




Cross-scale trade-off analysis for sustainable development: linking future demand for animal source foods and ecosystem services provision to the SDGs

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Abstract

Dietary transition towards higher consumption of animal source foods (ASF) associated with higher incomes across low and middle-income countries could have negative impacts on environmental systems and their potential in the long run to provide services necessary for achieving multiple Sustainable Development Goals (SDGs). In this article, we integrate economic, land use allocation, and biophysical models to investigate trade-offs between the five ecosystem services and their contributions to various SDGs associated with agricultural expansion to meet future demand for ASF, using Tanzania as a case study. Our results show that under the scenario of sustainable socio-economic development, between 2010 and 2030 in Tanzania, per capita income grows by 169% and the share of population at risk of hunger declines from 34.8% to 23%. These changes can be associated on a macro-level with positive contributions to achievement of SDG 1 (No Poverty) and SDG 2 (Zero Hunger). To satisfy feed demand for increased livestock production domestically, an increase by 21.4% of biomass production as compared to 2010 is needed. Analysis of alternative scenarios for meeting this new demand shows potential threats on a landscape level to achieving numerous SDGs and more generally to attaining sustainable food systems. Ecosystem-based contributions primarily decline to SDGs: SDG 3 (Health), SDG 6 (Clean Water), SDG 11 (Sustainable Cities), SDG 13 (Climate) and SDG 15 (Terrestrial Life). We find that higher crop productivity and redesign of agro-ecosystems to increase on-farm tree cover could significantly limit these losses. Alternatively, the growing demand for ASF could be satisfied with imports, which would allow for reducing the trade-offs locally. However, this would result in at least partially only displacing ecosystem service losses to the exporting countries.

Keywords Sustainable development goals (SDGs) · Animal source foods (ASF) · Ecosystem services · Integrated modeling · Tanzania · IMPACT · MESH · Livestock production

Introduction

Human diets have changed quite rapidly in the last few decades in many low- and middle-income countries (LMICs), broadly reflecting economic and social changes (Kearney 2010). This transition has raised concerns about its effects on biodiversity and the capacities of production systems to support the provision of ecosystem services over the long term (Springmann et al. 2016). Simultaneously, high levels of meat consumption, especially in high income countries are causing negative human health impacts. Red and processed meat have been linked to increased probability of cancer and other negative health outcomes (Boada et al. 2016). Therefore, a recent EAT-Lancet report (Willett et al. 2019) postulates significant reduction in the animal-source foods (ASF) consumption in high-consuming regions, to achieve

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sustainability in the global food systems. On the other hand, the authors recognize the nutritional value of ASF and the need to increase ASF consumption in low-income environments with low consumption rates. Meat, milk and eggs are high sources of high-quality nutrients and can play significant roles in boosting the diets of nutritionally disadvantaged groups, including children in low- and middle-income countries (Alonso et al. 2019).

Livestock therefore is, and most likely will remain for many years to come, a critical element of food systems. Consequently, to ensure sustainability of the global food system in the future, there is a need to not only change human diets, but also redesign the livestock sector to operate in ways that meet or enhance environmental and nutritional goals (Herrero et al. 2021). The key role in managing the trade-offs and co-benefits will belong to the agricultural management practices (Power 2010; Kozicka et al. 2020; Morris et al. 2020).

Sustainable Development Goals (SDGs) provide a consistent framework for identifying and measuring trade-offs and co-benefits across the food system and beyond. SDGs encompass overall human and ecosystem well-being that are inextricably connected across spatial and temporal scales. There still remain many knowledge gaps in the interactions between the SDGs, in particular in the methods to analyze them (Alcamo et al. 2020). In the case of changes in food consumption, the consequences for the SDGs are complex and the methods to quantify them are not yet well established. While higher ASF consumption would likely have a positive direct impact on SDG 2 (Zero Hunger), higher ASF production could hinder ecosystems and, as a result, have a negative impact on SDG 14 (Life Below Water) and SDG 15 (Life on Land). Moreover, biodiversity, ecosystems and the services they provide underpin many other SDGs (Wood et al. 2018) and hence the dietary transition could potentially set back the overall achievement of the sustainable development agenda.

There are numerous ecosystem services and the corresponding SDGs that are linked to agricultural practices. Among others, these are: pollination, pest control and soil nutrient storage and cycling (SDG 2), provisioning and regulating of water flows (SDG 6), carbon sequestration (SDG 13), providing security from natural hazards, climate change mitigation, and cultural services, and habitat for both wild and functional biodiversity (SDG 14 & 15) (DeClerck et al. 2016). It is hence crucial that alternative land-use strategies, especially those based on mainstreaming biodiversity, and their impact on the capacity of socioecological systems to manage the trade-offs and generate synergies between the SDGs are well understood and incorporated into the decision-making (Blicharska et al. 2019).

Understanding and managing positive and negative interactions and unintended consequences among SDGs may be key to achieving sustainable development. Linking

ecosystem services and biodiversity to the SDGs, especially in the context of future scenarios for socio-economic development can provide insights to possible pathways towards reaching all the SDG targets (Geijzendorffer et al. 2017). Since those targets are rarely dependent on a single ecosystem service and most services contribute to various targets across the SDGs, policymakers need to manage multiple ecosystem services taking into account their trade-offs and synergies and monitor their contribution to the SDG targets.

In this study, we investigate the relationship between the anticipated growth in the demand for ASF and the impact of ecosystem service provision on ten SDGs (SDGs 1, 2, 3, 6, 7, 9, 11, 13, 14, and 15) in a low-income country. We further assess the potential of diversified farming practices to mitigate the arising trade-offs. Our analysis is based on an integrated assessment framework that links simulations of changes in the global agricultural and food system to assessments of the provision of ecosystem services at landscape level, through the simulations of country-level demand for ASF and livestock-driven changes in land-use. A previous study identified 178 important and positive contributions ESS can make to specific SDG targets, based on a survey with a large pool of scientists and development practitioners (Wood et al. 2018). We used the ESS-SDG linkages identified in the previous study to explore how modelled changes in ecosystem services provisions may cascade onto the SDGs, following the approach in Johnson et al. (2019). This is the focus of our current study. It expands on the SDG linkages of a complementary analysis of diet-induced impacts on ecosystem services (ESS) in Tanzania, as an example of a developing country facing conflicts between competing objectives of securing nutritional security, economic prosperity and environmental sustainability (Enahoro et al. 2018). For analytical convenience, our study focuses on ASF from terrestrial animals. It does not include fish.

Materials and methods

The analysis in this study has two main components. The first part reports the development and application of an integrated modelling framework linking global economic change, environmental impact assessment and environmental simulation modelling in tracing impacts of anticipated changes in the demand for animal source foods to changes in ESS provision. This study component has been detailed in a separate publication (Enahoro et al. 2021). The study and the IMPACT model GitHub repository (IMPACT Development Team 2021) provide the details regarding the modeling assumptions, model coupling, and the full range of global change and landscape management scenarios analyzed.

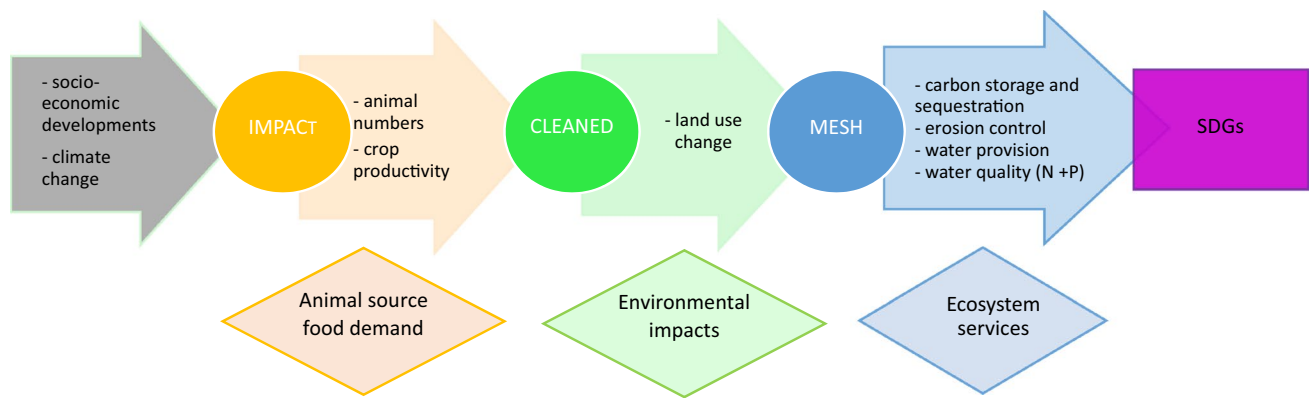


Fig. 1 Illustration of integrated quantitative modeling using CLEANED-R, IMPACT, and MESH

The second component of the study, reported here, focusses on translating the results from the integrated assessment modeling framework to measures of impacts on selected SDGs. This analysis allows for a discussion on the implications of countries' changing diets and corresponding land-use policies on their potential to attain the SDGs related to food consumption (directly) and food production (indirectly—through ESS provision), and on the potential for building or maintaining sustainability in future food systems.

Linking ASF demand to ESS provisions: IMPACT, CLEANED and MESH

Changing demand for ASF is associated to changes in ESS through a linking of the International Model for Policy Analysis of Agricultural Commodities and Trade (IMPACT) (Robinson et al. 2015) to an environmental simulation tool, CLEANED-R (Pfeifer et al. 2016), and to the Mapping Ecosystem Services to Human wellbeing (MESH) modelling platform (Johnson et al. 2019). IMPACT is a partial equilibrium model that can project country-level demand and supply for animal source foods given assumptions about growth in human populations and incomes, among other factors. Commodity supply is a function of yields, which in turn are determined by commodity prices, prices of inputs, available water, climate, and exogenous trend factors. Livestock yields follow region-specific exogenous growth trends that are due to improved animal stocks and management practices.

In IMPACT, there are two food security modules that indicate progress toward the SDG 2. The first module, based on work by Smith and Haddad (2000), estimates changes in child wasting (underweight) given changes in food availability at the country level. The second module, based on work by Fischer et al. (2005), estimates changes in the share of population at risk of hunger following changes in food availability. We apply both these measures to assess the macro-scenario implication for achieving SDG 2.

CLEANED-R is an environmental impact assessment tool that includes a module that can compute livestock-driven land use change at landscape to national level. The model was adjusted to define animal species and breeds that exactly match those of IMPACT. It combines parameters on animal numbers, livestock productivity, livestock feed ratio, with land cover and other spatial data to generate simulations of land use change.

MESH is an interface for scenario analysis which can be used to compute changes in the local provision of multiple ecosystem services associated with land use change. Figure 1 illustrates this linkage.

The steps of the analysis are outlined as follows: the effects of changing demands for livestock-derived foods on agricultural (crops, livestock) production, supply, and trade in 2030 were analyzed in IMPACT under a set of assumptions about socio-economic and climatic change (scenario). We focused on the year 2030 as this is the horizon of the Agenda for Sustainable Development.

Estimates of crop and livestock (beef, mutton, poultry, and pork) production derived from the model scenarios in IMPACT were used in CLEANED-R as inputs for computation of changes in land use related to agricultural production. To do this for Tanzania, country-specific rules for land cover changes were employed that had previously been derived from stakeholder consultations, historical data and literature (Morris et al. 2020). Conversion of land to livestock production was simulated to be restricted to non-protected areas, prioritizing land according to crop suitability as shown for grass used for pasture and maize in GAEZ data (IIASA/FAO 2012). CLEANED-R generated spatially explicit future land cover maps reflecting demand-induced transformation in livestock feed (maize crop used as livestock feeds, and pasture) production.

MESH used as input the data from CLEANED-R of alternative land use scenarios, assuming new agricultural production areas were either monoculture or agroforestry/

silvo-pastoral systems (new land was allocated exogenously to one of the two categories). From this, it calculated spatially explicit measures of the supplies of five ecosystem services. The ecosystem services of concern were freshwater supply, nitrogen retention by natural vegetation, phosphorus retention by natural vegetation, carbon sequestration, and soil erosion control. Supplies of each of these services across Tanzania were estimated using InVEST models accessed through MESH.

Full information on the water yield, nutrient delivery, carbon storage and sequestration, and sediment delivery models used to calculate these ecosystem services can be found at (Sharp et al. 2020). Briefly, water supply (surface runoff) was calculated using a simple water balance model with average annual precipitation for the period 2016–2045 as the input and annual evapotranspiration for the same period as the output. Evapotranspiration was adjusted based on vegetation type (including in cropland, to account for agricultural water use), root restricting layer depth, and plant available water content. Avoided nitrogen and phosphorus pollution, contributing to maintaining water quality, were calculated using a simple mass balance model, with nutrient load (fertilizer additions) as the input and nutrients filtered out of runoff and subsurface flow by natural vegetation and soils as the output, to give the balance of nutrient exports at the watershed outlet. Carbon storage and sequestration was calculated by estimating, for each land use land cover, the quantity of carbon stored in aboveground biomass, belowground biomass, soil, and dead organic matter. Soil erosion control was calculated by estimating the amount of sediment eroded by runoff (so excluding gully and channel erosion and sediment from landslides) and reaching the stream network, after removal of sediment that is retained by vegetation and topographic features (following Borselli et al. 2008).

Scenarios: IMPACT, CLEANED and MESH

The ASF demand scenarios for Tanzania in 2030 that represent plausible macro-conditions under which livestock sector policymakers in the country can expect to operate (Enahoro et al. 2019a, b) were analyzed with IMPACT. The scenarios were built based on the IPCC framework and consisted of the intersection of socio-economic pathway of global sustainability with future scenarios of global climate change. In the study, we considered a range of shared socioeconomic pathways (SSP) scenarios: conditions of global sustainability (optimistic, SSP1), global inequality (pessimistic, SSP4), and a dynamics-as-usual or middle-of-the-road trend (moderate, SSP2). The details and the results can be found at (IMPACT Development Team 2021).

The focus of this component of the study is on the impact of land-use change on the SDGs, and hence we report only one macro-level scenario—the SSP1 (Riahi et al. 2017),

simulated with the assumption of a climate change/greenhouse gas concentration trajectory—the Representative Concentration Pathway 6.0 (RCP 6.0). We selected SSP1 because of its assumptions of sustainable development, and hence the increase in income and food consumption will have a stronger positive impact on SDG1 and SDG2 on a macro-level, which then can be assessed vis a vis ecosystem impacts and their contributions to SDGs on a landscape level. Furthermore, the optimistic economic scenario leads to the highest increase in ASF production, and hence the greatest land use change, which could be used as an upper bound on land use changes expected from the changing demand. Finally, SSP1 and RCP6 are mutually compatible narratives (Engström et al. 2016). SSP1 narrative includes various elements that support a "sustainable" pathway, including land use policy and changing dietary preferences. However, SSP scenarios as implemented in the IMPACT model only include the population and income pathways. These are consistent with the reasoning presented here, but it is important to note that not all of the sustainability elements of the SSP1 scenario were included in the macro-level demand scenario.

This scenario was then coupled with a range of management options using the CLEANED-R and MESH models (Fig. 2). Crop productivity was assumed to either remain constant on the 2010 level or increase according to the IMPACT projections of demand/price-induced changes in productivity.¹ This was done to explore what happens if the crop productivity gains assumed in IMPACT cannot be achieved on the ground, such as the non-adoption of fertilizer or improved seed use. These improvements are implicitly assumed in IMPACT as part of the scenarios² and hence the direct implications for ESS of their realization cannot be calculated. They are de facto assumed not to affect ESS provision.

Two options for international trade were considered—allowing for imports to satisfy the new demand or producing the additional ASF domestically through agricultural expansion. In the 'trade' scenarios, the net imports were calculated with the IMPACT model. For the alternative scenarios, we considered a situation in which the imports were not possible. This could be for example due to market failures, or

¹ The GAEZ layer was adjusted linearly to ensure that the average crop productivity measures for IMPACT and CLEANED-R are equivalent in the baseline and alternative scenario runs (where productivity increase is assumed). Grassland does not have any GAEZ layer and has no productivity assumption in IMPACT. We have used the value of 9 tons per hectare biomass that can be fed to livestock.

² Productivity changes in IMPACT are a function of commodity prices, prices of inputs, available water, climate, and exogenous trend factors. In this study, all of these components were considered in the scenario of productivity growth.

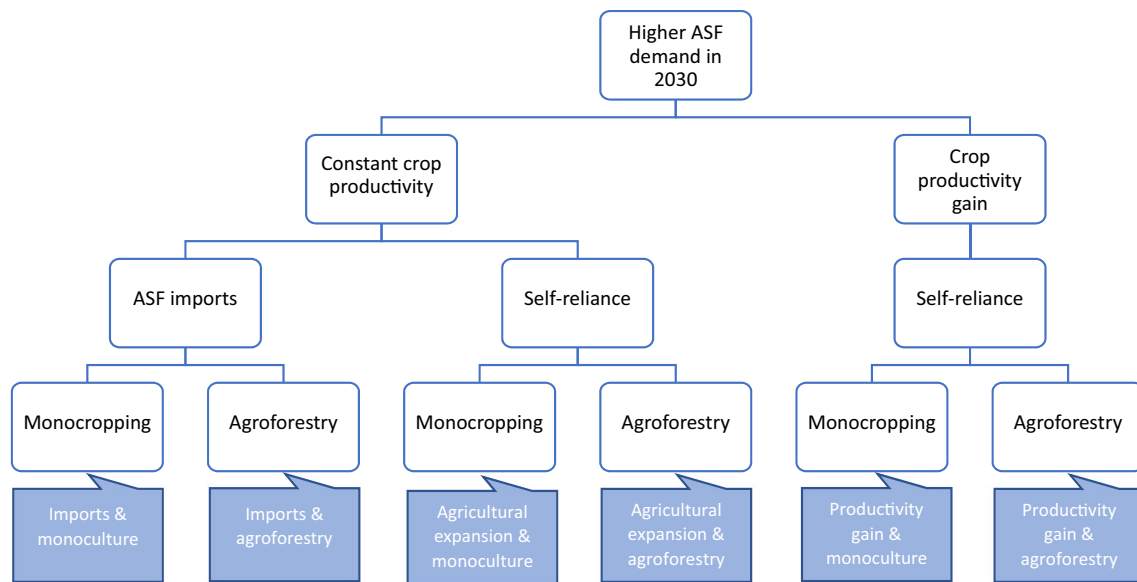


Fig. 2 Scenario tree. Note: monocropping refers to the production system where only one annual crop species (maize) is grown at any one time on the field. Agroforestry refers to a mixed system with trees and other crops (e.g., maize grown for fodder cropped with fruit or other trees). We are not reporting the results of the scenario

with crop productivity gain and trade (and hence it is not shown in Fig. 2) because the impact of the increased demand was almost fully ‘absorbed’ by the imports and higher domestic productivity, so no land-use change was required. Hence the ecosystem services did not change compared to the baseline scenario

the country’s policy to meet all its livestock demand locally. This was considered as a maximum for the domestic environmental impacts of new demand.

For each of these scenarios, the effect of increased agrobiodiversity on new agricultural land was considered. This was done by comparing the planting of mono-cropped annual crops (e.g., maize) to agroforestry/silvopasture (e.g., forage or maize grown³ for fodder cropped with fruit or other trees) systems. The amount of land that needs to be converted to produce this additional biomass depends on assumptions about increases in maize productivity and differences between maize yields in monoculture and agroforestry production systems. We assumed that maize yields in agroforestry are half of those in monocropped systems, meaning that the former requires approximately double the land area to produce the same amount of animal feed.

These options together defined national level management of land use, crop productivity, and the degree of agrobiodiversity in agricultural production systems. A total of six (6) scenarios were selected and simulated alongside a baseline scenario (a status quo for trade, crop productivity and other assumptions in IMPACT in year 2015), in CLEANED-R. The results of these seven (7) scenarios (baseline plus six alternative scenarios) were further analyzed with the MESH tool.

Linking ASF demand to sustainable development goals: MESH-SDG

The SDGs include 17 goals and each goal has a subset of targets against which countries monitor their progress towards goal attainment. In a previous study, 178 positive linkages between ecosystem services and SDG targets were identified by a large pool ($n = 244$) of experienced environmental scientists and development practitioners (Wood et al. 2018). In an extension of these findings, outputs of the ecosystem service assessment conducted in the present study are displayed in terms of their potential impacts on several of the SDGs based on where they can make an important and positive contribution to SDG attainment. All positive and important linkages identified in Wood et al. (2018) were included with the exception of linkages from food provision, which were subset to include only linkages considered viable through changes to crop production area with no changes to crop management. Specifically, linkages between food provision and SDG 6 (clean water), SDG 12 (sustainable consumption), SDG 14 (life at sea), and SDG 15 (life on land) were excluded. The list of linkages between ecosystem services and specific SDG targets considered in our analysis are provided in Fig. 3. We show how changes in ecosystem services may impact on ecosystem-based contributions to the SDGs using the percentage change in an ecosystem service weighted by the number of unique SDG targets to which

³ Tropical maize in the GAEZ database was used.

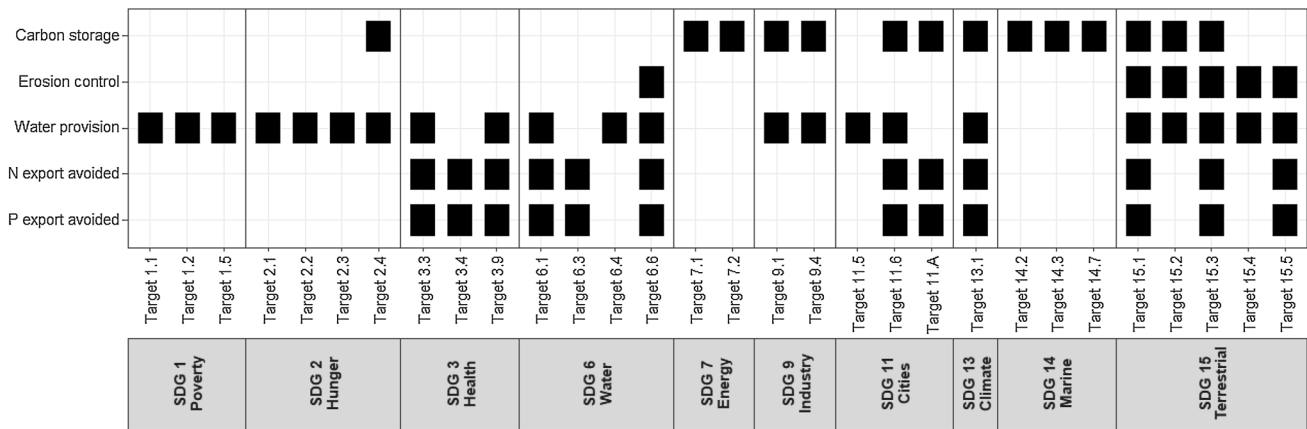
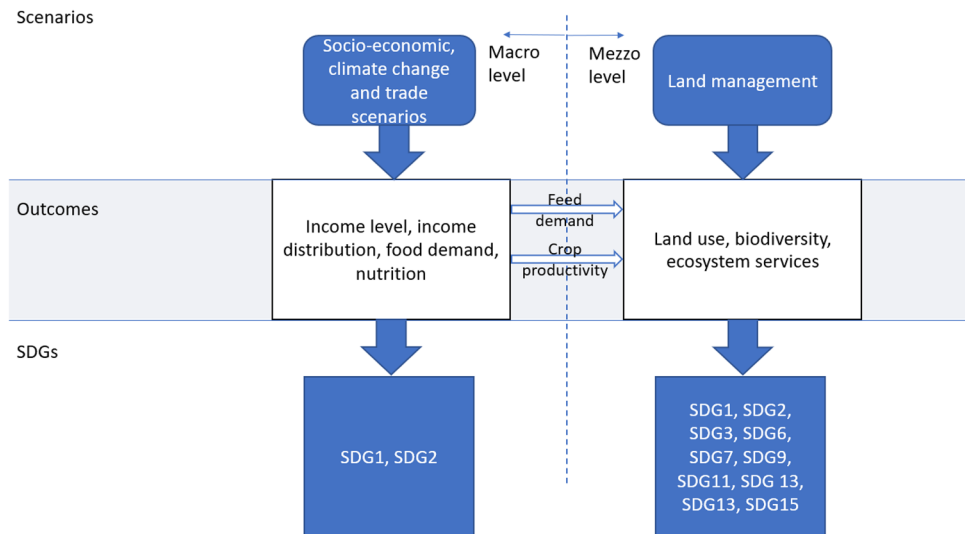


Fig. 3 Linkages between ecosystem services and the SDGs considered in the MESH-SDG plugin applied for this paper

Fig. 4 Scenarios, outcomes and their contribution on SDGs at macro- and mezzo-levels



that service “contributes” under a specific SDG goal, following Johnson et al. (2019). The overall impact of changes in ecosystem service supply on progress towards an SDG goal cannot be quantified precisely, as there is no information available on how far a goal can be achieved through ecosystem service enhancement alone. Our aim is instead to highlight where changes in ecosystem service provision are likely to affect multiple targets and goals. A major assumption we make is that each ecosystem service contributes equally to making progress towards achieving each of the SDG targets that it is linked to. For example, carbon storage is linked to SDG targets 7.1 and 7.2, and we assume an increase in carbon storage will have an equal impact in helping achieve each of these targets. This is a simplification of the reality that we considered necessary and suitable for the current purpose. The analysis was

done using an open access R script, MESH-SDG (Jones, et al. 2017).

Trade-off analysis between the SDGs

The assumed macro level scenario that encompasses the sustainable socio-economic development (SSP1) and climate change (RCP 6.0) scenarios implicitly assumes certain degree of progress towards the SDGs. Even though the SDGs were not directly targeted in the development of the IPCC scenarios, there are implications for the achievement of several SDGs imbedded in the resulting trajectories (TWI2050 2018). Shared socio-economic pathways (SSPs) explicitly assume levels of human population growth, income, and poverty, which constitute SDG1 (Fig. 4). Taking these scenarios as a starting point, based on the IMPACT model simulations (that include only the population and

Table 1 Land use change scenarios based on IMPACT results

Crop productivity	Productivity gain		Constant productivity			
	Productivity gain & monoculture	Productivity gain & agroforestry	Imports & monoculture	Imports & agroforestry	Self-reliance & monoculture	Self-reliance & agroforestry
% change in imports of livestock feed	0		18.1		0	
% change in livestock feed (maize) biomass required from in-country production	21.4		3.7		21.4	
new cropland (km ²)	6810	13,588	1508	2885	8123	16,186
New cropland production system	Monoculture	Agroforestry	Monoculture	Agroforestry	Monoculture	Agroforestry
% change in maize yields	0	– 50	0	– 50	0	– 50

income growth components of the SSP), we can conclude about the progress towards SDG2: developments in the food system and adjustments in the supply and demand equilibrium to satisfy increased food consumption levels, reduce the number of people at risk of hunger and number of malnourished children. For the required changes in food production, depending on assumed productivity and land-use scenarios, the changes in the ecosystem service provision eventually are linked to the SDGs related to: poverty; hunger; health; water and sanitation; energy; industry, innovation and infrastructure; sustainable cities and communities; climate action; life below water; and life on land.

This analysis is partial and hence does not show expected changes towards attainment of the targets themselves as this is dependent on several additional social, economic and political factors that we do not explicitly model in the analysis. However, the outputs can be used to identify which scenarios show the greatest potential to support the realization of SDG goals and targets. They are also useful to demonstrate the trade-offs between the goals across scales—from macro- to mezzo-level.

Results and discussion

Results of the analysis of the macroeconomic and climate change scenario (left-hand side of Fig. 4) with the IMPACT model link income to food security outcomes. As population and national income increase in Tanzania, the demand for certain food commodities increases. A per capita income growth of 169% from 2010 to 2030, and total population growth by 50% in the same period, is associated with a per capita growth in ASF sourced energy consumption of 38%. In the same time, the total average per capita food consumption grows only by 11.5% (2010–2030) in terms of calories (by 14% in terms

of weight). This relatively small increase illustrates the shift to higher-value foods as incomes rise. Poultry meat demand per person grows by 89% (1.4 kg per person per year), and beef demand by 42% (3 kg per person per year). It is important to note that even though the ASF consumption registers a significant increase, the ASF consumption remains relatively very low in 2030 as compared to the world average. The difference between Tanzania and the world average will remain stark in 2030—in Tanzania only 80 kcal/capita/day will come from meat consumption overall, as compared to 266 kcal/capita/day globally. For dairy and eggs, the difference will be slightly smaller, with 75.5 kcal/capita/day in Tanzania, versus 201.7 kcal/capita/day world average.

The macro-level scenario clearly has positive contributions to SDG1 and SDG2 within the socio-economic domain. Thanks to the improved socio-economic conditions, the share of population at risk of hunger in Tanzania declines from 34.8% in 2010 to 23% in 2030. However, as the overall population grows, in absolute numbers this decline is much more moderate—from 15.6 million to 15.5 million, while the number of malnourished children also declines only slightly—from 2.36 million to 2.31 million. This demonstrates that even though income and food security significantly improve, there is a need for additional measures to eradicate poverty, hunger and malnutrition on the way to achieving SDG1 and SDG2 by 2030.

Satisfying the increased demand for ASF and underlying demand for feed will impact ecosystems, with potential consequences for several SDGs (right-hand side of Fig. 4). This impact depends on the land-management, trade policy and productivity assumed in a mezzo-level (land-use) scenario (Fig. 3). A significantly higher production of biomass is required to satisfy the feed demand domestically—an increase by 21.4% compared to 2010 is needed or 3.7% if ASF imports are substantially increased (Table 1).

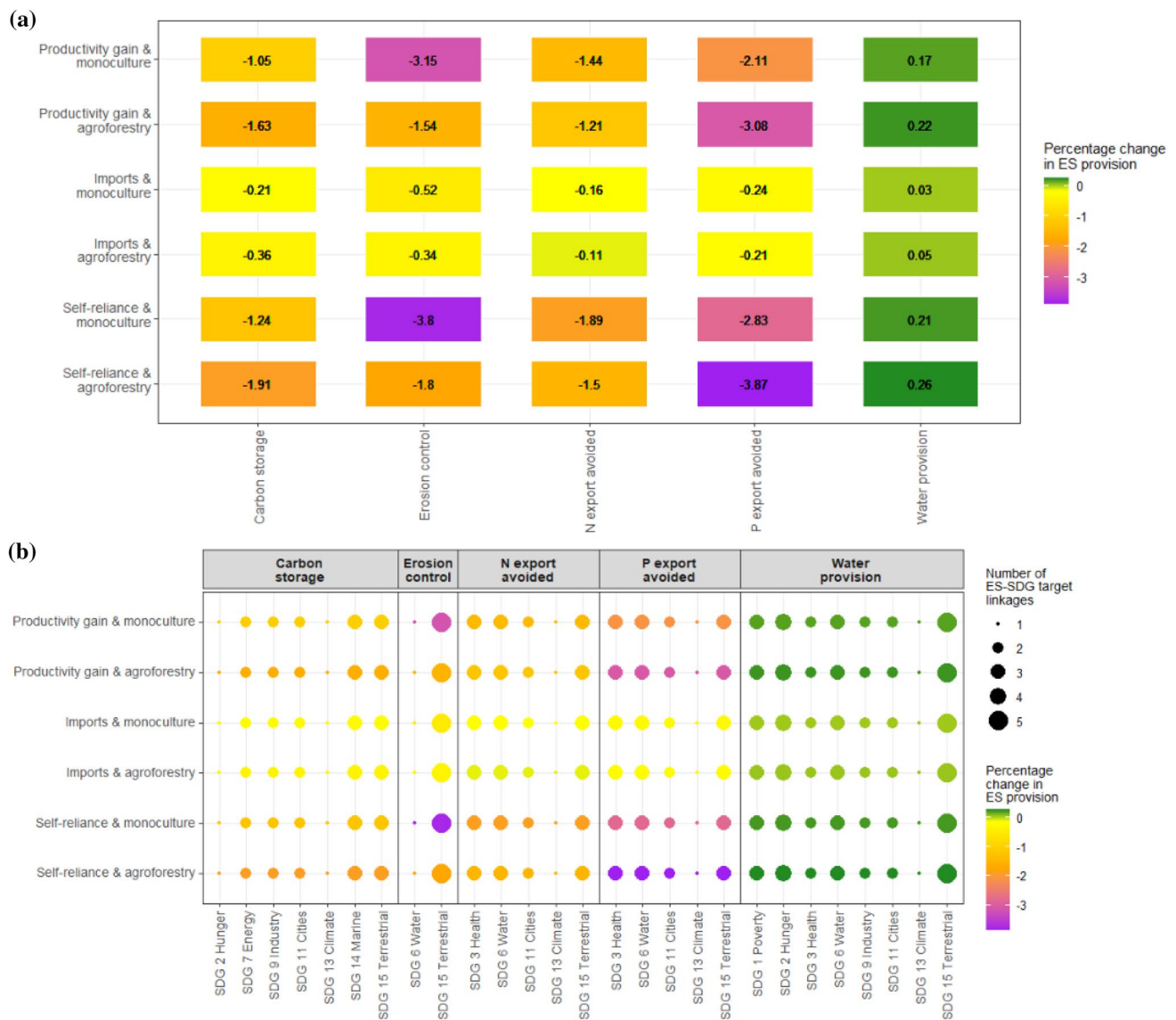


Fig. 5 **a** Changes in ecosystem service provision under six scenarios, and **b** relative impacts on ecosystem-based contributions to 10 SDGs by 2030, compared to 2015.

Changes in land use under each scenario were shown to cascade into changes in ecosystem service provision (Fig. 5a) with implications for their contributions to the SDGs (Fig. 5b). While our results suggest progress will be made towards meeting SDG 2 as a result of the macro-economic developments, there is a real risk of increased water pollution from nutrient and sediment exports and a loss of carbon storage with impacts on SDGs 3, 6, 7, 9, 11, 13, 14 and 15 (Fig. 5b). Losses in ecosystem service provision were highest under the self-reliance scenarios and lowest under the import scenarios. This suggests that the optimal national strategy for satisfying the growing demand for ASF while reducing trade-offs between food, water, climate and biodiversity goals is to increase ASF imports.

However, this would require increases in ASF production in those countries that export to Tanzania. This means that at a global or even regional scale, increasing imports would to some extent displace ecosystem service losses. The impact on ecosystem services in the exporting country would depend on its production technology and resource conditions. These displaced effects are not accounted for in this study and require further research to capture trade impact on ecosystem services provision. Ignoring the import scenarios, ecosystem service losses were substantially lower under the productivity gains scenarios due to smaller area of agricultural expansion, highlighting that closing yield gaps is key for win-win ecosystem service and ASF outcomes. It is important to note that scenarios

for increasing productivity, such as by increasing fertilizer and water inputs, intercropping with legumes, integrated crop-livestock farming, and switching to higher yielding or locally adapted varieties, are not explicitly modeled in this study. Neither are the implications for ESS provision and their contributions to the SDGs accounted for. Further research is needed to identify the best option for increasing maize productivity while maintaining ESS provision, but is likely to require agroecological intensification strategies compatible with a shift towards sustainable food systems (Wezel et al. 2020).

Increasing crop productivity in sub-Saharan Africa is arguably “a precondition for sustaining livelihood improvements in the region” (Jayne and Sanchez 2021). Agricultural growth is strongly correlated with overall GDP growth and improvements in the welfare in most of the African countries (Jayne et al. 2021). Hence sustainable agricultural growth would further accelerate the progress towards the Sustainable Development Goals. Agricultural R&D will play a major role in supporting farm technical innovation and adaptation, while policies are needed to strengthen agricultural marketing and trade, along with investments in infrastructure (ibid).

There were only minor differences in ecosystem service losses under monoculture versus agroforestry for all scenarios, despite that nearly double the land area was converted to cropland under the agroforestry scenarios (on account of their being lower maize yields, see Table 1). As natural land conversion to cropland is often associated with ESS losses, this result indicates that maize production in agroforestry systems, even when accounting for lower yields, very clearly helps reduce losses across all assessed ecosystem services compared to maize monocultures. However, it is important to emphasize that it is no substitute for the ecosystem services provided by the natural vegetation it replaces. The biggest benefits of agroforestry were to erosion control, where losses were approximately halved (compared to monocropped systems) under all scenarios highlighting that agroforestry can help Tanzania make progress towards SDG 6 and SDG 15 (Fig. 5b). Agroforestry was only partially able to mitigate the losses to carbon storage stemming from natural forest and grassland conversion to agriculture, and carbon storage losses in agroforestry systems remained higher than in monocropped systems under all scenarios due to the larger areas of land converted. This highlights that while agroforestry undoubtedly increases carbon storage relative to monocropped land, the primary focus should be on limiting agricultural land encroachment on natural vegetation for making progress towards climate mitigation (SDG 13) and multiple other SDGs impacted by climate change (Fig. 5b). With this conclusion we add to the ongoing calls to ensure sufficient natural habitat is spared from agricultural use, while simultaneously shifting to

biodiversity-friendly farming methods on agricultural land, to safeguard biodiversity and ecosystem services (Luskin et al. 2018; Loconto et al. 2020; Garibaldi et al. 2021).

Ecosystem functions that maintain water supply contribute to multiple targets across eight of the SDGs, yet changes to water supply were negligible under all scenarios. This suggests agricultural expansion alone is unlikely to noticeably change freshwater availability, probably because of high evapotranspiration rates from natural vegetation in areas that are most suitable for agriculture (which were prioritized for conversion to cropland in all scenarios). The largest losses in ecosystem services under the future scenarios were with respect to the proportion of phosphorus filtered and retained by natural vegetation, with up to 3.87% more phosphorus exported to streamways (self-reliance agroforestry scenario) (Fig. 5a). Increased nutrient exports would pollute freshwater systems with potential implications for progress towards at least five SDGs (Fig. 5b). While agroforestry systems were assumed to require fewer nutrient inputs due to improved soil quality relative to monocropped systems, the difference in nutrient inputs was not sufficient to compensate the loss in water purification services from converted natural habitat. While agroforestry—along with targeted fertilizer additions to reduce or eliminate losses—is part of the solution, avoiding agricultural expansion into natural vegetation is vitally important to retain water purification services.

The concept of sustainable diets, and sustainable food systems more broadly, is strongly linked to the sustainable development agenda, particularly to the SDG 2 (Zero Hunger) and SDG 12 (Responsible Consumption and Production). The changes that accompany a dietary transition are very complex and go far beyond food consumption. There remain many trade-offs and synergies that should be further explored (Salmon et al. 2018), but were not captured in our analysis. For example, higher meat consumption creates opportunities to improve food and nutritional security in developing countries, however it also enhances the risks of chronic ill health, such as from colorectal cancer and cardiovascular disease (Richi et al. 2015; Godfray et al. 2018). From the producer’s perspective, farming animals helps to increase and diversify income and, further, improve food security (Lammers et al. 2009; Neo and Chen 2009). Agricultural biodiversity is a crucial building-block of the smallholders’ resilience to future challenges, like climate change or crop disease outbreaks (Kozicka et al. 2020). In mixed crop–livestock farming systems, livestock further provide draft power to cultivate the land and manure to fertilize the soil. Our study has in addition not delved into impacts and trade-offs of higher ASF demand that will be associated with other nodes of the food value chain, namely, transportation, agri-processing, wholesaling, retailing or food preparation.

Conclusions

The aim of this study was to investigate the relationship between the anticipated growth in the demand for animal source foods (ASF) and the impact of ecosystem service provision on the Sustainable Development Goals (SDGs) under alternative farming practices in Tanzania until 2030. (Geijzendorffer et al. 2017) For this purpose, we integrated results from multiple models to capture linkages across the food system of increased future demand for food, through land use change, with the provision of ESSs. Next, we linked results to the Sustainable Development Goals framework to highlight potential trade-offs between different objectives of sustainable development. The SDGs that were captured in the framework were selected based on a previous study.

As a starting point for our analysis we took a macro-level scenario encompassing the income, distribution of wealth and poverty and corresponding consequences for the progress towards the SDG1 (No Poverty). Using a partial equilibrium analysis, we found that the higher income in Tanzania in 2030, will likely lead to an increase in food consumption, with disproportionately larger increase in the ASF consumption, leading to improved nutrition and lower hunger prevalence. Meeting higher demand for ASF requires higher feed production that can be satisfied either domestically or with imports and using alternative farming practices. These choices will have implications locally for provision of ESS and their impacts on SDGs. Meeting this demand through agricultural expansion will lead to significant losses to ESS provision by 2030, hampering ESS-based contributions to ten SDGs (SDGs 1, 2, 3, 6, 7, 9, 11, 13, 14, and 15). We found that the most viable solution for reducing ESS losses while meeting this rise in ASF demand is to increase productivity of animal feed production, thereby minimizing agricultural expansion, while favoring agroforestry over monocropped systems in all new cropland areas. This scenario would minimize impacts to freshwater supplies, carbon storage, clean water, and soil erosion control, which together make important and positive contributions to all ten SDGs.

We have taken (mainly) demand and climate assumptions as given, calculating a proxy of an upper bound of livestock-related land use changes associated with expanding demand, and experimented with the extents to which candidate land management options will potentially mitigate the negative outcomes from higher production. We have then assessed the multi-dimensional implications for SDGs. We have left out (1) the treatment of uncertainty around demand and climate change, and (2) a wide range of possibilities related to the trade in crops and livestock commodities, crop/livestock technologies, and the

associations of land management to SDG outcomes. Some of these themes are easily incorporated in the analytical framework using methods of scenario or sensitivity analysis. Other issues omitted in the current analytical framework will be more challenging to incorporate. For example, our specification of the sector does not easily account for impacts of future livestock demand that occur outside of the primary production of livestock, ignoring multiple layers of activities along livestock value chains and in the wider food systems. Advancements of the analytical models and methods in these directions will be useful.

Our framework allows for tracing impacts across temporal and spatial scales and linking socio-economic and bio-physical domains. It is, however, subject to limitations and caveats as a result of simplifications and omissions that are intrinsic to mathematical modeling and that often compound as a result of model integration. For example, SDGs depend on various elements of Shared Socioeconomic Pathway narratives, such as land use-policy, demographic structure, income distribution or changing dietary preferences, but these were not captured in the IMPACT model. As a result, our socio-economic scenario only includes the population and income pathways assumed in the SSPs.

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Author contributions M.K., S.J., E.G., and D.E. designed the project and developed the presented idea. S.J., D.E., and M.K. developed the modeling framework. S.J. and D.E. performed the numerical simulations. M.K. wrote the manuscript, with contributions from all authors. D.E. lead the project “Changing demand for animal source foods and their effects on the provision of ecosystem services”.

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Data availability The data used for this study, outputs from each modeling step and additional data supporting the findings of this study are available on GitHub at https://github.com/IFPRI/IMPACT/tree/master/DriverAssumptions/Special_Studies/Kozicka_et_al_2021_and_Enahoro_et_al_2021. IMPACT model information is available at <https://www.ifpri.org/project/ifpri-impact-model>. Complete CLEANED-R model documentation and the model source code can be found at <https://github.com/ilri/CLEANED-R>. MESH modelling platform is available at <https://naturalcapitalproject.stanford.edu/software/mesh>

Declarations

Conflict of interest The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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