Quantifying the trade-offs between biodiversity conservation and food security in Tanzania

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Abstract

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1 Introduction

Despite the United Nation's Sustainable Development Goal to end hunger by 2030 (UN, 2015), more than 700 million people faced hunger, around 2.8 billion individuals were unable to afford a healthy diet, and more than 2 billion people experienced food insecurity in 2023 (FAO et al., 2024). Food security is achieved by physical and economic access to nutritious and preferred food and is assessed through food availability, food access, food utilization, and food stability over time (FAO, 2008). Africa is the continent with the largest proportion of the population facing food security challenges, with around 20% experience hunger and over half being food insecure.

A primary cause of food insecurity in Africa is an inability of agricultural production to meet the demand for food (Hall et al.., 2017, Sasson, 2012) and one way to tackle food insecurity is to increase production by intensifying agricultural land use or expanding agricultural land area (Foley et al., 2011). However, implementing either of these two strategies can negatively impact biodiversity (Dudley and Alexander, 2017), which plays a fundamental role in maintaining ecosystem services essential for livelihoods in Africa (Archer et al., 2018).

In Tanzania, the agricultural sector accounts for approximately 25% of the national GDP, employs the majority of the population, and produces a wide range of food and cash crops, primarily through small-scale and rain-fed agriculture (URT, 2021). Despite this, around 58% of the population were food insecure between 2021-2023 (FAO et al., 2024). The agricultural productivity is low, and even though the production of major crops has increased the latest decades, this increase have been driven by agricultural land expansion rather than yield improvements (Mkonda and He, 2018). Besides, agricultural growth has been mainly led by large-scale non-poor farmers and has not resulted in significant improvement in poverty alleviation or nutrition (Pauw and Thurlow, 2011). Furthermore, biodiversity loss in Tanzania, could cause significant economic costs, biodiversity is essential in the natural resource sectors, contributing to approximately 65% of GDP (URT, 2014).

The trade-offs between increasing agricultural production and conserving biodiversity present challenges for effective policy-making and analysis. In this context, Computable General Equilibrium (CGE) models offer a flexible approach to assess trade-offs, as they allow for sector-specific analysis of production, trade, and prices, useful to evaluate feedback effects and unintended consequences in alternative futures.

Previously, CGE models have been implemented in global studies to assess the trade-offs between agricultural production and biodiversity conservation. Zabel et al. (2019) employed a CGE model to analyze the impact of the two strategies, cropland expansion and cropland intensification, on agricultural markets, including production, prices, and trade flows, and assessed biodiversity risk by identifying areas with overlap of high biodiversity value and high suitability for either strategy. The study found that implementing either strategy would decrease crop prices across the world, but also put biodiversity at risk and highlighted the importance of regional case studies.

In Tanzania, few studies have been carried out that consider agriculture, biodiversity objectives, and the economy. Capitani et al. (2016) integrated these factors by evaluating how agriculture and its environmental impacts play out in alternative development strategies. CGE models focusing on Tanzania have been studying agricultural growth, poverty and nutrition (Pauw and Thurlow, 2011), export bans on maize (Diao and Kennedy, 2016), livestock (Engida et al., 2015), tourism (Kweka, 2004) and biofuels (Arndt et al., 2010), and have not taken biodiversity objectives into account. In addition, the regional impact on agricultural markets of the different strategies of agricultural intensification and expansion is unknown.

In this study, we simulate scenarios in which changes in cropland area and cropland productivity have been decided to limit biodiversity loss to different degrees (Markoff et al., in review), in a static single-country CGE model to answer the following research question:

1. What impacts will the incorporation of biodiversity objectives in crop production have on food security in Tanzania?

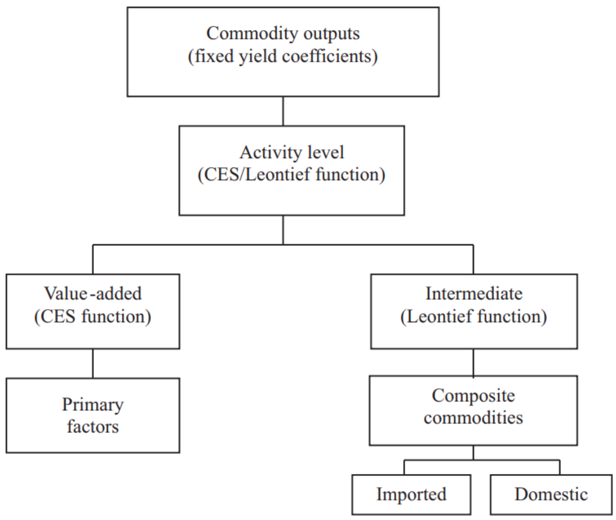
2 Methods

Given the importance of the agricultural sector to the Tanzanian economy and the inter-sectoral relationships a general equilibrium model is used. CGE models capture all these inter-linkages and therefore are suited to study policies that have economy-wide impacts. The model we use in this paper is an extended version of the The International Food and Policy Research Institute (IFPRI) standard CGE model (Lofgren et al., 2002).

2.1 The IFPRI standard model

The IFPRI model is a static single-country model. It describes production, consumption, and trade as a solution to a set of maximization problems for each representative agent in the model. A set of endowment and income constraints apply to the economy as a whole. Representative households consume according to a Stone-Geary demand function. On the production side, output is produced by combining intermediates and value added according to a CES / Leontief technology; see Fig. 1. In the value-added nest, all primary factors are substituted according to Cobb Douglas. Trade with the rest of the world is governed by Armington elasticity. The standard model is described in detail in Lofgren et al. (2002). The rest of the method section will discuss the new features we add to this standard model.

Figure 1: Standard IFPRI model production function, Lofgren et al. (2002)



2.2 Agricultural Production

We introduce many extensions to the standard model to mimic the structure of the Tanzanian economy in a more detailed way. First, the agricultural sector has two categories crops and livestock. Each has a different production structure.

Crop output is produced according a nested CES of the following structure:

$$Y = \min\left(\frac{1}{inta}\,INT\;,\;\frac{1}{iva}\,VA\right) \tag{1}$$

$$Int = \min\left(\frac{1}{ic_1}\,c_1, \frac{1}{ic_2}\,c_2, ..., \frac{1}{ic_n}\,c_n\right) \tag{2}$$

$$VA = \alpha^{va}\left(\delta^{va} N_c^{-\rho^{va}} + (1-\delta^{va}) KL^{-\rho^{va}}\right)^{-\frac{1}{\rho^{va}}} \tag{3}$$

$$KL = \alpha^{kl}\left(\delta K^{-\rho^{kl}} + (1-\delta) L^{-\rho^{kl}}\right)^{-\frac{1}{\rho^{kl}}} \tag{4}$$

$$L = \alpha^{l}\left(\sum_j \delta^l L_j^{-\rho^l}\right)^{-\frac{1}{\rho^l}} \tag{5}$$

Y	crop output	inta	units of INT used for each unit of Y
Int	intermediates composite	iva	units of VA used for each unit of Y
VA	value added composite	ic	units of commodity C used for each unit of Y
c_i	input of commodity i	α	productivity shifter
N_c	crop land	δ	share parameter
KL	capital labor composite	ρ	elasticity exponent
K	capital		
L	labor composite		
L_j	labor of type j		

A graphical representation of this nested crop production function is given in Figure 2.A. The production of the livestock sector is slightly different, Figure 2.B. The upper nest remains the same. The Value added equation is modified to combine the capital labor composite with a composite of animal feed and pasture land as following:

$$VA = \alpha^{va}\left(\delta^{va} FN_p^{-\rho^{va}} + (1-\delta^{va})KL^{-\rho^{va}}\right)^{-\frac{1}{\rho^{va}}} \tag{6}$$

$$FN_p = \alpha^{fn}\left(\delta^{fn} F^{-\rho^{fn}} + (1-\delta^{fn})N_p^{-\rho^{fn}}\right)^{-\frac{1}{\rho^{fn}}} \tag{7}$$

$$F = \alpha^{f}\prod_j F_j^{\delta f} \tag{8}$$

FN_p composite of commodities used for animal feed F and pasture land N_p

In the value-added nest of a crop production function, the substitution between cropland and the capital labor composite is derived according to:

$$\min \quad \omega_c\, \lambda N_c + \omega_{KL} KL$$

$$\text{s.t.} \qquad VA \;=\; \alpha^{va}\left(\delta^{va}\left(\lambda N_c\right)^{-\rho^{va}} + (1-\delta^{va})KL^{-\rho^{va}}\right)^{-\frac{1}{\rho^{va}}}$$

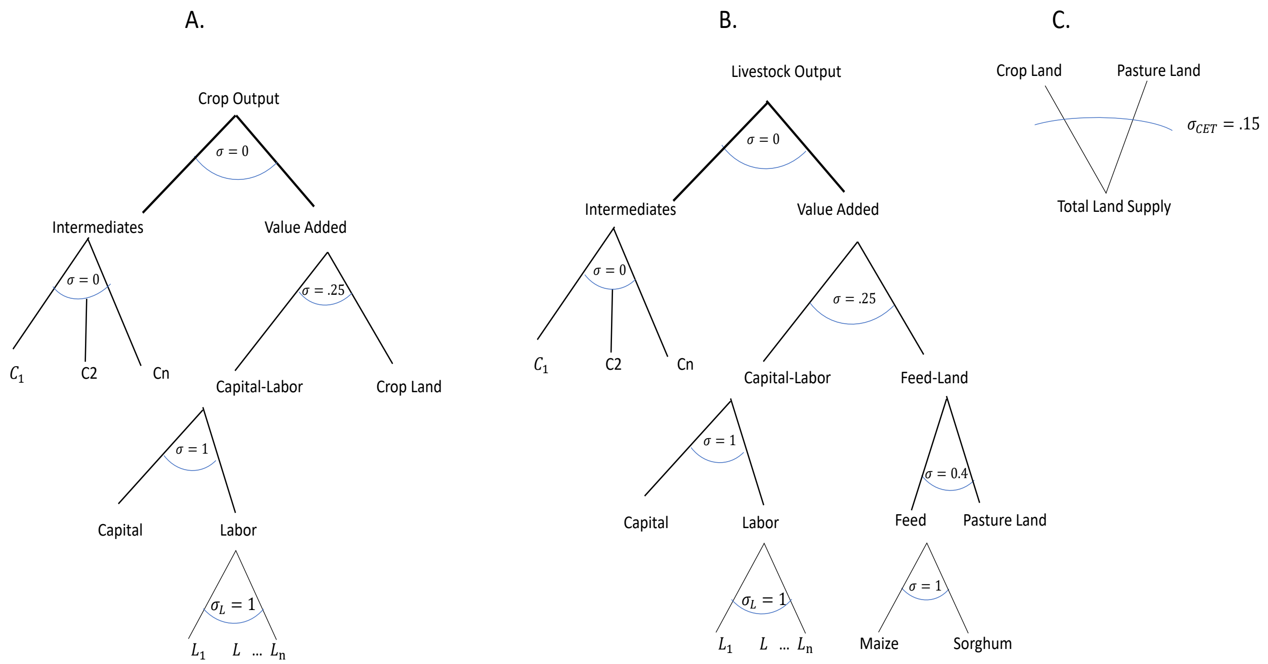
Where ω: factor price, λ land specific productivity shifter. Solving the FOC using Lagrangian method:

$$\frac{N_c}{KL} = \left(\frac{\delta}{1-\delta}\,\frac{\omega_{KL}}{\omega_c}\right)^{\sigma^{va}} \lambda^{-1}\,, \qquad \sigma^{va} = \frac{1}{1+\rho^{va}} \tag{9}$$

Eq. 9 states that land area and land productivity are proportionally and inversely related for fixed output.

The rest of activities (industries and services) are produced according to the standard IFPRI model with a small modification in which a function for labor disaggregation equation is introduced equivalent to eq. 5. The price systems in this economy are given by the zero-profit

Figure 2: Extended Model Structure



condition for each level of the CES function. In partricular, the price of output in the upper nest is given by:

$$P_Y = inta\ P_{INT} + iva\ P_{VA} \tag{10}$$

and the relative any wages of two types of labor m, q are

$$\frac{\omega_m}{\omega_q} = \frac{\delta_m}{\delta_q}\left(\frac{L_q}{L_m}\right)^{1+\rho^l} \tag{11}$$

2.3 Land transformation

In the standard IFPRI MODEL there is only one type of land. In order to model the possibility of land conversion between different uses, mainly between crops and pasture land. these are the two main competitive uses of land in Tanzania we introduce a transformation function. The total land supply is fixed in the model. However, land can be imperfectly allocated to crop land or pasture land. This transformation allows an imperfect transformation of the factor land into these two different uses. Mathematically:

$$\begin{aligned} \max \quad & \lambda \omega_c \, N_c + \omega_p \, N_p \\ \text{s.t.} \quad N &= \alpha^N \left(\delta^N N_c^{\rho} + (1-\delta^N) N_p^{\rho^N} \right)^{\frac{1}{\rho^N}} \end{aligned} \tag{12}$$

N_c: crop land, N_p: pasture land, λ land specific productivity shifter, L: total land supply.

Setting up the Lagrangian of this problem and solving for the optimal points we can write the elasticity of transformation is equal as:

$$\sigma_{CET} \;=\; \frac{1}{1-\rho^N} \;=\; \frac{\partial \ln(\frac{N_c}{N_p})}{\partial \ln(\frac{\omega_p}{\omega_c})} \;<\; 0 \tag{13}$$

$$\frac{\lambda \omega_c}{\omega_p} \;=\; \frac{\delta^N}{1-\delta^N} \left(\frac{N_p}{N_c} \right)^{1-\rho} \tag{14}$$

Where $\lambda \, \omega_c$ is the price of an augmented unit of crop land.

For a given λ, ω_c is inversely related to crop land supply N_c. This setup allows the price of land to differ by land type. The conversion is done endogenously where we get the changes in the quantity of land in each type as part of the model solution.

2.4 Data

We use the social accounting matrix (SAM) for Tanzania which represent the economy for the year 2015 (Randriamamonjy and Thurlow, 2017). The original SAM includes 70 domestic production activities, which we aggregate into 21 activities, from which 11 are crop activities and 2 are livestock activities. In the SAM factors of agricultural land, labor (urban and rural), and four types of capital are included. Households are classified into rural farmers, rural non-farmers, and urban categories, with each category further divided into five income groups.

2.5 Scenario design

Incorporation of biodiversity objectives

To evaluate the role of incorporating biodiversity objectives in crop production, we simulate three scenarios with different assumptions of agricultural production and biodiversity impact, co-designed through expert questionnaires, interviews, and workshops (Markoff et al., in review). The scenarios are qualitative described as follows:

- **Scenario A - Agriculture in Focus:** Agricultural output is maximized, while environmental concerns are disregarded and only biodiversity that supports agriculture is maintained.

- **Scenario B - Balance of Agriculture and Conservation:** Agricultural output is maximized, while biodiversity preservation is considered, and the negative impacts on biodiversity are limited to a socially acceptable loss of species richness.

- **Scenario C - Conservation in Focus:** No further biodiversity loss, and no or low increase in agricultural production.

In each of these scenarios, changes in cropland area and cropland productivity have been quantified in relation to biodiversity impact (defined as species richness loss). This generates a range of agricultural production but also negative biodiversity impact from high (A), moderate (B), to low (C). As model input we are using the average values of estimated production changes in each scenario (as displayed in Fig. 3).

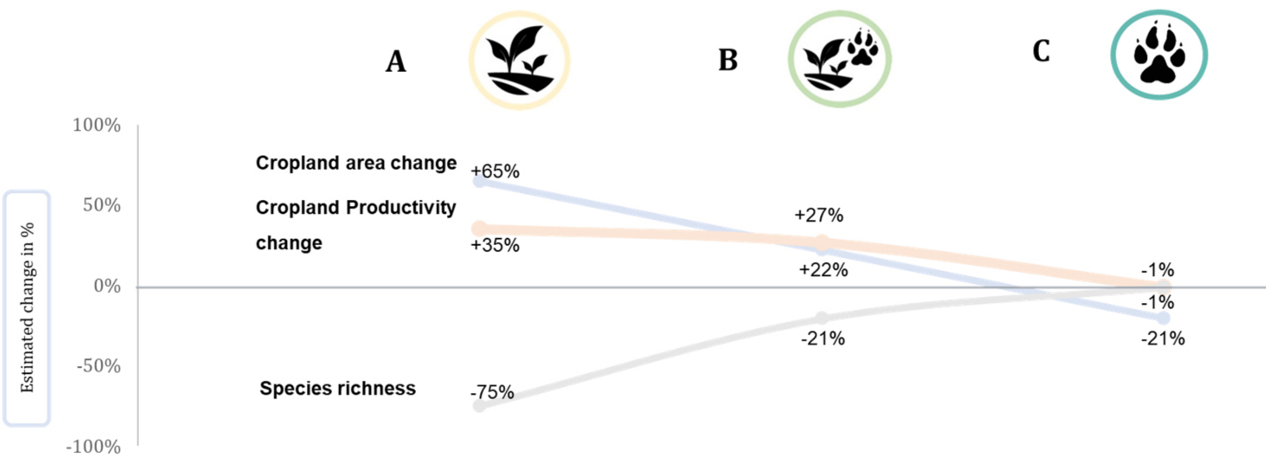


Figure 3: Average estimates of changes in cropland area, cropland productivity and species richness in scenario A, B and C.

Simulation of strategies

To represent the co-designed scenarios, we need to model two strategies: shifts in cropland area and shifts in cropland productivity. To simulate a change in cropland area, the total land supply is increased or decreased exogenously. As the total land supply includes both cropland area and pastureland, the increase is adjusted to reflect only cropland area change, in proportion to the cropland and pastureland shares in Tanzania, extracted from the GTAP 11 database. Changes in cropland productivity are simulated via an exogenous increase or decrease in only cropland productivity.

In each scenario, we simulate the impact of the two strategies together (both expansion/ contraction and intensification/extensification) and separately (only expansion/contraction, only intensification/extensification) to be able to compare how the separate strategies contribute to changes in each scenario.

The simulation does not account for potential changes in the future population dynamics or the effects of climate change. However, since these potential changes are not applied in any scenarios, we maintain the ability to compare scenarios.

Impact on food security

We evaluate the impact on food security of our scenarios in line with two of the dimensions of food security defined by FAO (2008): food availability and food access. Food availability is achieved by having appropriate quantities of quality food available from domestic production or imports. We evaluate this based on changes in agricultural output as well as imports and exports of agricultural commodities. In addition, we display agricultural output with net export subtracted to indicate the change in the availability of food for domestic consumption. Food accessibility is achieved by having adequate resources to access food. We evaluate this based on changes in prices of crop and livestock commodities and real income. In addition, we evaluate changes in GDP and private consumption of agricultural commodities. To represent food, agricultural activities have been grouped to include all crop and livestock commodities.

2.6 Closures

The IFPRI model and the extensions introduced are based on the microeconomic behavior of producers and consumers under a set of endowment constraints that determine the equilibrium point. The macroeconomic environment is not explicitly modeled in the current model, however. Consequently, we have to determine exogenously how the macroeconomic variables work. For instance, for the savings and investment accounts where these have to be equal, we have to determine how one of them is determined, and the other variable then has to follow. [1] . For a detailed discursion n the closures see for instance **??**.

It is well known that the results of CGE models are sensitive to the closure rules **?**. Therefore, a careful choice of the closure environment that fits reality and helps to answer the research question adequately is necessary. In this sense, we motivate the choice of macroeconomic closures. The government deficit is fixed ... Furthermore, this leads to avoiding misleading welfare gains by an increased government spending in a one-period static model like the one used here.

The world price of each commodity is fixed. This is a standard assumption for the small open economy that fits the case of Tanzania. For the balance of payments, we fix the real trade balance is assumed, implying fixed foreign savings while the exchange rate is fixed. Fixing foreign savings would require fixing the real net exports, which would be inadequate when running shocks targeting the production side of a small open economy, since these policies are expected to affect the trade balance.

[1]other models concerned explicitly with these variables and how they impact the economy might need to describe these macroeconomic variables in more detail

For the saving-investment closure, investment as a share of total absorption is fixed at the base share, which implies that saving rates adjust if needed to ensure that the ratio of investment level to absorption remains constant.

The labor market is defined by fixed factor endowments. The factors are mobile across sectors. We assume factors are fully employed, which implies that factor prices are the market clearing variable. They adjust in the aftermath of any changes in market conditions to equate supply and demand.

3 Results

3.1 Food Availability

Food availability improves in both Scenarios A and B. With net exports of agricultural commodities subtracted from total agricultural output, the resulting domestic availability increases by 13% in Scenario A and 9% in Scenario B. In these scenarios, agricultural output and exports are increasing while imports of agricultural commodities are decreasing. However, as the net export only represents around 7% of the total output in the baseline data, the changes in import and export have a small impact on the availability of crop and livestock commodities. In Scenario C, there are the opposite trends, domestic availability decreases by 3%, while agricultural output and exports decrease, and imports increase (See Fig. 4).

Both land expansion and cropland intensification contribute to an increase in output and a decrease in imports. However, the strategies have an opposite impact on exports; only increasing land supply decreases exports, while only intensifying increases exports.

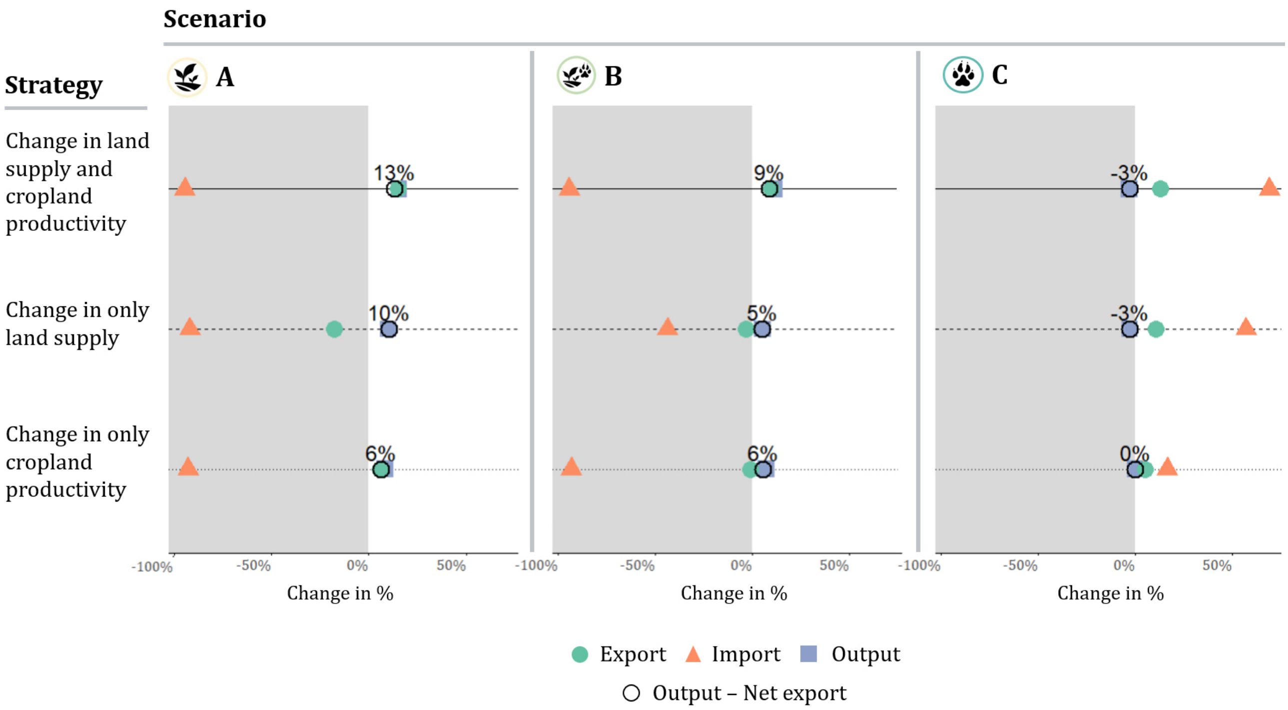


Figure 4: Changes in agricultural output, imports and exports of agricultural commodities, as well as domestically available agricultural commodities (calculated as agricultural output with net agricultural exports subtracted) if both changes in land supply and cropland productivity are implemented together or separately in Scenario A, B, and C. The text labels represent domestically available agricultural commodities in each scenario, and the gray areas represent negative values.

3.2 Food Accessibility

In Scenario A and B, food accessibility improves by a decrease in prices of agricultural commodities, with the most significant price reduction occurring in Scenario A (-8%), followed by a smaller decline in Scenario B (-6%) (See Fig. 5). The price reduction is larger in the crop commodity price index (-11%, -9%) compared to the livestock commodity price index (-3%, -1%). In Scenario C, the prices increase by 2% for crop commodities and 1% for livestock commodities. An increase in land supply decreases prices of both crop and livestock commodities, while an increase in cropland productivity generates lower crop prices, but higher livestock prices, resulting in a higher impact on crop commodities compared to livestock commodities in each scenario.

Figure 5: Change in price indexes of agricultural commodities, presented separately for crops and livestock, as well as combined, if both changes in land supply and cropland productivity are implemented together or separately, in Scenario A, B, and C. The gray areas represent negative values.

In addition to the impact on prices, food accessibility is also improved in Scenario A and B by an increase of total real income, while it is worsened by a decrease in Scenario C (see Fig.6). In this scenario, all household groups experience a decrease in income (total -1%) while the impact on real income of increasing cropland productivity varies in Scenario A and B, which gives a lower total increase in Scenario A (+3%) compared to Scenario B (+4%). Increasing agricultural land area positively impacts the real income of all household groups, while the real income of urban poor households decreases with an increase in cropland productivity. In addition, increasing cropland productivity has a larger impact, in both Scenario A and B and the rural non-farmers have the largest positive impact in income, with a higher increase in the lower income groups. In contrast, the equivalent variation, is positive for all household groups in Scenarios A and B and the farming households have the largest positive impact, with a larger impact in the middle-income groups (see Fig.7). As with changes in real income, increasing cropland productivity has a larger impact than expanding cropland area, and the EV is negative for all household groups in Scenario C.

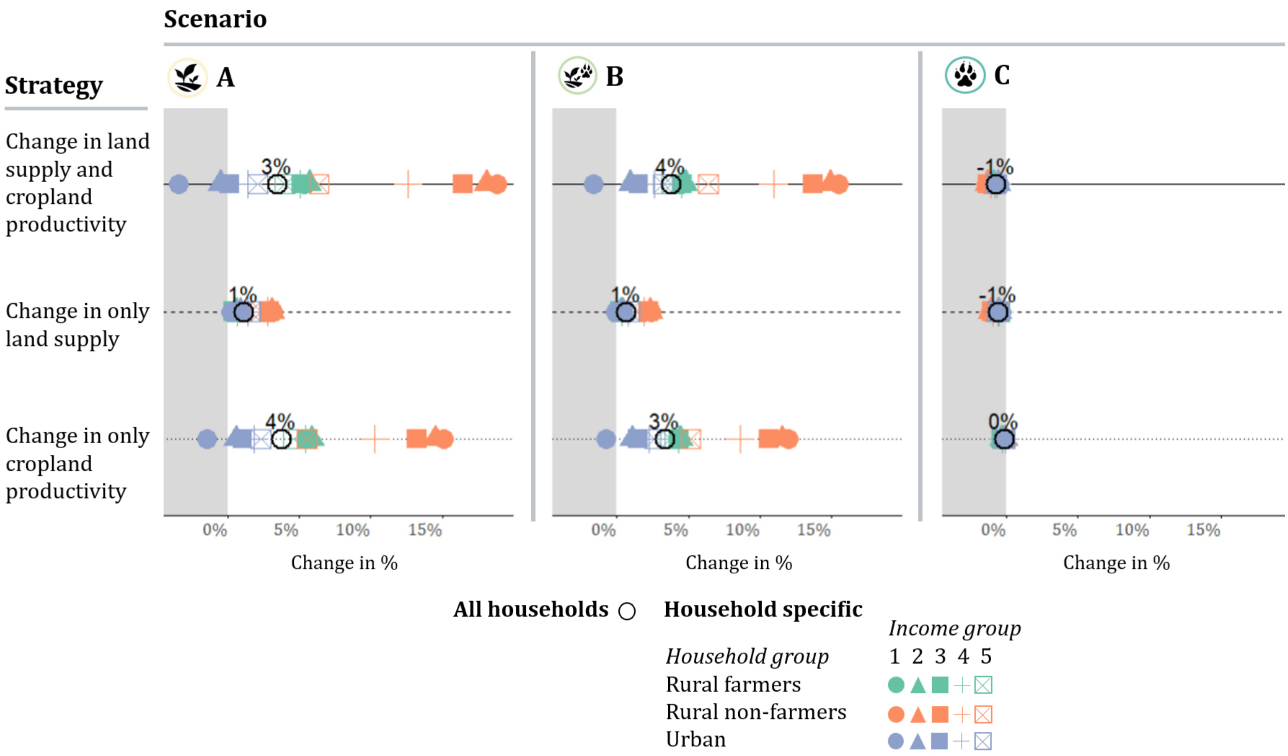


Figure 6: Changes in real income (total and household specific),if both changes in land supply and cropland productivity are implemented together or separately, in Scenario A, B, and C. The gray areas represent negative values.

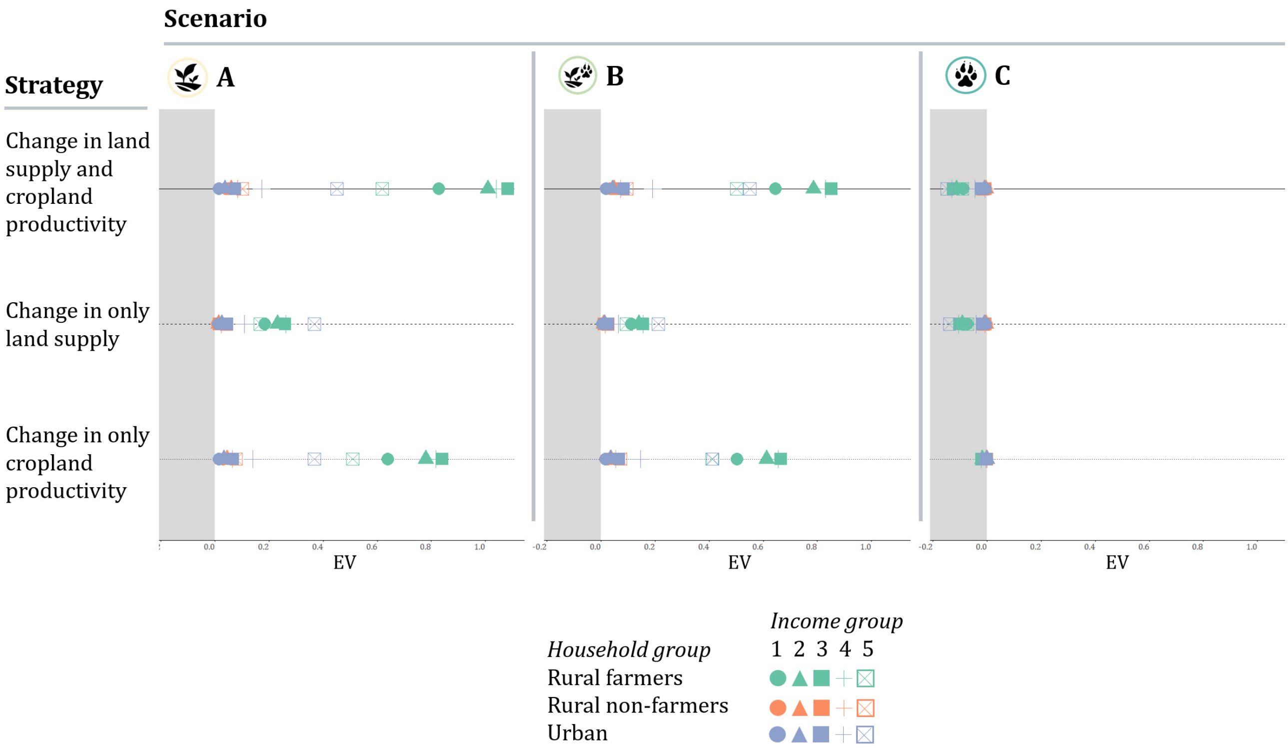


Figure 7: Changes in EV for different household groups, if both changes in land supply and cropland productivity are implemented together or separately, in Scenario A, B, and C. The gray areas represent negative values.

3.3 Additional indicators

In addition to food availability and food access, we display the impact on GDP, private consumption, and domestic absorption of agricultural commodities (see Fig. 8). All three indicators show the same pattern: the largest increase occurs in Scenario A, followed by a smaller increase in Scenario B, and a decrease in Scenario C. Increasing cropland productivity has a larger impact than increasing cropland, both in Scenario A and Scenario B.

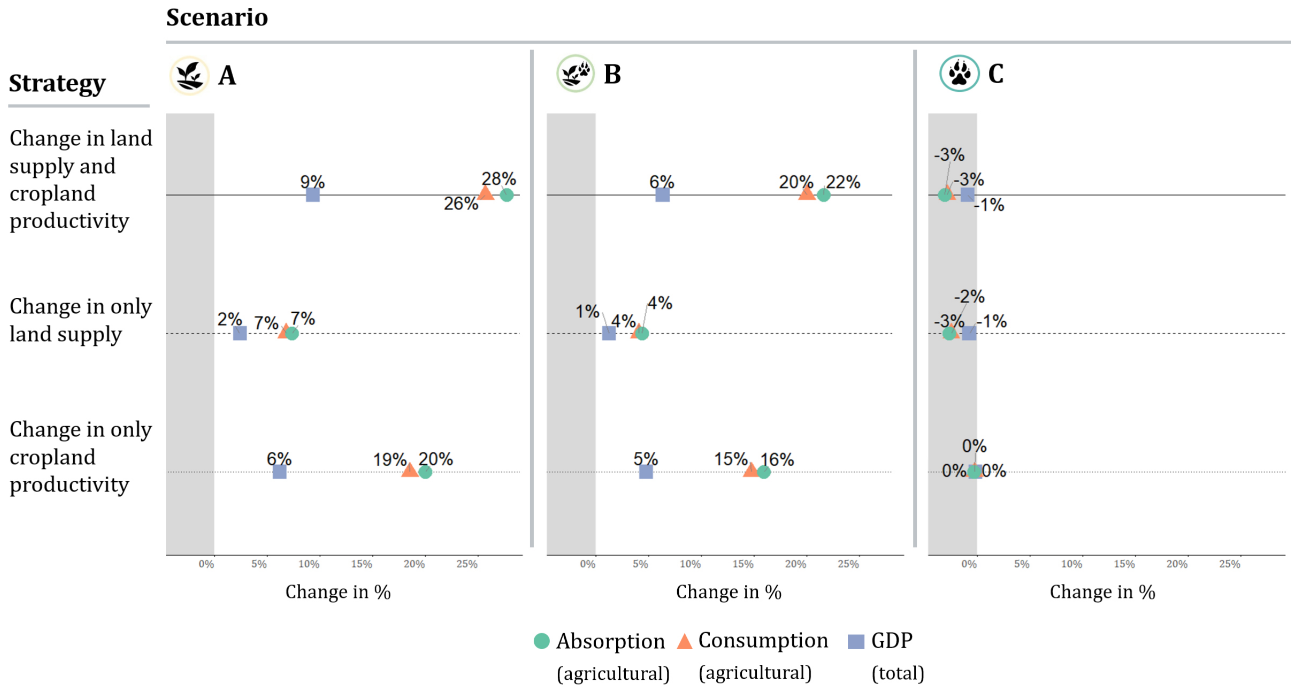


Figure 8: Changes in total GDP, consumption of agricultural commodities and domestic absorption, if both changes in land supply and cropland productivity are implemented together or separately, in Scenario A, B, and C. The gray areas represent negative values.

4 Discussion

Only considering biodiversity conservation and thereby reducing agricultural production, as in Scenario C, has negative impacts on all the indicators that we evaluate for food security in our study. These results are in line with Henry et al. (2022), showing that strict conservation scenarios will negatively impact human health, especially in low-income regions such as Sub-Saharan Africa. On the other side of the spectrum, with the expectation of real income, only focusing on maximizing agricultural production generates the largest positive impacts in all other indicators. However, even though Scenario A is defined as maintaining all biodiversity that is important for agriculture, it could be expected that other sectors will be negatively affected with an expected loss of species richness of up to 75%. One example of this is wildlife tourism, the key foreign exchange earner in Tanzania, contributing to approximately 4.3% of the total GDP in Tanzania in 2023(URT, 2024). This is also highlighted by stakeholders involved in the co-design process, that if an agricultural increase is implemented as defined in Scenario A, the tourism industry will be severely negative impacted or have to be changed to a different type of tourism, while it in Scenario B, it could stay on a similar level to today (Markoff et al., in review). Also, the findings from Kweka (2004) highlight the potential substantial impact on the economy of tourism by increases in real GDP, total welfare, and exports. Considering the cost of biodiversity loss in sectors other than agriculture in Scenario A, Scenario B may be a better option not only for biodiversity but also for the Tanzanian economy.

Comparing the potential of cropland intensification and expansion, both have a positive impact on food security. Food availability could be increased by either intensification or expansion; agricultural output in Scenario A is the only indicator in which expansion has a larger impact than intensification, which could be explained by that the expansion represents a much higher percentage increase (+65%) than the intensification (+35%). In Scenario B, in which expansion and intensification are estimated on a similar level, both contribute similarly to food availability. In the indicators for food accessibility, while expansion is positive for all indicators, intensification has a larger impact, in both scenarios A and B, however heterogeneous considering the changes in real income across different household groups and increases the prices for livestock commodities. This could be explained that when we increase the total land area, land is allocated both to cropland and pastureland, and indicates that only focusing on crops may have negative impacts on households that are dependent on livestock.

Furthermore, we acknowledge that we only consider two dimensions of food security and to not discuss how nutrition and food stability over time is influenced. In addition, we have only focused our analysis on changes in livestock and crop products, but we acknowledge that there are also other activities that brings food.

5 Conclusions

Limiting biodiversity loss completely would cause significant trade-offs to food security, with less food available for consumption, less food access, higher prices of both livestock and food products, and a decrease of income for all household groups. However, limiting biodiversity loss to a threshold that is socially acceptable, would still result in an increase in food availability, a decrease of prices, and an increase of income for most household groups. In our scenario setting, intensification has a stronger impact than expansion.

Our study illustrates a case study on how CGE modeling can benefit from the integration of qualitative data, which can be valuable for future use in different contexts.

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Appendix