Guatemala. Environment International,** 1998. 24(7): p. 739-747.

43. **Verburg, P.H. and K.P. Overmars, Combining top-down and bottom-up dynamics in land use modeling: exploring the future of abandoned farmlands in Europe with the Dyna-CLUE model. Landscape Ecology,** 2009. 24(9): p. 1167.

44. **Verburg, P.H., B. Eickhout, and H. van Meijl, A multi-scale, multi-model approach for analyzing the future dynamics of European land use. The Annals of Regional Science,** 2008. 42(1): p. 57-77.

45. **Verburg, P.H., et al., A spatial explicit allocation procedure for modelling the pattern of land use change based upon actual land use. Ecological Modelling,** 1999. 116(1): p. 45-61.

46. **Veldkamp, A. and L.O. Fresco, CLUE-CR: An integrated multi-scale model to simulate land use change scenarios in Costa Rica. Ecological Modelling,** 1996. 91(1): p. 231-248.

47. **MINIRENA, Rwanda National Land Use Planning Guidelines.** 2017, Ministry of Natural Resources, Rwanda Land Management and Use Authority: Kigali.

48. **Government of Rwanda, Rwanda National Land Use and Development Master Plan- Scenarios.** 2014, Government of Rwanda: Kigali.

49. **Sharp, R., et al., InVEST User's Guide. 2**016, The Natural Capital Project, Stanford University, University of Minnesota, The Nature Conservancy, and World Wildlife Fund: Stanford.

50. **Johnson, J.A., et al., Mapping ecosystem services to human well-being: A toolkit to support integrated landscape management for the SDGs. Ecological Applications, In Press.**

51. **Banerjee, O., J.R.R. Alavalapati, and E. Lima, A framework for ex-ante analysis of public investment in forest-based development: An application to the Brazilian Amazon. Forest Policy and Economics,** 2016. 73: p. 204-214.

52. **REMA, Rwanda State of Environment and Outlook, 2015: Greening agriculture with resource efficient, low carbon and climate resilient practices.** 2015, Rwanda Environment Management Authority: Kigali.

53. **Nahayo, L., et al., Agricultural impact on environment and counter measures in Rwanda. African Journal of Agricultural Research**, 2016. 11(25): p. 2205-2212.

54. **Nahayo, L., et al., Seasonal Drinking Water Quality Monitoring for the Community Wellbeing in the Eastern Rwanda Journal of Environment Protection and Sustainable Development,** 2018. 4(1).

55. **Chaplin-Kramer, R., et al., Landscape configuration is the primary driver of impacts on water quality associated with agricultural expansion. Environmental Research Letters,** 2016. 11(7): p. 074012.

56. **REMA, Rwanda State of Environment and Outlook,** 2017: Achieving Sustainable Urbanization 2017, Rwanda Environment Management Authority: Kigali.

57. **World Bank and Government of Rwanda, Future drivers of growth in Rwanda: Innovation, integration, agglomeration and competition.** 2018, World Bank: Washington DC.

58. **Muvundja, F.A., et al., Balancing nutrient inputs to Lake Kivu. Journal of Great Lakes Research,** 2009. 35(3): p. 406-418.

59. **Uwimana, A., et al., Effects of agricultural land use on sediment and nutrient retention in valley-bottom wetlands of Migina catchment, southern Rwanda. Journal of Environmental Management,** 2018. 219: p. 103-114.

60. **Christian, S.B. and K. Vedaste, Water Pollution Study: Draft report.** 2017, Prepared for the Rwanda Ministry of Environment: Kigali.

61. **Johnson, J.A., et al., Global Futures: Modelling the Global Economic Impacts of Environrmental Change to Support Policy Making.** 2019, World Wide Fund for Nature WWF-UK: Surrey.

62. **Crossman, N., et al., Global Socio-Economic Impacts of Future Changes in Biodiversity and Ecosystem Services: State of Play and Approaches for New Modelling.** 2018, University of Adelaide: Adelaide.

63. **Laniak, G.F., et al., Integrated environmental modeling: A vision and roadmap for the future. Environmental Modelling & Software,** 2013. 39: p. 3-23.

64. **Martínez-López, J., et al., Towards globally customizable ecosystem service models. Science of The Total Environment,** 2019. 650: p. 2325-2336.

65. **Banerjee, O., et al., OPEN IEEM+ESM Platform Concept Note.** 2019, Inter-American Development Bank: Washington DC.

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