ACHIEVING GREEN GROWTH THROUGH TERRESTRIAL NATURAL CAPITAL RESTORATION IN RWANDA

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List of Acronyms

AET: Actual Evapotranspiration

AFR100: African Forest Landscape Restoration Initiative

AGROFOR: Agroforestry Scenario

BAU: Business as Usual

CFSVA: Comprehensive Food Security and Vulnerability Analysis

CGE: Computable Generalized Equilibrium

CLUE: Conservation of Land Use and its Effects

CIF: Crop Intensification Program

COMBI12: Agroforestry and Land Consolidation Scenario

COMBI: Agroforestry, Land Consolidation, Fertilizer and Irrigation Scenario

DEM: Digital Elevation Model

ELD: Economics of Land Degradation

ESM: Ecosystem Services Modelling

ES: Ecosystem Services

FERTIRRIG: Fertilizer and Irrigation Scenario

FONERWA: Rwanda Green Fund

GDP: Gross Domestic Product

GIS: Geographic Information System

GGKP: Green Growth Knowledge Platform

GGCRS: Green Growth and Climate Resilience Strategy

GGGI: Global Green Growth Institute

IEEM: Integrated Economic Environmental Modeling

InVEST: Integrated Valuation of Ecosystem Services Tradeoffs.

ISRIC: International Soli Reference and Information Centre

LANDCON: Land Consolidation Scenario

LULC: Land use Land Cover

MINAGRI: Ministry of Agriculture and Animal Resources

NDR: Nutrient Delivery Ratio

NCA: National Capital accounting

NST: National Strategy for Transformation

NIS: National Institute of Statistics

OECD: Organization for Economic Cooperation and Development

PSTA: Strategic Plans for the Transformation of Agriculture

SEEA: System of Environmental Economic Accounting

SDGs: Sustainable Development Goals

SDR: Sediment Delivery Ratio

SFABE: Sustainable Forestry Agroforestry and Biomass Energy

SRTM: Shuttle Radar Topography Mission

SSA: Sub-Saharan Africa

UNEP: United Nations Environment Program

UNFCC: United Nations Framework Conversion on Climate Change

USLE: Universal Soil Loss Equation

WAVES: Wealth Accounting and the Valuation of Ecosystem Services

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Executive Summary

Climate change and its effects have become the paramount challenge of modern times, and countries worldwide have used various policy incentives and interventions in order to improve their resilience. Many countries have expended considerable effort to address these challenges by achieving sustainable development goals (SDGs) to guide green growth, mitigate land degradation, preserve terrestrial natural capital, and enhance land assets. However, government strategies are often limited by economic constraints, and thus it has become critical not only to craft effective solutions, but to maximize their efficiency. Traditional measures such as gross domestic product (GDP), while useful, have been inadequate alone, and more effort is needed to assess natural capital and ecosystem services changes, as these have traditionally been under-or unaccounted for in policy making. As a result, there is a critical need to develop more robust and innovative methodologies and models that can more readily and completely account for flows, benefits, and co-benefits resulting from different development pathways to better guide policy creation and implementation.

Rwanda, a growing country in Sub-Saharan Africa, has suffered significant damage to its environment and ecosystem services over the last few decades, and has begun the process of using policy to reverse this trend. Though aggressive strategies have achieved some success, growing social, environmental, and economic constraints have made increasing the effectiveness of these strategies critical. To this end, this study utilizes an innovative integrated economic and environmental model (IEEM) coupled with land use land cover (LULC), and ecosystem service models (IEEM+ESM) to understand how various policy interventions could affect economic, poverty amelioration and environmental outcomes. We construct a base scenario using the "business as usual" approach, then compare it to five other approaches that prioritize various policy interventions, including agroforestry expansion on farm-lands, cropland consolidation, fertilizer and irrigation improvements in agriculture, and combined approaches. We use general equilibrium based IEEM platforms to assess macroeconomic trade-offs, and utilize LULC maps to understand spatial distributions and effects of policy scenarios. Further, we use ecosystem services modeling to understand changes in ecosystem services flows resulting from the policy interventions. Through integrated and innovative methods, we are able to understand how land degradation due to erosion can affect not only economic indicators such as GDP, poverty reduction, genuine savings, and unemployment, but also land assets, land use changes, ecosystem service supply, and terrestrial natural capital. Results suggest that investments in productive infrastructure for fruit plantations to reduce imports and increase food and nutritional security alone might not be sufficient. These, coupled with gradually expanded irrigated agriculture, land consolidation to increase productivity, and increased fertilizer application following an integrated approach for land asset management and conservation can enhance economic well-being, help counter environmental degradation, and increase ecosystem services supply.

1. Introduction

The Republic of Rwanda has consistently demonstrated its willingness to be a responsible member of the global community through seeking and achieving global solutions to address climate change and its related concerns. Rwanda is among the countries that have ratified the United Nations Framework Convention on Climate Change (UNFCCC), and has adopted the Paris Agreement COP21, as well as the Kigali amendment to the Montreal protocol. The cost of climate change in Rwanda has been estimated at 1% of gross domestic product (GDP) per year by 2030, largely due to extreme events such as flood and droughts, infrastructure damage, deterioration in water quality, and soil erosion, among other effects (Downing et al., 2009).

The last five decades have seen humans totally transform ecosystems, resulting in substantial net gains to their well-being and economic development, but at the cost of degrading many ecosystem services (Bagstad et al., 2020; Rukundo et al., 2018). Agriculture is one of the greatest contributors to land use/landcover change (Brown et al., 2017; Rukundo et al., 2018). Globally, land degradation contributes to 24 billion tons of fertile soil lost due to erosion, which impacts 3.2 billion people annually. In Sub-Saharan Africa (SSA), land degradation resulting from agriculture is more pronounced due to pressure driven by population growth (Bagstad et al., 2020; Rukundo et al., 2018) By the year 2030, 540 million people will depend on land for income and food security in Sub-Saharan Africa (SSA) alone (Buckingham et al., 2020). The cost of land degradation is estimated at 3% of SSA's annual agricultural GDP (Uwimana et al., 2018).

This estimated deficit has led to political strategizing for this potential economic decline, and has played a key role in supporting policy for green development. Because of its susceptibility to climate change related issues, Rwanda has taken additional measures to increase resilience and promote sustainable management of the environment, which is reflected in its National Environment and Climate Change Policy (Ministry of Environment, 2019a). Such policy development emphasizes consideration of environmental and climate change impacts in decision making across the public and private sectors. Further, it encourages civil society efforts to support Rwanda's transition towards a green economy through sustainable land and natural resource use, food security, preservation of biodiversity, social protection, improved health, and disaster risk reduction. There is widespread consensus by stakeholders and policy makers that land restoration and sustainable management are pivotal to maintaining ecological functionality, addressing food security issues, and promoting human well-being in degraded landscapes (Buckingham et al., 2020; Verdoodt and Ranst, 2006).

Rwanda has taken great strides in reducing poverty and malnutrition in the country; the agricultural sector has grown on average by 6% over the last decade, which has greatly improved food security (Government of Rwanda, 2019). According to the Comprehensive Food Security and Vulnerability Analysis (CFSVA) report, 81.3% of all households are food secure, maintain an acceptable diet, and require a low percentage of their budget to cover food needs (Ministry of Agriculture and Animal Resources [MINAGRI] & National Institute of Statistics [NIS], 2018). Despite these successes, crop yield, due to climate effects, is still below the potential production level (MINAGRI, 2018). Rwanda's economy is dependent on agriculture, which accounts for 43.0% of its GDP by providing 90.2% of country's food resources and supporting 80% of the labor force (Rukundo et al., 2018). The acreage of arable land is estimated at 1.5 million hectares, mostly found on steep slopes (Masozera et al., 2008: Rukundo et al., 2018). Rwanda's heavy reliance on rain-fed agriculture for both the livelihood of its people and national exports directly translates to the country's vulnerability to climate change.

An analysis of rainfall trends in the country have shown that rainy seasons are becoming shorter and more intense, increasing erosion risk and thus raising concerns for agriculture and land management overall. Such climate related concerns have led to the development of numerous government initiatives which aim to proactively address these issues using the country's sustainable development goals (SDGs). Rwanda, joining other United Nations Member States, adopted 17 SDGs as "a universal call to action to end poverty, protect the planet, and ensure that all people enjoy peace and prosperity by 2030" (United Nations Development Program [UNDP], 2020). In order to address these SDGs, countries have taken action within their governments to develop supporting policies and strategies. Rwanda's initiative PSTA 4, a strategic plan for agriculture transformation developed in 2018 by the Ministry of Agriculture and Animal Resources, directly contributes to SDG 2: Zero hunger, which aims to end all forms of hunger and malnutrition by 2030.

The government's priorities for agriculture include irrigation, improved access to agriculture inputs, erosion control, livestock development, extension services, and land use consolidation through the Crop Intensification Program (CIP). In conjunction with these priorities are the priorities of PSTA 4: (i) innovation and extension, (ii) productivity and resilience, (iii) inclusive markets and value addition, and (iv) enabling environment and responsive institutions. In the scope of these goals, PSTA 4 posits that accessibility of food will be enhanced through higher household incomes combined with greater resilience to market and production shocks. Resilience to such threats includes improved storage capabilities, early warning and market information schemes, and insurance schemes, which will help the country as a whole strategize against food insecurity such that all households have sufficient resources to obtain food to reach their zero-hunger goal.

1.1. Land Asset Restoration and Management

Rwanda's population size and growth rate have increased considerably over the past 30 years, growing from 7.09 million with a 0.2% annual growth rate in 1990 to 12.3 million with a 2.6% growth rate in 2018 (World Bank, 2020). These increases in population size and growth rate have resulted in a rapid rise in population density, which in the last thirty years has increased from 295.5 to 498.7 per square kilometer land area (Rodriguez-Manotas et al., 2018). Rwanda's population relies heavily on agriculture and natural resources for their livelihoods, and these growth trends are causing increasing strain on the environment. Currently, 70% of the active population is employed in agricultural production (International Fund for Agricultural Development [IFAD], 2019) and approximately, 96% of rural households are depend on agriculture for their livelihoods (National Institute of Statistics of Rwanda [NISR], 2018). Anything that impacts or benefits the availability of natural resources will have direct and significant effect on the livelihood of the citizenry.

In addition to the population changes, Rwanda's economy has shown considerable change over the last few decades. While the gross national income has risen from $1.73 billion USD in 2000 to $9.51 billion USD in 2018 (World Bank, 2020), Rwanda's GDP per capita over that time has risen from $225 USD to $787 USD (Government of Rwanda, 2019); GDP has also increased at an average of 7.9% per year since 2000 (Government of Rwanda, 2019). These changes in economic performance are invariably linked to greater demand for natural resources, which is further exacerbated by growing population. This phenomenon has led to significant changes in land use and land cover patterns, which have been accompanied by reduction in biomass, biodiversity, and ecosystem services (Bagstad et al., 2019; Banerjee et al. in press). Achieving sustainable economic growth with increasing pressures on its natural capital base poses formidable challenges for Rwanda.

In 2019, the United Nations general assembly highlighted the need for ecosystem restoration awareness and technical assistance in order to restore 150 million hectares of degraded land (Buckingham et al., 2020). In SSA, this is driven by the African Forest Landscape Restoration Initiative (AFR100), which aims to restore 100 million hectares by 2030. There is a general understanding of the critical role that restoration efforts can serve to revitalize rural livelihoods, mitigate climate change, reduce food insecurity, and increase water and energy availability (Buckingham et al., 2020). These factors, worsened by limited employment opportunities, have caused an unprecedented conversion of natural forests and wetlands into agricultural lands (Rukundo et al., 2018). Further, the situation has raised pressure to revise land tenure requirements, which has further discouraged farmers from committing long term practices such as land restoration (Olson and Berry, 2004).

Rwanda is at crossroads in terms of the socio-economic pressure on land resources because of demographic pressures such as forced resettlement, recent conflicts, high population density, land terrain, and climatic factors that result in land degradation (Rukundo et al., 2018). Currently, 40.5% of Rwanda's arable land is under threat of erosion and requires soil maintenance (Rukundo et al., 2018). The main task at hand is to increase land use and tree cover as part of economic development and poverty reduction strategies (Buckingham et al., 2020; Verdone and Seidi, 2016). Collective efforts have focused on smallholder producers through interventions that focus on enhancing agricultural productivity to increase food security and stimulate economic growth (Clay and King, 2018).

Land degradation continues to be is a major concern in Rwanda, with field-reported soil losses ranging from 35 to 246 tons ha/yr (Olson and Berry, 2004). The loss of soil and its resulting nutrient losses have reduced the capacity to feed 40,0000 Rwandans annually (Uwimana et al., 2018; Verdone and Seidl, 2016). This decline can be attributed to increasing rural population and land fragmentation that has put additional pressure on subsistence farming households (Olson and Berry, 2004; Clay and Lewis, 1990). Thus, it is inevitable that without proper measures, land degradation will result in environmental deterioration in affected areas (Clay and Lewis, 1990). Previous government mitigation measures involved physical or biological approaches that entailed terracing to reduce soil loss, use of green manure to increase soil organic content, and farmer outreach with the goal of shifting agricultural management practices (Olson and Berry, 2004). However, these soil conservation measures have often been met by resistance from local farmers, as these measures have failed to address land reform and gender issues (Olson and Berry, 2004; Rukundo et al., 2018).

Investments in initiatives such as agroforestry restoration can support livelihoods and biodiversity by improving ecosystem quality and resilience, and provide new opportunities for rural livelihoods by providing clean water, reducing soil erosion, providing wildlife habitat, securing adequate water, and increasing the supply of energy supplies, biofuels, and forest products (Banerjee et al., 2020.; Banerjee et al., in press; Lal et al., 2017a). In addition, such investments can play a critical role in mitigating climate change by sequestering carbon (Ministry of Environment, 2019; Government of Rwanda, 2011). Such investments can boost food productivity through enhanced soil fertility and moisture conservation, as well as provide immediate benefits including job opportunities and increases in income, thus contributing to multiple sustainable development objectives.

Various demographic, economic and environmental trends explain Rwanda's environmental degradation. These trends also highlight the necessity of agroforestry restoration investment. If implemented, these initiatives could be critical in the process of regaining ecological functionality and in helping Rwanda live up to its commitments of achieving a countrywide reversal of natural resource degradation.

1.2. Financing of Natural Resource Priorities

Rwanda’s plan is to continue sustainable economic initiatives, and achieve its goals to become a high income, climate resilient, low carbon economy by 2050 (Gatete, 2016; Ministry of Environment, 2019a). The development and implementation of the country’s Green Growth and

Climate Resilience Strategy (GGCRS) has acted as an initial push towards reaching this vision. The GGCRS focuses on: (i) achieving energy security and a low carbon energy supply to support green industry development, (ii) achieving sustainable land use and water resource management to support food security, sustainable urban development, and preservation of biodiversity and ecosystem services, and (iii) achieving societal protection and disaster risk reduction from climate change impacts within vulnerable areas.

To continue the progress fostered by GGCRS, Rwanda created the 2012 Rwanda Green Fund (locally called FONERWA) - an environment and climate change fund to be used as a tool to implement the country's green strategies and showcase meaningful change. To achieve these goals, FONERWA provides loans and grants to government institutions, private sectors, and civil society organizations for green projects, which can include green job creation, forest and water body protection, improved access to off-grid clean energy, and other means to mitigate the effects of climate change. Since its creation, FONERWA has mobilized more than 170.1 million USD from its development partners and financed 33 green projects of varying size (Government of Rwanda, 2019).

Such resilience funding strategies and government developments have demonstrated Rwanda's ability to mobilize resources and improve self-reliance by financing a large share of the country's budget from domestic resources. The proportion of domestic budget funded by local taxes and loans increased from 55% in 2005 to 84% in 2018/19. Further, the share of external grants declined from a high of 44.3% in 2005 to 16% in 2017/18 (United Nations Development Program [UNDP], 2019). This improved self-reliance has further led to the development of the 2017 National Strategy for Transformation (NST 1) and the 2018 Strategic Plan for Agriculture Transformation 4 (PSTA 4), which aim to address some of the medium- and long-term visions and strategies for further sustainable development in the country.

With the initiation of NST 1, considered the most ambitious transformation plan anchored on Vision 2050, Rwanda emphasized the importance of the private sector beyond traditional partnerships (Government of Rwanda, 2018; Republic of Rwanda, 2018a). NST 1 proactively pursues innovative partnerships to move beyond traditional financing schematics and consider new ways to finance the private sector to support sustainable development. Supporting NST 1 is the recently approved National Environment and Climate Change Policy (Ministry of Environment, 2019a) which focuses on emphasizing green economic transformation, enhancing natural ecosystems function, and promoting climate change adaption, mitigation, and response, among other goals. Additionally, the National Land Policy (Ministry of Environment, 2019b) aims to strengthen land administration and management to promote sustainable land use development.

Rwanda was one of the first African countries to sign the Gaborone Declaration in 2012, announcing its need to apply National Capital Accounting (NCA) as a tool to inform national policies on sustainable development. Currently, the country's NCA initiative informs the planning processes for different strategies and policies by considering the important contributions of natural resource sectors to the economy. In 2013, Rwanda also joined the WAVES (Wealth Accounting and the Valuation of Ecosystem Services) global partnership to support its NCA efforts (Government of Rwanda, 2019).

Donor agencies have also highlighted the need to reduce land degradation by addressing agricultural issues on a regional basis while considering land reforms and gender issues that continue to plague the sector (Olson and Berry, 2004). To this end, donor agencies led by World Bank provided aid of about $48 million dollars to increase agricultural productivity through institutional and technical capacity development, which was mainly enabled by agricultural research and extension systems that promoted efficient cropping and post-harvest technologies (Olson and Berry, 2004). This approach involved integrated management of critical ecosystems by local communities through commercial and export agriculture. The overall goal of this initiative was to develop a coherent approach by integrating local communities, the private sector, and farmers to develop small scale infrastructure (Olson and Berry, 2004; Rukundo et al., 2018). While these governmental initiatives have been developed to provide support in reaching the country's SDGs, such strategies require scientific support and data in order to justify climate mitigation action and inaction.

2. The Integrated Economic-Environmental Modeling Linked with Ecosystem Services Modeling (IEEM+ESM) Approach for National Planning

Rwanda's long-term vision (Vision 2050), medium-term plan (NST 1), and related sector and district strategies overlap with the preparation for and adoption of SDGs. As such, the country's initiatives and its SDGs have been integrated into the national planning framework (Government of Rwanda, 2019). Partnerships between governments, the private sector, civil society, and external development partners are increasingly aligning under the country's sustainable development vision.

The United Nations' 17 Sustainable Development Goals (SDGs) provide a blueprint for sustainable management solutions. Until recently, SDG indicators have been difficult to accurately measure, and a variety of methods have made comparisons between the progresses of different policies overly complex (Banerjee et al., in press). The ongoing development and refinement of the global indicator framework is directly helping to solve this issue. However, more investments and partnerships to further develop capacities to produce required data for effective monitoring of SDGs are critical in continuing to perfect these systems. The Government of Rwanda has taken important steps towards an effective domestication of Agenda 2030 by integrating and localizing the SDGs in Vision 2050, the medium-term development strategy, NST 1 (2017-2024), and related sector and district strategies following the roadmap approved by the Cabinet in December 2015. Accordingly, NST 1 captures the ambitious nature of SDGs across all its three pillars (economic, social and transformational governance), and thus mirrors the three dimensions of sustainable development. The Ministry of Finance and Economic Planning (MINECOFIN) has been mandated to coordinate SDG implementation, and is supported by a multi-stakeholder structure that allows for an all government approach and includes other players such as development partners, civil society, the private sector, and citizens.

Our study, supported by Green Growth Knowledge Platform[1] and GIZ's The Economics of Land Degradation (ELD) initiative, focuses on establishing the link between flows and benefits fromland assets. Our study explores management and policy prescriptions to combat land degradation, restore ecosystems, and create co-benefits such as sustainable agriculture, food security, improved human health, inclusive economic growth, improved employment, and climate change mitigation. Our approach 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.

The Integrated Economic-Environmental Modeling (IEEM) Platform, linked with ecosystem services modeling (IEEM+ESM) is an innovative decision-making framework for exploring complex public policy goals and analyzing synergies and trade-offs between alternative policy portfolios (Banerjee, Cicowiez et al. 2016, Banerjee, Cicowiez et al. 2019, Banerjee, Cicowiez et al. 2019, Banerjee, Cicowiez et al. 2019). The IEEM+ESM Platform was originally developed to integrate natural capital and ecosystem services in economy-wide analytical approaches to deepen the understanding of synergies and tradeoffs between economic outcomes and natural capital and ecosystem services supply, with the ultimate goal of providing a more advanced integrated economic-environmental decision-making tool (Banerjee, Crossman et al. In Press). The IEEM+ESM approach is invaluable for its ability to analyze changes in land use and ecosystem services driven by public policy; further, it assesses impacts on standard economic indicators of concern, such as GDP and employment, as well as changes in wealth and ecosystem services. The

1 The platform was established in 2012 with 4 founding members including the Organization for Economic Co-operation and Development (OECD), the Global Green Growth Institute (GGGI), the United Nations Environment Program (UNEP) and the World Bank. The GGKP is a global community of organizations and experts committed to collaboratively generating, managing and sharing green growth knowledge and data to mobilize for future sustainable development. This project is under the specific program of knowledge generation part, which is working closely with established expert working group and natural capital expert group. The aim of this working group is to mainstream natural capital in green growth planning and operations.

IEEM+ESM approach has rapidly demonstrated its utility and is thus gaining popularity; by the end of 2020, about 25 countries will have implemented some form of IEEM+ESM Platforms.

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. Our linkage of IEEM with ecosystem services modeling makes it possible to also capture the environment's contribution of non-provisioning services. The economy 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 wastes are generated and returned to the environment. To mitigate and repair environmental damage, public and private sectors make investments into the environment. IEEM's underlying data structure captures all these interactions quantitatively. IEEM generates metrics such as GDP, employment impacts, and government revenue, all of which can be easily used in national budget and policy making. Beyond these standard indicators, IEEM also delivers metrics such as inclusive wealth, genuine savings, changes to natural capital stocks, and changes to ecosystem services supply, which can provide a richer analysis on economic impact than GDP could provide alone. These indicators are critical in assessing the sustainability of public policy and how well they fulfill sustainable development and natural capital goals.

The IEEM+ESM platform, thus, integrates natural capital and ecosystem services represented by the System of National Accounts using the System of Environmental Economic Accounting (SEEA) framework to assess synergies and tradeoffs resulting from land use and management simulations. The IEEM Platform is publicly available[2] and IEEM's mathematical structure is documented in Banerjee and Cicowiez (2020). The database for IEEM is an environmentally extended Social Accounting Matrix (SAM) and its construction is described in Banerjee, Cicowiez et al. (2019). A user guide for a generic version of IEEM, applicable to any country with the corresponding database, is available in Banerjee and Cicowiez (2019). IEEM has been applied to hundreds of questions of public policy and investment and has demonstrated its robustness in a range of applications[3].

Our assessment, based on policy scenarios, is informed by intensive literature review and stakeholder inputs at national workshops, and uses an innovative modeling framework to identify changes in the terrestrial natural capital and respective ecosystem services flows by

[2] All IEEM models, databases and documentation will be available here: https://www.iadb.org/en/topics/environment/biodiversity-platform/the-idbs-biodiversity-platform%2C6825.html
[3] For a sample, see: https://publications.iadb.org/en/publications?keys=IEEM

comparing the impacts of business as usual and restoration interventions. Our study directly contributes to SDG 15: Life on land and SDG 13: Climate action, and indirectly contributes to SDG 12: Ensure sustainable consumption and production patterns, SDG 1: End extreme poverty, SDG 8: Decent work and economic growth.

3. Methodology

3.1. Study Area

Rwanda is a small land-locked country in SSA that is located in Central Africa in the Great Lakes region. To the west, it shares its border with Democratic Republic of Congo, while to the north it shares its border with Uganda, to the east, Tanzania, and to the south, Burundi. (National Institute of Statistics of Rwanda [NISR], 2018; World Population Review [WPR], 2020). The country has wide diversity of topography, soils, biodiversity, and ecological regions. It is a hilly country with altitudes of less than 1500 meters in the eastern plateau, rising to between 1500 and 2000 meters in the central plateau area and to above 2000 meters in the west and north.

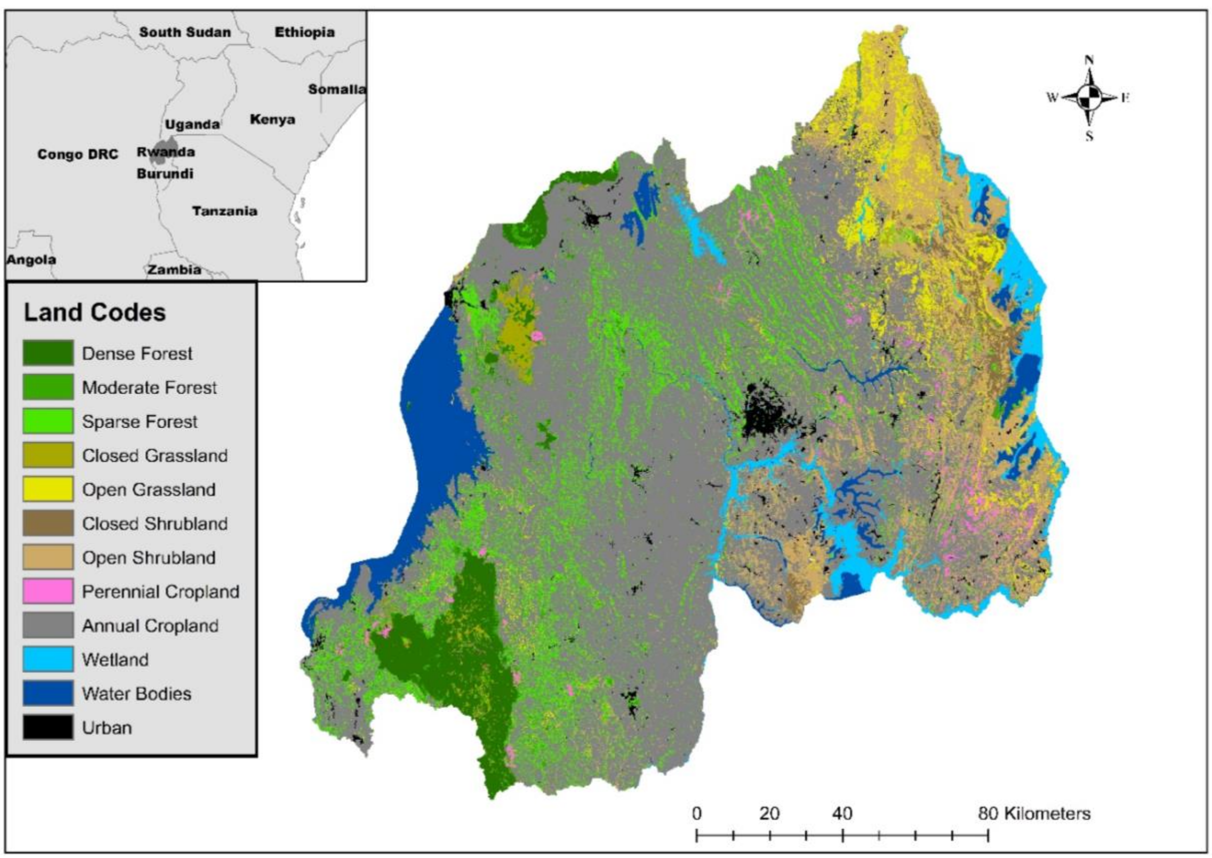

Figure 1. Rwanda 2015 Land Cover (RCMRD, 2017)

Rwanda is an equatorial country with an annual rainfall of below 1000mm for the lowlands and above 2000 mm for the highlands (Verdoodt and Ranst, 2005). The country, with mountains in the west and savanna to the east, has several large lakes, most notably Lake Kivu on its western border (Rukundo et al., 2018). The country has total area of 26,338 km^2 and a population of 12.5 million that is predominantly rural (83.5%). Rwanda is a high-altitude nation ranging from between 970 and 4507 meters, with steeply sloping highlands in the western and central parts of the country that have often suffered from land degradation through soil erosion. Agriculture is dominant in the central and western parts of the country due to relatively higher soil fertility in the west (Clay and Lewis, 1990). This farming pattern has led to half of all farms in the country having slopes greater than 18% (Bagstad et al., 2019). Conversion of land from forest and woodland to cropland has been the most dominant change in Rwanda's land cover, particularly from 1990 to 2015 (Republic of Rwanda, 2018b; Bagstad et al., 2019). Rapid increase in population led to an average annual decrease of 1.6% forest area from 1960–2000 (Habiyaremye et al., 2011), which was exacerbated by soil erosion and environmental degradation during the past conflicts (Ordway, 2015; Bagstad et al., 2019).

Without sustainable management, much of Rwanda's farmland has the potential for land degradation. Most studies in the 1990s advocated for change in soil management practices as an adaptation strategy to land degradation (Olson and Berry, 2004). These involved practices such as fallowing and manuring strategies to boost soil organic matter, and the deployment of terraces and drainage networks (Clay and Lewis, 1990; Clay and King, 2019).

Changing land management solutions involve an integrated approach (Republic of Rwanda, 2000). The Rwandan government ministries, in cooperation with non-governmental and development agencies, have come up with strategies to improve productivity of small-scale agricultural and woodlot management activities in the country over the last two decades (Government of Rwanda, 2018; Government of Rwanda, 2011; MINECOFIN, 2013). The resulting outreach campaign strategies mainly consist of promoting crop and timber yields, reducing soil erosion, and increasing forest cover (Verdone and Seidl, 2016). The country has made efforts towards soil degradation prevention and mitigation through terracing and other measures; however, topographic conditions along with high and often intense rainfall makes it challenging (World Bank, 2018). Soil acidity adds to the challenge by negatively impacting the availability and uptake of several nutrients; according to Rwanda's state of environment report (Rwanda Environment Management Authority, 2015), about three-quarters of Rwanda's soils are acidic, with a pH below 5.5, and are deficient in nitrogen or in phosphorus. Decision makers have also realized the key role that the public has in the implementation of successful restoration programs in Rwanda, and are emphasizing an integrated approach, including productivity increasing measures and utilization of research, extension, and partnerships (Buckingham et al., 2020; World Bank, 2018; Lal et al., 2017).

3.2. Modeling Approach

We built on the IEEM model for Rwanda developed in Banerjee, Bagstad et al. (in press).This IEEM Platform uses the country's most recently published natural capital accounts (Republic of Rwanda, 2018c, Republic of Rwanda, 2019, Bagstad et al., 2019) and Ecosystem Service (ES) models to explore the economic and environmental impacts of various actions and policies aimed at stimulating green growth.

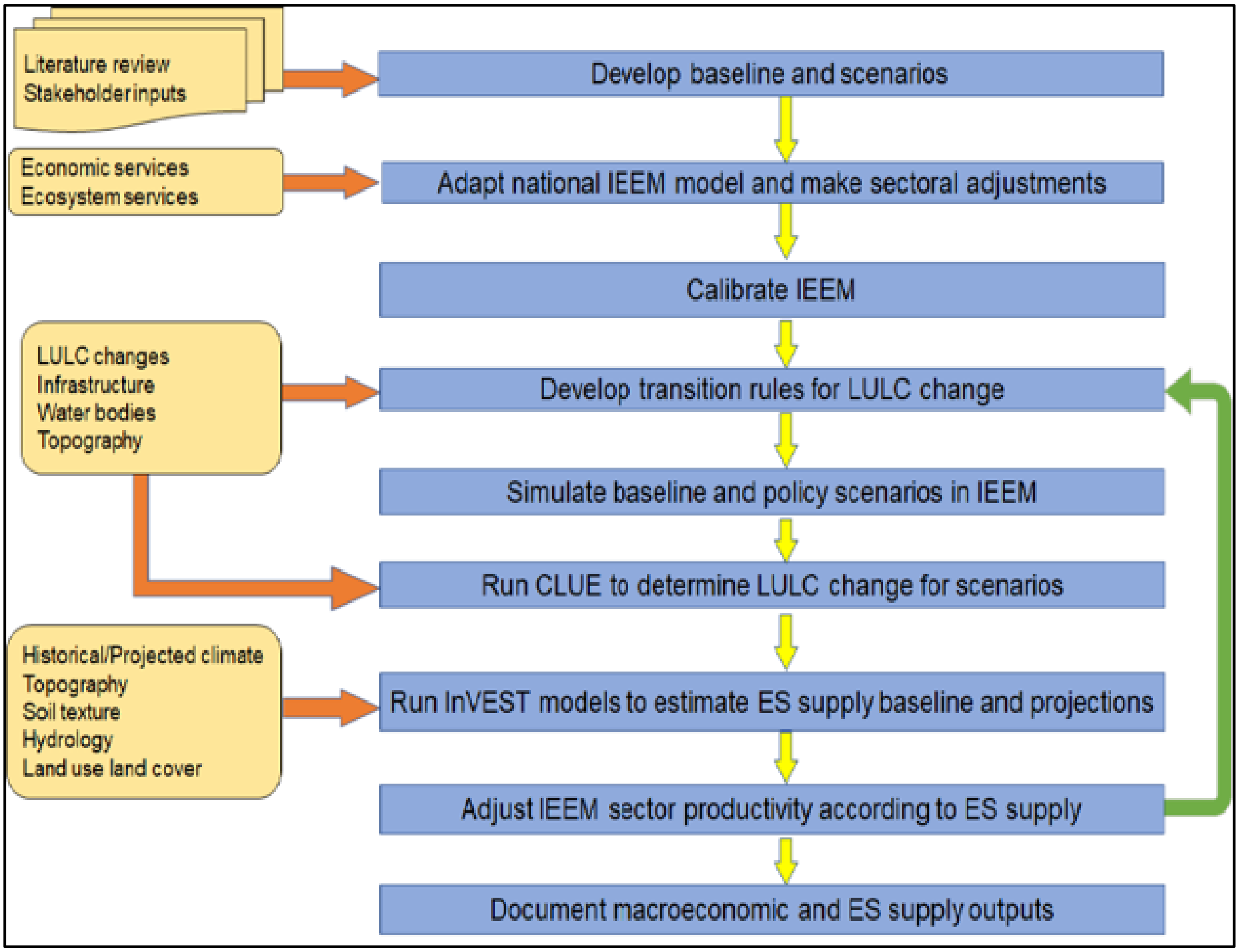

Figure 2. Modeling Workflow

We utilized ES models to quantify the physical supply and use components of ecosystem accounts in Rwanda. We applied the Integrated Valuation of Ecosystem Services Tradeoffs (InVEST) models (Sharp, Tallis et al. 2018), building on prior work done to use these models in the country. We applied the Integrated Economic-Environmental Modelling (IEEM) platform coupled with spatially explicit ES models (IEEM+ESM) (Banerjee, Cicowiez et al. 2019), and applied it using the ELD methodological framework to capture terrestrial land assets policy and investment impacts on ES for which, in many cases, markets do not yet exist. Using a national version of IEEM, the first step was to generate a baseline projection, which acted as a reference scenario to be compared to all other scenarios. While the full period of analysis is from 2015 to 2035, in order to incorporate erosion mitigation services in the baseline, we ran the IEEM baseline and scenario projections in 5-year increments. The first 5-year period, 2015 to 2020, produced baseline results for economic and natural capital indicators and demand for land. We allocated projected estimates of demand for land spatially using the CLUE framework-based land use land cover (LULC) change model. We provide an overview of the LULC modeling approach in section 3.4.

The IEEM model for Rwanda is calibrated based on our Social Accounting Matrix for Rwanda with a base year of 2014 (Banerjee et al., 2019; Banerjee et al., in press). 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 (Republic of Rwanda 2018c, Republic of Rwanda 2019). with IEEM calibrated, we designed and described scenarios to evaluate public policy and investment alternatives. We developed a baseline (BASE) scenario and five groups of policy scenarios (see scenario development in section 3.3).

The next step was to implement the policy scenarios in IEEM; here, the interventions act to expand irrigated agriculture and increase fertilizer application, land consolidation, and horticultural trees populations on farmland as part of the agroforestry strategy. We implemented these interventions in IEEM for the first time period of 2015 to 2020 and generated estimates for impacts on the economy, natural capital, and demand for land. We spatially allocated the demand for land for each scenario with the CLUE based LULC change model to generate new LULC maps for the year subsequent 5 years.

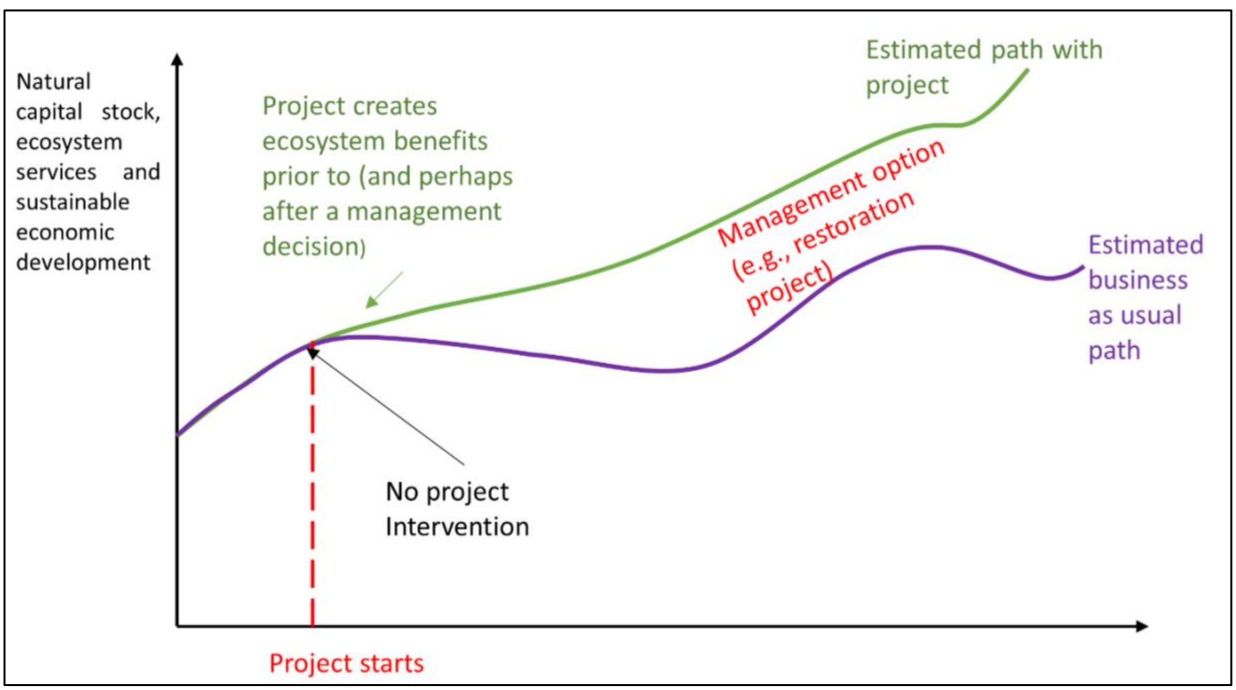

Figure 3. Schematic of Natural Capital Stock and Ecosystem Services Flows

We ran the InVEST ES model with these new maps for subsequent 5-year period and estimated ES supply for each scenario. Based on results from the baseline projection in and scenario results from next 5-year time step, we calculated the difference in the indicator of interest, tons per hectare per year of soil erosion, for each scenario. The result is the change in ES supply attributable to the scenarios. Schematic of policy scenario assessment is depicted in Figure 3.

Changes in ES supply can affect the economy through a number of mechanisms; for example, increased soil erosion for example reduces agricultural productivity (e.g., Borselli et al., 2017; Panagos et al., 2017; Panagos et al., 2018; Pimentel, 2006), and increased soil erosion and nutrient run-off affect water quality, which can affect water treatment costs, human health and tourism values (Banerjee et al., 2020; Chaplin-Kramer et al., 2016; Stockholm Environmental Institute, 2009). In our study, we focus on how changes in erosion mitigation ES affect agricultural productivity and thus, affect the economy (Banerjee et al., in press; Banerjee et al., 2019).

3.3. Scenario Development

We engaged stakeholders, the scientific community, and a broader audience of conservation managers, government officials, and private sector managers by demonstrating the values of terrestrial ES in natural capital context, and how this information can inform the real-world decisions that they make. Through the project inception meeting held on December 10 2019 in Kigali, we solicited from stakeholders what prior work had been undertaken and solicited existing data via inputs from government ministries, bilateral institutions, international and other non-governmental organizations, universities and research institutions, the private sector, and other stakeholders. Based on intensive inception workshop, we developed and refined policy scenarios to assess sustainable land management options in the country.

In the inception meeting, the we outlined the Rwandan government's status in achieving the SDGs through current GGKP and ELD natural capital projects, and expressed how these efforts could benefit from additional research on land use, land conservation, and economic resilience through a natural capital approach to better inform policy makers on best addressing SDG challenges. Ms. Sun Cho of GGKP further described how the goal of this platform's project working group is to bring natural capital in green growth planning and operation into the mainstream through addressing some key knowledge gaps, including sustainability metrics, data, and policy. GGKP pilot projects have already launched with the goal of identifying natural capital gaps in order to achieve the country's SDGs.

Natural capital, or the value of environmental resources, has previously not played a central role for the transformation to a green economy in Rwanda. Through contribution of research studies, this project aims to incorporate natural capital metrics in monetary and biophysical terms to inform decision making within current policy to better achieve SDGs and support the development of a green economy.

Figure 4. Stakeholder Meeting in Kigali on December 10, 2019

Stakeholder discussions highlighted how our modeling approach can be used to improve already existing programs and initiatives through providing information on how to allocate funds to reach developmental goals. Among the discussion between the inception meeting attendees, we highlighted key policy questions related to agriculture and forestry. The data provided by the attendees and follow ups with their networks improved our scenario assumptions. The discussion and follow up highlighted the underlying goal for Rwanda to encompass an 80% productive landscape, wherein the use of the land can contribute to a green economy and improved livelihoods.

In addressing agriculture, it was deemed essential to ensure sustainability within the agriculture system in the face of rapid population growth, land scarcity, and challenges involving land use. Land management practices must also be assessed such that related concerns, like soil erosion, may be addressed. Forestry plays a complex role, as there is beneficial use in both the ecosystem services, such as carbon sequestration, and economic services, such as timber production. In exploring the role of agriculture, forestry, and agroforestry with the country's SDGs, it was also suggested that we lean on current supporting policies, such as NST 1 and PSTA 4 as previously described.

We discussed the use of combining information from multiple, interrelated models in order to inform decision making within the scope of green growth through terrestrial national capital restoration. Such models, as described in section 3.2, include IEEM, ESM, CGE, and LULC models, combined in the IEEM+ESM approach; the IEEM+ESM approach renders these models compatible with shared concepts with the System of National Accounts. In applying the IEEM+ESM framework, the project will explore different scenarios – each scenario and time period having a different LULC map – including a baseline scenario, forestation scenario, agroforestry scenario, and agriculture transformation strategy scenario.

This work builds on previous IEEM+ESM applications in Rwanda (Banerjee, Bagstad et al. 2020) by integrating feedbacks between modeling components. Specifically, changes in erosion mitigation services that arise from a given policy translate into agricultural productivity shocks which in turn are implemented in IEEM (Banerjee, Cicowiez et al. 2019, Banerjee, Crossman et al. In Press). IEEM is then used again to generate a revised LULC change projection and the iteration process is repeated until the end of the analytical period.

Below are the resulting scenarios we used for policy assessments.

Scenario 1: Only agroforestry expands with fixed forestland (AGROFOR)

This scenario assumes an increase in agroforestry area to a total of 1,110,476 hectares by 2030 based on the Ministry of Natural Resources' strategy (2014). The Government of Rwanda proposes that about 705,162 hectares of this increase would be on steep sloping land, and that of 405,314 hectares would be on flat or gently sloping land. In this scenario, we assume that the additional land for agroforestry used to meet the target (1.11 million hectares) comes from conversion of arable land and open grassland categories. A hectare of expansion in agroforest land will mostly be fruit crops under a national food-security and land-restoration program, with a target of over 10% of tree-and-shrub cover. We model this expansion such that up to 80% of arable land and open grass-lands are planted with trees, and expand into open shrub lands. In the agroforestry system, trees compete with food crops for nutrients, space, moisture, and sunlight; we model intensification such that it is optimal in regular croplands (e.g., not more than 10 % of trees area in cropland).

As outlined in the Green Growth Climate Resilient Strategy (GGCRS) adopted by the GoR, the cumulative investment needs under the 'sustainable forestry, agroforestry and biomass energy (SFABE)' program is about $229.6 million for the business-as-usual (BAU) case, while it is $285.2 million for middle-level sustainability over a period of 2016 and 2030. Out of this investment, the explicit share of agroforestry is about $117.46 million over this 14-year period (Isaac et al. 2016).

Scenario 2: Cropland consolidation (LANDCON)

The government of Rwanda, through the Strategic Plan for Agriculture Transformation (2018-24), plans to boost agriculture production by scaling up consolidated cropland[4] from the current 635,603 hectares to 980,000 hectares in 2024 (54.2% increase in consolidated cropland). We implement this scenario of cropland consolidation such that both food crops area and export crops yield increase. Crop productivity increases by 30% in newly consolidated cropland throughout 2019-2024 (International Fund for Agricultural Development [IFAD, 2019]). From 2024 through 2050, we used average annual yield growth so that the crop production doubles by 2050 (Ray et al., 2013). As outlined in Rwanda's Strategic Plan for Agriculture Transformation, the cost of this agriculture expansion is about $2.96 billion over 2018-2024 period.

Scenario 3: Both agroforestry and cropland consolidation (COMBI12)

This is the combined scenario comprised of the 1st and 2nd scenarios. Here, agroforestry expands to 1,110,476 hectares by 2050, and the cropland consolidates from the current 635,603 hectares to 980,000 hectares by 2024. We implement this scenario of cropland consolidation and agroforestry expansion, where the interplay of agroforest program along with cropland cover is allowed. The newly expanded cropland and agroforest area is allowed to come from conversion of arable land and open grasslands.

Scenario 4: Agriculture – improvement in fertilization and irrigation (FERTIRRIG)

Farmers' adoption of fertilizer use is quite low in Rwanda compared to other African countries. The average use of fertilizer currently in Rwanda is 32 kg/ha/year, which is significantly below the world average of 140.55 kg/ha/yr (World Bank, 2020). Rwanda's crop intensification program has subsidized fertilizer for crops such as maize, wheat, rice, Irish potatoes, beans, and cassava.

[4] The land use consolidation was implemented in Rwanda through 2008 Crop Intensification Program (CIP). Through land consolidation, farmers consolidate their land parcels to cultivate one selected crop while maintain land ownership (MINAGRI, 2009). This results in cultivation of priority crops, increased crop yields, and improved food security among farm households (Nilsson, 2019). Participation in consolidation is voluntary but it is a prerequisite for landowner to join the CIP program which distributes agricultural inputs such as fertilizers and seeds. The program facilitates soil and water conservation practices and is emphasized in national policies (e.g., Strategic Plan for Agriculture Transformation 2018-24).

In Rwanda, out of 635,603 hectares of agricultural land, only 48,508 hectares (7.6%) are under irrigation. The Rwandan government plans to increase this irrigated area to 10.4% by 2024 (102,284 hectares). During our project inception meeting, the discussants also acknowledged the corresponding need for increased water (irrigation) along with fertilizer use. In this context, we analyze this scenario of increasing the fertilizer use by 134% (75 kg/ha) in tandem with a modest increase in irrigable area by 0.6%/year through 2035.

As laid out by the Rwandan strategic plan for agricultural transformation, the overall increase in productivity over the seven-year period (2016/17-2023/24) is about 87% in Maize, 86% in wheat, 171% in cassava, 5% in paddy rice, 71% in Irish potatoes, 83% in beans, 43% in coffee, and 14% in tea. The plan also estimated that the cost of integrated input use including fertilizers is about $450 million, and that of use of improved irrigation methods is about $450 million over a period of 2018-2024.

Scenario 5: Comprehensive implementation of policies (COMBI)

In this scenario, we implemented Scenarios 3 and 4 together and examined the interactions of agroforestry and improvements in agricultural productivity, in the context of economic development with sustainable environment. We expect that the land conversion under this combined scenario would take place while Rwanda meets its strategic plan on agriculture phase 4 (PSTA 4) which delineates priority investments in agriculture for the period of 2018-2024. This scenario is in sync with the National Agricultural Policy (2018) which outlines Rwanda's aim to become "a nation that enjoys food security, nutritional health and sustainable agricultural growth from a productive, green and market-led agricultural sector", the National Irrigation Master Plan (Malesu et al., 2010), and Vision 2050, which aims to enhance agricultural productivity for food security and transform the rural economy under its pillars on Agriculture, Food Security and Rural development (The New Times, 2016).

In all of the non-BASE scenarios, we assume that associated investment costs are financed through foreign borrowing. 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 so that there is no additional domestic and/or foreign financing beyond what is required to finance the simulated increases in government investment; (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, and thus the simulations are neutral in terms of changes in regional net foreign assets. The non-trade-related payments of the balance of payments (transfers and foreign investment) are non-clearing and follow exogenously imposed paths.

3.4. Land Use Land Cover Change Model

The LULC Change Model provides the linkage between IEEM and ESM. It was used to spatially allocate LULC change numerically estimated by IEEM for each scenario and time step across the country. The LULC Change Model was developed using the Conversion of Land Use and its Effects (CLUE) model framework, a flexible and spatially explicit land use and land cover modeling framework (Verburg and Overmars, 2009). It had three overall stages: (i) development of a geographic information system (GIS) for Rwanda; (ii) preparation of the initial LULC data layer based on IEEM scenarios; and (iii) distribution of LULC change based on IEEM outputs according to predefined decision criteria. At the core of our LULC Change Model was decision criteria or land use allocation rules for spatially assigning IEEM LULC changes across the LULC data layer.

The openly available CLUE model was developed to simulate land use change using empirically quantified relations between land use and its driving factors along with dynamic modelling of competition between different land use types (Verburg and Overmars, 2009). The model makes use of user inputs to spatially allocate the desired demand within a set margin of error. Using a raster-based system the model will continue to calculate different allocation metrics until the solution criteria are met. We used CLUE framework to project land use and land cover data 5 years into the future, and the results were used in the other two modeling steps. Maps required in CLUE include current land cover and maps for independent variables. Table 1 represents a list of LULC mapping data sources.

Table 1. Variables and Data Sources Used for LULC Mapping

Variables	Source
Slope	Regional 30m DEM
District	Rwanda Land Management and Use Authority
Water bodies	Rwanda 2015 Land Use Map
Urban	Rwanda 2015 Land Use Map
Water Treatment	Rwanda Water and Sanitation Corporation
Roads	Open Street Map
Irrigation	Rwanda Ministry of Agriculture and Animal Resources
Hydropower	Rwanda Energy Group

We used an ordinal logistic regression model to estimate the suitability of Rwanda for each land cover type (Verburg and Overmars, 2009). This was constrained by additional location factors and neighborhood influences, along with the elasticity to change of each land use, where higher elasticity signifies lower probability of change to another land use. In practice, the least elastic land use for the simulation is set near 1, completely inelastic, while the land use that experiences the most change is set near 0 for completely elastic. We defined the transition matrix such that transitions from urban and water uses were limited and forests transitioned from sparse to dense. Other transition routes were left open allowing all but urban areas and water bodies to change into the agroforestry land.

Thus, the spatial data we used in developing the GIS for Rwanda includes the 2015 LULC map, a digital elevation model, watershed and subwatershed, and protected areas. Data sources for these, plus additional spatial data and parameters used to run the ecosystem service models, are described in Appendix A. The 2015 LULC map was used as a baseline for allocating scenario-based LULC change (Figure 1). This map was extracted from Rwanda Land Cover 2015 Scheme I, developed for Green Houses gases inventories to support researches on Land use, land-use change and forestry (RCMRD, 2018). Once the LULC Change Model was developed, we extended the baseline LULC projection to the year 2035, in 5-year increments (2020, 2025, 2030, 2035). Decision criteria for allocating LULC change in the BASE and the other scenarios were developed through expert elicitation per our stakeholder inception meeting, and included experts involved in implementing Rwanda's Land Use and Irrigation Master Plan.

Decision criteria for the scenarios were as follows. For agroforestry 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 Banerjee et al. (2020); (ii) not located within protected areas or urban areas; (iii) classified in the base map as open shrubland, grassland, or annual or perennial cropland; and (iv) subject to the slope (steep or low or gentle slope). The eligible land use areas were selected with neighborhood effects, which means that agroforestry pixels allocations were near other agroforestry pixels. All new agroforestry pixels were reclassified as open shrubland, consistent with the base map LULC classes. The process for allocating IEEM results for the AGROFOR, LANDCON, FERTIRRIG, COMBI12, and COMBI scenarios followed the same allocation rules described above.

For each modeling time step and in all scenarios, we also accounted for urban expansion. Future urban growth was based on planned urban extents based on Banerjee et al. (2020). Pixels designated as new urban areas were selected evenly around current urban centers. This expansion occurred by the projected amount for each 5-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. Conversion of forests located farther from urban centers to urban land was less pronounced.

3.5. Ecosystem Service Modeling

We used the Integrated Valuation of Ecosystem Services Tradeoffs (InVEST) 3.8.0 modeling software (Sharp, Tallis et al. 2018) to quantify carbon storage, nutrient regulation (nutrient delivery ratio (NDR) model), and annual and seasonal water yield in Rwanda. We ran this model for 2015, and for 5-year increments for BASE and the other five scenarios. We used the erosion and overland sediment retention (sediment delivery ratio [SDR] model) to provide feedback to the IEEM model in Rwanda between 2015 to 2035 at five-year intervals.

By combining the Universal Soil Loss Equation (USLE, Renard et al., 1997) with a connectivity index, we estimated an annual proportion of soil loss for each cell in the study catchment as per Borselli et al. (2008). Further details of the SDR model can be found in Sediment Delivery Ration model- InVEST User Guider (Sharp et al., 2016).

Table 2. Biophysical Table Used in Invest SDR Model Simulations

LULC_type	lucode	usle_c	usle_p
Dense forest	1	0.001	1
Moderate forest	2	0.005	1
Sparse forest	3	0.01	1
Woodland	4	0.06	1
Closed grassland	5	0.08	1
Open grassland	6	0.08	1
Closed shrubland	7	0.08	1
Open shrubland	8	0.08	1
Perennial cropland	9	0.04	See Table 3
Annual cropland	10	0.17	See Table 3
Wetland	11	0.077	1
Water body	12	0	1
Urban	13	0.1	1
Agroforestry	7	0.08	1

Source: Adapted from Bagstad et al., 2019

We derived primary SDR model parameters from (Bagstad et al., 2019), including the c and p factors for different land cover types, the Borselli IC_o, and the maximum SDR. The maximum SDR, k_b and IC_o were set at default values of 0.8, 2, and 0.5, respectively. We utilized a 30m SRTM digital elevation model (DEM) raster of Rwanda and its neighbors from maps.rcmrd.org. The data were resampled and void-filled at 210 m resolution as an input of the SDR model. Threshold flow accumulation was set at 23, a rounded number of 210 m cells in a 1-km^2 contributed watershed (Sharp et al., 2016).

The soil erodibility raster was derived from the ISRIC African SoilGrids 250 m using Williams et al. (1995). The rainfall erosivity raster came from Global Rainfall Erosivity Database (Panagos et al., 2017). Watershed and sub-watershed shapefiles were extracted from Rwanda Water and Forestry Authority. Tables 2 and 3 illustrate the values of c and p factors used in our SDR model.

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Table 3. Soil Erosion Interpolated and Extrapolated p Factors in Rwanda, By Province

Province	Interpolated – 2015	Extrapolated – 2020	Extrapolated – 2025	Extrapolated – 2030 & 2035
Eastern	0.647	0.515	0.328	0.140
Kigali City	0.690	0.521	0.315	0.109
Northern	0.616	0.452	0.281	0.110
Southern	0.705	0.585	0.352	0.119
Western	0.722	0.582	0.358	0.135

Source: Adapted from Bagstad et al., 2019 and Banerjee et al., 2019

SDR estimates annual soil loss at ith cell by RUSLE equation

$$ulse_i = R_i \times K_i \times LS_i \times C_i \times P_i \quad \textbf{Eq. 1}$$

where

R_i is rainfall erosivity [units: MJ.mm(ha.hr)$^{-1}$]
K_i is soil erodibility [units: ton.ha.hr (MJ.ha.mm)$^{-1}$]
LS_i is a slope length-gradient factor (dimensionless)
C_i is a crop-management factor (dimensionless)
and P_i is a support practice factor (dimensionless)

The scenarios substituted the following model inputs: (i) LULC data for the appropriate scenario and year; (ii) updated fertilizer application and irrigation rates for the FERTIIRRIG and COMBI2/COMB scenarios for the NDR model; and (iii) updated estimates of the effects of terracing on soil erosion for the SDR model in AGROFOR and COMBI12/COMBI scenarios. Because of the terracing in agroforestry, which plays a key role in reducing soil erosion, we modeled SDR for agroforestry using an aggressive terracing program proposed by Vision 2020.

Table 4. Spatial data sources used in the Rwanda InVEST models

Models	Dataset	Data source	Spatial resolution	Year	Data processing notes
All	Land cover	Regional Centre for Mapping Resources for Development (RCMRD) Scheme II land cover classification	30 m	2015	Resample to 210m resolution
Annual & seasonal water	Monthly precipitation	WorldClim CNRM_CM6-1	2.5m	2021-2040	
Annual & seasonal water	Reference evapotranspiration	Global Aridity Index and Potential Evapotranspiration (ET0)	30 arc second	2015	Extracted from Bagstad et al.(2020)
Annual water	Depth to root restricting layer	International Soil Reference and Information Centre (ISRIC) African SoilGrids 250 m	250 m	n/a	Extracted from Bagstad et al.(2020)
Annual water	Plant available water fraction	ISRIC African SoilGrids 250 m	250 m	n/a	Extracted from Bagstad et al.(2019)
Nutrient delivery ratio (NDR)	Nutrient runoff proxy	Quick flow results from seasonal water yield model	210 m	2015-2035	Seasonal water yield model outputs for equivalent year
Seasonal water	Ecoregions	World Wildlife Fund	Polygon data	n/a	Extracted from Bagstad et al.(2019)
Seasonal water	Hydrologic soil group	ISRIC African SoilGrids 250 m	250 m	n/a	Extracted from Bagstad et al.(2019)
NDR, Seasonal water, Sediment delivery ratio (SDR)	Void-filled digital elevation model	Regional Centre for Mapping Resources for Development (RCMRD) Scheme II land cover classification	30 m	n/a	Resample to 210 m
SDR	Rainfall erosivity	Panagos et al. (2017)	30 arc arc-seconds	2015	Extracted from Bagstad et al.(2019)
SDR	Soil erodibility	Derived from ISRIC African SoilGrids 250 m	250 m	n/a	Extracted from Bagstad et al.(2019)
NDR, SDR, water	Watershed & subwatershed boundaries	Rwanda Water and Forestry Authority	Polygon data	n/a	Derived from Bagstad et al.(2019)

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, (Trabucco et al., 2006) for all scenarios. As such, we did not include the potential effects of climate change in our ecosystem service models. Vision 2020 calls for having 90% of land protected against soil erosion, as opposed to 80% in 2010 and 20% in 2000 (MINECOFIN, 2013). The Rwanda Water Resources Management sub-sector strategic plan (2011-2015) calls for 852,000 ha of additional land to be protected from erosion using radical and progressive terracing (Ministry of Natural Resources, 2011). To extrapolate p factors into future years for scenario analysis, we considered projection of 90% coverage with 100% efficiency by the year 2030 and future years. By using the projected usle_p values, we assumed that terracing is implemented by farmers in our future projection, both in the baseline and five future scenarios.

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 was 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. 2016).

3.6. Ecosystem Services Supply Feedback in IEEM

Erosion and erosion mitigation services occur in the baseline business as usual case and in the future scenarios. We establish severe erosion (greater than 11 tons/ha/yr) in the baseline by identifying the number of pixels exhibiting severe erosion. We estimate the area subject to severe erosion as the number of pixels exhibiting severe erosion multiplied by the spatial resolution of the land use land cover raster (e.g. 10 pixels X 30m X 30m). We then identify the number of pixels in the scenario that exhibit severe erosion and multiply it by the spatial resolution of the raster as with the baseline. If the area of severe erosion is greater in the scenario than in the baseline, erosion is increasing due to the scenario (policy or investment intervention).

Based on Panagos et al. (2017), we relate the presence of severe erosion to a reduction in agricultural productivity of 8%. To create a feedback between changes in ES and IEEM, we apply the following formula to the base and to the scenario for crops:

$$LPL_d = \frac{SER_d}{TAA_d} \cdot 0.08 \qquad \text{Eq. 2}$$

where:

LPL_d is the land productivity loss by subscript *d* Department;

SER_d is the agricultural land area (hectares) subject to severe erosion of >11t/ha/year in each Department, and;

TAA_d is the total agricultural area, both crop and livestock, by Department.

0.08 is the agricultural productivity shock derived from Panagos et al. (2017)

This calculation for both the baseline and scenario enables implementation of the agricultural productivity shock arising from erosion will be applied in IEEM.

We implement this agricultural productivity shock in IEEM for the year 2020 and generate new results for the period of 2020 to 2035 for economic and natural capital impact indicators and demand for different land use. We ran the LULC change model and ES model for the 2015 to 2035 period, and estimate changes in ES supply and the resulting changes in agricultural productivity. This feedback between IEEM and ES models results in scenario impacts on the economy, which includes both natural capital stocks and ES service supply changes.

4. Results

4.1. Economic Impacts

In this section, we discuss the results from the scenarios implemented in the Rwanda IEEM+ESM framework. The economic implications of the five scenarios are provided in two ways in comparison to the baseline results. In the first way, we compare the first and last year of simulation with respect to the base year to assess the overall change in a given indicator of economic performance that results from implementing that scenario. In the second way, we show trend across the two decades of analyses, ranging from 2015 to 2035. This is useful in determining, if, for instance, the trend in the given indicator of economic performance is one of a smooth change over time or if there are any sudden changes likely to occur.

In this report, we also make use of various indicators of economic performance to measure the economic impact of implementing different scenarios. This helps us better determine in which specific aspect a scenario performs well and in which ones it performs poorly. If a scenario consistently performs better than others across multiple indicators of economic performance, however, it could be an indicator of a relatively improved solution. Thus, this approach allows us to more effectively compare the scenario results across a set of macroeconomic indicators.

The indicators of economic performance used in this report include gross domestic product (GDP), private consumption, and fixed investment. While GDP at market prices measures the gross values added of all resident producers at market prices, plus taxes less subsidies on imports, GDP at factor cost measures sum of net value added by all the producers in the domestic territory of the country along with consumption of fixed capital during an accounting year. Whereas fixed investment is the accumulation of physical assets, private consumption, which is an important part of GDP and a driver of economic growth, is a measure of consumer spending on goods and services.

The rest of the economic indicators reported are absorption, genuine saving, and headcount ratio. Absorption is the total demand for all final marketed goods and services regardless of the origin of the goods and services themselves. Genuine saving measures the net annual increase or decrease in the stock of capital over time; positive value indicates that we are leaving more for the future generations, a negative value shows the opposite. We also measured the impact of implementing the scenarios on poverty level. This is presented both as actual numbers and in headcount ratio terms, which represents the change in the percentage of the population below the poverty line that is attributable to implementation of the scenario.

The change in macro-economic indicators during 2035-2015 in USD across all the five scenarios are presented in Table 5. The annual average growth rate during the same period are presented in Table 6.

Table 5. Real Macroeconomic Indicators in 2035 with respect to Base

(2019 US$ Million, Difference with respect to Base)

Macroeconomic Indicator	AGROFOR	LANDCON	COMBI12	FERTIRRIG	COMBI
Absorption	4	1,163	1,175	315	1,472
Private Consumption	-54	1,078	1,025	289	1,298
Fixed Investment	58	85	150	26	174
Private Fixed Investment	58	85	150	26	174
Exports	-5	105	100	20	119
Imports	-8	91	82	17	99
GDP at Market Price	7	1,178	1,193	317	1,493
GDP at Factor Cost	-40	1,078	1,032	292	1,310
Net Indirect Tax	-4	63	61	16	76

Source: Integrated Economic-Environmental Modeling and Ecosystem Services Modeling results for Scenarios.

The LANDCON scenario, which is expected to boost agricultural production by scaling up the consolidated land by 54% with an overall productivity increase of 30%, increased absorption by US$ 1.2 billion (0.16% growth per annum). The GDP at market price increased by US$ 1.2 billion with most of this coming from private consumption (US$ 1 billion). The exports under LANDCON scenario increased by US$ 105 million and imports by US$ 91 million. This is due to fact that we boosted the yield of crops by 3% per annum, resulting in greater production of export-oriented crops; the increase in imports was due to increase in private consumption.

The COMBI12 scenario combines the AGROFOR and LANDCON scenarios together; the results as depicted in Tables 5 and 6 indicate that the LANDCON impact was considerably greater than AGROFOR impact. The average annual growth in GDP was about 0.19%, and private consumption grew by 0.22%. Interestingly, the unemployment rate dropped by 0.12% per annum due to LANDCON scenario as additional arable land was brought under cultivation. As a result of this decrease in unemployment rate, the real wages also went up by 0.22%, which is important for improving the disposable income of the rural labor force. The FERTIRRIG scenario looks at the impact of increasing fertilizer use by 134% (75kg/ha) and a moderate annual increase in irrigation acreage by 0.6% per year from the current levels. The GDP increase was only a moderate US$ 317 million (0.05% per annum); most of this came from increase in private consumption as in the other scenarios.

Table 6. Real Macroeconomic Indicators Average Growth from 2015-2035

(% per annum, Difference with respect to Base)

Macroeconomic Indicator	AGROFOR	LANDCON	COMBI12	FERTIRRIG	COMBI
Absorption	0.001	0.164	0.166	0.045	0.207
Private Consumption	-0.012	0.230	0.219	0.063	0.276
Fixed Investment	0.039	0.057	0.100	0.017	0.116
Private Fixed Investment	0.076	0.112	0.196	0.034	0.227
Government Fixed Investment			0.000		0.000
Real Exchange Rate	-0.031	0.136	0.110	0.045	0.149
Exports	-0.005	0.110	0.105	0.021	0.125
Imports	-0.004	0.047	0.042	0.009	0.051
GDP at Market Price	0.001	0.193	0.195	0.053	0.243
GDP at Factor Cost	-0.007	0.187	0.179	0.051	0.227
Unemployment Rate	0.020	-0.125	-0.112	-0.034	-0.141
Wage	-0.040	0.229	0.197	0.059	0.250

Source: Integrated Economic-Environmental Modeling and Ecosystem Services Modeling results for Scenarios.

As discussed earlier, the COMBI scenario is the combination of all the four scenarios; as expected, it showed the cumulative impact of all other individual scenarios as measured by macroeconomic indicators such as GDP at market price, private consumption, exports, imports, and absorption. The model predicted GDP impact both at market price and at factor cost under COMBI scenario at US$ 1.49 billion and US $1.31 billion, respectively. In implementing these scenarios, we assumed that all fixed investment would from private fixed investment (from foreign borrowing) as opposed to government fixed investment. The real exchange rate as shown in Table 6 indicated a moderate appreciation by 0.15% per annum in the COMBI scenario, which may be attributable due to the growth in GDP and exports.

In Figure 5, we depict how the model estimated year to year change in private consumption in real 2019 US$ million. As seen in the figure, the AGROFOR scenario performs poorly compared to all the other scenarios, and the real private consumption goes below the baseline by 2035. When we consider this standalone AGRIFOR policy, it showed negligible overall impact mainly because it did not boost the economic output. Unlike agriculture, agroforestry does not yield benefits unless harvested for its economic value. Overall, the LANDCON scenario showed the dominance relative to other individual scenarios. Increase in agricultural production increases the disposable income of agricultural households, further enhancing their aggregate consumption. This is a key revelation that Rwanda's strategic plan for agricultural transformation indeed helps in advancing agricultural production as well as boosting the economy. This is further revealed in Figure 6, which shows that the value-added measure of GDP, which is an increase in the value of goods or services as a result of the production process, was the highest (0.18% per annum) under LANDCON scenario.

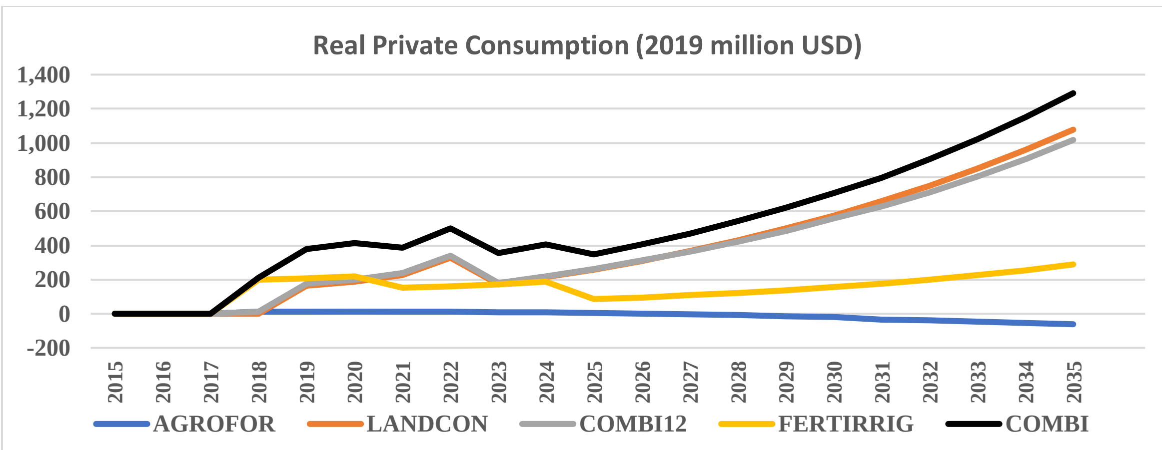


Figure 5. Model estimated change in Private Consumption for Scenarios

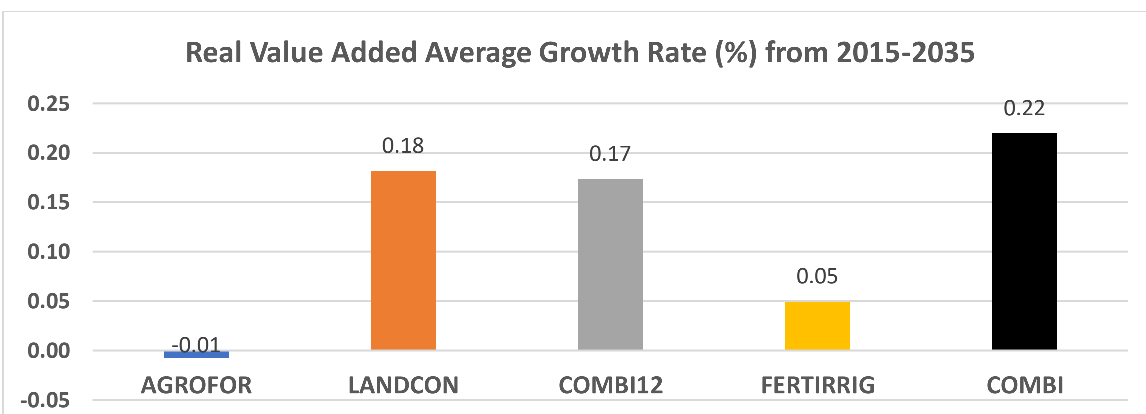


Figure 6. Average Annual Growth Rate of Real Value Added for Scenarios

The change in real GDP at factor cost, which is measured based on the cost of production without accounting for indirect taxes, showed exponential growth in the overall COMBI scenario; most of this GDP growth came from LANDCON, followed by FERTIRRIG scenarios. Given that the agriculture sector contributes to nearly one-third of Rwanda's GDP, the LANDCON and FERTIRRIG scenarios increase agricultural activities and production leading to growth in real GDP. Though the AGROFOR scenario does not necessarily contribute towards real GDP growth in the long run, it is an important sector that would also contribute towards sustainable economic growth in the region if designed to yield economic returns.

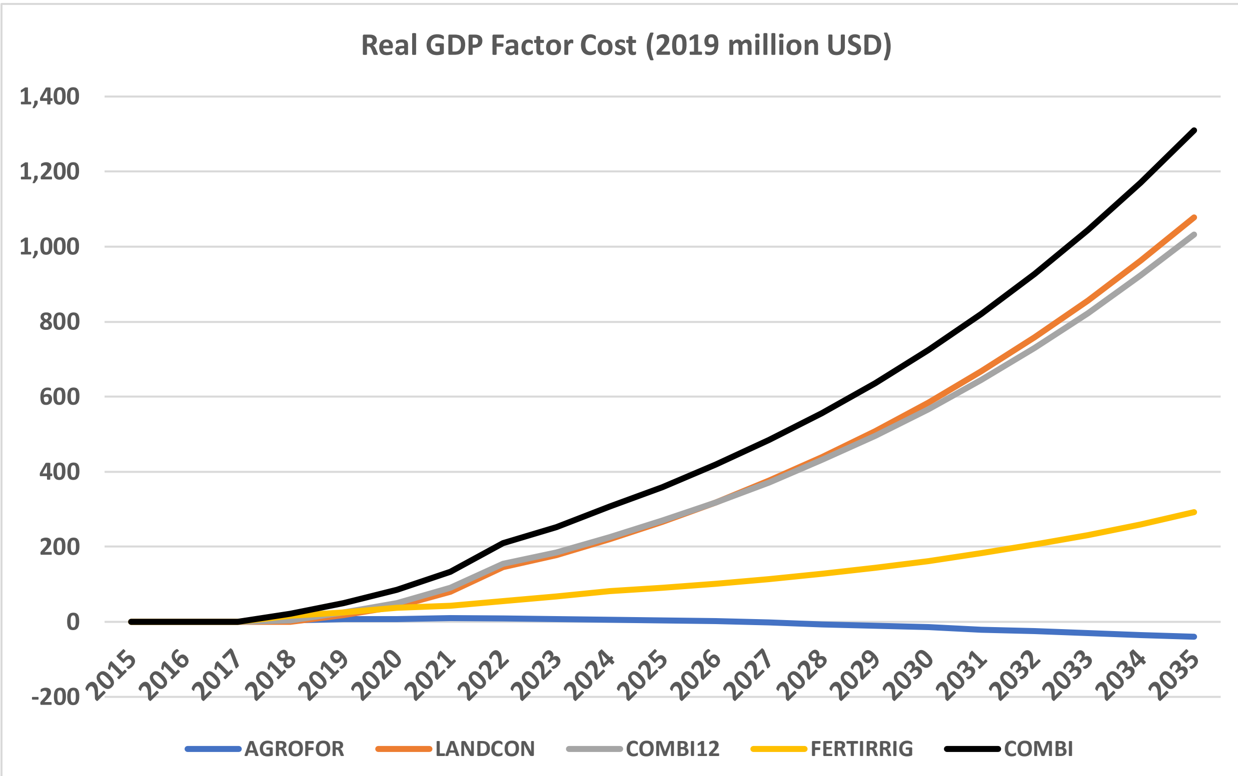


Figure 7. Change in Real GDP At Factor Cost Compared to the Base Case

The IEEM model also determines the change in poverty line based on the endogenous change in commodity prices for a given scenario. The poverty headcount ratio, which is the percent of the population living below the Rwanda's national poverty line, was also calculated. Figure 8 provides the share of population below the poverty line and headcount ratio in Rwanda. As seen from the bottom panel of Figure 8, the headcount ratio relative to base case drastically reduces in the COMBI scenario; most of this impact on poverty reduction is attributed to LANDCON and FERTIRRIG scenarios. The impact on poverty is incidental with respect to the shocks implemented in the initial years of the simulation (headcount ratio reduces by around -2.0% during 2019-2024), and then the estimates smoothen through 2035, with the decline in headcount ratio reaching to -1.4%. The top panel of the figure shows the expected number of people that would be under the poverty line each year through 2035.

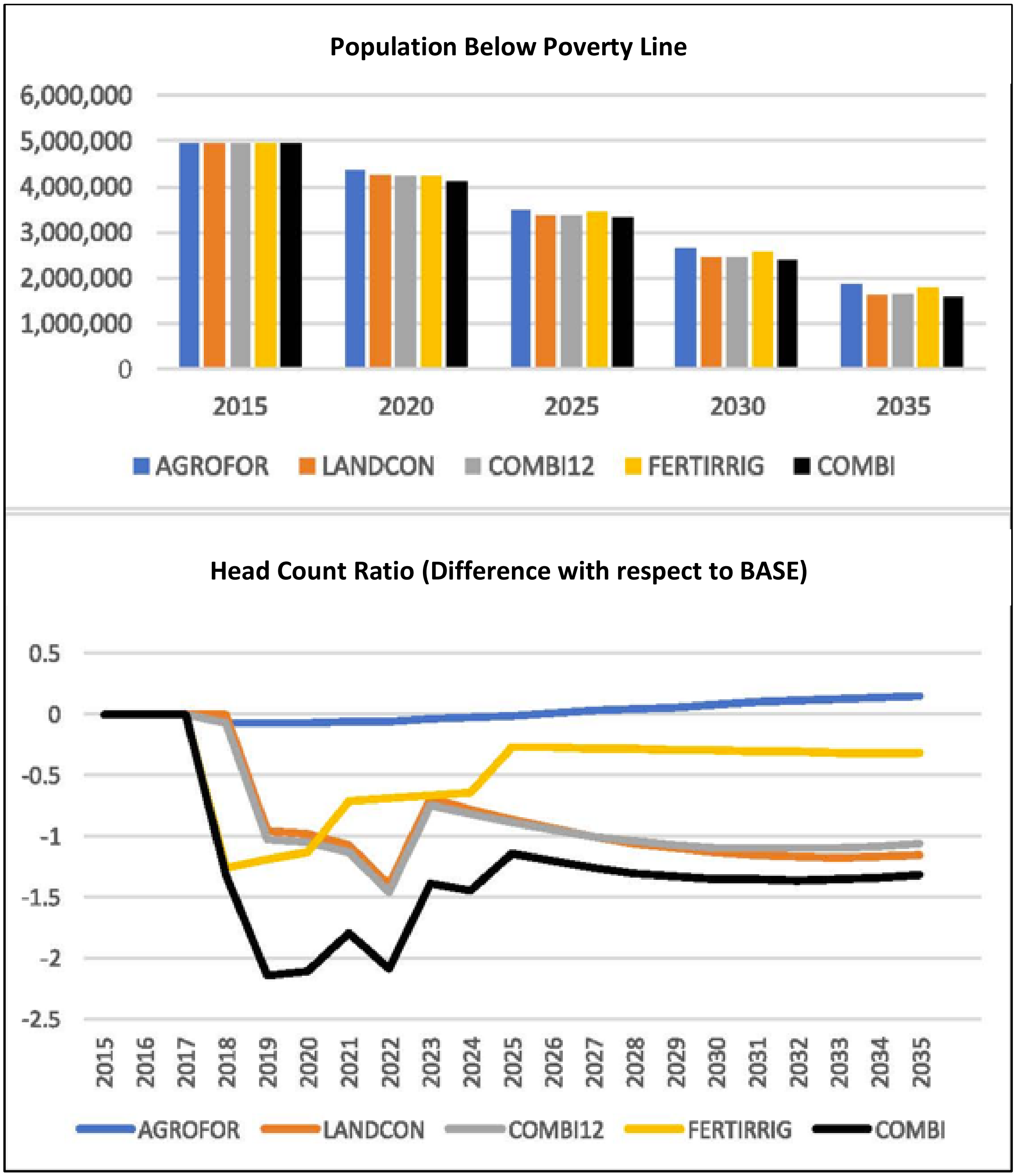


Figure 8. Share of Population Below Poverty Line and Headcount Ratio in Scenarios

In consistent with other impacts, the COMBI scenario shows stronger impact in terms of reduction number of Rwandans being below the national poverty line. This is again attributable to growth in agricultural production due to land consolidation and due to increased access to fertilizers and irrigation towards crop-productivity improvement. Interestingly, the AGROFOR scenario leads to lower headcount ratio of poverty through 2024, but the impact subsides in the later periods. This is because as long as the agroforestry is actively pursued as an economic activity, it contributes towards socio-economic benefits. However, once the activity is stopped, the factor markets reaches back to its general equilibrium, implying no further employment generation for the agriculture sector in the later periods under AGROFOR sector.

In terms of the level of accumulated real genuine savings over time, the model estimated that LANDCON scenario pointedly contributed towards increases in savings through 2035. Since there is borrowing during the program implementation years, the overall genuine savings are negative through 2024, but gradually increase in the later years. AGROFOR showed a small drop in genuine savings, but the COMBI policy revealed that Rwanda's genuine savings would increase in the long run.

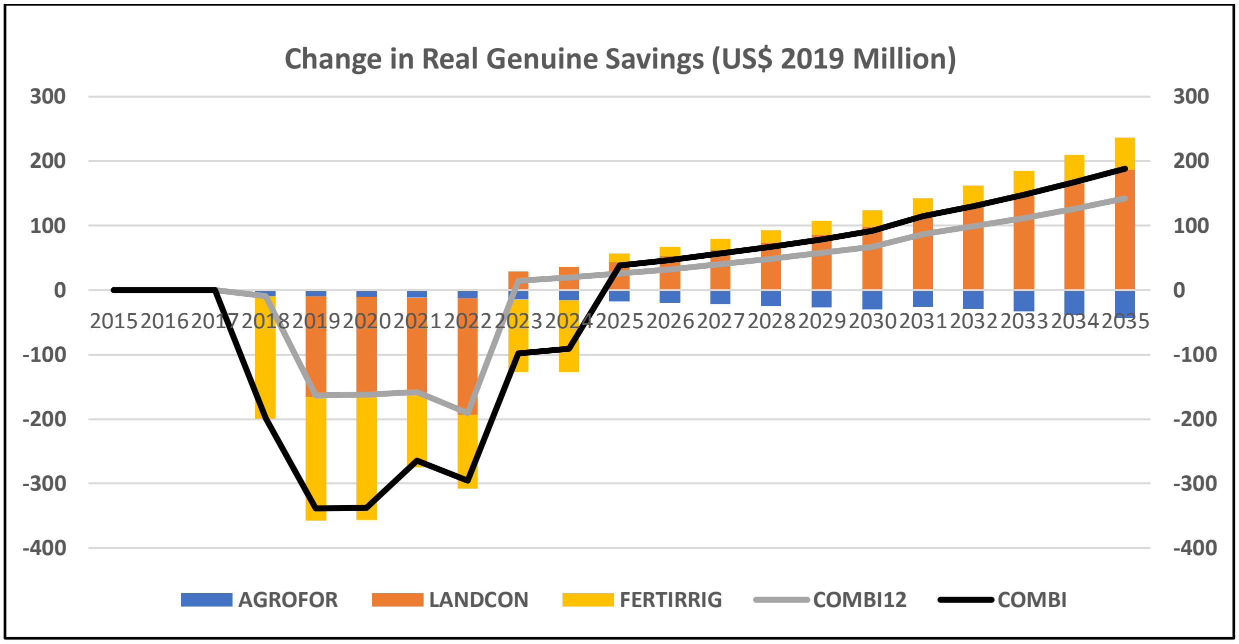


Figure 9. Change in Real Genuine Savings with respect to Base

As predicted by the IEEM model, the LANDCON scenario outperforms the other scenarios in terms of improvement in private consumption, real exchange rate, exports, imports, GDP at factor cost, unemployment rate, and wages. AGROFOR comes in last in almost all the indicators of economic performance, save that it resulted in relatively more fixed Investment compared to the FERTIRRIG scenario. The impacts associated with the given scenario are linked with model predicted outcomes through transmission mechanisms. For instance, productivity enhancing measures such as increased fertilization and irrigation lead to an increase in agricultural total factor productivity, which in turn leads to increases in output and reductions in agricultural factor use. The lower agricultural factor use frees up capital, labor, and land for use in other productive sectors of the economy. These gains lead to increase in output and improvements in wages, household income, consumption, savings, and reduced unemployment. Efficiency improving measures such as technological changes in agriculture can lead to lower costs, leading to greater disposable income for consumption of other goods and services, including education and health services. Given these economic implications, it is clear that designing combinations of strategic measures such as land-consolidation, fertilization, and irrigation along with agroforestry expansion would be beneficial for the overall Rwanda's economy.

4.2. Land Cover Impacts

Rwanda's natural capital accounts provide data on forest cover, cropland, and tree plantations on farmland. We constrained changes to land use related impact in terms of existing non-productive forest, forest plantations, and total forest land and focused on new tree plantations on farm land. The results show that the land assets change across scenarios largely due shifts in livestock and agriculture (fruit crops on farmlands as part of agroforestry investing and perennial crops in lieu of non-perennial crops).

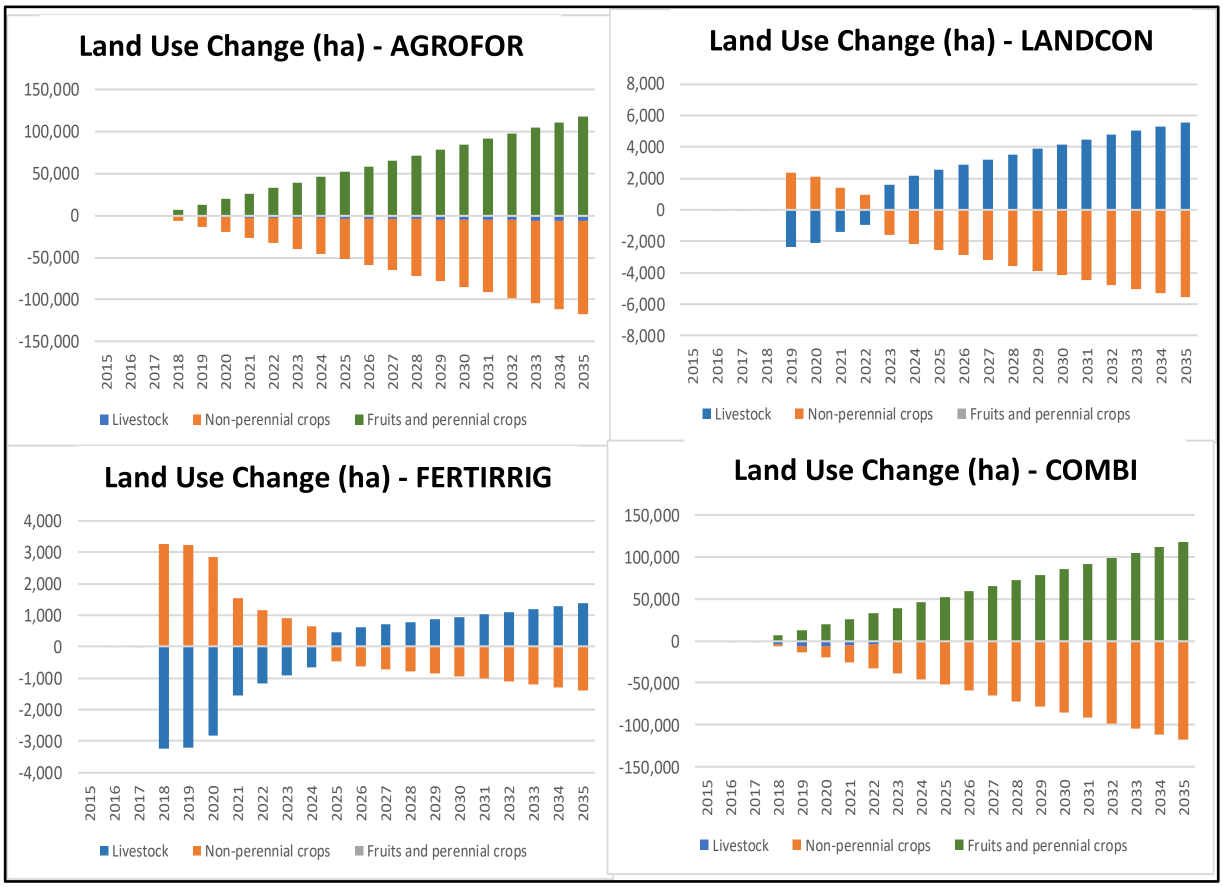


Figure 10. Land Use Change (hectares) with respect to Base across Scenarios

Figure 10 depicts the land use change pattern across the four scenarios (COMBI12 is excluded from the panel). The AGROFOR scenario shows that by 2035, the land under fruits and perennial crops increases by 117,580 hectares; most (94%) of this comes from conversion of non-perennial cropland, and 6% comes from the conversion of livestock (pasture and grassland). In the case of the LANDCON scenario, the model predicts a relatively smaller magnitude of land use change, with only 5,567 hectares of pasture and grassland expansion coming from conversion of land under fruits and perennial crops. The COMB12 scenario, which is not depicted in the panel, was essentially dominated by the AGROFOR scenario.

Figure 11, shows that the FERTIRRIG scenario results insignificant land conversion, with only 1,378 hectares of pasture and grassland getting converted from non-perennial cropland. The COMBI scenario, since it includes all the three individual scenarios, shows 117,580 hectares of expansion in fruits and perennial cropland and a small 196 hectares expansion in pasture and grassland, all coming from conversion of non-perennial cropland. These results are also depicted in Figure 12 as net land use change during 2015-2035 across all the scenarios.

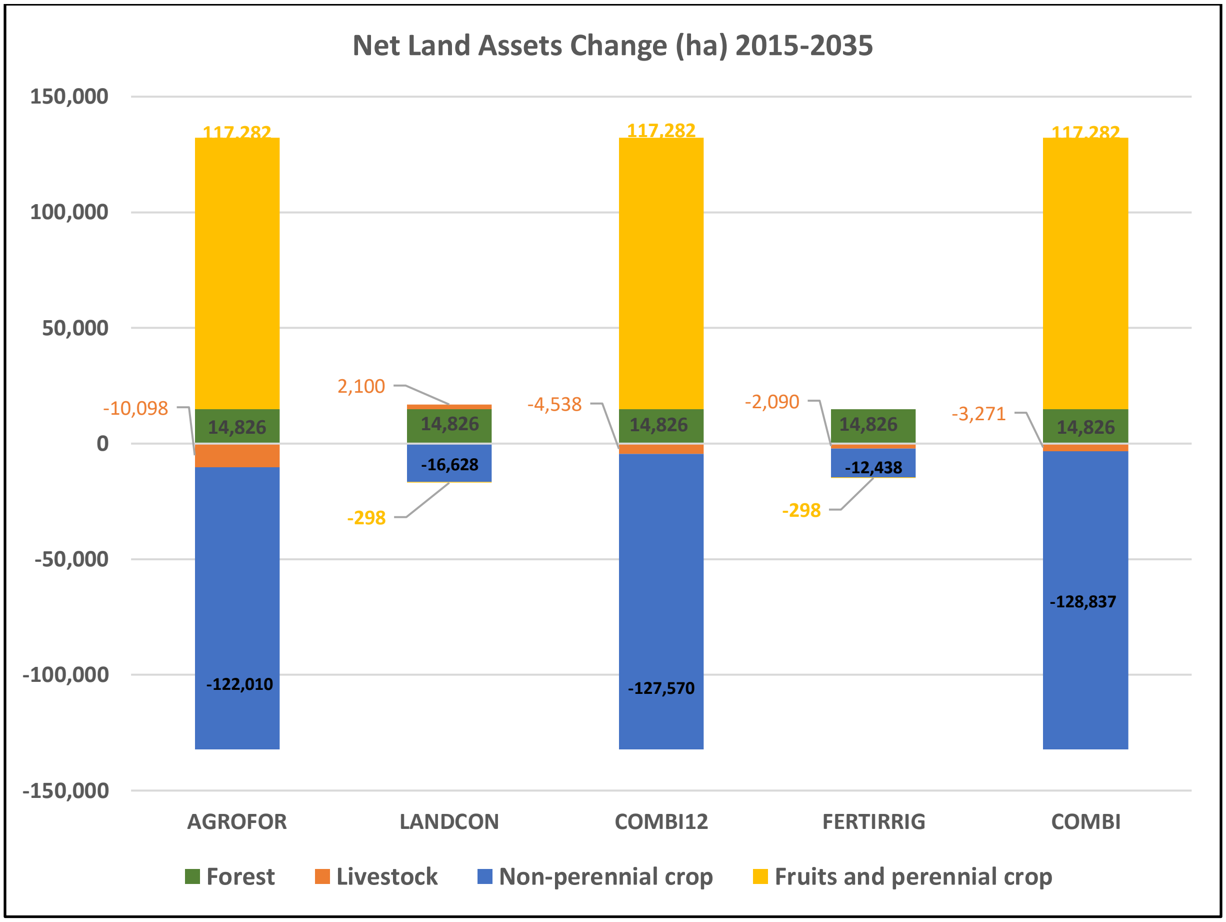


Figure 11. Net Land Assets Change Across Scenarios

In the LANDCON scenario, the pasture and grassland cover expand due to intensification of the land-use activities. In terms of similarity, AGROFOR and COMBI12 have comparable effects, and LANDCON, FERTIRRIG, and COMBI have comparable effects. The most substantial differences in LULC changes across scenarios were found in AGROFOR and LANDCON (Figure 11 and Figure 12). The IEEM model takes into account of the economic activities of livestock sector along with all other sectors; as a result, the pasture and grassland conversion in the AGROFOR scenario drastically reduces in the COMBI scenario. The land use agroforestry expands away from non-perennial crop land to meet the target of agroforestry expansion in the AGROFOR scenario.

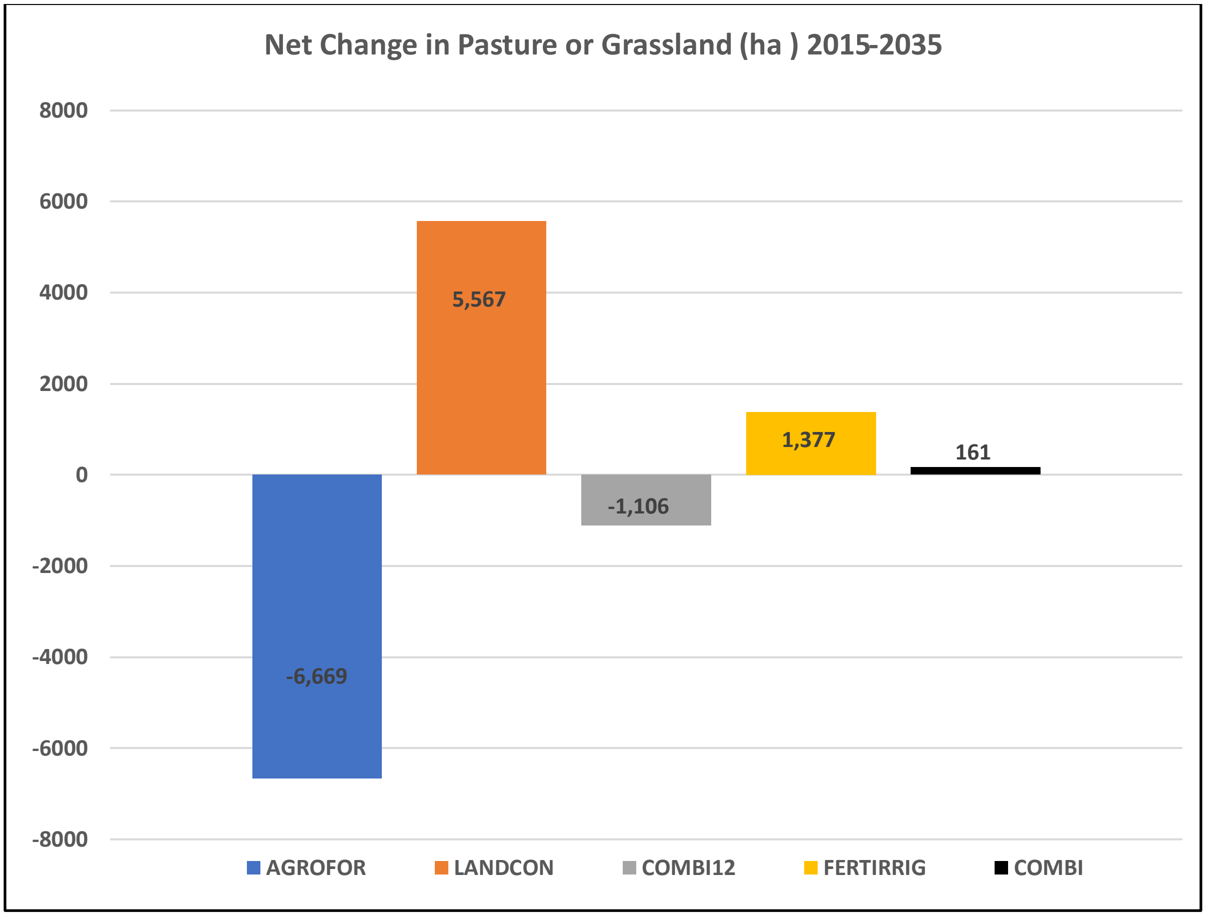


Figure 12. Net Land Use Change (hectares) in Pasture or Grassland

Land cover maps show that the vast majority of changes occur at or near urban centers in the base case. All cases with the exception of AGROFOR reveal that most spatial differences between scenarios are largely caused by the switch over to fruit tree planting on farmland (Figure 13). This change on land cover is widespread, and shows the greatest shift in actual land use over the BASE scenario. Another difference here is the shift of perennial agriculture to western Rwanda in all scenarios without agroforestry. Scenario results indicate that perennial crops tend to move toward the water bodies; while this pressure might dissipate somewhat if controlled for crop type, the phenomenon nevertheless exists. This shift is not seen as much in the AGROFOR, COMBI12 and COMBI scenarios.

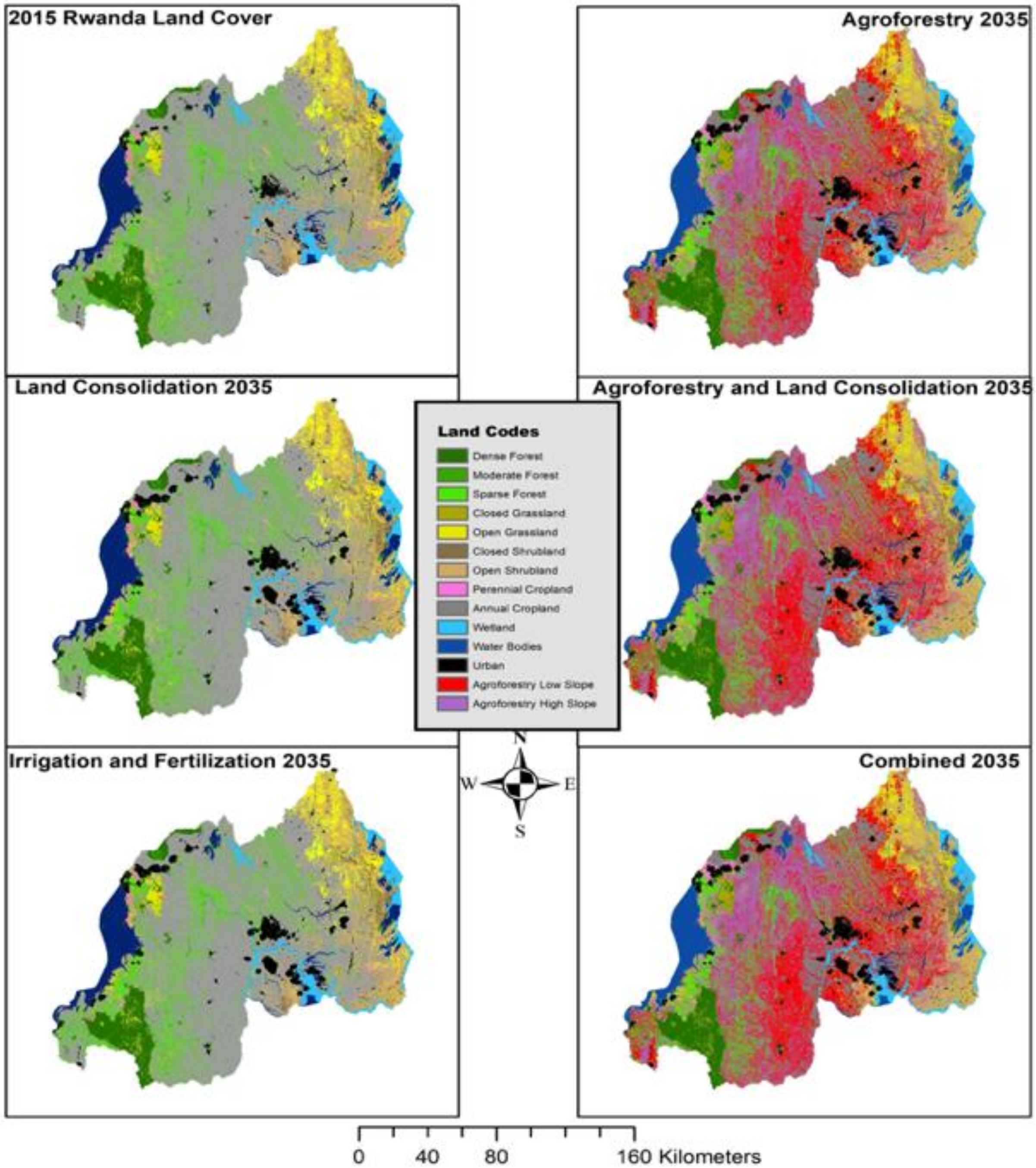


Figure 13. Land Cover Projections for Scenarios with respect to 2015

We can also observe that open grassland in northwestern Rwanda gets converted in these scenarios to agroforests and croplands. AGROFOR, COMBI12, and COMBI scenarios suggest that agroforestry on high slope land is dominant in central and northwest Rwanda, while agroforests on low slope land are dominant in southern Rwanda. The simulation for land consolidation results in slightly lower demand for agriculture, and thus a slightly higher cover of shrubs and grasslands compared to the other non-agroforestry scenarios.

4.3. Ecosystem Services Impacts

InVEST based Ecosystem service models enabled the quantification of changes in ecosystem services for all scenarios until 2035, and compared the base scenario to the other five scenarios at a national scale. Table 7 reports these changes in ecosystem services as the percent difference from the BASE in 2035.

Table 7. Ecosystem Services Impacts Expressed as the Percent Difference Between Scenarios and Baseline in 2035

		2015 and 2035 BASE Difference	Percent Difference between Scenario and Base In 2035				
	2015 BASE	**BASE**	**AGROFOR**	**LANDCON**	**COMBI12**	**FERTIRRIG**	**COMBI**
Carbon storage	492.45 mil.Mg	-0.15%	11.75%	0.10%	11.81%	0.15%	11.77%
Annual water yield	7.53 mil.m^3	-0.22%	15.96%	0.01%	15.93%	-0.01%	15.92%
Quick Flow	3.70 mil.m^3	4.83%	-24.07%	-0.12%	-24.24%	-0.13%	-24.29%
Local recharge	4.74 mil.m^3	2.70%	19.23%	0.01%	19.33%	0.02%	19.39%
Sediment export	14.03 Mg	-9.83%	-40.48%	-0.47%	-40.60%	-0.50%	-40.51%
Nitrogen export	7.20 mil.kg	0.41%	-75.05%	-0.32%	-74.36%	112.51%	-60.74%
Phosphorus export	3.58 mil.kg	-0.35%	-72.27%	-0.33%	-73.14%	114.78%	-59.22%

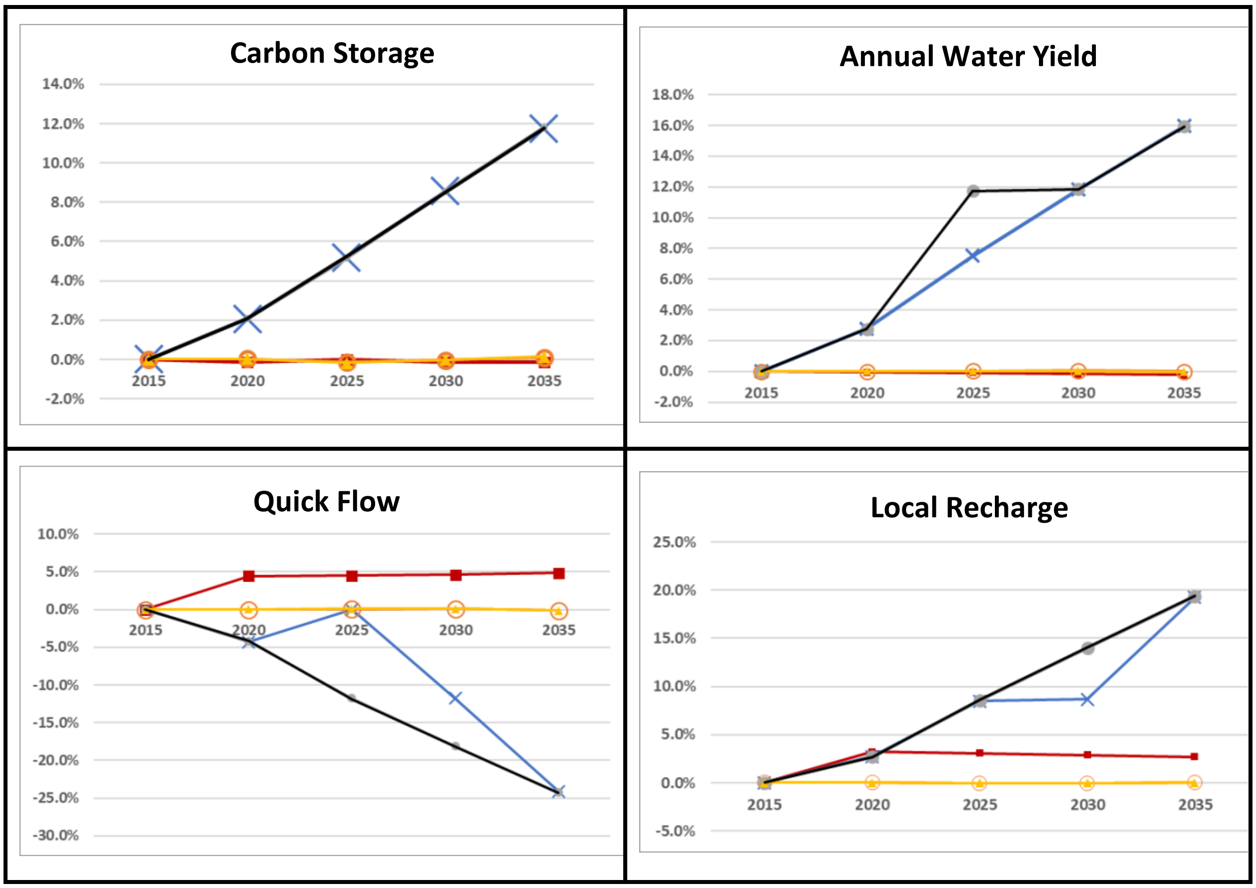
Source: Integrated Economic-Environmental Modeling and Ecosystem Services Modeling results for Scenarios.

Carbon storage increased across all five scenarios, depicting improved ES. Annual water yield increased in four scenarios, excepting a marginal decrease showcased in the FERTIRRIG scenario. Increases in annual water yield indicate less evapotranspiration and more runoff, but the implications are not straightforward (Bagstad et al., 2019). Analysis of local recharge and quick flow reveal better indicator changes in water yield (Sharp et al., 2016). Local recharge increased and quick flow decreased in all five scenarios, which represents enhanced ES. Quick flow reduction typically signifies improvement in water quality, while local recharge increase represents improvement in dry-season flows. Fruit tree plantation activity represented by AGROFOR, COMBI12, and COMBI scenarios reflect substantial ES change compared to LANDCON and COMBI12 scenarios.

The AGROFOR, COMBI12, and COMBI scenarios also led to larger reductions in sediment export, depicting erosion control caused largely due to expanded tree plantations on arable land and grasslands. LANDCON and FERTIRRIG scenarios also represent a slight decrease in erosion, though the decrease is much lower than the one could observe in the base case without policy interventions.

Nitrogen and phosphorus export decreased substantially in AGROFOR, COMBI12, and COMBI scenarios, signifying larger ES improvements. The FERTIRRIG scenario, on the other hand, showed substantial nutrient export, largely expected due to increased fertilizer application and irrigation. While both substantially increased the application of nutrients to croplands, tree plantation in the COMBI scenarios was enough to retain most of nitrogen and phosphorus, signifying improvement in land assets and associated ES.

Differences between LANDCON and FERTIRRIG scenarios are notable for almost stable water yield, a decrease in sediment export and quick flow, and smaller increases in carbon storage and local recharge services. The difference is pronounced in terms of nutrient exports, where FERTIRRIG leads to a substantial increase in nitrogen and phosphorus as compared to a slight decrease in the LANDCON scenario.



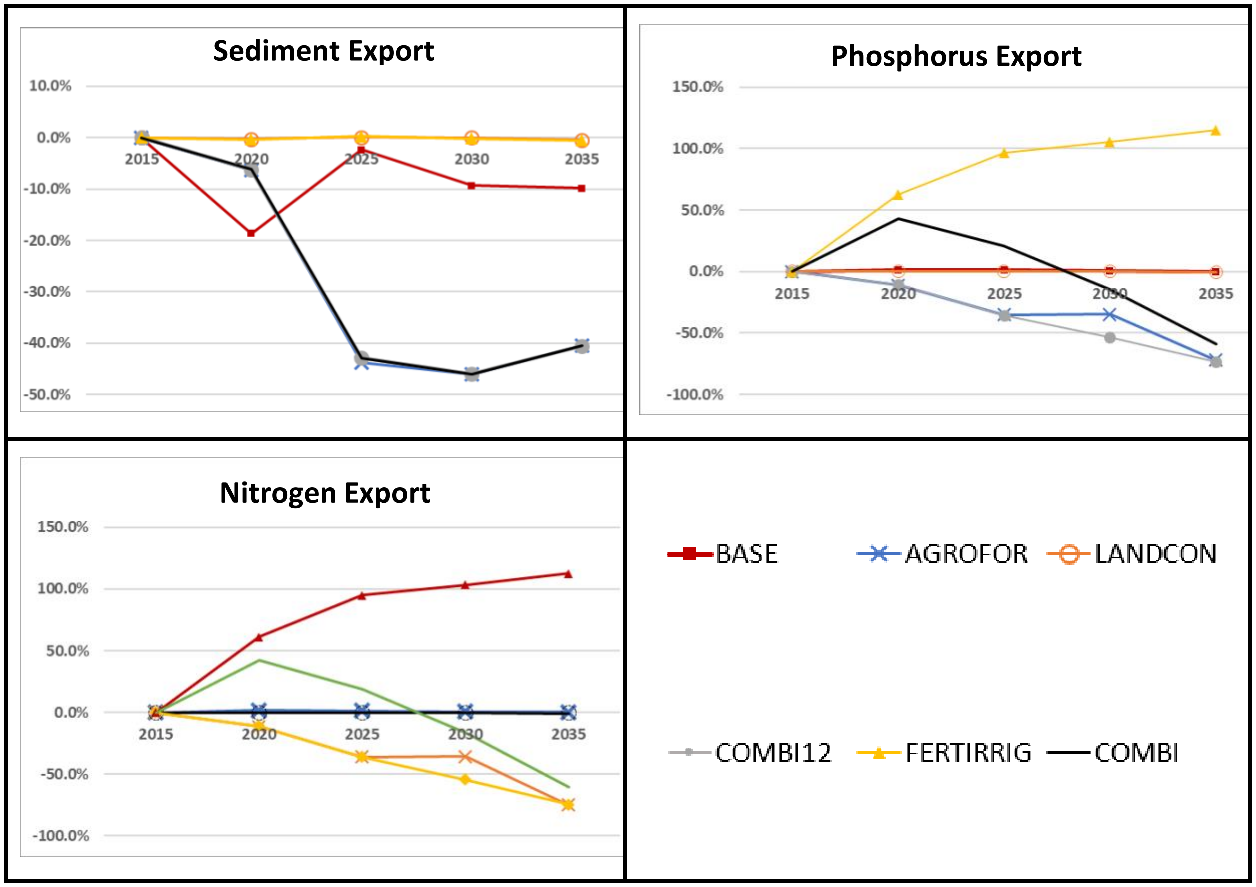


Figure 14. National-Scale Trends in Ecosystem Services for Baseline and Scenarios from 2015-2035

These changes reflect favorable ES changes in terms of carbon storage and water yield vis a vis the business as usual case. The quick flow was reduced in all scenarios rather than being positive as in the base case, signifying ES improvements. Local recharge increased in LANDCON, though FERTIRRIG decreased as compared to the base scenario. Sediment, nitrogen, and phosphorus exports were much lower for three tree planting on arable land and grassland scenarios, signifying prospects for fostering green growth in Rwanda.

The annual water yield is heavily affected in AGROFOR, COMBI12 and COMBI scenarios (Figure 15). This results in drastic eastward expansion of water surplus regions. However, much of this benefit seems to disappear when combined only with land consolidation policies (LANDCON). Land Use policies that do not include agroforestry have a nearly flat trend for carbon storage, while those that do include agroforestry such as AGROFOR, COMBI12, and COMBI scenarios illustrate a widespread increase in carbon storage (Figure 16).

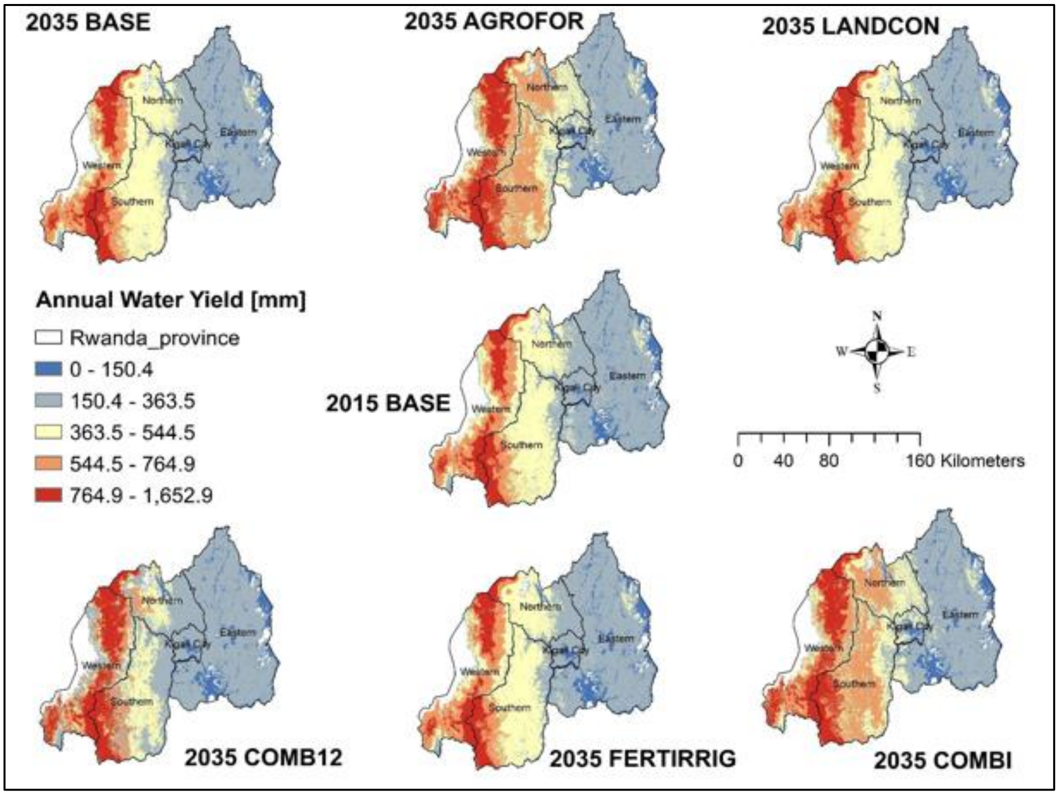


Figure 15. Scenario Results for Annual Water Yield

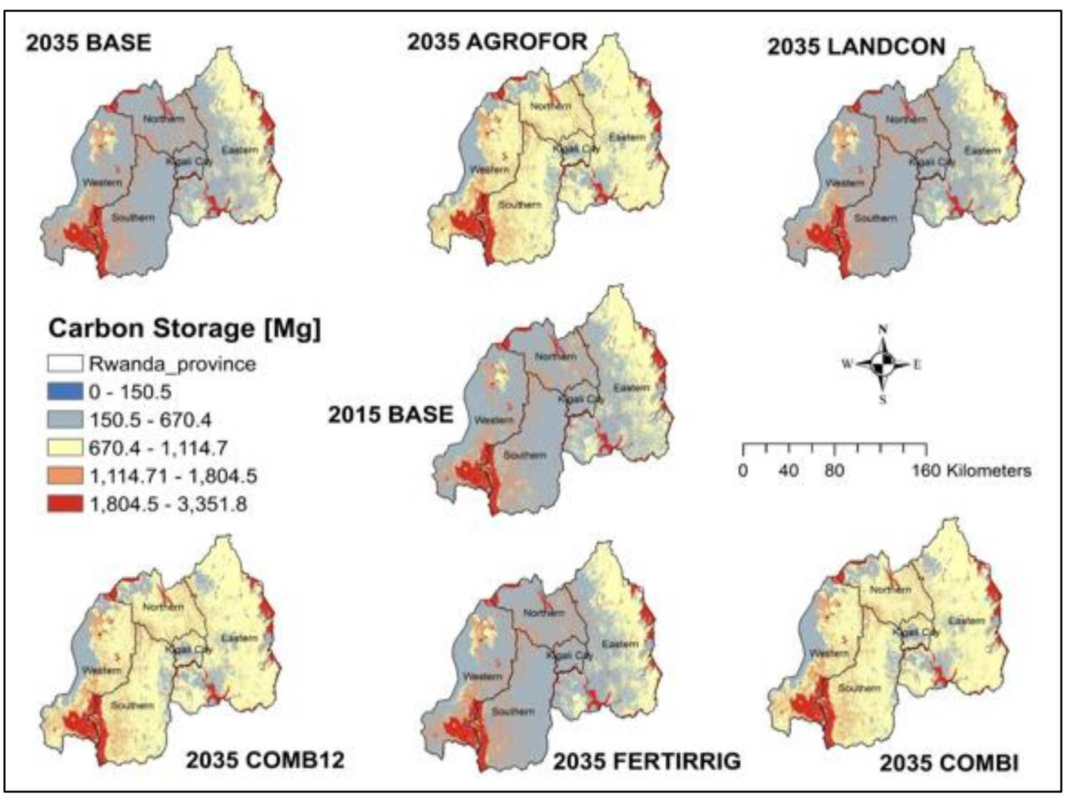


Figure 16. Scenario Results for Carbon Storage

Figures 16 and 17 show how carbon storage and water quick flow, respectively, change between 2015 and 2035 in the BASE, AGROFOR, COMBI12 and COMBI scenarios. The maps indicate that the northwest and south-central regions of the country experience the greatest change in these scenarios. It is important to note that ecosystem extent improvements are a better predictor for simple models like carbon sequestration than for more complex models like sediment and nutrient retention, which depend not just on LULC but also on soils, topography, climate and agricultural practices (Bagstad et al. 2019).

Agroforestry aids in slowing runoff especially well in the western and southern regions, as the estimated quick flow in AGROFOR, COMBI12, and COMBI scenarios is significantly reduced in 2035 (Figure 17). Conversely, local groundwater recharge rates are not heavily affected by the implementation of agroforestry, and seem to be less impacted by the spread of agroforestry on both high slope and low slope farm lands (Figure 18). The quick flow, local recharge, and annual water yield suggest that agricultural and grazing land are dominant in low slope and relatively lower rainfall areas in the central and eastern parts of the country. Our results tend to suggest eastward expansion of water surplus regions. However, much of this benefit seems to disappear when combined only with land consolidation policies.

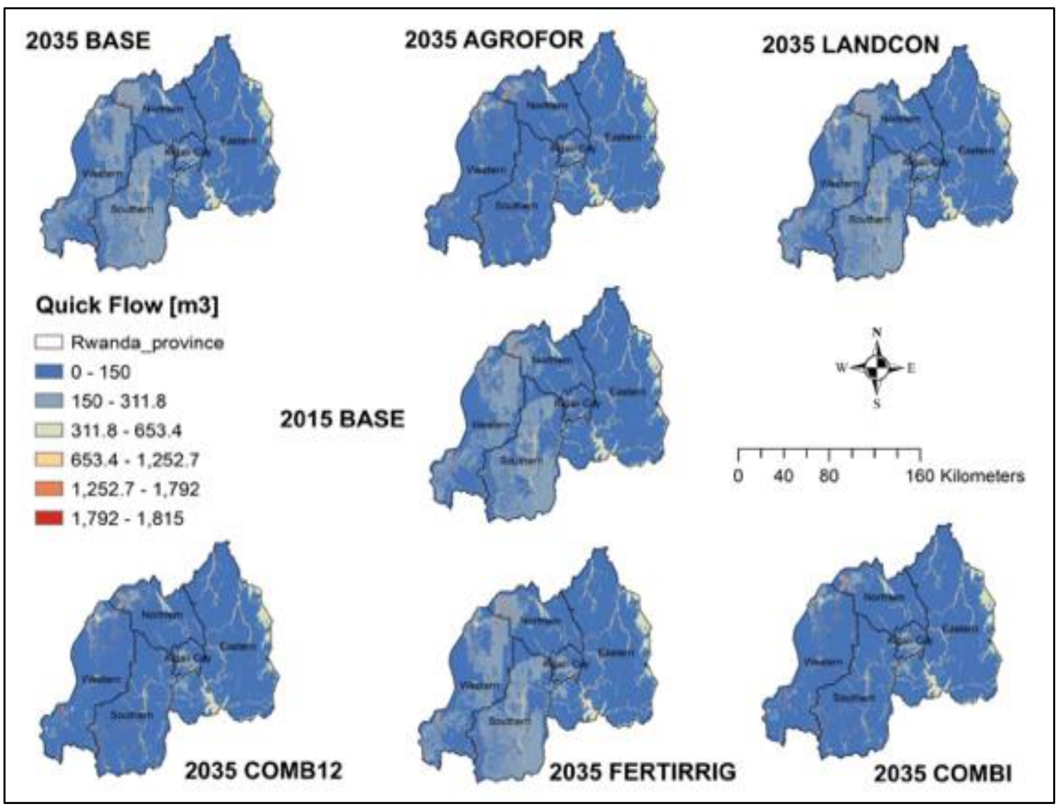


Figure 17. Scenario Results for Quick Flow

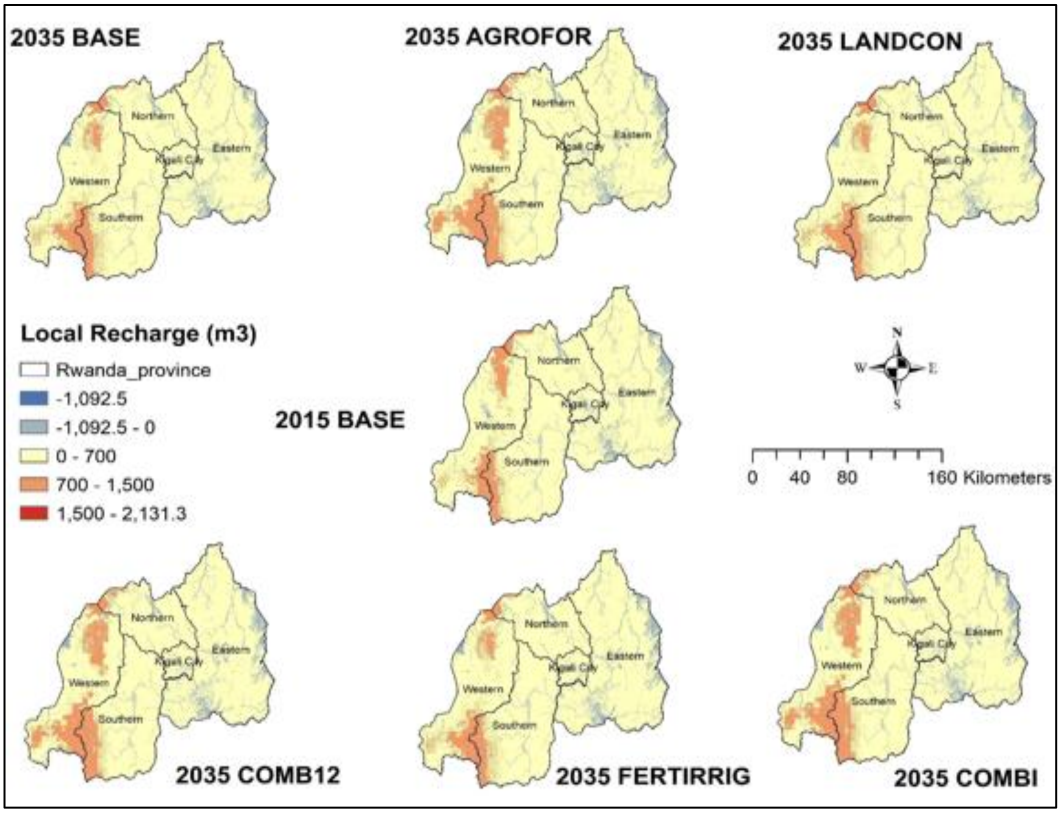


Figure 18. Scenario Results for Local Recharge

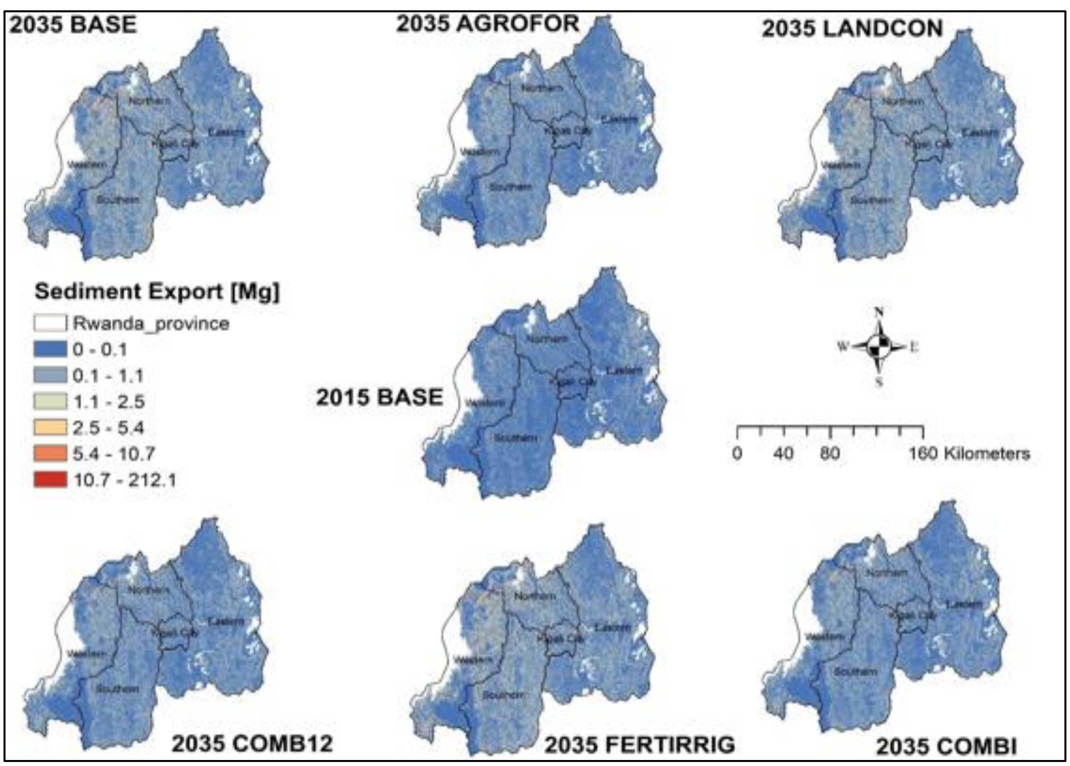


Figure 19. Scenario Results for Sediment Export

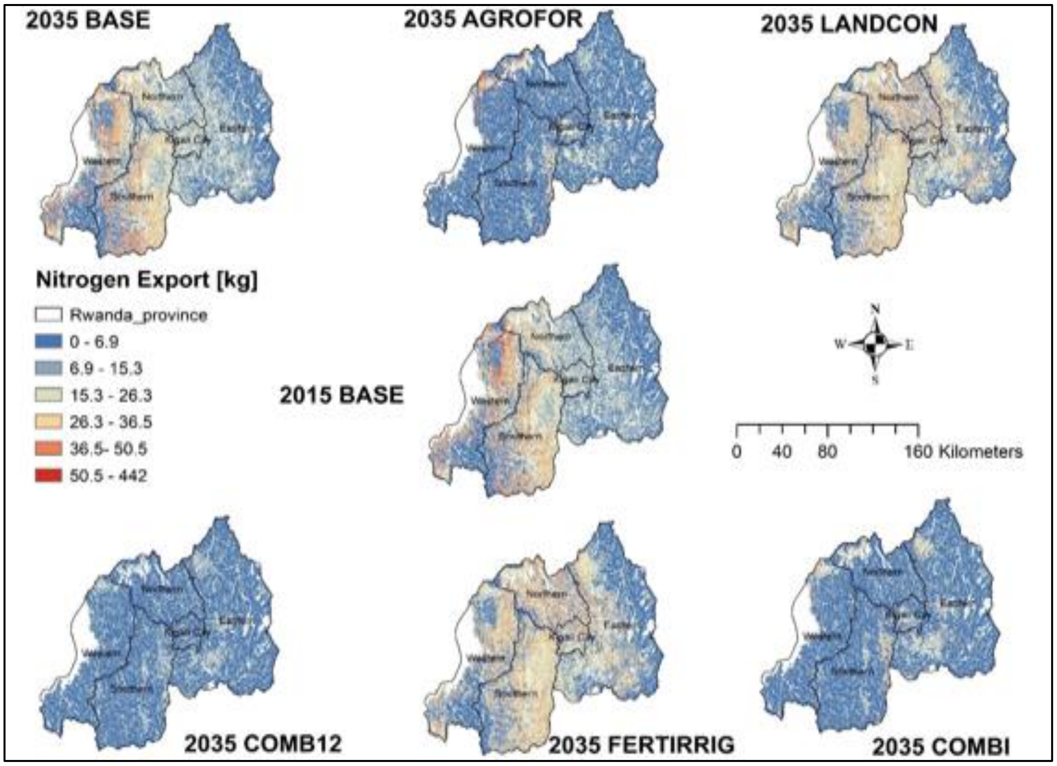


Figure 20. Scenario Results for Nitrogen Export

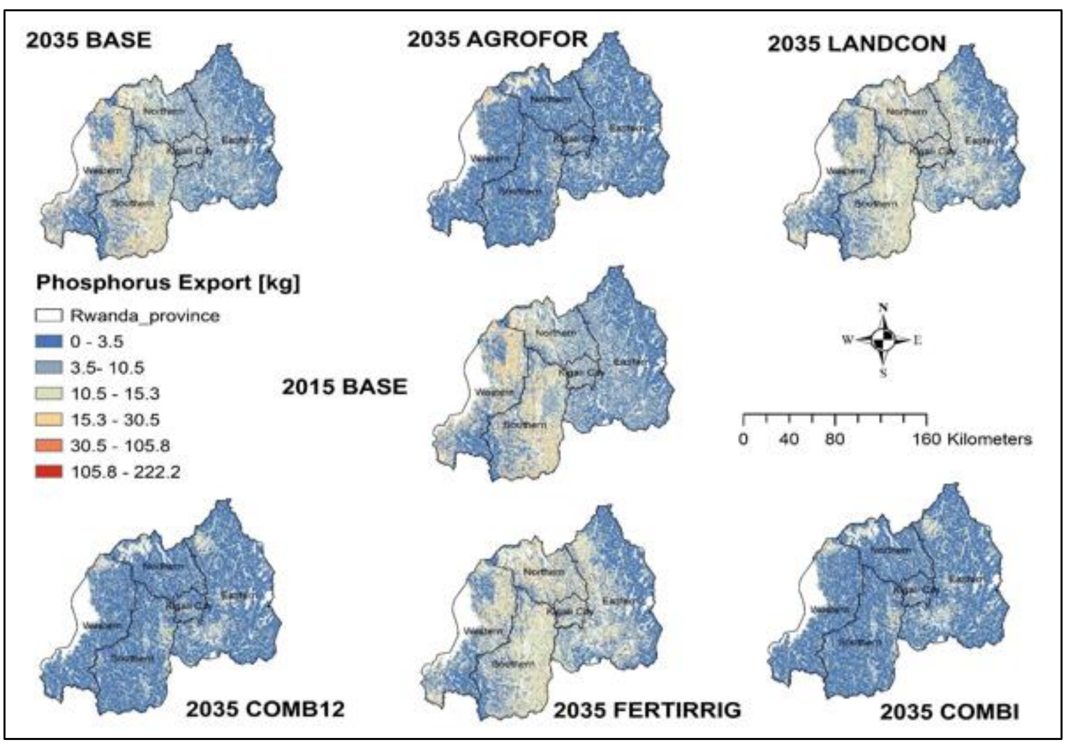


Figure 21. Scenario Results for Phosphorus Export

Sediment exports are constrained by the implementation of agroforestry policies over more business as usual strategies. With increasing urbanization and mechanization, it becomes more prudent to control and couple it with fertilizer application, irrigation, and land consolidation (Figure 19). Agroforestry policies significantly reduce nitrogen and phosphorous exports compared to BASE scenarios, though without agroforestry, additional fertilization and irrigation could increase annual nutrient exports (Figure 20 and Figure 21).

4.4. Cost Benefit Analysis

Although the various scenarios considered have a similar modeling time frame, the costs and benefits associated with them do not coincide. Thus, their overall economic performance, in terms of net present value (NPV) has to be determined to compare them. The NPV of each policy scenario was calculated to facilitate informed decisions pertaining to changes in the terrestrial natural capital and respective ES flows by comparing the impacts of business as usual and restoration interventions. This grounding in rigorous economics will generate a strong business case for investment in reverting land degradation in the Rwanda and will provide a model for other countries to follow.

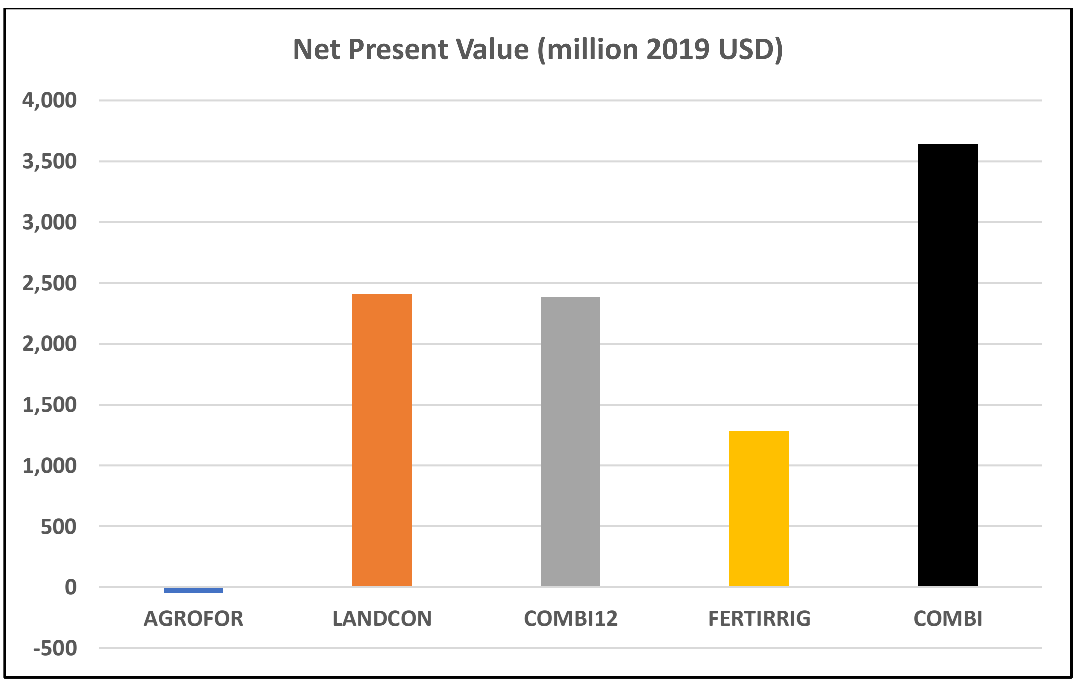


Figure 22. Net Present Values of Scenarios

In our NPV analyses for different policy scenarios, we used equivalent variation (EV) to measure of change in welfare (Banerjee et al., 2017; Banerjee et al., 2018). The EV can considered as amount of income that would be needed to keep the welfare level constant without the policy intervention. The NPV metric, often required for foreign financing as assumed in our case for policy scenarios, was estimated using a discount rate of 12% following Banerjee et al. (2018) and Banerjee et al. (in press). Here it is critical to note that the investment is financed through foreign borrowing, so there is a very limited trade-off potential. The investments are essentially costless to the government and therefore one would generally expect NPV to be positive.

NPV was calculated using the formula

$$\sum_{t=2018}^{2035} \frac{EV_t}{(1+r)^{2018-t}} \qquad \text{Eq. 3}$$

where

EV: equivalent variation to represent the estimated national welfare impact of the shocks considered in each non-base scenario; it is defined as the amount of money paid to an individual with base prices and income that leads to the same satisfaction (or utility) as that generated by a price and income change.

r: discount rate; 12% in the central case

We find that COMBI outperforms all other scenarios, leading to a $3.64 billion positive welfare impact by 2035. By the end of the period, welfare would increase by $2.41 billion in COMBI and $2.38 billion and $1.28 billion in LANDCON, COMBI12, and FERTIRRIG, respectively. AGROFOR, on the other hand, has a small negative welfare impact, estimated at $47 million. Figure 23 reflected expected trend of higher NPV with lower discount rates for the scenarios, reflective of time value of money.

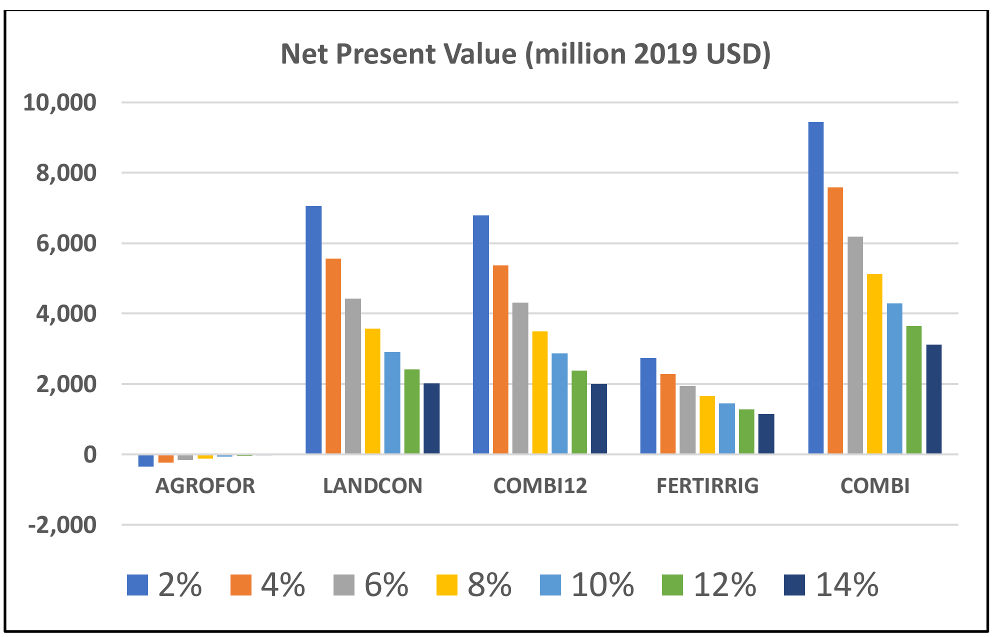


Figure 23. Net Present Values of Scenarios at different discount rates

Our results highlight that if the Government of Rwanda's objective is to maximize welfare impact, an emphasis on the agroforestry option may be misguided, particularly since welfare impacts are negative. However, combination scenarios provide maximum positive welfare changes; our analysis suggests that a suite of policies focusing on land consolidation and agricultural interventions, coupled with agroforestry to mitigate land asset deterioration and erosion control would be most beneficial.

5. Conclusion and Transition Potential

In order to provide timely and accurate data on how proposed policies and interventions will affect environmental, economic, and social outcomes, more robust modeling efforts are critical. To this end, we utilized an IEEM model to assess various scenarios in Rwanda's sustainability plans to understand the potential effects. We developed a base scenario with a business as usual approach, and compared it to five other scenarios, including interventions focused on agroforestry, cropland consolidation, agriculture. We ran these scenarios in the IEEM model with a focus on soil degradation due to its cascading effects on economy, society, and the environment. Furthermore, we use ecosystem services modeling to understand how different scenarios increase or decrease various ecosystem services, and we use LULC change mapping to understand the spatial effects of the interventions. We found that the flow-on regional economic impacts and spillovers arising from increased fruit plantations on farmlands, land consolidation, and increased fertilizer application and irrigation intensity can have a significant impact on the regional economy, wages, employment, and household well-being.

The IEEM model based macroeconomic impacts of the policy scenarios showed that the AGROFOR scenario implemented alone had negligible economic impacts, even though policy induced land use change was significant in impacting non-perennial cropland. Economic impacts under the LANDCON scenario were positive and greater compared to other two individual scenarios. Land consolidation coupled with boosting agricultural productivity provided greater economic benefits in terms of GDP growth, absorption, increase in private consumption, reduction in unemployment, and improvement in wages. The LANDCON scenario also showed the potential to lift more Rwandans above the national poverty line. Similar trends on economic impacts were observed under FERTIRRIG scenario, but with lesser magnitude. Increase in fertilization and irrigation showed gradual increase in GDP and drop in headcount ratio under poverty.

The COMBI scenario, which included expansion in agroforestry area, land consolidation, and increased fertilization and irrigation, indicated an outcome that would provide stronger positive economic impacts when all these policies are implemented simultaneously. This is because the productivity increase on the existing and new cropland help boost overall crop production, resulting in lower crop prices, thereby improving private consumption as well as the export potential of the country. The combined scenario showed drastic reduction in poverty headcount ratio, particularly in the immediate years of policy implementation, which is attributed to intensity of economic activities during the policy phase when nearly 5 million people were below the poverty line. By 2035, the COMBI scenario resulted in less than 1.6 million Rwandans in poverty.

The land cover change in the IEEM model revealed a drastic expansion of agroforestry under fruits and perennial cropland under AGROFOR scenario, most of which came from non-perennial cropland. Due to interaction of alternate land-use activities, pressure on livestock based pasture and grassland reduces under the COMBI scenario. Under LANDCON and FERTIRRIG scenarios, the net year to year change in non-perennial cropland, though small, was positive throughout the policy implementation stage, but in the long-run (post-2025), the trend reversed towards expansion in grassland and pasture due to livestock activities. However, when all the three individual scenarios are implemented together, the COMBI case showed an overall gradual expansion in fruits and perennial cropland with the reduction in non-perennial cropland, but did not negatively affect grassland and pastureland. This means that boosting agricultural productivity would significantly help in reducing the pressure on cropland to meet the demand for crop production, which further helps in agroforestry expansion and acreage consolidation. This shows a significant need for designing and implementing the policies on agriculture, forestry, and land use change in tandem, as they interact with each other to provide the best possible socio-economic and environmental benefits.

The approach developed here can be of critical importance to substantiate a business case for both public and private investment, particularly when the full-cost recovery of public investments is increasingly common. Furthermore, demonstrating economic welfare impacts to decision makers can help leverage public investment by catalyzing financing from both development and environmentally oriented international institutions. Our work quantified societal benefits, including the promotion of prosperity and enhancement of quality of life for all those involved in food and agricultural value chains from production to utilization and consumption. The integrated modeling approach can enhance understanding of policymakers, the scientific community, and a broader audience of conservation managers, government officials, and private sector managers by demonstrating the values of terrestrial ES in a natural capital context, and can inform the real-world decisions that they make.

6. Limitations

Despite the key tradeoffs identified related to nutrients and water use, these are far more difficult to monetize than our economic analysis. Erosion and associated productivity adjustment is one pathway to explore feedback into IEEM; however, there are other feedback relationships that might be explored, including nutrient and resource competition with existing crops while planting trees on farmlands, climate adjustments in terms of frequency and intensity of precipitation, temperature increases, impact on farm productivity, water quality impacts, exporting fruits to regional markets rather than constraining it primarily for domestic consumption, and changing food consumption patterns with increasing affluence in the country, among others. LULC change and associated impacts are brought to the forefront through our IEEM and ES modeling, but internalizing them requires policy initiatives such as incentives for ES payments and public private partnership initiatives. Conservation incentives and ES supply increase payments are potential policy options that can be considered at national and sub-national levels, and at landscape level with neighboring countries. Our study emphasized temporal changes in ES, though empirical evidence-based case studies within the country would be useful in providing more data. Data availability for model calibration and regionalization remains a challenge. Preparation of land accounts, water accounts, and mineral accounts by Rwanda have been helpful, though a national ecosystem-quality monitoring program would provide a more significant benefit for this study and ones like it. With SDGs adoption and monitoring of progress towards various goals, data collation and improvement in data quality can help calibrate and improve effectiveness, land asset management, and ES supply estimates.

7. Transition Potential

Our study applied 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. Our study underpins the central role of natural capital in macro-economic output and facilitates improved decision-making. Our approach can easily be scaled up to compare the benefits from efforts applied in different regions, countries, and contexts. Beyond Rwanda, the results will give impetus to efforts by global initiatives like the World Bank WAVES program, the UN Green Economy, GGKP, UNCCD, UNFCC, and AFR 100, and provide a pathway for other governments committed to natural capital accounting and ecosystem services assessments.

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