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SPECIAL FEATURE: ORIGINAL ARTICLE

Globally-Consistent National Pathways towards Sustainable Food and Land-use Systems

# Sustainability implications of Rwanda's Vision 2050 long-term development strategy

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## Abstract

Improving livelihoods in Rwanda requires overcoming food insecurity and malnutrition. Vision 2050 is Rwanda's long-term development strategy, yet little is known about its potential trade-offs for the country's biodiversity, forest cover, and greenhouse gas (GHG) emissions. Scenario analysis can provide insights into how to achieve such goals more sustainably. Here, we use the Food, Agriculture, Biodiversity, Land-Use, and Energy (FABLE) Calculator, a simple integrated assessment tool, to explore potential sustainability implications by 2050 through two scenarios: (1) Current Trends and (2) Vision 2050. The Vision 2050 pathway incorporates components of the government's long-term development strategy and associated national agricultural policy targets. It includes greater increases in crop productivity and decreases in post-harvest losses, and shifts to more sustainable diets, compared to the Current Trends pathway. Results show that the Vision 2050 pathway would, relative to Current Trends, lead to a greater decrease in agricultural land area and an increase in non-forested natural land-cover area, with consequent decreases in GHG emissions from agriculture, increases in carbon sequestration, and increases in the share of land that can support biodiversity conservation. Shifts to a healthier diet in the Vision 2050 pathway would only be compatible with national agricultural priorities if these diets favor consumption of foods that underpin sustainable livelihoods in Rwanda, such as beans, cassava, potatoes, sweet potatoes, banana, and corn. We discuss the potential for integrated land-use planning and adoption of agroecological farming practices to help Rwanda achieve food security, livelihood, biodiversity, and climate mitigation goals in tandem.

**Keywords** Integrated assessment models · FABLE · Prospective analysis · Agroecology · Rwanda · Vision 2050

## Introduction

Food insecurity, poverty, and malnutrition are complex problems facing multiple countries in Africa (Adeyeye et al. 2021) including Rwanda (Weatherspoon et al. 2019). While poverty rates fell by one-third between 2005 and 2017 in Rwanda, 38% of households are estimated to live in poverty (National Institute of Statistics Rwanda 2018) and 33% of children under 5 are stunted, linked to malnutrition, and driven by insufficient quantity and quality of food in diets (National Institute of Statistics Rwanda 2020). Single policies in the agricultural and food systems sectors, such as an increase in agricultural productivity, a reduction of food waste, and the promotion of healthier diets, can help achieve food security, poverty reduction, and diet-related health objectives, but may lead to unforeseen trade-offs across sectors (Nsabuwera et al. 2016) and with environmental goals

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(Liu et al. 2018). Achieving food, poverty, nutrition, and environmental goals requires integrated assessments and coordinated policies (Liu et al. 2018; van Soest et al. 2019).

The Rwandan government's Vision 2050 (from here on called Vision 2050) is a long-term development strategy aimed at transforming the national economy and improving living standards, including eradicating chronic malnutrition and reducing diet-related diseases (Ministry of Finance and Economic Planning 2020). Vision 2050 sets out the government's aim to shift Rwanda to an upper, middle-income country by 2035, and high income by 2050, with agriculture and productivity increases playing a prominent role. The strategy includes an ambition to increase agricultural productivity to 15 times its 2020 level, with these productivity increases expected to reduce the share of land that is used for agriculture at a national level. Vision 2050 was recently complemented by the National Land Use and Development Master Plan, NLUDMP 2020–2050 (Republic of Rwanda 2020) (from here on called NLUDMP), with one objective of creating a better-informed land-use balance sheet based on spatial and economic analysis.

The challenge for governments when setting national development targets is that it is often difficult to know which policies will deliver the desired outcomes (Takahashi et al. 2020), and how to implement them without unintended or detrimental consequences (Shah and Wu 2019) within and across sectors and scales (Béné et al. 2019). Meeting the Vision 2050 and NLUDMP objectives to improve food security, and reduce poverty and malnutrition rates, will require careful planning, and aligned interventions to select those most likely to have the desired impacts, exploit synergistic interactions among goals, and avoid trade-offs. While there is evidence associating rising income with increased food security and reduced diet-related diseases in Rwanda (Habyarimana et al. 2016), the relationship is not straightforward (Weatherspoon et al. 2019). For example, stunting, which is a sign of malnutrition, has reduced in Rwanda at a slower rate than poverty (Moss et al. 2016). Research suggests that nutritional health does not necessarily increase with agricultural productivity. An impact assessment of Rwanda's Integrated Developed Program estimated that such policy successfully increased maize, wheat, cassava, and bean production each by at least 100%, but that this was linked to a reduction in dietary diversity including an increase in consumption of roots and tubers and a decrease in consumption of meat, fish, and fruits (Del Prete et al. 2019).

As is presented in the NLUDMP, Rwanda needs to improve living conditions and nutrition for millions of people while halting and reversing the loss of its biodiversity, forest cover and declining soil health, all in the context of a rapidly changing climate and global food market instability. Rwanda is a land-locked country located at the heart of the Albertine Rift eco-region. It is home to 40% of the continent's mammal species (402 species), hosting a huge diversity of birds (1,061 species), reptiles and amphibians (293 species), and higher plants (5,793 species) (REMA 2018). Yet, protected areas, a key mechanism for safeguarding biodiversity, cover just 9% of Rwanda's land area (UNEP-WCMC and IUCN 2022) and the conservation value of these protected areas has been severely degraded due to armed conflicts (Hanson 2018). Forest cover declined from 61% in 1990 to 20% in 2010 (Rukundo et al. 2018), with some improvement thereafter reaching 30% in 2019 (Republic of Rwanda 2019), but nevertheless further exacerbating threats to biodiversity.

A range of plausible socio-economic and climate scenarios show that halting further biodiversity loss will require safeguarding more of the biodiversity-rich forest, wetlands, and grasslands where natural processes predominate (van Soesbergen et al. 2017), but competition for land will make this challenging. Loss of natural land has been driven mainly by agricultural expansion (Rukundo et al. 2018), fueled by population pressure and changing diets. Generally, landholdings in Rwanda are very small with more than 60% of households cultivating less than 0.7 ha (REMA 2018). The small size of landholdings together with a shortage of arable land is associated with the adoption of intensive agricultural practices to increase productivity, leading to declining soil fertility (REMA 2009). At the same time, agriculture is the leading source of greenhouse gas (GHG) emissions in Rwanda. In 2018, agriculture represented 49.3% of the country's total GHG emissions (6,755.68 $CO_2$e), followed by the energy sector (34.9%) and waste sector (34.9%) (Republic of Rwanda 2021). Meeting Rwanda's climate mitigation objectives will require changes to carbon emissions and storage on agricultural land.

It will be difficult to design effective policies to solve Rwanda's poverty, food production, nutrition, biodiversity, soil health, and climate mitigation challenges in tandem, because there are many interactions and implications to consider. For example, providing fertilizer subsidies may effectively increase agricultural productivity, but overuse of fertilizers exacerbates the decline in soil health, water quality, and biodiversity (Shah and Wu 2019). To our knowledge, there has not been an integrated assessment done for Rwanda, taking all these implications into account, simultaneously. As a first step to account for such possible synergies and trade-offs across sectors, the present article seeks to show how integrated assessment models (IAMs) can shed light on the cross-sector implications of single- or multiple-sector policies.

IAMs are models that simultaneously capture processes within, and interactions between, several systems, such as land, food, climate, and economic systems (Keppo et al. 2021). The FABLE Calculator is an excel-based IAM that includes agriculture, land-use change, food security, biodiversity, bioenergy, and global trade systems (Mosnier et al. 2020). Here, we used the FABLE Calculator to assess cross-sector outcomes for two development scenarios to 2050: (1) Current Trends, which follows business-as-usual (BAU) assumptions about diet shifts, agricultural productivity, and post-harvest losses, and (2) a Vision 2050 pathway, which assumes a shift to healthier diets, an increase in agricultural productivity, and a reduction in post-harvest losses, in line with Rwanda's Vision 2050 (Table 1). We address the central research question: What are possible synergies and trade-offs between environmental and social outcomes from now to 2050, in the context of Rwanda's Vision 2050 plan, and the subsequent NLUDMP?

## Materials and methods

### FABLE Calculator

The FABLE Calculator (Mosnier et al. 2020) was created under the auspices of the FABLE Consortium, as part of the Food and Land-Use Coalition, as a modeling tool that would: (a) be simple enough to be adapted and used by national stakeholders with knowledge of Excel; (b) be complex enough to represent the national reality of the interactions between the sectors included, from 2000 to 2050; and (c) be open source and easily accessible. The vision is that the calculator serves as a tool for stakeholder engagement and capacity building for IAMs, and as a tool to support policy planning once it is adapted to more realistic national contexts.

The FABLE Consortium has enabled capacity building and national adaptation of 20 calculators in Argentina, Australia, Brazil, Canada, China, Colombia, Germany, Ethiopia, Finland, Indonesia, India, Mexico, Malaysia, Norway, Russia, Rwanda, Sweden, United Kingdom, United States of America, and South Africa. To ensure consistency in global trade, regional models were also created to cover the rest of the world, grouping countries into six regions: Rest of Asia and Pacific, Rest of Central and South America, Rest of North Africa, Middle East and Central Asia, Rest of Europe, and Rest of Sub-Saharan Africa. Of these existing country and regional models, several articles, conference papers, and policy reports have been already published (FABLE 2019, 2020, 2021, 2022; Jha et al. 2022a, b; Mosnier et al. 2022; Navarro Garcia et al. 2022; Rasche et al. 2022; Schneider and Steinhauser 2020; Wang et al. 2022).

The model assumes that agriculture is the main driver of land-use change and includes projections of demand, supply, import, and export data of up to 76 livestock and crop products, compared with the 15 products included in the NLUDMP. For every crop analyzed in economic terms, the consequent sustainability impacts are also studied, such as the resulting GHG emissions, the aggregated impact on land use including forests and land which can support biodiversity conservation, or the structure of food intake of the population, whereas the NLUDMP only includes some of these sectors. The model uses historic data on population, Gross Domestic Product, or GDP, commodities (supply demand, imports, exports, and productivity), land cover, food waste, and food losses, as well as data on various sustainability indicators, using sources cited within the calculator and its documentation (Mosnier et al. 2020). Then, it extrapolates projections to 2050 with shifters, using the year 2010 as a base for most indicators. In this way, the calculator is a demand-driven IAM that aims to meet demands for agricultural products through allocating feasible areas of cropland, pasture, forests, and natural land on a 5-year time step taking account of user-defined land constraints.

We used the FABLE Calculator to assess the sustainability implications of two scenarios for Rwanda's development pathway to 2050: (1) Current Trends and (2) Vision 2050. These scenarios differ in their assumptions about diet shifts, productivity and post-harvest losses, and the evolution of imports and exports (Table 1).

### Model assumptions

Both pathways incorporate the Vision 2050 policy document and the Sector Strategic Plan for Agriculture under Rwanda's National Strategy for Transformation (PSTA-4) assumptions for population growth, which estimates a growth rate of 2.77 between 2000 and 2050. Livestock productivity is also assumed to follow a BAU growth rate in both pathways. Agricultural land is assumed to not expand, reflecting the availability of land as a limiting factor, as described in PSTA-4. Changes in forest cover resulting from afforestation or reforestation, changes in protected areas, population activity, and share of energy from biofuels are assumed to stay at current levels, all of which are referenced and defined in the FABLE Calculator Documentation (Mosnier et al. 2020). Climate change is assumed to impact productivity for corn, rice, soy, and wheat, according to a representative concentration pathway of 6.0, a stabilization scenario where total radiative forcing is stabilized after 2100, complemented with national averages of the impacts estimated by the crop model GEPIC using climate estimates from the model HadGEM2-es, without $CO_2$ fertilization effects (Mosnier et al. 2020; van Vuuren et al. 2011). Food waste is modeled with the FABLE Calculator based on FAO (Gustavsson et al. 2011) values on losses during distribution and from households, and later differentiated by large regions, in this case for Sub-Saharan Africa. For a more detailed description of the assumptions on diet, crop productivity, post-harvest losses, imports, and exports, please refer to the Annex, in the Electronic Supplementary Material. For a description of the rest of the

**Table 1** Assumptions of changes anticipated between 2010 and 2050 in the Current Trends and Vision 2050 pathways

| | Current Trends | Vision 2050 |
|---|---|---|
| GDP | GDP increases between 2000 and 2050 by 10.5 | |
| Population | Population increases between 2000 and 2050 by 2.77 | |
| Diet | Current national diet | EAT–Lancet recommendations |
| Share of food waste | Current (same share as in 2010) | Reduced (differentiated by food groups, compared to 2010 values) |
| Share of total consumption that is imported | Increased imports for wheat, palm oil, rice, milk, corn, raw sugar, and pork | |
| Exports | Exports are multiplied by 1.5 by 2050, for tea, coffee, and cassava | Exports are multiplied by 3 by 2050 tea, coffee, and cassava |
| Livestock productivity | BAU growth (same productivity growth as over 2000–2010) | |
| Crop productivity | BAU growth (same productivity growth as over 2000–2010) | High growth (higher productivity growth as over 2000–2010) |
| Agricultural land expansion | No productive land expansion beyond 2010 value | |
| Afforestation | No afforestation/reforestation target | |
| Population activity | Middle<br>A moderately active lifestyle that includes physical activity equivalent to walking about 1.5–3 miles per day at 3–4 miles per hour, in addition to the activities of independent living | |
| Climate change impacts on crop productivity | Climate change impacts on the productivity of four crops: corn, rice, soy, wheat. For rice, it includes irrigation and rain-fed shifter, for both yield and water use. Does not include the impact of fertilizer use | |
| Protected areas | No expansion of protected areas beyond current levels | |
| Post-harvest loss | Constant share of supply available lost during storage and transportation after 2010 | Reduced share of supply available lost during storage and transportation compared to 2010 |
| Biofuels | Stable biofuel demand as 2010 | |

The justification and sources for all scenarios relevant to the current analysis are described in Table A.1, in the Electronic Supplementary Material assumptions, please refer to the FABLE Calculator Documentation (Mosnier et al. 2020).

## Results

### Market balance of key agricultural products

In the Current Trends pathway, national food consumption in 2050 is dominated by cereals (1.94 Mt), banana (1.8 Mt) milk (1.3 Mt), potato (0.9 Mt), cassava (0.8 Mt), sorghum (0.7 Mt), corn (0.7 Mt), sweet potato (0.6 Mt), and beans (0.5 Mt), which cover approximately 70% of total consumption for that year. The top five commodities for food consumption are banana (1.5 Mt), milk (1.1 1000 $m^3$), potato (0.8 Mt), cassava (0.7 Mt), and sweet potato (0.5 Mt). Sorghum, corn and other cereals become the main commodities used for feed, with a total of 0.2, 0.1, and 1.9 Mt, respectively. The main exports of Rwanda remain tea and coffee, with a total of 0.032 and 0.025 Mt, respectively. The main goods that are imported are other cereals (2.0 Mt), milk (0.5 Mt), nuts (0.3 Mt), corn (0.3 Mt), and wheat (0.3 Mt). Except for corn, the rest of the six key goods of Rwanda are not imported, meaning that they are produced domestically, mostly for food consumption by 2050.

In comparison, the Vision 2050 pathway foresees by 2050 a reduction in total consumption of potato (− 0.8 Mt), cassava (− 0.7 Mt), sweet potato (− 0.5 Mt), other cereal (− 0.3 Mt), banana (− 0.3 Mt), milk (− 0.3 1000 $m^3$), and beans (− 0.09 Mt), and an increase in nuts (0.5 Mt). Aside from this commodity, the main difference between 2030 and 2050, and between both pathways, in terms of consumption is more demand for food consumption of corn (+ 0.0024 Mt), sorghum (+ 0.0020 Mt), wheat (+ 0.0019 Mt), rice (+ 0.0013 Mt), and beef (+ 0.0010 Mt). Exports for tea and coffee increase to 0.065 and 0.051 Mt, respectively, and the commodities for feed remain the same as in Current Trends, albeit with slightly smaller quantities. Imports remain relatively similar except for a large increase in imported nuts (0.8 Mt), which are mostly consumed for food.

### Food security

The implications of the two pathways for food security, measured in food intake per capita, are shown in Fig. 1.

The Current Trends pathway attains levels of daily food intake per capita above Minimum Daily Energy Requirements (MDER) starting in 2015 and maintains these levels until 2050. In contrast, the Vision 2050 pathway does not attain levels above MDER for most of the period. This is mostly a result of the assumed differences in diets in the pathways, given that other drivers of food consumption remain constant. A more detailed analysis of the reasons why

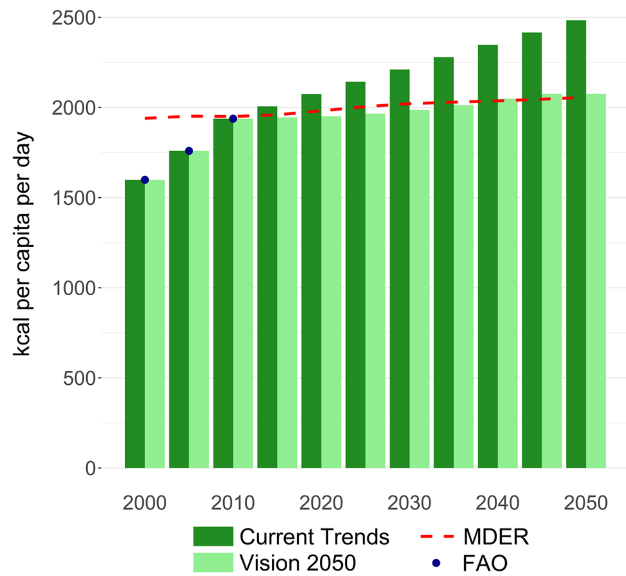



**Fig. 1** Comparison between Current Trends and Vision 2050 for daily food intake per capita

the EAT–Lancet diet does not lead to levels of kilocalorie consumption above MDER is the reduction in consumption of the product group categorized in the model as "Roots", which includes the main products consumed in Rwanda of cassava, potato, and sweet potato. The same goes for other key products for current consumption in the country, such as beans, fruits, and vegetables. This reduction also happens in the Current National diet, by 2050, but is much less marked. Figure A.9 in the Annex focuses on the differences of the main crops for both pathways, in terms of the consumption at the start (2015) and end (2050) of the projection period.

A revision of the EAT–Lancet recommended values, so that they include a higher consumption of the products that are key to the Rwanda economy, such as sweet potato, potato, cassava, and beans, was carried out, improving the levels of food security above MDER. Further work is needed to find out the best recommendations for a sustainable diet for Rwanda that takes account of the current structure of agricultural production, so that targets of both food security and sustainable diets can be achieved, as is described in the section "Discussion".

The product groups that are mostly consumed by 2050 in Rwanda in the Current Trends pathway, as a share of total consumption, are cereals (30%), oils (18%), pulses (13%), roots (10%), and fruits and vegetables (9%), while Vision 2050 foresees in the same year an increase in the most consumed product categories of cereals (+ 6%), oils (+ 4%), pulses (+ 2%), roots (+ 3%), and fruits and vegetables (+ 2%). The main differences between the pathways are an increase in the consumption of nuts (+ 139%) and red meat (51%) for Vision 2050, coupled with a decrease in the consumption of several group categories, including the most decrease in beverage and spices (−93%), roots (−87%), and pork (−72%).

The only possible comparison between the above results and the information reported in the NLUDMP for food security is the consumed fruits and vegetables, reported as 400 g per capita for the entire period. In contrast, the Current Trends pathway goes from 414 to 325 g per capita between 2000 and 2050, while the Vision 2050 pathway goes from 414 to 267 g per capita. When compared to a suggested 500 g per capita in the standard for a healthy diet utilized in the current analysis, none of the pathways reach this level, for any year.

Another measure of food security is the fat and protein intake, shown in Table 2, comparing various years between the two pathways.

The Vision 2050 pathway does not reach MDER values for 2030 and 2050, and fat intake is lower in 2030 than recommended values, and higher in 2050. The Current Trends pathway does attain appropriate MDER, fat, and protein intake, thus contributing to the food security of Rwanda by 2030 and 2050. In contrast, the NLUDMP assumes a protein total of 56 g, much lower than the results obtained in both Current Trends and Vision 2050 pathways, by 2050.

## Land-use change

Figure 2 shows the different changes in land cover, for both scenarios.

In 2010, Rwanda was covered by 58% cropland, 17% pasture, 14% forest, 1% urban, and 10% other natural land, as shown in Fig. 2 for both pathways. Starting in 2015, the projections to 2050 are a direct result of the scenario choices within each pathway, particularly increases in crop productivity, decreases in post-harvest waste, and dietary change. Other scenario assumptions that affect land-use change, such as afforestation or protected area targets, were not included as these are not highlighted in the current policy nor the Vision 2050 policy. In the NLUDMP, the closer scenario of land-use categories (LUCA) would be LUCA B, assuming “a freezing strategy is suggested to stabilize the amounts of both agricultural lands and forests” (Republic of Rwanda 2020).

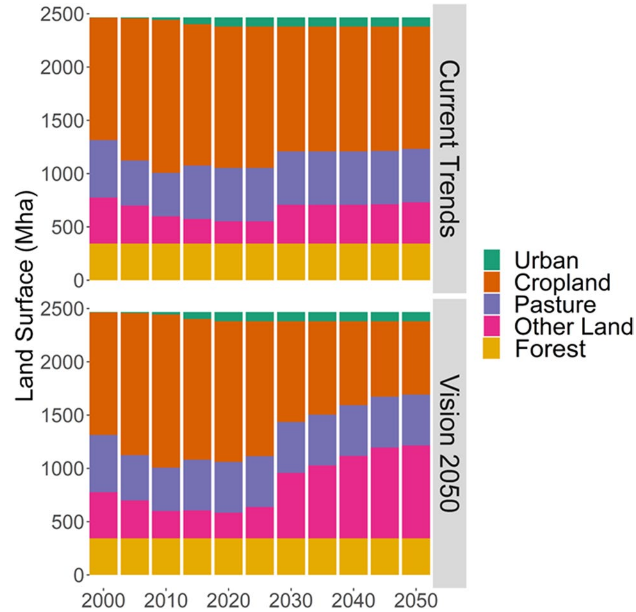



**Fig. 2** Comparison between Current Trends and Vision 2050 for area by land cover

By 2030, the FABLE Calculator estimates that the main changes in land cover in the Current Trends pathway are a decrease of cropland area and a small increase of pasture and other natural land, with these trends continuing until 2050. This results from an increase in sorghum, coffee, other vegetables, ground nut, and pepper of 130 kha between 2010 and 2030, that is counteracted by a decrease in various crops, including corn, cassava, potato, beans, wheat, sweet potato, and banana of 395 kha. The decrease in area of these latter crops is explained by the change in diets. For the Vision 2050 pathway, the change is similar except that the crops that increase are sorghum and other vegetables, while the crops that decrease are the same as for Current Trends, but the decrease is greater, of up to 538 kha.

The NLUDMP land-use allocation balance sheet for 2050 reports the following results (compared to Current Trends and Vision 2050 pathways, respectively): (a) Cropland: 1,094 kha (1,148 and 689); (b) Pasture: 110 kha (500 and 476); Forests 724 kha (344 both pathways); Urban 288 kha (86 for both pathways); Other natural land: 206 kha of

**Table 2** Comparison of fat and protein intake between historical values (FAO), and Current Trends and Vision 2050, for both years 2030 and 2050

| | FAO (2010) | Current Trends (2030) | Vision 2050 (2030) | Current Trends (2050) | Vision 2050 (2050) |
|---|---|---|---|---|---|
| Kilocalories (MDER) | 1,938 (1,950) | 2,162 (2,021) | **1,941 (2,021)** | 2,409 (2,057) | **2,013 (2,057)** |
| Fats (g) (recommended range) | **23.2 (43–65)** | 50 (48–72) | **40 (43–65)** | 77 (54–80) | **71 (45–67)** |
| Proteins (g) (recommended range) | 51.8 (48–170) | 59 (54–189) | 54 (49–170) | 66 (60–211) | 60 (49–170) |

Highlighted in bold are the pathways and years when the target is not met wetlands and 155 of bare high slopes (387 and 872). The most important differences in these results are a much less use of land for crops in the Vision 2050 pathway, due to imports of nuts, and much more pasture for both FABLE pathways, compared to the NLUDMP. This is partly a result from meat intake modeled. NLUDMP assumes in its Level 1, or BAU assumptions, a current daily intake of livestock products of 6 g, which increases with more ambitious assumptions, until reaching 15% of food from livestock at the Level 3, or Commercial Agriculture. The results in the FABLE model for the closest year, 2020, and considering pork, milk, eggs, red meat, poultry, and animal fat categories, are 126 g per capita per day for the Current Trends (~6% of total dietary intake) and 87 g per capita per day for Vision 2050 (~7% of total dietary intake).

Figure 2 also shows an important trade-off, resulting from the pathway assumptions related to livestock productivity and consumption of livestock products. Livestock productivity is assumed to follow a BAU growth assumption, and therefore, the area of pastures remains constant for both pathways during the entire period. Also, the consumption of livestock goods remains relatively constant and changes in a similar way for both pathways. Hence, the decrease in cropland, which is more acute for the Vision 2050 pathway, is compensated by an increase in other natural land, rather than pasture. This highlights how increases in crop productivity coupled with little change in livestock consumption and productivity can lead to an increase of natural land cover that could potentially benefit biodiversity.

## Biodiversity conservation

The main indicator associated with biodiversity conservation in the FABLE model is "land where natural processes predominate" defined as landscapes that have low levels of human modification or have relatively ecologically intact vegetation (FABLE 2022). Land where natural processes predominate accounted for an estimated 14% of Rwanda's terrestrial land area in 2010. Most of the land where natural processes predominate is protected, and this land is dominated by forest or other natural land cover (Fig. 3).

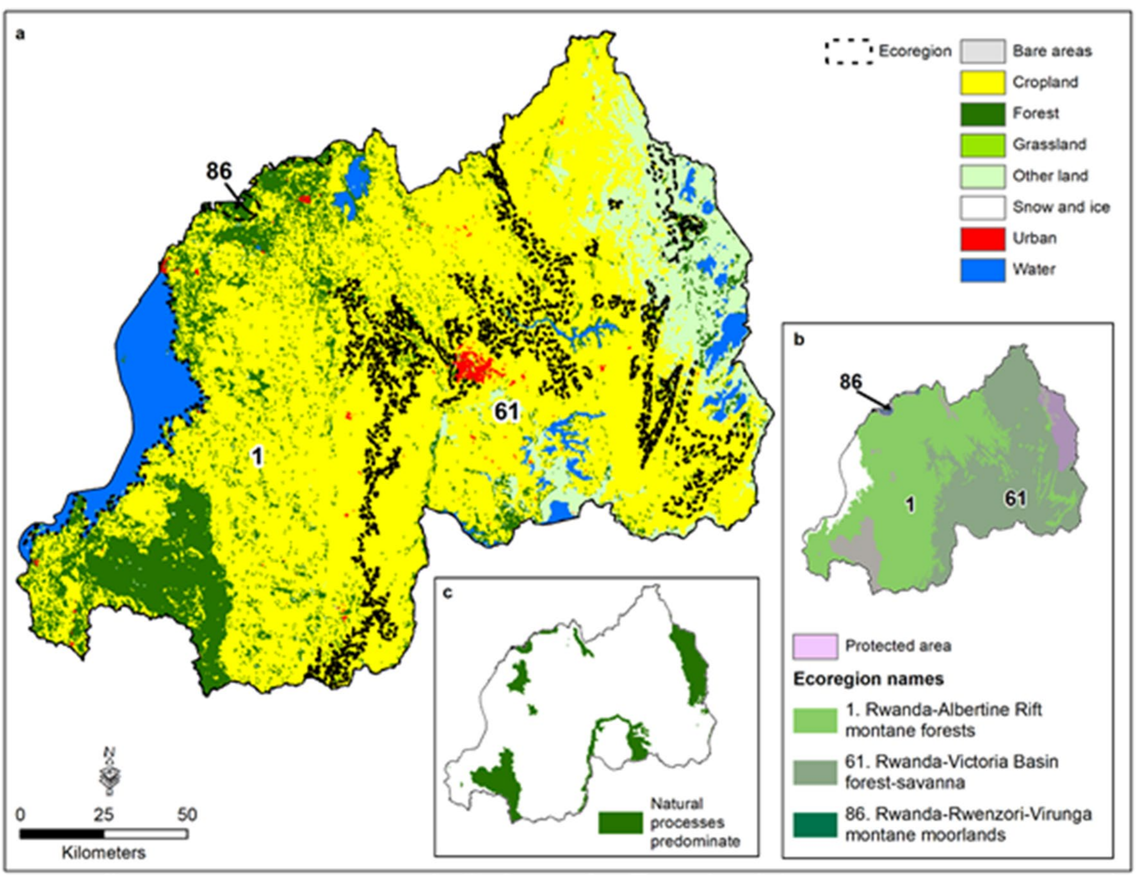



**Fig. 3** Distribution of **a** land cover, **b** ecoregions and protected areas, and **c** land where natural processes predominate, in Rwanda. Data sources: land cover from ESA-CCI land-cover maps for 2010, reclassified for use in FABLE; ecoregions from Dinerstein et al. (2017), and protected areas from UNEP-WCMC and IUCN (2022)

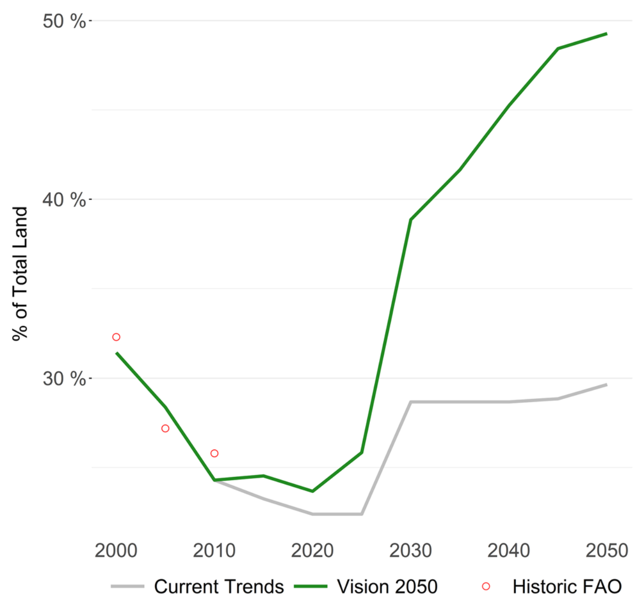



**Fig. 4** Percentage of total land which can support biodiversity conservation

The share of forest cover, which is one type of land cover where natural processes predominate, remains stable over the period 2010 to 2050, for both pathways (Fig. 4). Forest covers 344,000 ha of land, made up of 124,000 ha of protected forest and 220,000 ha of unprotected forest; other natural land where natural processes predominate amounted to 387,000 ha by 2050 in Current Trends and would more than double to 872,000 ha in Vision 2050, replacing 459,000 ha of cropland and 25,000 ha of pastureland. This means that, by 2050, the category called "land where natural processes predominate" covers 20% of land in Current Trends (of which 29% is forest and 54% is other natural land), compared to 39% (of which 15% is forest and 76% is other natural land) in the Vision 2050 pathway. The main explanation of this increase in land where natural processes predominate is the drastic decrease in cropland discussed in the Land use change section of these results.

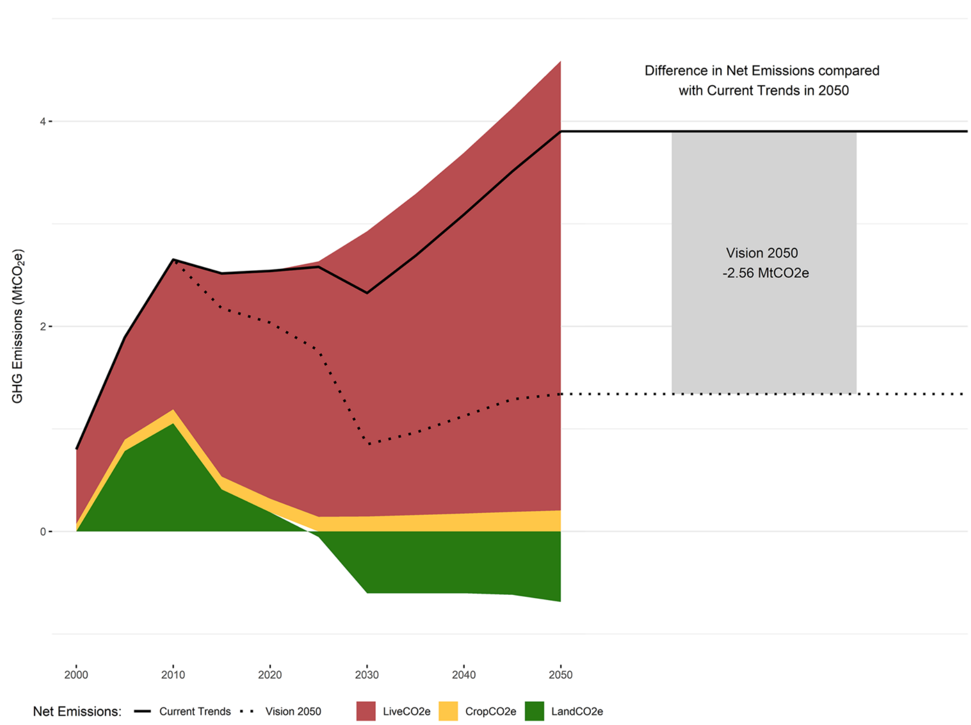
In terms of biodiversity, the NLUDMP considers land with conservation value to include only national parks, protected wetlands, water bodies, and forests, which comprised 1,081 Tha in 2019. The FABLE biodiversity indicator is based on different datasets, which may alter the amount of land suitable for natural processes and conservation. However, a comparison is not possible at this stage, as the FABLE Calculator does not include wetlands and water bodies.

## GHG emissions

Figure 5 shows the different changes in GHG emissions, for both pathways.

The evolution of GHG emissions is similar for both pathways. Under the Current Trends pathway, annual GHG from the AFOLU sector increases between 2000 and 2020, from 0.8 to 2.5 Mt $CO_2$e, and continues increasing until 2050 reaching 3.9 Mt $CO_2$e. In 2050, nitrogen

**Fig. 5** Projected Agriculture, Forestry and Other Land-Use (AFOLU) emissions and removals between 2010 and 2050 by main sources and sinks. The continuous line is the total emissions in the Current Trends pathway, while the dotted line represents the Vison 2050 pathway. Live $CO_2$e includes emissions from livestock (nitrogen dioxide + methane). Crop $CO_2$e includes emissions from crops (carbon dioxide + nitrogen dioxide + methane). Land $CO_2$e includes emissions from land-use change (deforestation + other land-use change − sequestration)



dioxide from livestock is the largest source of emissions, with 2.6 Mt $CO_2$e per year, while there is 0.7 Mt $CO_2$e per year of carbon sequestration. Over the period 2020–2050, the strongest relative increase in GHG emissions is computed for nitrogen dioxide, with an increase of 248%.

The Vision 2050 pathway leads to a reduction of AFOLU GHG emissions by 66%, reaching a 2050 level of 2.6 Mt $CO_2$e per year less than Current Trends, a gap that is highlighted in the right side of Fig. 5. This difference is explained by a 34% reduction in emissions from nitrogen dioxide from the livestock sector and a 65% increase in carbon sequestration. The most important drivers of this change are a reduction in the demand for livestock products, the simulated decrease in cropland, and the land-use change from cropland to other natural land. Most emissions are a result of the livestock sector, namely from nitrogen dioxide (reaching 2.58 Mt$CO_2$ in Current Trends and 1.98 in Vision 2050) and methane (reaching 1.98 Mt$CO_2$ in Current Trends and 1.59 in Vision 2050). No comparison could be made with the NLUDMP, as it does not include an analysis of GHG emissions.

### Validity of the model assumptions

Our analysis showed that the FABLE Calculator productivity projections for sweet potato, potato, and beans fall within the range of current and future yields identified from literature, as is shown in the shaded areas of Figure A.5. For corn and banana, the projected yields exceed the ranges estimated in published literature by around 2020 and 2030, respectively. Cassava yield reaches almost 60 T/ha by 2050 in the Vision 2050 pathway, which is almost double the uppermost range in the literature (27.5 T/ha). The projections from the FABLE Calculator are similar to the PSTA-4 productivity estimates for some products, such as corn, sweet potato, and beans, while for others, the PSTA-4 tends to underestimate productivity compared to ranges found in literature and FAO estimates. The lowermost range of cassava yields found in the literature is higher than the estimated yield from the FABLE Calculator, PSAT 4, and FAO. No projections of productivity are done in detail in the NLUDMP. A more complete list of the exact FABLE productivity values obtained in both pathways is found in Table A.6 in the Annex.

The projections on post-harvest loss of the PSTA-4 fall within the ranges of the FABLE Calculator only for some goods, such as corn and banana, whereas the projections of the PSTA-4 for cassava, sweet potato, potato, and beans are much higher than those of the FABLE Calculator, indicating that the calculator underestimates post-harvest losses (Table A.7 and Figure A.8).

## Discussion

This section explores in more detail three main implications of the results: (a) alternative means for increasing productivity, which consider agroecological production systems, (b) implications of land-cover change and the importance of integrated land-use planning, and (c) the definition of a sustainable diet for Rwanda which can attain food security by 2050, leveraging the current structure of demand and supply in the agricultural sector.

### More sustainable increases in productivity

The objective of the present article was to explore possible synergies and trade-offs between environmental and social dimensions in the context of Rwanda's Vision 2050 plan, presenting the results from research and policy engagement to co-design and model national mid-century pathways toward sustainable land-use and food systems. Such prospective analysis showed the possibilities of synergies in various sectors, such as an improvement in the food security of Rwanda by adopting healthier diets, coupled with an improvement of a decrease of land area used for crops, which would entail the consequent positive trade-off of more land available where natural processes predominate. Thus, our results complement the Vision 2050 plan and NLUDMP, by exploring possible futures with similar drivers, as well as some implications for sustainability.

Another driver of these results is the increase in crop productivity, as shown in Table A.4 for 2000 and 2010 and the PSTA-4 and NLUDMP in comparison, as well as in Table A.6 for the results of the FABLE model, for all 5-year periods until 2050. The results for the FABLE Vision 2050 pathway comprise 2050 productivity values for the key products in two categories: (a) those that fall within the range of values presented in the NLUDMP, which are sweet potato (15.12 T/ha), potato (28.39 T/ha), beans (3.67 T/ha), and banana (19.37 T/ha); compared to (b) those that surpass the productivity values deemed as best internationally by the NLUDMP, such as corn (49.10 T/ha) and cassava (56.07 T/ha). These values point to the exploration realized in the previous sections on integrated land-use planning possible futures, but also to the limitations of these models and the need to calibrate them, so that they correspond best to actual observed productivity values.

Just as importantly, these results beg the need to go beyond the model results into the implications of the model predicaments for real life in Rwanda. Namely, productivity increase, or the intensification of crop production, is indeed at the center of both Vision 2050 and the NLUDMP, as well at other developmental projects carried out in the past in Rwanda, such as the 2010 Crop Intensification Program

(CIP) (Kathiresan 2011). What the present article adds to both government planning documents is to evaluate the implications of such productivity increases on other sectors, such as biodiversity and GHG emissions, taking other factors or assumptions into account. What the present article does not discuss, as neither Vision 2050 nor the NLUDMP discuss, is how the increase in productivity will take place, especially in a context of previous social, economic, and ecological inequalities of the country. It is beyond the scope of this article to delve into this important topic of the inclusion of social justice implications of agricultural intensification (Clay 2018; Clay and Zimmerer 2020), but the next paragraphs give an overview of possible alternatives of intensification, perhaps akin to the category presented in Clay (2018) as sustainable intensification and agroecological intensification.

The pathways modeled by the FABLE Calculator assume substantial improvements in crop productivity by 2050, particularly for the Vision 2050 pathway. How such increases in productivity are achieved is not modeled explicitly and could be due to large-scale increases in inputs, such as fertilizer, mechanization, irrigation, or more intensified larger farms. These activities have countless impacts on sustainability goals that have not been explicitly considered in this study.

Pursuing productivity increases through high-input, intensive farming is highly unlikely to reduce agriculture's GHG emissions and will further exacerbate the negative impact of agricultural land on biodiversity, highlighting the need for a shift to agroecological and other sustainable practices. For example, an increase in productivity due to an increase in fertilizer could lead to changes in soil health and water pollution, which could have unintended effects on other aspects of productivity, food security, or other sustainability indicators. While the implications are not modeled here, seeking the increases in productivity assumed under the Vision 2050 pathway through an integrated land-use planning focus and agroecological approaches rather than energy and agrochemical intensive approaches will help Rwanda jointly achieve biodiversity conservation and food production goals. Research shows that, while yield increases more through agrochemical intensification, this leads to significant losses in species richness (Beckmann et al. 2019). Agroecological approaches, such as crop diversification (intercropping, cover crops, and embedding natural habitat), can increase yields while simultaneously benefiting biodiversity (Beillouin et al. 2021; Tamburini et al. 2020). Moreover, pursuing energy and agrochemical intensive approaches creates farm dependencies on big companies and markets. Agroecological intensification can help farmers create resilient and productive systems and livelihoods, while providing substantial co-benefits for nature (Jones et al. 2022; Wezel et al. 2020).

Future research could explore which practices could help Rwanda increase the production of food toward increasing food security (i.e., poultry or red meat) while maintaining a low level of impact to the environment (i.e., crop-fish or crop-livestock farming) toward a renewed Vision 2050 strategy which incorporates sustainability aspects. For example, across Africa, studies have found a decrease in average productivity when maize is produced in improved fallow systems (Sjogren et al. 2010) or in agroforestry systems (Ogol et al. 1999); and an increase when maize is intercropped with legumes, mustard, or sesame (Wale et al. 2007) or produced in crop rotations (TerAvest et al. 2015). For maize, a review of field experiments from Africa (Kenya, Ethiopia, and Malawi) published in Jones et al. (2021) shows yields range from 1.7 to 5.9 T/ha in diversified farming systems (including agroforestry, intercropping, associated crop species, and crop rotations). The target maize yield for 2023 in the PSTA-4 was 3.2 T/ha, which is substantially lower than the upper range of maize yields attainable in diversified farming systems. These data imply that productivity increases in Rwanda could potentially be achieved through ecological intensification approaches, at least for certain crops, but careful assessments are needed to identify which practices are most likely to lead to the positive yield outcomes.

## Integrated land-use planning

Agricultural land abandonment in both pathways opens opportunities for restoration projects that regenerate natural ecosystems, providing more space for biodiversity to thrive, and contribute to climate mitigation goals. The natural land supporting biodiversity conservation more than doubles in Current Trends and more than triples in the Vision 2050 pathway. The differences between both pathways are driven primarily by larger increases in productivity freeing up more agricultural land for restoration. The model does not account for the potential negative impacts on biodiversity of more productive farming. Achieving these productivity increases in both pathways through agroecological means, which involve low-input, diverse farms and landscapes, would help secure the biodiversity conservation benefits under both pathways by facilitating the movement of species within agricultural landscapes and to and from existing and restored natural land. Moreover, a major assumption in the model is that restored land will include a diversity of local plant species arranged to increase landscape connectivity and complexity. Opting for mono-species plantations of Eucalyptus or other species will create restored land areas of little value to biodiversity conservation and is likely to exacerbate environmental problems (e.g., soil degradation). Care needs to be taken to ensure that any restoration efforts involve plant species and configurations that allow biodiversity to flourish. This can still include species and varieties of cultural and nutritional value and non-wood forest products of commercial value that benefit not only biodiversity but also local livelihoods and diets (Vinceti et al. 2013).

This shift from agricultural to restored vegetation cover could occur anywhere in the country. Priority could be given to restoring natural habitat in areas of high biodiversity or carbon value (Jung et al. 2021) and adjacent to existing land where natural processes predominate in the Rwanda-Albertine Rift montane forests and Virunga montane moorlands (Fig. 3) to strengthen the biodiversity value of contextually intact habitat (Mokany et al. 2020).

## Sustainable diets for Rwanda

Implementing the EAT–Lancet diet in Rwanda does not result in average kilocalorie consumption above an MDER threshold, which is considered as a proxy for food security in the FABLE Calculator. A reason for this result is that the EAT–Lancet universal healthy reference diet suggests an increase in consumption of some foods (i.e., nuts), whose benefits should not be understated (Satija et al. 2016, 2017) but which moves Rwanda toward a deeper import dependency on some of these foods (i.e., increased imports of nuts from 0.3 to 0.8 Mt). Another unintended effect of implementing this diet is the detrimental effect that the shift in the structure of food consumption has on those crops produced in Rwanda which are considered best for livelihoods and sustainability, such as beans, cassava, potatoes, sweet potatoes, banana, and corn.

A suggested solution to this dilemma, where a diet considered healthy could lead to calorie insufficiency, is to incorporate the lessons provided by the EAT–Lancet recommendations into a nationally tailored diet. Such a diet should ensure that Rwandan farmers can continue to cultivate the recommended six key crops, so that domestic produce provides a significant contribution to meeting a food security target. The EAT–Lancet recommendations acknowledge that the universal healthy diet they recommend is merely a recommended average, which can vary according to local conditions, preference, and cultures (Willet et al. 2019). Also, as shown in Table 2, in 2010, Rwanda fell below the recommended consumption value of fat but remained within limits of the protein intake.

In this direction, a future sustainable diet for Rwanda would aim to incorporate recommendations of a healthy diet, while considering current production and consumption structures, and suggesting changes to 2050 which are realistic given these structures. In 2019, Rwanda consumed much more fruits and pulses, and much less meat, vegetables and milk, than the global average. The EAT–Lancet recommends that of the total diet, 35% of consumption is taken from cereals, 14% from oils, 12% from nuts, 11% from pulses, and 6% from milk. The commission also acknowledges that these ranges are intermediate, and that some countries where undernutrition is currently associated with a low intake of protein rich foods might see a benefit of higher intake of protein rich foods, such as eggs, or meat. If including nuts into the diet of Rwanda would lead to an over dependence on their imports, then the question becomes which other protein source could be most beneficial for Rwanda, in terms not only of nutrition, but of land availability and sustainability? Answering this question is strategic for the country and is beyond the scope of this article.

The results also highlight the over reliance Rwanda has on tubers and starchy vegetables, such as potato, sweet potato, and cassava. Some of these products have been associated with morbidity (Muraki et al. 2016; Borgi et al. 2016), and the EAT–Lancet Commission recommends a limit on their consumption to 100 g per day. In both pathways, the 2010 consumption levels of cassava, potato, and sweet potato were 230, 250, and 180 g per capita per day, clearly above the limit set by the EAT commission, and one of the explanations of the different results of the pathways. A recommendation would then be to devise a diet that is sustainable for Rwanda, where the consumption of tubers and starchy vegetables decreases and is substituted by goods with less health risks, which can also be produced locally. There have been various reviews of these alternative products for several countries in Africa which could inform this strategic change in diets (Akinola et al. 2020).

Just as important to take into consideration is the relationship between Rwanda's agricultural policies and the country's food security, as this last indicator is reflected in national diets. For example, the Crop Intensification Program (CIP) was a land consolidation policy introduced in Rwanda from 2008 to 2012, increasing area under cultivation of key crops 18-fold from 28,016 to 602,000 ha. The CIP ensured that Irish potato, cassava, beans, maize, wheat, rice, banana, and soybean were prioritized in the land-use consolidation scheme (Kathiresan 2012). Some authors suggest that production of those prioritized crops significantly increased as a result of the land consolidation program, to the extent that, over the period 2008 to 2012, maize production increased fivefold; wheat and cassava about threefold; Irish potato, soybean, and beans about twofold, and rice by 30% (Kathiresan 2012). However, other authors debate these results, arguing that such success could be differentiated if farmer heterogeneity and cultivating strategies are considered, in terms of the achieved productivity increases for the targeted crops (Kim et al. 2022). Either way, a result of the program seems to have been the increase in production of certain goods like roots and cereals, which are then overconsumed at the expense of nutritionally important foods, such as meat, fish, and fruits (Del Prete et al. 2019; Willett et al. 2019); a result of a country that has shifted from producing enough to producing a surplus of the former.

## Conclusion: limitations and future research priorities

The present article has carried out a scenario analysis using the FABLE Calculator of Rwanda's long-term development strategy in different sectors, namely agriculture and livestock, and their implications for sustainability indicators. What has been gained is an integrated analysis of key agricultural drivers and changes in time, along with simultaneous effects on various sustainability indicators, projected in time. This is done with an Excel model that is complex enough to mirror with adequate loyalty real-life trends, but also simple enough, so that it can be adapted by local stakeholders and interested actors, such as the FABLE Rwanda team and other members of the FABLE Consortium. However, as with any method, IAMs like the FABLE Calculator have also some limitations on what they can achieve.

Given the fact the model currently uses data from FAO and assumes simple relationship causal links in the agricultural sector (i.e., supply is driven by demand), the objective of this article is not to carry out a wide and encompassing analysis of the reality of Rwanda. The model does incorporate various assumptions in its structure, as well as in the way the scenarios are framed and defined. The results obtained are highly sensitive to these assumptions, so they should be interpreted only as exploration of possible futures, given these initial assumptions, not as a given reality. The comparison of the FABLE Calculator results with those of Vision 2050 follows the same limitation: it would be a strong comparison if the assumptions leading both exercises are similar, which may not be the case, as the assumptions in Vision 2050 are not exactly the same as in FABLE and not explicit.

More specific limitations entail the FABLE Calculator using FAO data from 2000 to 2010 to extrapolate yield projections to 2050, yet yields in FAO data were unusually high in 2010 for all products analyzed. Rwanda's CIP seems to be the driver of the upward trend in crop production in 2010–2011, which involved the application of 44,000 MT of fertilizers to boost Rwandan agricultural production (Republic of Rwanda 2011). This explicit policy of productivity intensification led to an excess in production for three agricultural seasons, for the first time since 1994 (Republic of Rwanda 2010). The rapid productivity increases during the historical reference periods used by the FABLE Calculator are likely to explain why for some goods, such as corn, cassava, and banana, simulated productivity reaches values beyond those found in the other literature. A revision of the projections in FABLE could be made in future analyses, for example, using a different starting year for the projections and calibrating productivity increases, so they do not grow beyond a more realistic benchmark.

Additionally, there are many important socio-economic and ecological dimensions for Rwanda that are not integrated in the scenario exploration and would have a strong impact on the results, such as the inclusion of inequality, poverty, colonial governance, and other similar social justice and political ecology topics, as well as their links to environmental sustainability. Incorporating them into such scenario analysis exercises is a promising future agenda for research and would inform planning documents such as Vision 2050 in a much better way. Finally, the FABLE Consortium encourages all country teams to refine their calculators, in terms of adapting assumptions, causal relationships, and data sources that are more adequate for the local context. An important next step is to change all possible FAO data sources for national ones, adapting the respective categories (i.e., land use, key agricultural goods, and diets) accordingly.

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**Data availability** The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.



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