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Economic, land use, and ecosystem services impacts of Rwanda's Green Growth Strategy: An application of the IEEM+ESM platform

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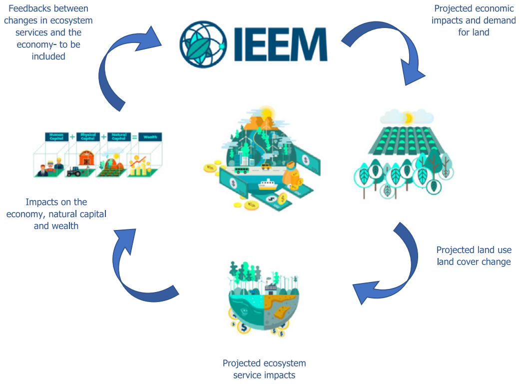
HIGHLIGHTS

- This paper develops the IEEM+ESM Platform, a new decision-making framework.
- IEEM+ESM shows policy impacts on the economy, natural capital, ecosystem services.
- IEEM+ESM elucidates synergies and trade-offs between alternative policy portfolios.
- We apply IEEM+ESM to analysis of green growth in Rwanda.
- Results show best policy mix to maximize economic and environmental performance.

GRAPHICAL ABSTRACT



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ABSTRACT

We develop and link the Integrated Economic-Environmental Modeling (IEEM) Platform to ecosystem services modeling (ESM). The IEEM+ESM Platform is an innovative decision-making framework for exploring complex public policy goals and elucidating synergies and trade-offs between alternative policy portfolios. The IEEM+ESM approach is powerful in its ability to shed light on (i) change in land use and ecosystem services driven by public policy and the supply and demand responses of businesses and households; and (ii) impacts on standard economic indicators of concern to Ministries of Finance such as gross domestic product and employment, as well as changes in wealth and ecosystem services. The IEEM+ESM approach is being adopted rapidly and by the end of 2020, IEEM+ESM Platforms will be implemented for about 25 countries. To demonstrate the insights generated by the IEEM+ESM approach, we apply it to the analysis of alternative green growth strategies in Rwanda, a country that has made strong progress in reducing poverty and enhancing economic growth in the last 15 years. The case of Rwanda is particularly compelling as it faces intense pressure on its natural capital base and

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Integrated Economic-Environmental Modeling (IEEM) Platform
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ecosystem services, already with the highest population density in Africa, which is projected to double by 2050. In applying IEEM+ESM and comparing the outcomes of Rwanda's green growth policies, increasing fertilization of agricultural crops shows the largest economic gains but also trade-offs in environmental quality reflected through higher nutrient export and reduced water quality. Combining crop fertilization with forest plantations better balances critical ecosystem services and their role in underpinning economic development as Rwanda progresses toward its target of middle-income status by 2035. This application to Rwanda's green growth strategy demonstrates the value-added of the IEEM+ESM approach in generating results that speak to both economic outcomes and impacts on market and non-market ecosystem services.

1. Introduction

The Integrated Economic-Environmental Modeling (IEEM) Platform (Banerjee et al., 2016b; Banerjee et al., 2019f; Banerjee et al., 2019d) linked with ecosystem services modeling (IEEM+ESM; Banerjee et al., 2019b, Banerjee et al., 2019c) is an innovative framework for exploring complex public policy goals and evaluating their synergies and trade-offs. The IEEM+ESM Platform was developed to enhance economy-wide decision-making by integrating rich information on natural capital stocks and ecosystem services- the benefits people obtain from nature (Daily et al., 2009; Millenium Ecosystems Assessment, 2005), services for which in many cases markets do not yet exist. Most regulating ecosystem services (e.g., soil erosion and nutrient regulation, flood regulation, and natural pest control) lack a market price due to missing markets. Where these services are not quantified or valued, they are not taken into account in decision making and implicitly assigned a value of zero. As renowned economist David W. Pearce wrote, "…valuation is always implicit or explicit; it cannot fail to happen at all" (Pearce et al., 2006, p6). The IEEM+ESM Platform explicitly accounts for how public policy and investment affects future ecosystem service supply.

IEEM+ESM provides a powerful framework for evaluating (i) change in land use and ecosystem services driven by public policy and investment, and the supply and demand responses of businesses and households; and (ii) impacts on standard economic indicators of concern to Ministries of Finance such as gross domestic product (GDP) and employment, as well as changes in wealth and ecosystem services, which are indicators of long-run sustainable economic development and income growth. The IEEM+ESM approach is being adopted rapidly; its implementation is anticipated in about 25 nations by the end of 2020. We apply IEEM+ESM to the analysis of alternative green growth strategies in Rwanda, in order to demonstrate the insights the approach can yield. In the last decade, Rwanda has made important advances in reducing poverty (from 58.9% to 38.2% between 2000 and 2017) and inequality while enhancing productivity and economic growth (NISR, 2019; World Bank and Government of Rwanda, 2018). 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 is formidable. 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 (Rukundo et al., 2018; Bagstad et al., 2020). To address these challenges, Rwanda has made a strong commitment to green growth, which is embodied in its Green Growth Strategy (Republic of Rwanda, 2011).

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 (World Bank, 2012). 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 (Republic of Rwanda, 2011), Vision 2020 (Republic of Rwanda, 2000) (with a transition toward the new Vision 2050 currently in preparation), the Economic Development and Poverty Reduction Strategy (Republic of Rwanda, 2013), The National Strategy for Transformation (Republic of Rwanda, 2017), 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 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 (Bagstad et al., 2020). While a range of methods may be applied, spatial planning is frequently undertaken in a top-down manner or through participatory scenario development and analysis (McKenzie et al., 2012). These approaches suffer from three main limitations: (i) scenario design and land allocation decisions often 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—extreme or "bookend" cases that may make headlines but that lack the specificity required for real policy and decision making (Crossman et al., 2018; Banerjee et al., in press) These economic considerations are critical to Ministries of Economics, Finance and Planning to inform allocation of scarce government budgets and revenue projections. This paper 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 IEEM model for Rwanda based on the IEEM Platform approach developed in (Banerjee et al., 2016b; Banerjee et al., 2019f; Banerjee et al., 2019d). The IEEM Platform for Rwanda is calibrated with the country's recently published natural capital accounts (Government of Rwanda, 2018; Government of Rwanda, 2019; Bagstad et al., 2020) and ecosystem service models (ESM) to explore the economic and environmental impacts of specific actions toward achieving green growth. The section that follows describes relevant aspects of Rwanda's Green Growth Strategy related to fuel, timber, food, and food security—key aspects of Rwanda's development that we use to develop scenarios for modeling. Section 3 provides an overview of the linked Integrated Economic-Environmental Modeling and ecosystem services modeling (IEEM+ESM) framework and scenarios. Section 4 presents the results. Section 5 provides analysis and policy insights, and Section 6 concludes by discussing the importance of an integrated economic-environmental framework when evaluating complex development challenges such as those embodied by green growth.

2. Rwanda and its fuel, timber and food provisioning ecosystem services

2.1. Study area

Rwanda is a landlocked nation located in the central African highlands with a mean latitude of 1.9403° South, longitude of 29.8739°

East, and elevation of 1598 m (Fig. 1). Eighty percent of Rwanda's land area drains into the Nile River system via the Akagera River and 20% into the Congo River by way of Lake Kivu and the Rusizi River. With a surface area of 26,338 km^2 and a population of 12.2 million, Rwanda is the most densely populated country in Africa (World Bank and Government of Rwanda, 2018) and its population is predicted to more than double by 2050 (Republic of Rwanda, 2011). Much of the population farms small plots in rural parts of the country, though urbanization is increasing as well. Nationally, from west to east, there is a general trend of decreasing elevation, relief, and precipitation; forests and agricultural land are more frequent in the western and central parts of the country with greater grazing land in the east. From the 1990s to 2015, there has been notable conversion of forests and woodland to croplands (Government of Rwanda, 2018), with associated impacts on ecosystem services, such as reductions in erosion and nutrient regulation and carbon storage (Bagstad et al., 2020).

As Rwanda's economy and those of other low-income African countries grow, there is increasing risk that current production models will undermine ecosystem integrity thereby hindering prospects for long-run sustainable economic development (Egoh et al., 2012, IPBES, 2018a, IPBES, 2018b, Marques et al., 2019, Bagstad et al., 2020). Rwanda is committed to designing an economic development pathway that maintains its natural capital base and the critical life-supporting ecosystem services it generates (GDSA, 2016). In Rwanda and across Africa, recent experience and economic analysis alike are demonstrating how green growth can improve economic performance while conserving the natural capital base upon which it depends (UNEP, 2015).

2.2. 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 (Government of Rwanda, 2018). 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 (MINIRENA, 2014). Rwanda's natural forests are under threat from encroachment and land conversion due to population pressures (REMA, 2009) and are mostly contained within the country's four national parks (Banerjee et al., 2018). Forest plantations supply most of the fuelwood and timber used in the country and help offset pressures on natural forests. Their renewal is urgently needed, though; half of Rwanda's plantations are reaching the end of their productive cycle and they generally have low species diversity and genetic quality (Isaac et al., 2016).

With 29.5% of households connected to the electrical grid in 2017 (RDB, 2019), Rwanda depends strongly on biomass for energy. In 2016/2017, 97% of Rwandan homes used biomass as their main cooking fuel, with 79.9% using firewood and 17.4% using charcoal (NISR, 2018a;

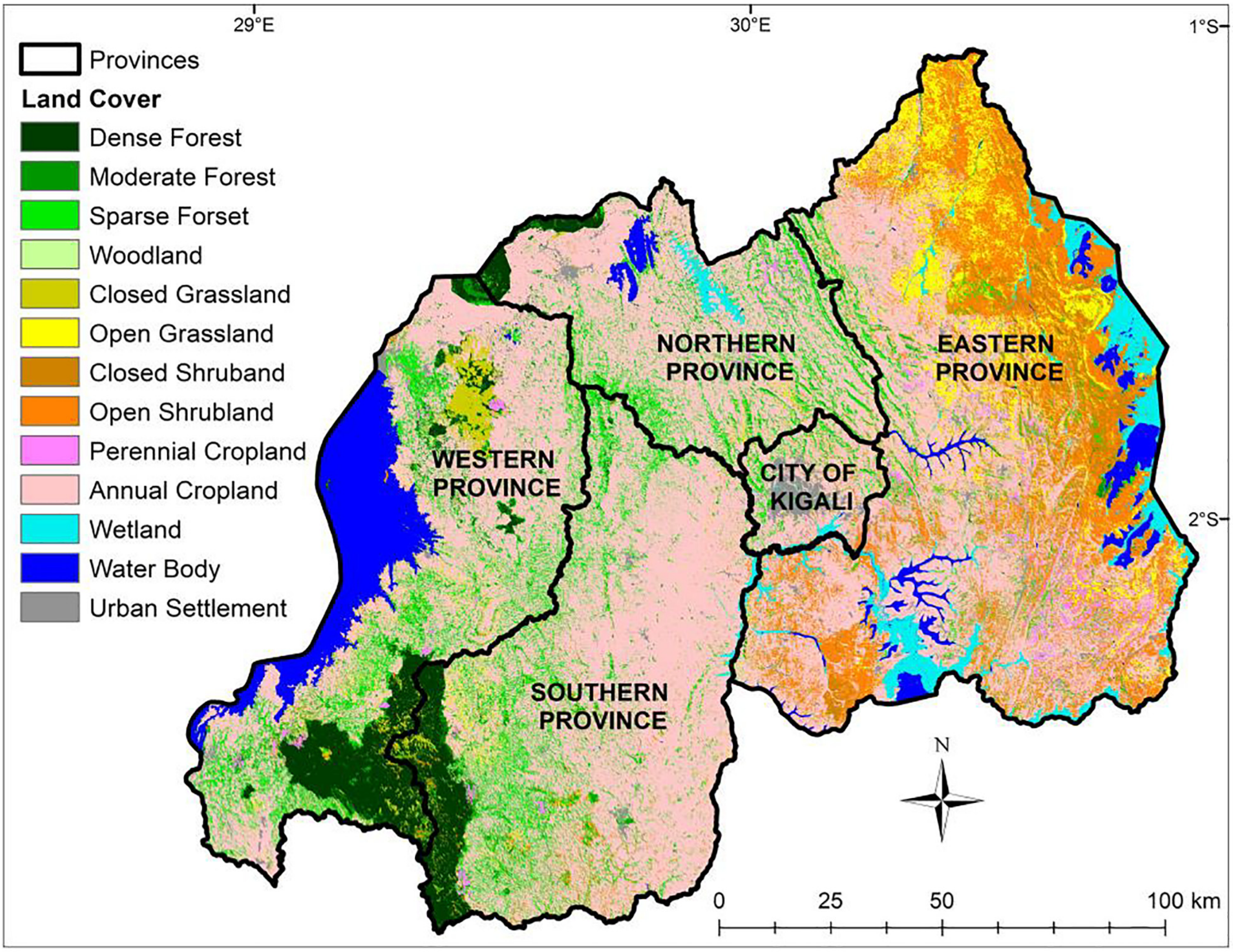

Fig. 1. Land use-land cover map for Rwanda, 2015. Source: Authors' own elaboration based on data from the Regional Centre for Mapping of Resources for Development (RCMRD), Rwanda Land Cover 2015 Scheme II (RCMRD, 2017).

NISR, 2018b). Total demand for woody biomass in 2009 was 4.8 million tons, which includes demand for fuelwood (3.2 million tons), charcoal (226,000 tons) and construction material. Kigali, the capital city, accounts for just over a quarter of total demand. Rwanda's sustainable woody biomass supply potential in 2009 was estimated at 3.2 million tons, indicating a deficit of around 1 million tons (Drigo et al., 2013).

Given the volume of charcoal and fuelwood consumption, this sector is also an important source of income and employment in Rwanda. In 2009 the value of the charcoal market was 37.9 billion Rwandan Francs (RWF), 59% of which was in the Kigali Province alone. The charcoal market is the main source of income for over 50,000 households in Rwanda and 30,000 households in Kigali alone. The size of the fuelwood market is more difficult to quantify, though it has been estimated at 58.9 billion RWF with the total woody biomass energy sector contributing to about 3.4% of Gross Domestic Product (Drigo et al., 2013).

Fuelwood and charcoal demand is the main driver of deforestation in Rwanda (Nahayo et al., 2013) with land scarcity acting as a primary constraint to the conservation of forest resources. In a business-as-usual scenario, fuelwood demand in 2020 is projected to reach 5.7 million tons (Drigo et al., 2013). To reduce pressure on natural forests and emissions from fuelwood and charcoal use, both demand- and supply-side measures are required. On the supply-side, it is necessary to expand forest plantations on degraded and unproductive lands, increase on-farm trees through well managed agroforestry systems, manage existing forest plantations to increase yields, and increase the efficiency of fuelwood and charcoal use (Dyszynski and Hogarth, 2011). On the other hand, demand-side measures that encourage substitution to other energy sources are urgently needed, including electrification and use of liquefied petroleum gas, particularly in urban areas.

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 (i) expanding forest plantations, (ii) renewing older plantations, and (iii) promoting agroforestry for the provision of multiple ecosystem services. In this paper, 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 (Bill, 1987; Pennise et al., 2001; Nahayo et al., 2013; Banerjee et al., 2019f).

The total cost of achieving these targets under a medium sustainability scenario (considering activities important for forest plantations, agroforestry and biomass energy development, plus those in the Strategic Plan for the Forest Sector) is US$285,581,699 over a 14-year period (Isaac et al., 2016). Potential sources for financing both investments are expected to be pursued from largely non-reimbursable grants from facilities such as the Green Climate Fund, the Global Environment Facility and Reducing Emissions from Deforestation and forest Degradation (REDD+) mechanisms.

In considering options for Green Growth, country context is important, particularly in the case of Rwanda, as it is an almost entirely human-dominated landscape. The expansion of forest plantations is pursued as an interim development strategy due to extreme land scarcity in Africa's most densely populated country. While encouraging restoration of natural forest ecosystems for multiple use may be an ideal, forest plantations are necessary to contend with increasing demand for energy and wood products while ensuring sufficient land is available for meeting food security goals. Mixed species plantations with native species are encouraged thus providing some biodiversity benefits and resistance to pest and disease (Dyszynski and Hogarth, 2011; Republic of Rwanda, 2011), while building soil structure, organic matter content and sequestering carbon, thereby contributing to a nature-based solution to climate change mitigation (Griscom et al., 2017). Where agroforestry systems are concerned, their multiple benefits include poverty alleviation through income generation and diversification, biodiversity benefits, energy and water security, and sequestration of carbon by increasing above and below-ground carbon sinks (Roose and Ndayizigiye, 1997; Montagnini and Nair, 2004; Hardcastle, 2009; Alavalapati and Mercer, 2004).

2.3. Food and food security

Agriculture is the second largest component of Rwanda's economy, averaging around 32% of GDP over the last two decades (NISR, 2019). 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 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 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 (Kaindaneh and Ntabana, 2014). These practices include increasing soil conservation infrastructure with progressive and bench terraces, expanding irrigated agriculture from the current 28,796 to 94,269 ha (including 42,500 ha of irrigation in marshlands), and rehabilitating 20,000 ha of irrigation infrastructure. Irrigation opens 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.

Western and central Rwanda have high annual rainfall which the country has traditionally exploited for rainfed seasonal agriculture. Rising seasonal variability in precipitation patterns brought about by climate change makes it increasingly difficult for farmers to know when to plant crops to capture precipitation at the appropriate times which affects agricultural yields. Irrigation infrastructure improves resilience to climate change by reducing vulnerability to increasingly variable precipitation patterns. Irrigation contributes to mitigating the impacts of the increasing frequency and intensity of droughts (Zou et al., 2012; Scott et al., 2014; Iglesias and Garrote, 2015), and gives farmers greater control of water resources and the timing and quantity of their application. Irrigation also allows for crop diversification, crop intensification including double cropping, and increasing yields which is critical for land-scarce Rwanda as demand for food continues to grow rapidly. Finally, irrigation infrastructure is a critical component of Integrated Water Resource Management strategies, allowing for the more efficient allocation of water among competing human, agricultural and industrial uses while mitigating flood and landslide risk through the control of timing and flow of water (Warnest and Hogarth, 2011). Finally, soils of irrigated crops make important contributions to carbon storage (Follett, 2001; Abraham et al., 2014).

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 (Ministry of Agriculture and Animal Resources, 2013; Kaindaneh and Ntabana, 2014). 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 (Ministry of Agriculture and Animal Resources, 2013).

Rwandan soils are generally nutrient-poor. Fertilizer application rates in Rwanda are some of the lowest globally and there is a pressing need to increase application rates to ensure food security to feed the country's growing population. Increasingly, inorganic fertilizer is applied together with organic fertilizer. Rwanda's Green Growth Strategy details a staged approach to expanded fertilization by increasing inorganic fertilizer application rates, followed closely by the application of organic fertilizer. There are demonstrable benefits to the Rwandan Government's integrated strategy of applying inorganic and organic fertilizers in terms of improved soil structure, soil carbon, and water and nutrient retention (Adamtey et al., 2009; Chien et al., 2009; Hao et al., 2008; Zhang et al., 2016). Many of the problems related to inorganic fertilizer application arise from their overuse and poor soil and field management practices. Finally, it is important to note that the target fertilization application rates outlined in Rwanda's Green Growth Strategy are still half those of global averages (AGRA, 2019).

In this paper, we focus on two specific measures of Rwanda's Green Growth Strategy aimed at achieving food security, which are to: (i) rehabilitate and expand irrigation areas, and (ii) increase fertilizer use to 45 kg/ha/yr. The investment cost for achieving these targets is estimated at US$972.5 million (Isaac et al., 2016). Potential sources for financing both investments are expected to be pursued from largely non-reimbursable grants from Overseas Development Assistance and other forms of development aid.

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 dynamic 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 (Dervis et al., 1982; Dixon et al., 1982; Shoven and Whalley, 1992; Dixon and Rimmer, 2002; Arrow, 2005; Lofgren et al., 2002). Full documentation of the IEEM Platform and a mathematical model statement is available in (Banerjee and Cicowiez, 2020; Banerjee and Cicowiez, 2019). 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 (SEEA) Central Framework (United Nations, European Commission et al., 2014) into an economy-wide model; (ii) environmental modeling modules that capture the specific dynamics of each natural capital asset. For example, the forest sector behaves very differently from a conventional manufacturing sector. Forests grow, and can be harvested, deforested, degraded, or improved. IEEM's environmental modules capture features specific to each natural capital asset; and (iii) IEEM indicators that go beyond measures of income flows such as GDP to reflect impacts on the three dimensions of sustainable development embodied in the concept of wealth, namely the economy, society and the environment (Stiglitz et al., 2010; Stiglitz et al., 2009; Lange et al., 2018; Polasky et al., 2015).

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 (Guerry et al., 2015) 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 (Fig. 2), 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 land use-land cover (LULC) change for each scenario and period of analysis. While our presentation of the IEEM+ESM workflow focuses on new policies and how they may impact LULC, a range of other activities could affect LULC and resulting ecosystem service supply, such as changes in private sector land management practices and conservation activities implemented by both the public and private sector, among others. 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 paper, our ESM focuses on climate change mitigation through carbon storage, water provisioning services quantified as annual water yield, quick flow and local recharge, erosion mitigation in terms of sediment retention and export, and water quality and soil fertility maintenance quantified as nitrogen and phosphorus load, export, and retention. We modeled these ecosystem services using the Integrated Valuation of Ecosystem Services Tradeoffs (InVEST) software platform (Sharp et al., 2018). As one of the 16 countries committed to developing natural capital accounts through the Wealth Accounting and Valuation of Ecosystem Services Partnership, these ecosystem services were deemed priority services for the country (World Bank, 2018; Bagstad et al., 2020).

Given the relatively short time horizon of 2015 to 2035 considered in this analysis, we held most biophysical model parameters in the ecosystem service models constant. The primary sources of change in our ecosystem service model runs are thus LULC change as reflected by the scenario-based maps, plus model parameters related to agricultural practices, including fertilizer application and terracing rates. Below, we discuss each of the three main components (IEEM, LULC change and ESM) of the workflow presented in Fig. 2.

Additionally, it is important to briefly discuss model calibration and validation. In the case of IEEM and CGE models in general, model calibration and validation are interpreted somewhat differently than many other types of models since they are not predictive models. In scenario modeling such as that implemented in this paper, the fundamental assumption is that in undertaking a specific policy scenario, all other things are held constant—the assumption of “all else being held equal.” Of course, in a real-world economy, a policy is implemented at the same time as many other policies, investments, economic shocks, and changes in agent behavior and preferences, to mention a few. For this reason, CGE model calibration and validation are interpreted somewhat differently than in the conventional modeling.

CGE model calibration refers to the solution of the model to reproduce the underlying data—the Social Accounting Matrix (King, 1981;

Fig. 2. Integrated Economic-Environmental Modelling (IEEM) + Ecosystem Service Modeling workflow. ES: Ecosystem services; LULC: Land use-land cover; BASE: Baseline (policy status quo) projection.

Pyatt and Round, 1985; Breisinger et al., 2009)—in the base year. A CGE model that is to be applied in policy analysis is thus first calibrated to these data. CGE model validation is usually limited to two types. First, results of the CGE modeling exercise are verified to confirm that they have been computed correctly and are traceable to relationships in the model's theory and data. This also implies that the model results are robust to some variation around model free parameters, specifically, model elasticities, which are a measure of a variable's sensitivity to a change in another variable. The second type of validation is the verification that the explanation of results legitimately reflects the way in which the CGE model functions (Dixon and Rimmer, 2013). This is important for assuring that relevant features of the economy are considered in the modeling exercise and thus the modeling framework is fit for the purpose.

In the case of IEEM, our model has now been developed and applied to 10 countries including Rwanda and Zambia in Africa, and Guatemala, Costa Rica, Colombia, and others in Latin America, as well as hundreds of policy simulations. In each of these exercises, we and other expert collaborators have carefully verified the precision of the results calculated and conducted systematic sensitivity analysis of free model parameters. In the case of Rwanda, we counted on the expertise of 18 individuals associated with Rwandan and international institutions that collaborated on the Science for Nature and People Partnership Project “Rwanda Natural Capital Accounting” (SNAPP, 2020). The background and expertise of the team included environmental economists, geographers, conservation scientists, and government planning and policy-making officials. We have also traced modeling results back to the underpinning theory and data of the model, often through a detailed description of the transmission pathway of a particular policy shock. This experience demonstrates the robustness of the IEEM modeling framework for a range of policy applications (Banerjee et al., 2019d; Banerjee et al., 2019b).

Regarding ecosystem service models, model calibration and validation are interpreted in the more conventional way. Due to a lack of calibration data, however, the use of uncalibrated ecosystem service models is still relatively common globally (Schägner et al., 2013). While the absolute values of such models are less reliable than calibrated models, such models are still useful for showing direction of effects and relative quantities of change in scenario analyses, which account for their continued use (Chaplin-Kramer et al., 2019). In the Rwandan case, data were available to calibrate water yield models but not those for sediment and nutrient regulation.

3.1. An IEEM model 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 (European Commission et al., 2009) and the SEEA (United Nations et al., 2014). CGE models are considered the ‘workhorse’ of policy analysis (Jones, 1965) and indeed offer the only robust means of exploring policies that can have a wide-reaching impact on multiple sectors of the economy (Arrow, 2005).

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 startup costs and increases the timeliness of evidence-based policy advice (Banerjee et al., 2016b; Banerjee et al., 2019b). For example, the SEEA provides information on timber harvest volumes in both volumetric and value terms. Prior to the SEEA, while the value of timber harvest is recorded in a country's System of National Accounts, timber harvest volumes, if provided, may not be reported in one consolidated source and may not necessarily correspond exactly to the harvest values reported in the System of National Accounts. Early work in Brazil required consultation of individual annual forest operational plans to estimate annual timber harvest volumes. Consistency with the values reported in the System of National Accounts was not assured and thus some data reconciliation was required (Banerjee and Alavalapati, 2010).

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 and non-provisioning ecosystem services. The environment and the provisioning services that it provides is represented by the SEEA, namely mineral and energy, land, soil, timber, fisheries, and water accounts. Our linkage of IEEM with ecosystem services modeling makes it possible to also capture the environment's contribution of non-provisioning services. The economy on the other hand is 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. Through economic activity and household consumption of goods and services, emissions and waste are generated and returned to the environment. To mitigate and repair environmental damage, investments are made in the environment by the public and private sectors. IEEM's underlying data structure captures all these interactions quantitatively.

To calibrate IEEM, we constructed a Social Accounting Matrix for Rwanda with a base year of 2014 (King, 1981; Pyatt and Round, 1985; Breisinger et al., 2009; Banerjee et al., 2019e). 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 new land and water accounts (Government of Rwanda, 2018; Government of Rwanda, 2019). 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. The amount of land demanded by agriculture, livestock and forest plantations grows in the baseline until 2035. The distribution of land between agriculture and livestock is endogenous and based on demand and relative prices. The land available for both agriculture and livestock together grows between 0.04% and 0.06% annually, based on the growth trend in Rwanda's Land Accounts (opening stock of 2014 and closing stock of 2015). The source of this land is discussed in the Section 3.3. Forest plantations grow by about 0.37% annually, which is half of the growth rate exhibited between the opening and closing years of 2014 and 2015 in the Land Accounts. These rates of growth translate into expansion by 2035 of agricultural land, livestock land and forest plantation land by 11,730, 2487, and 14,851 ha, respectively. Urban growth is also taken into account in the BASE scenario and all other scenarios except COMBI2, where no urban expansion is included.

FOR1: FOR1 assumes an additional 110,400 ha of forest plantations beyond BASE in the same year; while to simulate competition between land uses, there is a simultaneous reduction in the exogenous component of land available for agriculture and livestock. Specifically, for each hectare of forest plantation expansion, there is an exogenous 0.25-ha reduction in the land available for both agriculture and livestock. Forest planting occurs at a rate of 7360 ha per year between 2018 and 2032, which is close to the average planting rate in 2015 (MINIRENA, 2014). We classify newly planted forests in the LULC Change Model as “sparse forest” and do not change this over time; in other words, we do not account for forest succession.

Agroforestry systems are implemented on 85% of cultivated land (975,084 ha). This scenario only considers their investment cost, while benefits attributed to agroforestry systems such as enhanced soil fertility, slope stability and biomass accrue to households and society. These benefits are not monetized, though they are quantified through the ecosystem services modeling component of IEEM+ESM. The total investment cost of expanding forest plantations and agroforestry is US $285,581,699 over a 14-year period, for an annual investment of US $20,398,693 (Isaac et al., 2016). By 2035, the area dedicated to agriculture, livestock and forest plantations in this scenario are 1,237,534, 118,786, and 318,657 ha, respectively.

FOR2: FOR2 assumes an equivalent increase in forest plantations as in FOR1, with the difference being there is no competition between land uses and thus no simulated reduction in the exogenous component of land available for agriculture and livestock. As in BASE, the land available for agriculture and livestock together grows at between 0.04% and 0.06% annually. Forest planting occurs at a rate of 7360 ha per year beginning in 2018 and ending in 2032.

FUEL: This scenario simulates the introduction and use of more efficient household cookstoves and charcoal kilns, which both reduce raw fuelwood requirements and improve household health by reducing exposure to smoke and particulates. Gains are modeled through a 25% increase in household fuelwood consumption efficiency, implying that energy produced from fuelwood can be achieved using only 75% of currently used total woody biomass (Isaac et al., 2016).

Various studies have measured improvements in household air quality arising from the more efficient use of fuelwood (Duflo et al., 2008; Lambe and Ochieng, 2015; McCracken and Smith, 1998). Some studies have used this information to estimate associated economic benefits. For example, García-Frapolli et al. (2010) using data from Habermehl (2007), account for the number of work hours lost that were attributable to acute respiratory disease, eye disease and burns arising from open cookstoves in the home (Habermehl, 2007; García-Frapolli et al., 2010) In this scenario, we used their approach to estimate the number of lost work hours avoided and attributed that to more efficient household fuelwood use. The hours saved translate into the equivalent of 0.5% of the labor value added in the baseline; given this gain in labor value added and the fact that more than half of fuelwood consumption occurs in rural areas, we implemented a rural household labor productivity shock of 0.125% as a proxy for the improved health benefits of improved household air quality. The total investment cost of implementing efficient cook stoves and kilns is US$4,529,051 over a 5-year period beginning in 2018 for an annual investment of US $905,810 (Isaac et al., 2016). Land availability for agriculture, livestock, and forest plantations, follows the trend described in BASE.

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. Based on past gains reported by the Ministry of Agriculture and Animal Resources (2016), we applied a yield gain of 25% across all crops for newly irrigated areas (Ministry of Agriculture and Animal Resources, 2016). To maintain a conservative approach, we did not consider possible increases in the price of crops due to quality improvements and seasonality but do account for increases in agricultural total factor productivity. Land availability for agriculture, livestock, and forest plantations follows the trend described in BASE. An agricultural development package that includes this irrigated agricultural expansion is estimated to cost US$972,466,629 (Kaindaneh and Ntabana, 2014). We imposed costs and yield improvements according to a logarithmic function beginning in 2018 and concluding in 2035.

FERT: This scenario increases the area and quantity of fertilizer applied to all cropland to 45 kg/ha/yr. This rate of application results in a total of 55,000 million tons of fertilizer applied nationally, which is consistent with Rwanda's Strategic Plan for the Transformation of Agriculture (PSTA III). With fertilizer use totaling 35 billion tons in 2013 (Ministry of Agriculture and Animal Resources, 2014), this implies a 57% increase. Under a fertilization regime such as that of Rwanda's Crop Intensification Program, yields were found to double for key staple crops (Green World, 2014). In this scenario, we applied a 50% increase in crop yields to 50% of Rwanda's total cultivated area, implemented as an increase in agricultural total factor productivity. We assumed that this increase in fertilizer application will occur according to a logarithmic function between 2018 and 2035. The increased production costs arising from fertilizer application are absorbed by producers. Land availability for agriculture, livestock, and forest plantations follows the trend described in BASE.

COMBI1: This scenario is the joint implementation of FOR1, FUEL, IRRIG, and FERT. As in FOR1, for each hectare of forest plantation expansion, there is an exogenous 0.25-ha reduction in the land available for both agriculture and livestock together (between 2018 and 2032).

COMBI2: This final scenario is the same as COMBI1 but does not account for urban expansion. A comparison of the results of COMBI1 and COMBI2 enables the understanding of the impacts of urbanization and analysis of land-use trade-offs given Rwanda's limited land endowment. Section 3.3 describes urban growth as modeled in all scenarios except COMBI2.

All of the non-BASE scenarios assume that associated investment costs are financed through a non-reimbursable foreign grant. For all scenarios, IEEM requires the specification of the equilibrating mechanism for three macroeconomic balances at the macro level. For the non-BASE scenarios these are: (i) the impact on the government fiscal balance is cleared through changes in income tax rates on households; this assumption ensures that the simulations are budget neutral. In other words, there is no additional domestic and/or foreign financing beyond baseline values; (ii) private investment in Rwanda is endogenous and adjusts to the available savings; and (iii) the real exchange rate adjusts to equilibrate foreign exchange inflows and outflows by influencing export and import quantities, thus the simulations are neutral in terms of changes in regional net foreign assets. The non-trade-related payments of the (local) balance of payments (transfers and foreign investment) are non-clearing and follow exogenously imposed paths.

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 (Fig. 2) is to develop a national LULC Change Model. The LULC Change Model was developed using the ArcMap Model Builder version 10.3 and has three overall stages: (i) development of a geographic information system (GIS) for Rwanda (relevant datasets used for LULC modeling are listed in Appendix A of the Supplementary Material, Table A1); (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 (Fig. 3). 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 (Veldkamp and Fresco, 1996; Verburg et al., 1999; Verburg et al., 2008; Malek et al., 2019; Verburg and Overmars, 2009).

The spatial data we used in developing the GIS for Rwanda include the 2015 LULC map, a digital elevation model, hydrography, Rwanda's Land Use Master Plan (Government of Rwanda, 2014; MINIRENA, 2017), protected areas, political/provincial boundaries, and roads. Data sources for these, plus additional spatial data and parameters used to run the ecosystem service models, are described in Appendix A of the Supplementary Material. The 2015 LULC map is the starting point for allocating scenario-based LULC change (Fig. 1). This map was developed through the SERVIR program using Landsat 7/8 imagery with 30-m resolution through supervised classification. As part of the largest ongoing

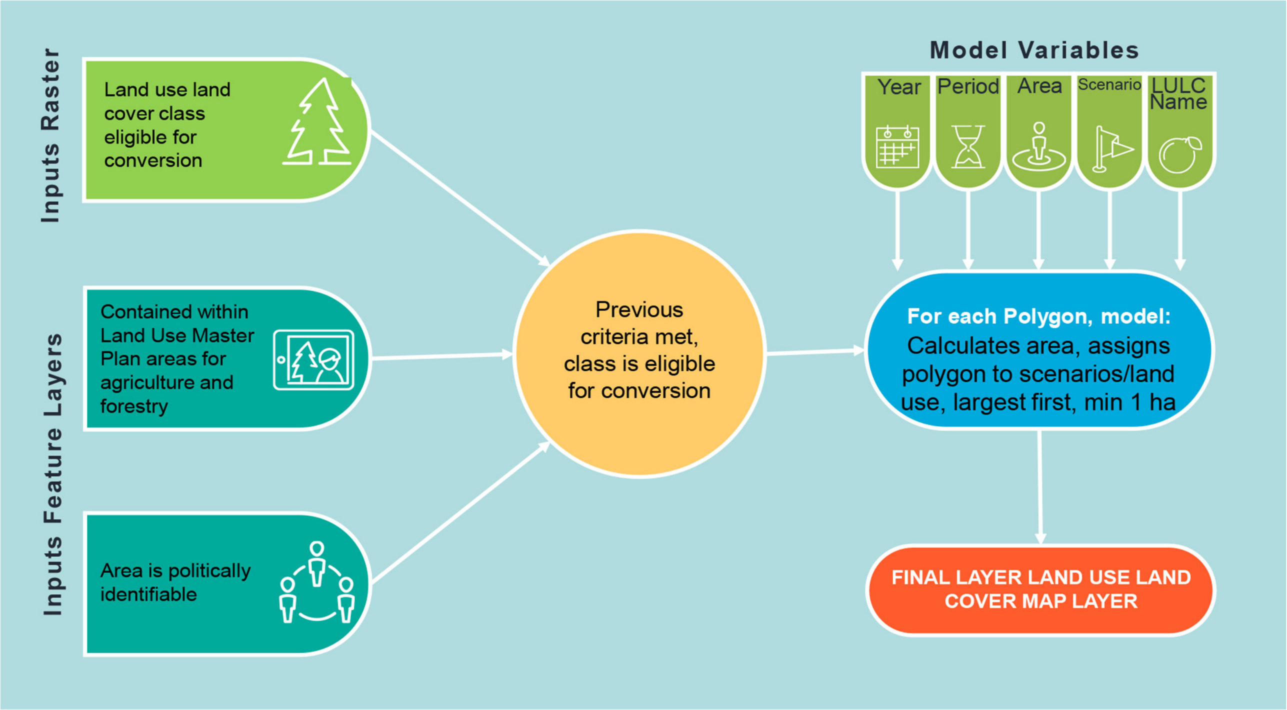

Fig. 3. Land use-land cover (LULC) change modeling workflow.

mapping initiative in Africa, SERVIR-Eastern and Southern Africa at the Regional Centre for Mapping of Resources for Development, has been supporting countries in generating Landsat-derived land cover maps for greenhouse gas (GHG) emissions inventories. These maps are generated in close consultation with end users and contribute to the United Nations Framework Convention on Climate Change (UNFCCC) reporting to quantify the GHG inventory.

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; Table 1). Decision criteria for allocating LULC change in the BASE and the other scenarios were developed through expert elicitation, including experts involved in implementing Rwanda's Land Use Master Plan. Decision criteria for the BASE were as follows. For agriculture and livestock land use expansion, pixels were deemed eligible for conversion subject to the following criteria if they are: (i) contained within areas designated for agriculture in Rwanda's Land Use Development Master Plan; (ii) not located within protected areas; (iii) classified in the base map as open or closed shrubland or grassland but not annual or perennial cropland; and (iv) subject to the above criteria, the largest contiguous areas are selected first, with a minimum size of 1 ha. All new agriculture and livestock pixels are reclassified as annual cropland, consistent with the base map LULC classes. The process for allocating IEEM results for the IRRIG, FERT, COMBI1, and COMBI2 scenarios follows the same allocation rules described above.

Based on the LULC classes in Rwanda's 2015 LULC map, Table 1 shows the baseline projection of LULC in 5-year increments from the base year of 2015 to 2035.

Fig. 4 shows the designated areas for agriculture and forestry activities in the Land Use Master Plan. Areas eligible for forest plantations are generally sparsely distributed throughout the country. Much of the areas eligible for 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. Fig. 4 also shows the baseline LULC projections in 5-year increments to 2035.

In the FOR1 scenario, 110,400 ha are required to meet the scenario target for expanding forest plantations. Pixels were deemed eligible for conversion to forest plantations subject to the following criteria if they are: (i) designated as Forest Management areas in Rwanda's Land Use Development Master Plan; (ii) not located within protected areas; (iii) classified as open or closed shrubland or grassland; and (iv) subject to the above criteria, the largest contiguous eligible areas are selected first, with a minimum size of 1 ha. All new forest plantation pixels are reclassified as sparse forest, consistent with the base map LULC classes.

In applying these criteria, only 1032 ha were available for conversion to forest plantations. Given the need to identify another 109,368 ha for forest plantations, areas outside those identified for Forest Management in the Land Use Master Plan were made available. With this exception, the FOR1 selection criteria were again applied to select the remaining areas.

For each modeling time step and in all scenarios except COMBI2, we also accounted for urban expansion. Future urban growth is based on planned urban extents from Rwanda's Land Use Master Plan. Pixels designated as new urban areas are selected evenly around current urban centers. This expansion occurs by the projected amount for each 5-

Table 1
Baseline land use-land cover (LULC) projection from 2015 to 2035 (ha).

	Dense forest	Moderate forest	Sparse forest	Closed grassland	Open grassland	Closed shrubland	Open shrubland	Perennial cropland	Annual cropland	Wetland	Urban
2015	115,428	47,155	268,487	31,392	117,260	49,749	281,534	33,947	1,307,426	86,809	36,232
2020	115,561	47,117	271,063	31,306	113,474	49,728	277,122	33,756	1,300,889	88,434	50,476
2025	115,553	46,992	273,560	31,277	109,785	47,244	274,225	33,581	1,293,451	88,361	65,019
2030	115,531	46,840	275,828	30,369	108,792	47,183	267,395	33,376	1,285,868	88,266	79,760
2035	115,512	46,667	278,018	29,219	105,373	47,054	263,191	33,157	1,278,235	88,139	94,836

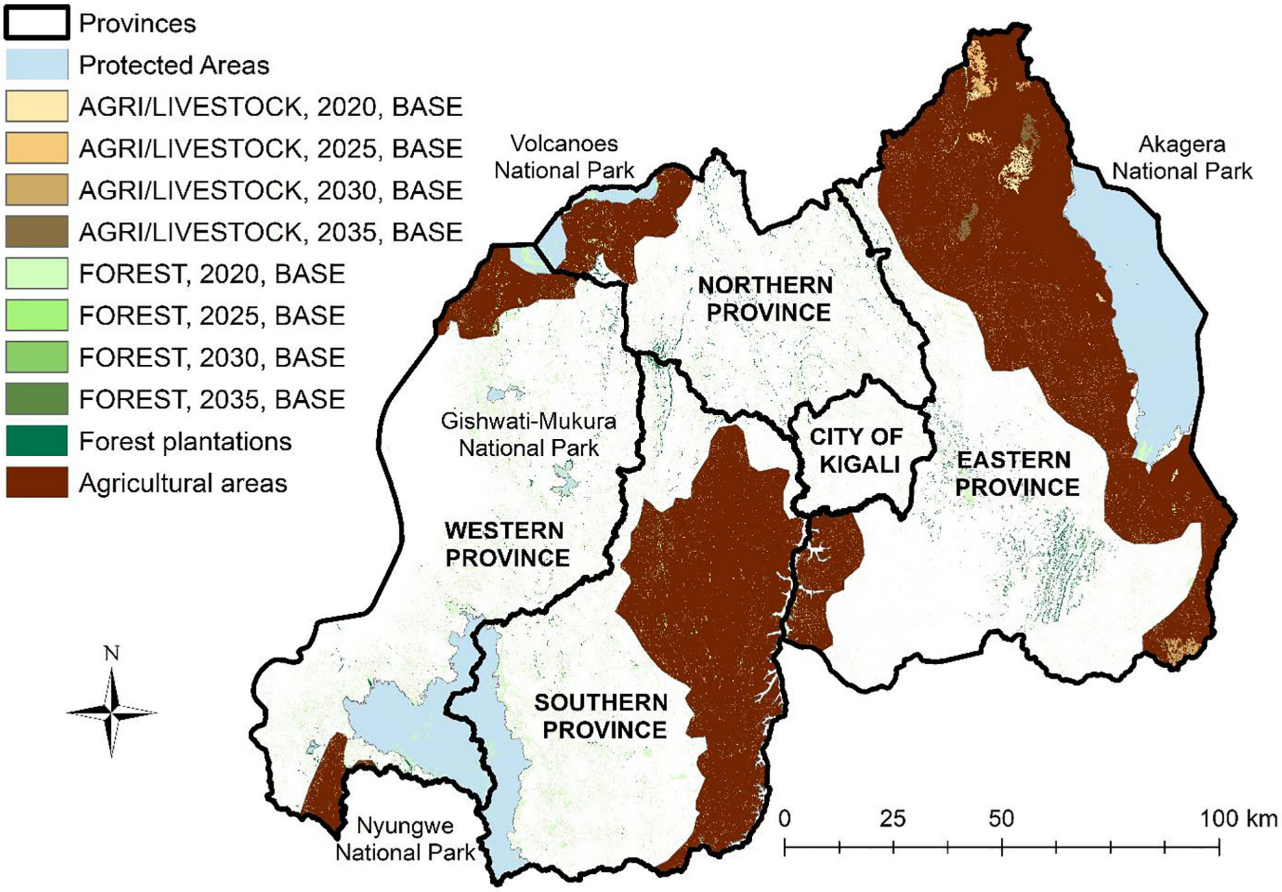

Fig. 4. Rwanda Land Use Master Plan areas and conversion to agriculture and livestock in the baseline (BASE) 5-year increments from 2020 to 2035. AGRI, FOREST, and LIVESTOCK indicate expansions in agricultural, forestry, and livestock land use, respectively.

year time step, prior to any agriculture, livestock or forestry expansion. Two important consequences of this approach to urban expansion are: (i) urban pixels are the same across the BASE and all scenarios; and (ii) with urban areas expanding evenly outward from their center, all LULC classes are eligible for conversion to urban uses. This therefore has consequences for agriculture, livestock and forest plantation areas. Indeed, with many agricultural areas located around urban centers, we find that urban expansion consumes area that was or would have otherwise been used for agriculture and livestock. Recent developments of the IEEM+ESM Platform enable consideration of economic feedbacks of this type of interaction between land use, land availability and the economy (Banerjee et al., 2019b; Banerjee et al., 2019c; Banerjee et al., 2019a). Conversion of forests located farther from urban centers to urban land is less pronounced.

3.4. Ecosystem service modeling

We used the InVEST 3.3.3 modeling software (Sharp et al., 2018) 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 (Appendix B of the Supplementary Material). We used recent historical average precipitation (WorldClim version 1.4; (Hijmans et al., 2005)) and evapotranspiration data (CGIAR Global Aridity Index and Potential Evapotranspiration Database version 1.0, (Zomer et al., 2006)) for all scenarios, i.e., we did not include the potential effects of climate change in our ecosystem service models. We provide relevant information about all model input datasets (i.e., sources, spatial resolution, year) used in Appendix A of the Supplementary Material, Table A1.

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 (Johnson et al., 2019). 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-m spatial resolution.

The InVEST carbon storage model matches land cover to estimated carbon pools data using a lookup table. Its annual water yield model uses the Budyko curve method to estimate actual evapotranspiration (AET), then subtracts AET from precipitation to estimate annual water yield. 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 (Sharp et al., 2018).

Detailed methods are described in the Supplementary Material, including spatial data inputs and literature sources for model parameterization (Appendix A), methods for deriving soil erosion model support (P) factors based on terracing data for Rwanda (Appendix B), and water model calibration (Appendix C), all drawing on recent studies (Rukundo et al., 2018; Bagstad et al., 2020). We summarized final results for all ecosystem service models at the national scale and for Rwanda's five provinces using ArcMap 10.3.

4. Results

4.1. Economic impacts

In comparing national-scale macroeconomic indicators between BASE and scenarios for 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 (Table 2). FOR1 also shows a small negative impact on private consumption, fixed investment, and genuine savings. Increasing fertilization boosts GDP and genuine savings by US$2781 and US$713 million, respectively. The joint impact of all scenarios represented by COMBI generates the largest gains with a US$3591 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 (Fig. 5) and genuine savings impacts, and a strong reduction in poverty. FOR1 shows a small (0.1%) increase in poverty by 2035.

As a percentage difference from 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 (Table 3). Imports are less responsive with changes ranging from 0.1% in IRRIG to 5.7% in COMBI1. Scenarios result in faster fixed investment growth, up to 6.8% 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 markedly in FERT (11.0%). Unemployment increases by 2.2% in FOR1, by 1.3% in FUEL and less in FOR2 (0.3%). The FERT scenario is strongly poverty reducing, by 17.5%.

In terms of sectoral economic activity, Agricultural activity grows across scenarios with the exception of FOR1, most strongly by 23.6% in FERT (Table 3). 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%. Manufacturing is positively impacted in all scenarios, up to 9.4% in FERT, as is the Services sector with a maximum increase of 6.4% in COMBI1.

4.2. Natural capital impacts

Rwanda's natural capital accounts provide data on forest cover, land, and water. Relative to the BASE, agricultural and livestock land use decline by 25,377 and 2284 ha, respectively in FOR1 (Fig. 6). Forest land use increases by 110,400 ha to meet the forest cover target. FUEL land use changes little in relation to the BASE. In IRRIG, agricultural land use falls by 803 ha while livestock use increases by 828 ha. FERT land-use changes are more pronounced, with a 10,039 ha decline in agricultural land use in relation to BASE; 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 and a 8593 ha increase in livestock. Forest cover increases by 110,400 ha.

Table 2
Difference in macroeconomic indicators for baseline versus scenarios (FOR1, FOR2, FUEL, IRRIG, FERT, and COMBI) for 2035; millions of 2014 U.S. Dollars. GDP: gross domestic product. Values in parenthesis are negative.

	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

Water consumption increases markedly in the FERT and COMBI scenarios by over 7.23 and 7.20 million m^3, respectively. There was reduced water consumption in FOR1 and FUEL (197,252 and 216,860 m^3, respectively) and slightly increased water consumption in FOR2 and IRRIG (250,663 and 503,455 m^3, respectively). Table 3 reports these changes in both land use and water consumption as the percent difference from the BASE in 2035.

4.3. Ecosystem services impacts

Ecosystem service models enable quantification of cumulative changes in ecosystem services for all scenarios (i) over time, from 2015 to 2035 (Fig. 7) and (ii) for 2035 when comparing BASE to other scenarios, similar to the presentation of macroeconomic indicators, at national and provincial scales (Fig. 8). 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 (Fig. 7). 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.

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 mainly 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. 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 (Fig. 8). 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 forest plantations are established) 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 (Fig. 8). Distinct 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 reduced cropland loss and impervious urban area increases 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.

Figs. 9 and 10 show how carbon storage and water quick flow, respectively, change between 2015 and 2035 in the BASE, FOR1, and

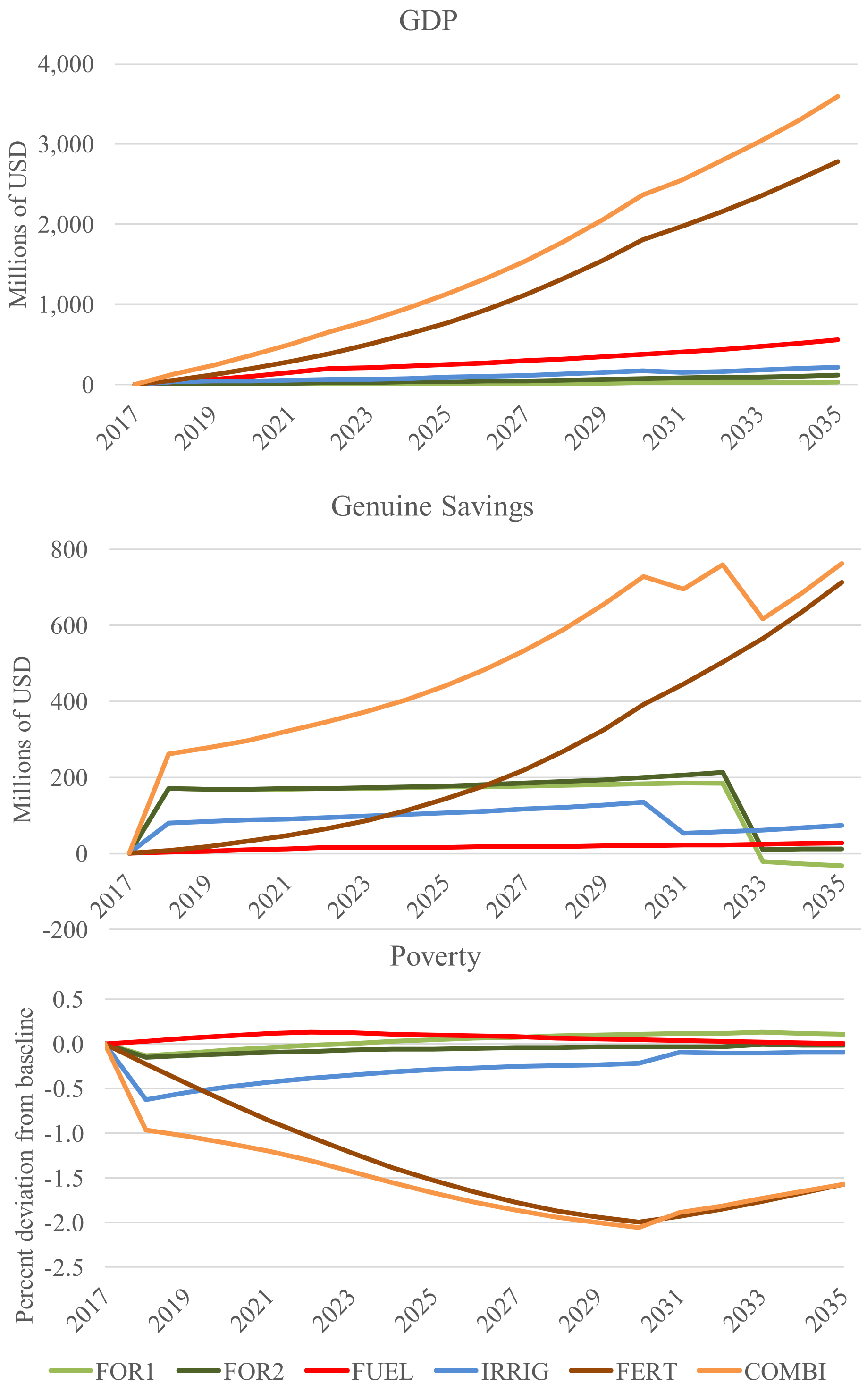

Fig. 5. Percent deviation from baseline by scenario for key macroeconomic indicators.

COMBI scenarios. The dashed circles on the maps indicate areas that experience the greatest change in the scenarios, which are in the northwest and south-central regions of the country.

5. Discussion

5.1. Integrated analysis of development scenarios and their implications

In this discussion, we first use IEEM+ESM's multidimensional approach to evaluate all scenarios across all dimensions, followed by discussing the caveats of our study, prospects for fostering green growth in Rwanda, and next steps for advancing the IEEM+ESM approach. The integration of model results for macroeconomic and environmental/ecosystem services indicators is at the heart of the innovative IEEM+ESM approach (Table 3).

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

Table 3

Macroeconomic, System of Environmental-Economic Accounting (SEEA) Central Framework, and ecosystem services impacts expressed as percent difference between scenario and baseline (BASE) for each scenario in 2035. GDP: gross domestic product.

		Difference between BASE in 2015 and 2035	Percent difference between scenario and BASE in 2035						
		BASE	FOR1	FOR2	FUEL	IRRIG	FERT	COMBI1	COMBI2
Macroeconomic indicators (IEEM)	Absorption	329.3	-0.1	0.2	1.2	0.5	6.7	8.4	8.4
	Private consumption	311.9	0.0	0.3	1.9	0.5	8.2	10.7	10.7
	Fixed investment	350.5	-0.2	0.1	0.1	0.5	6.4	6.8	6.8
	Exports	427.3	1.3	0.9	3.1	0.8	11.0	16.4	16.4
	Imports	361.2	0.2	0.2	0.9	0.1	4.4	5.7	5.7
	GDP	332.7	0.1	0.3	1.6	0.6	8.1	10.5	10.5
	Genuine savings	364.9	-0.5	0.2	0.4	1.1	10.8	11.6	11.6
	Indirect tax income	317.0	0.0	0.3	1.2	0.5	7.9	9.8	9.8
	Real exchange rate	-1.2	-0.1	0.4	0.8	1.2	7.0	8.7	8.7
	Wages	113.8	-1.5	-0.1	-0.6	0.6	11.0	9.3	9.3
	Unemployment*	-48.6	2.2	0.3	1.3	-0.5	-8.9	-6.2	-6.2
	Poverty*	-79.4	1.2	-0.2	0.0	-1.1	-17.5	-17.4	-17.4
	Agricultural activity	178.6	-1.6	0.1	0.2	1.6	23.6	23.5	23.5
	Livestock activity	166.2	-1.6	0.1	0.1	0.7	8.7	7.7	7.7
	Forestry activity	394.8	2.6	2.2	-3.3	0.2	2.9	2.2	2.2
	Manufacturing activity	353.8	0.4	0.5	1.6	0.5	9.4	11.9	11.9
	Services activity	401.0	0.3	0.3	0.7	0.5	4.8	6.4	6.4
SEEA Central Framework: Land & water-use change	Agricultural land use	0.9	-2.0	0.0	0.0	-0.1	-0.8	-2.8	-2.8
	Livestock land use	2.1	-1.9	0.0	0.0	0.7	8.6	7.1	7.1
	Forestry land use	7.7	53.0	53.0	0.0	0.0	0.0	53.0	53.0
	Water use	223.6	-0.4	0.5	-0.5	1.1	15.7	15.6	15.6
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

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. In terms of genuine savings, the FOR scenarios have a positive impact on the natural capital stock component of genuine savings due to forest plantation expansions. Both FOR1 and FOR2 result in some of the largest gains in ecosystem services supply over BASE—with increased carbon storage and local recharge and reduced nitrogen and phosphorus exports; the gains in FOR1 are slightly larger.

FUEL scenario results are positive across macroeconomic 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. Two main transmission pathways 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, household consumption, and savings possibilities. Ecosystem services in FUEL are essentially unchanged from BASE since there is little change in LULC.

The IRRIG scenario results in positive changes to macroeconomic indicators (notably wages, employment, household welfare, and genuine savings) 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. However, in the short run and due to the inflow of foreign exchange required to finance the investment in irrigation, an appreciation of the real exchange rate 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, a reduction in forest natural capital stocks 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 m^3/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$2781 million and US$713 million, respectively. While agricultural product prices may fall as a result of the increase in total factor agricultural productivity and the large increase in output in FERT, 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 m^3/yr).

The COMBI1 scenario, which is the joint impact of FOR1, FUEL, IRRIG and FERT, shows strong positive effects on the economy—resulting in

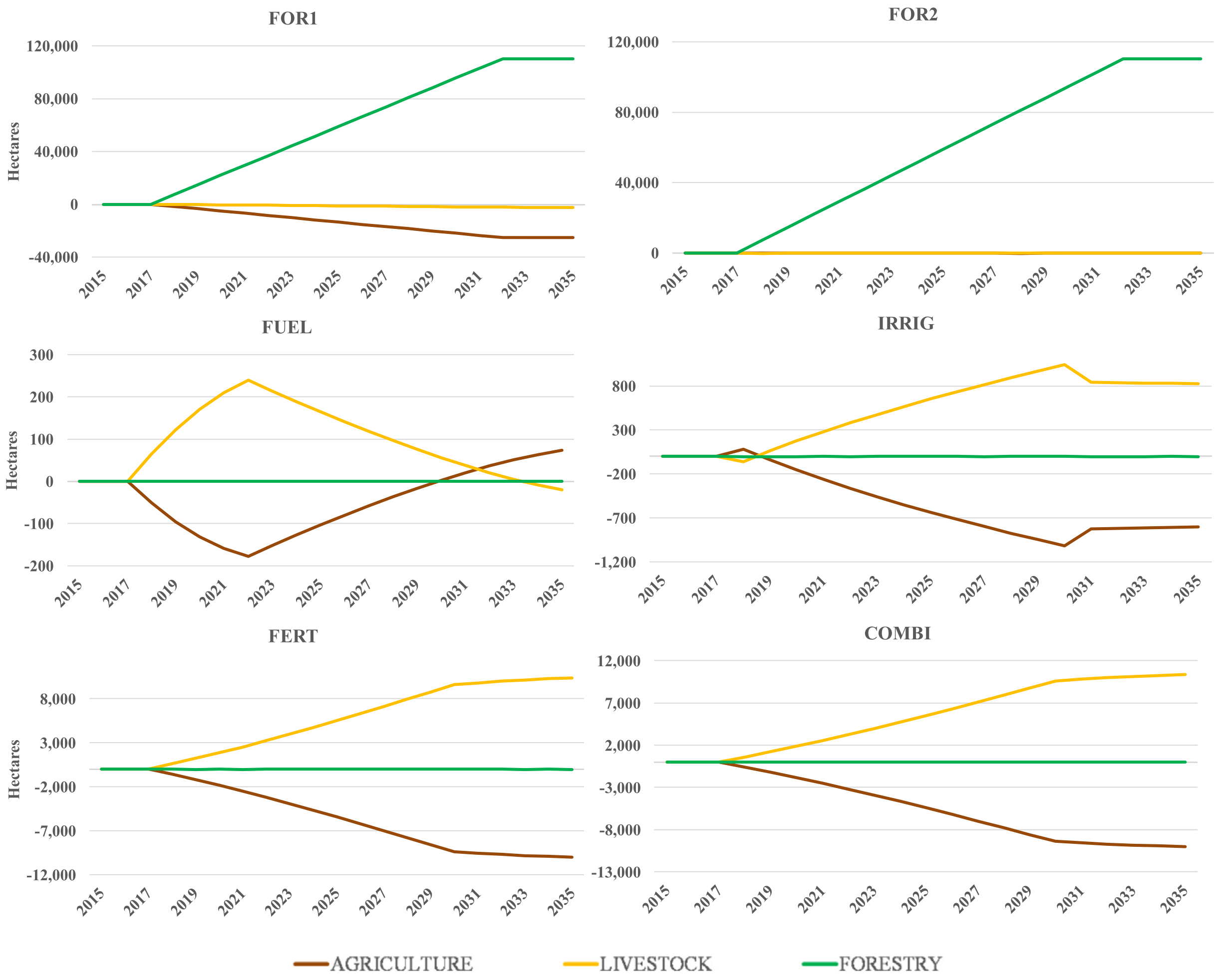

Fig. 6. Changes in land use by scenario. Difference from baseline (BASE) in hectares, by year.

GDP gains of US$3591 million and a US$763 million increase in genuine savings. The reduced agricultural land availability arising from FOR1 is more than compensated through fuelwood efficiency enhancement and the productivity implications of increased irrigation and fertilizer use. Its poverty-reducing impact (1.57%) 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 contributions of additional forest plantations, but also increases in nitrogen and phosphorus export (42% and 45%, respectively), along with substantially greater water use (7.2 million m^3/yr). Nutrient exports are somewhat lower than in FERT, because additional forest plantations provide greater nutrient uptake (Tomer et al., 2015; Aufdenkampe et al., 2011).

Sector activity across scenarios generally increases relative to BASE, 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 forest plantation expansions with those of increasing natural forest management, an issue we explored in earlier work (Banerjee et al., 2016a). 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.

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, household income, consumption, and savings, and reduced unemployment.

5.2. Caveats

Despite the key trade-offs identified related to fertilizer and water use, water quality and quantity are more difficult to value monetarily. 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 (Banerjee et al., 2019b; Banerjee et al., 2019c). 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 considered.

Various limitations and uncertainties apply to the results of our ecosystem services models, as described below and in Appendices A-C of the Supplementary Material. Notably, the absolute values resulting

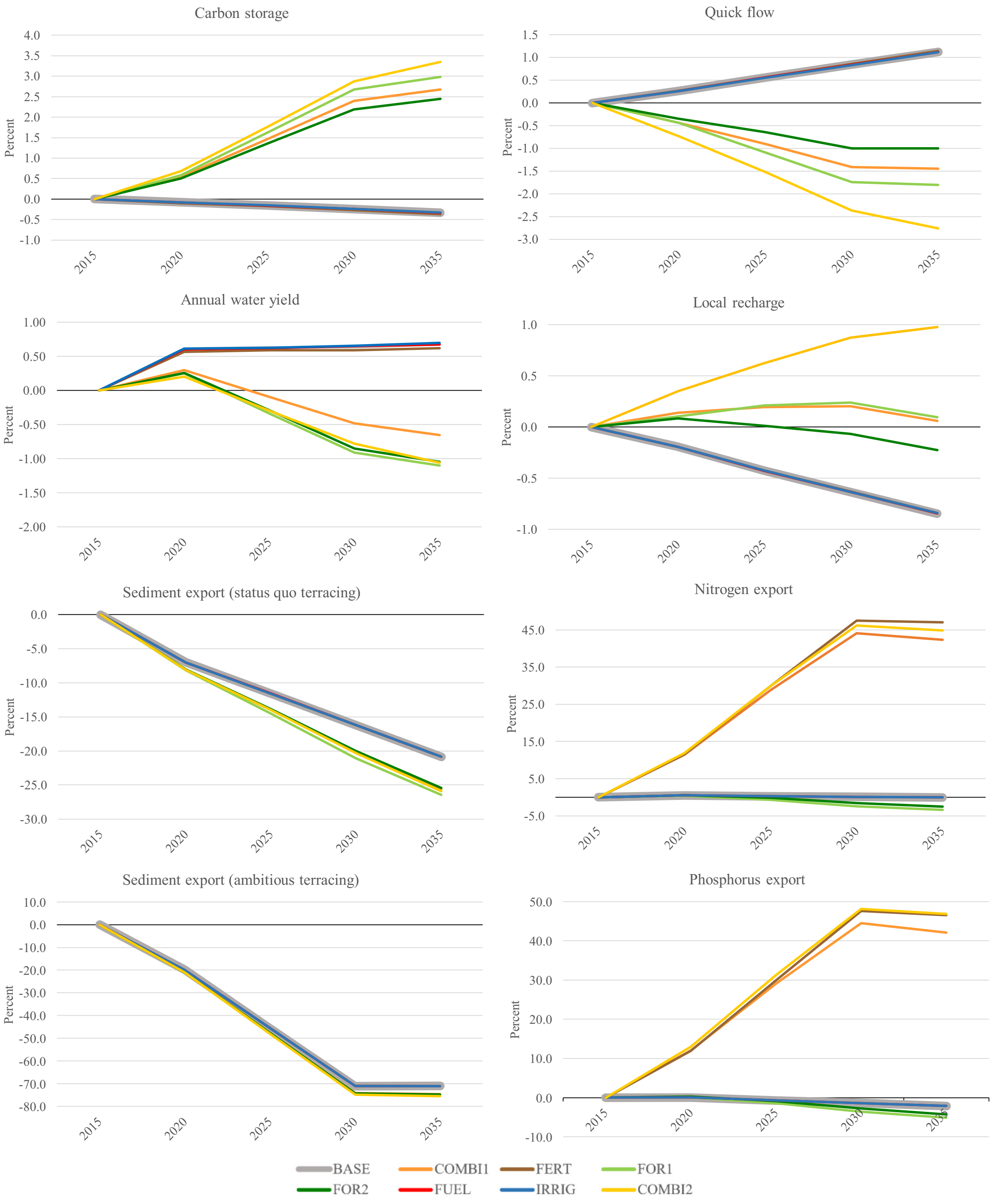

Fig. 7. Percentage change in ecosystem services at the national scale for Rwanda for baseline and scenarios from 2015 to 2035.

from uncalibrated models are less reliable than those of calibrated models. However, uncalibrated models remain frequently used to show the direction of effects and relative quantities of change in scenario analyses (Chaplin-Kramer et al., 2016). Our water yield models are calibrated ($R^2 = 0.72$; Appendix C). However, data limitations prevented the calibration of the remaining models. Our carbon storage estimates diverge substantially from the results of Rwanda's national forest inventory (Deutsche Forstservice GmbH (DFS) et al., 2016), due to large differences in the scope of that study with national scale ecosystem accounts, which prevent their direct comparability (Bagstad et al., 2020). Water-quality data needed to calibrate soil erosion and nutrient models are scarce in Rwanda (Muvundja et al., 2009; Uwimana et al., 2018).

We attempted to calibrate the SDR model using total suspended solids (TSS) data for eight small watersheds near Lake Kivu from Muvundja et al. (2009), the only study we found reporting TSS-derived annual sediment load data in Rwanda. We adjusted the Borselli kb parameter to a value of 0.37, which gave the best fit to two randomly selected watersheds from the Muvundja et al. (2009) study. However, when modeled and measured data were

Fig. 8. Percent changes in ecosystem services relative to baseline (BASE) by scenario at the national and provincial scale for 2035.

compared for the remaining six watersheds, we obtained an extremely low calibration coefficient ($R^2 < 0.01$). At least three reasons may explain why the model had such poor watershed-level explanatory power: (i) TSS data were from 2006 to 2008, and land cover data used in calibration were for 2010, a difference that introduces error in a country with relatively rapid land cover change; (ii) the underlying Revised Universal Soil Loss Equation does not account for soil erosion processes like gully and streambank erosion, as well as mass erosion that may occur in mountainous environments; and (iii) we had relatively high uncertainty about local-scale soil support (p) factors. Additionally, TSS calibration data were for a very small, and not necessarily representative, part of the country. Given these limitations, our final model used the default Borselli kb parameter value of 2. We recognize the need for more complete monitoring data that would allow calibration of sediment regulation models. We similarly lacked data to calibrate the nutrient delivery ratio model, reducing our confidence in the absolute values of nutrient export results.

Filling these data gaps 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 (Christian and Vedaste, 2017). Until such calibration data become available, the results of our ES models should be considered to be less reliable than their calibrated counterparts and such uncertainty should be considered when applying model results to decision making.

Finally, we did not include the effects of climate change in our ecosystem services models. Downscaled climate change projections for Rwanda suggest a warmer and wetter future climate, with increased water stress in the summer dry season owing to higher seasonal potential evapotranspiration (Haggag et al., 2016). Such changes would be expected to impact future ecosystem services supply and could be modeled using approaches like InVEST (Bai et al., 2019; Fu et al., 2017). Some ecosystem services models require direct input of climate parameters such as precipitation and evapotranspiration and could be

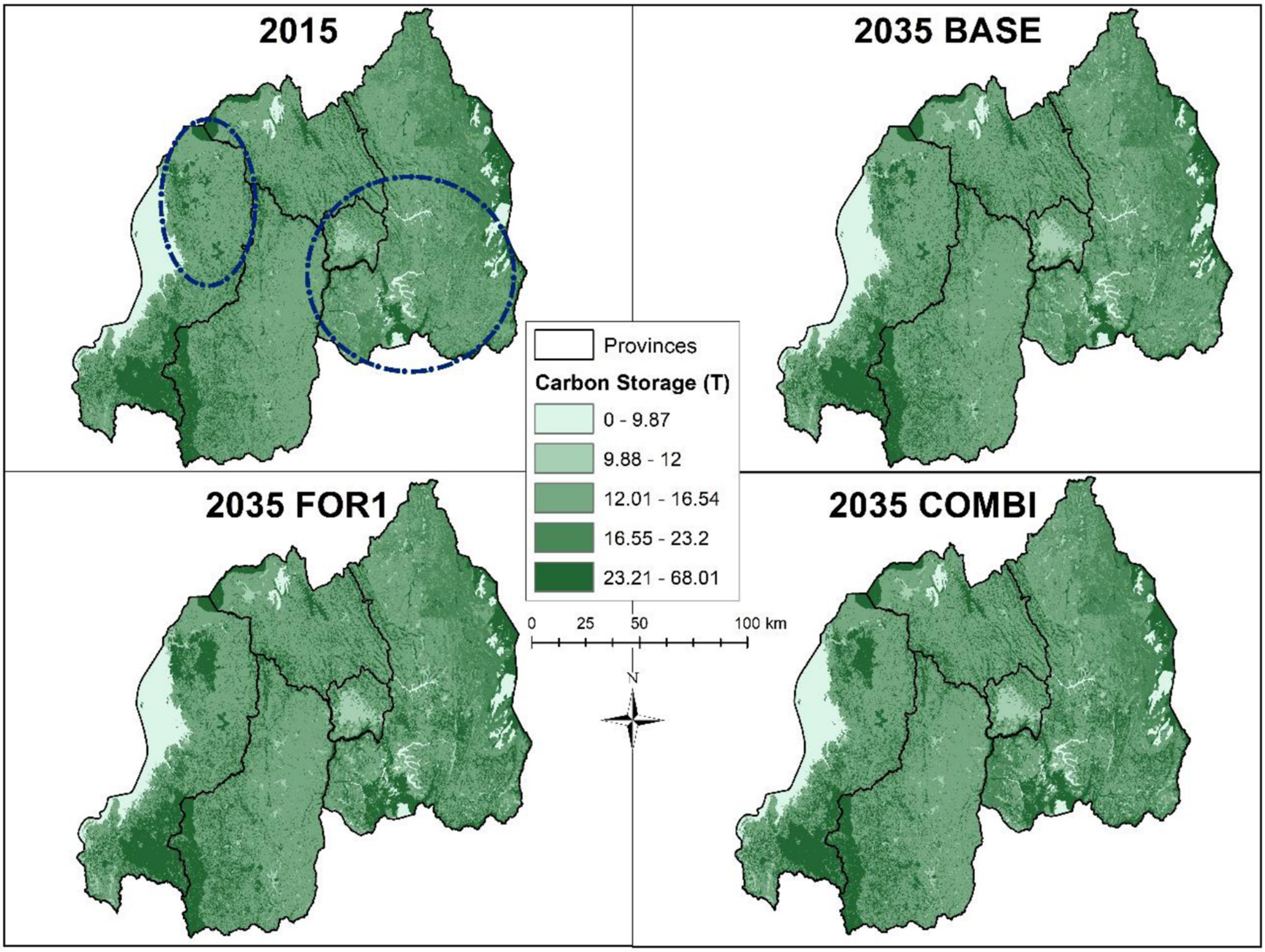

Fig. 9. Carbon storage for baseline (BASE) in 2015 and 2035, and forest plantations 1 (FOR1) and combination (COMBI) scenarios in 2035, in tons. Dashed circles indicate areas that experienced the greatest change in the scenarios.

included in the ecosystem services models applied in this analysis. All ecosystem services models require a LULC map as an input and therefore in future looking policy analysis with IEEM+ESM, climate change could also be accounted for in LULC change modeling by adjusting land suitability decision rules to reflect climate change impacts. As far as the IEEM model itself is concerned, climate change considerations could be incorporated in producing the baseline forecast, however if the policy scenarios include the same climate change considerations, there would be no impacts on the results.

5.3. Implications for green growth in Rwanda

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 provide the greatest gains, helping reverse a 25-year trend of forest loss in Rwanda (Rukundo et al., 2018; Bagstad et al., 2020) (Fig. 7). Of these, the FOR scenarios yield reductions in nutrient export. 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 Rwanda's surface waters matter because localized problems already exist with water quality and availability, particularly in the dry season (REMA, 2015; Nahayo et al., 2018; Nahayo et al., 2016). 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 dilutes concentrations of nutrients and other water pollutants. Water demand and water quality related to food production are thus the two most notable ecosystem service trade-offs that emerge from our analysis, as has also been observed in other systems (Power, 2010; Raudsepp-Hearne et al., 2010). While we did not explicitly quantify the tradeoffs between agricultural intensification and land degradation, such tradeoffs also exist and are problematic for sustainable development practice. For example, extensive fertilization and its mismanagement can lead to land degradation as noted in regions as diverse as China, India, and West Africa (Chinnasamy et al., 2019; Djagba et al., 2019; Luo et al., 2019; Nkonya et al., 2016a; Nkonya et al., 2016b). Further, increased irrigation can lead to increasingly intensive soil tillage, exposing soil to erosion and soil loss (Bilgili et al., 2018; Hillel et al., 2008).

Better water-quality outcomes may be possible if forest planting can be carefully targeted to intercept sediment and nutrients before they reach major waterways (Chaplin-Kramer et al., 2016; Hamel et al., 2015). A COMBI-type outcome that produces both positive economic and ecosystem service outcomes may thus be possible with very careful targeting of tree planting with an aim to protect water quality (i.e., along water courses). Achieving these multiple benefits may require a payment for ecosystem services-like incentive system informed by ecosystem service models (whose feasibility and implementation are currently being explored; (Tetra Tech and LTS Africa, 2018). However, green growth scenarios that reduce nutrient inputs into Rwanda's agricultural system, i.e., the FOR scenarios, could best ensure greater water-

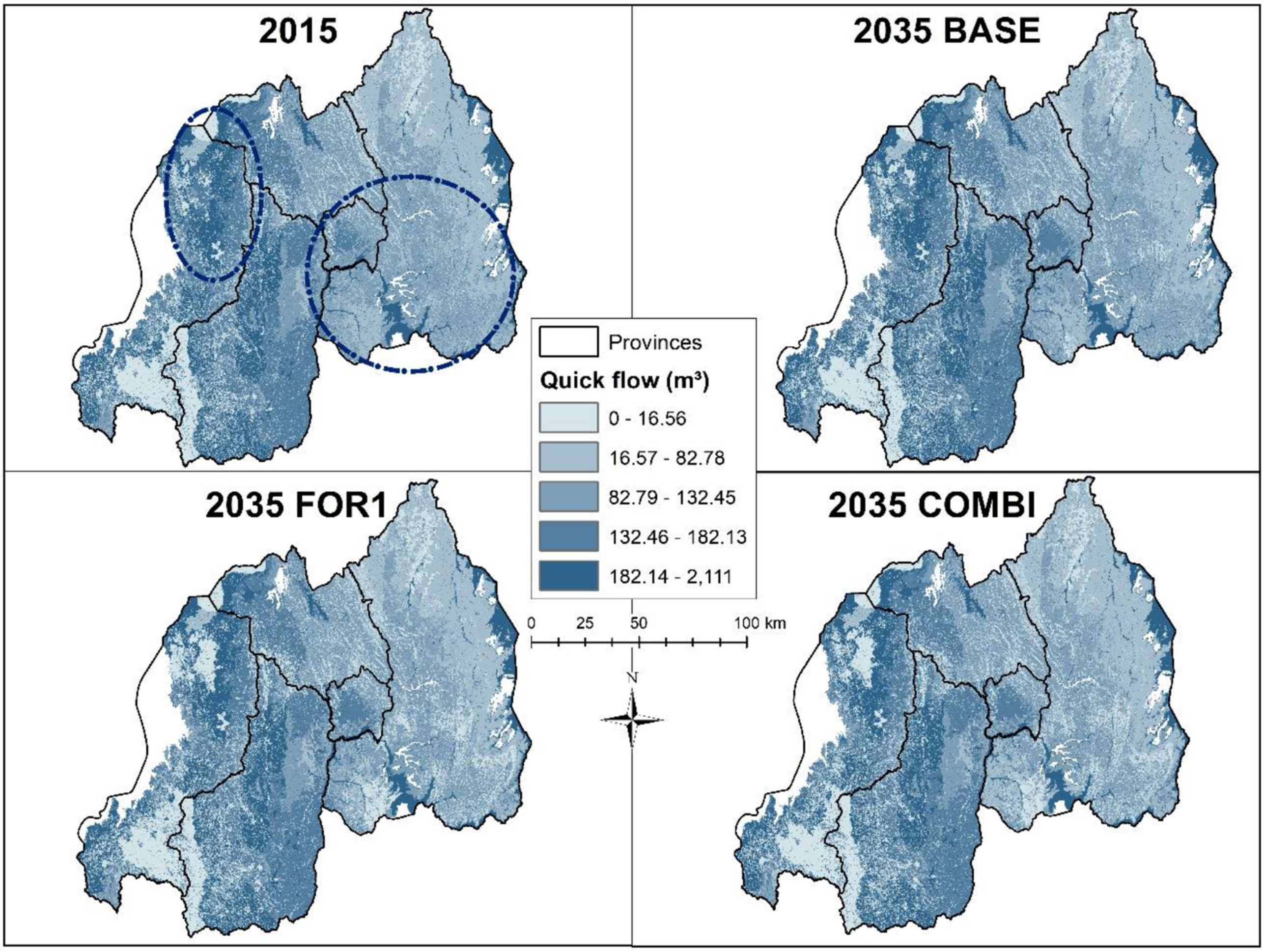

Fig. 10. Water quick flow for baseline (BASE) in 2015 and 2035, and forest plantations 1 (FOR1) and combination (COMBI) scenarios in 2035, in cubic meters. Dashed circles indicate areas that experienced the greatest change in the scenarios.

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 (REMA, 2017; World Bank and Government of Rwanda, 2018), but it comes with its own localized impacts to ecosystems and ecosystem service supply.

Changes in ecosystem services, and their contributions to human well-being, are not equally distributed across Rwanda (Figs. 8–10). Changes in the Northern, Western, and Southern provinces generally mirrored national-scale trends, while those in Kigali City are influenced by urbanization. The most substantial differences in LULC changes across scenarios were found in the Eastern Province, the flattest and driest region of Rwanda. Eastern Province ecosystem service trends thus 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. Water quantity and quality effects stemming from Rwanda's development choices in the Eastern Province may also have effects on neighboring Tanzania and Uganda, who share the Akagera watershed with Rwanda.

5.4. 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 past experience with linking CGE models with LULC change (Verburg et al., 2008) and recent efforts to link these with ecosystem services models at the global scale (Johnson et al., 2020). Previous approaches differ in three important ways. First, their workflow and sequence of analysis differ: generic scenarios and LULC projections were drawn from previous work and used as the basis for ecosystem service model runs. Shocks were derived based on changes in ecosystem services supply and were then implemented in a CGE model. By contrast, our approach begins with the implementation of a specific policy measure in IEEM, which leads to changes in demand for land and LULC change. This LULC change results in changes in future ecosystem services supply. Second, their scenarios do not evaluate specific policy measures, rather they tend to consider broad potential trajectories such as sustainable development versus business as usual development. Finally, 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 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 (Laniak et al., 2013). Economic-environmental analysis is fundamentally an interdisciplinary pursuit and these initial discussions are necessary from a technical standpoint but are equally important to bring analytical depth that one discipline alone cannot provide. Once these discussions have occurred 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 (Bagstad et al., 2020; Rukundo et al., 2018). The data needed to build IEEM+ESM applications–social accounting matrices, SEEA Central Framework accounts, and ecosystem services data and models–are somewhat scarcer in Africa than elsewhere. However, progress is being made toward each, which makes our approach increasingly transferrable to other nations in Africa and beyond. Almost all countries of the African continent measure economic activity according to the System of National Accounts. This ensures that the basic building blocks for the construction of a CGE model and IEEM are likely to exist for most African countries. What does tend to vary across countries is public access to this data, the quality of these accounts, the vintage and level of disaggregation of the supply and use tables, and the availability of integrated economic accounts, all of which are important elements for the development of a robust IEEM framework. SEEA Central Framework accounts have been developed in Botswana, Madagascar, Uganda, Zambia and are underway elsewhere in Africa (World Bank, 2018). Finally, ecosystem service models have increasingly developed for a wide range of locations across Africa (Leh et al., 2013; Turpie et al., 2008; Willcock et al., 2014; Willemen et al., 2018; Recuero Virto et al., 2018).

To more rapidly apply IEEM+ESM in other countries, however, wider adoption of methods to efficiently reuse economic, LULC, and ecosystem service models and data would reduce startup resource requirements dramatically (Martínez-López et al., 2019; Villa et al., 2014). This is the approach we are taking in the development of an OPEN IEEM+ESM Platform for the Latin American and Caribbean region (Banerjee et al., 2019a).

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 to the analysis of synergies and trade-offs between strategies. The metrics generated by the IEEM+ESM Platform go beyond measures of income flow represented by GDP, capturing 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 increasingly possible for many countries around the globe who are implementing the SEEA, including Rwanda.

Our analysis 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, or ecosystem service modeling and analysis. An economic model alone, for example, would not be able to show the land-use or ecosystem services implications of a simulated policy, nor would a stand-alone ecosystem service model illustrate the macroeconomic consequences and feasibility of policy alternatives. We show for example that increasing fertilization has very strong positive economic impacts for Rwanda; however, the associated stress on water resources (use and quality) increases markedly. Increased nutrient export can have diverse consequences 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 while reducing soil erosion and providing nutrient uptake. We thus provide strong economic and environmental arguments for a portfolio approach to achieving green growth targets where fertilization, irrigation, and improving fuelwood use efficiency through forest plantations can deliver important economic benefits. Forest cover expansion provides fuelwood and other raw material, reduces nutrient and sediment exports, reduces quick flow and enhances water recharge, all while increasing above- and below-ground carbon stocks for climate change mitigation.

Our analysis is spatially explicit 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, it was helpful to highlight the higher rate of LULC change in the Eastern Province and its effects on ecosystem services. The ability to focus on specific subnational regions can facilitate important discussions on locally important trade-offs and synergies between economic, environmental and social objectives. Our analysis for Rwanda—Africa's most densely populated country with a very limited land endowment—illustrates the importance of reconciling government plans and targets with the realities of current natural capital availability, threats, and vulnerabilities.

CRediT authorship contribution statement

Onil Banerjee: Conceptualization, Methodology, Software, Formal analysis, Writing - original draft. **Kenneth J. Bagstad:** Conceptualization, Methodology, Software, Formal analysis, Writing - original draft. **Martin Cicowiez:** Conceptualization, Methodology, Software, Formal analysis, Writing - original draft. **Sebastian Dudek:** Software. **Mark Horridge:** Conceptualization. **Janaki R.R. Alavalapati:** Conceptualization, Funding acquisition, Project administration, Writing - review & editing. **Michel Masozera:** Conceptualization, Funding acquisition, Project administration, Writing - review & editing. **Emmanuel Rukundo:** Writing - review & editing, Data curation. **Evariste Rutebuka:** Writing - review & editing, Data curation.

Declaration of competing interest

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

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2020.138779.

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