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ORIGINAL ARTICLE

Linking ecosystem services provisioning with demand for animal-sourced food: an integrated modeling study for Tanzania

Dolapo Enahoro[1] · Marta Kozicka[2,3] · Catherine Pfeifer[4,5] · Sarah K. Jones[6] · Nhuong Tran[7] · Chin Yee Chan[7] · Timothy B. Sulser[8] · Elisabetta Gotor[2] · Karl M. Rich[4,9]

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Abstract
Standard tools that can quantitatively track the impacts of higher global demand for animal-sourced food to their local environmental effects in developing countries are largely missing. This paper presents a novel integrated assessment framework that links a model of the global agricultural and food system, a landscape-level environmental impact assessment model, and an ecosystem services simulation model. For Tanzania, this integrated assessment showed that a projected increase in the demand and production of foods of livestock origin with optimistic economic growth between 2010 and 2030 leads to an improvement in food security. However, resulting transitions in land use impact negatively on the future provisioning of ecosystem services, increasing phosphorus, nitrogen, and sediment in runoff and reducing water quality in areas downstream of the agricultural expansion. Losses in ecosystem services are lowest when diversified farming practices are adopted in areas of agricultural land expansion. The role of land management in the environmental impacts of expanded livestock production is highlighted, as is the need for a new generation of analytical tools to inform policy recommendations.

Keywords Scenario analysis · Integrated assessment · Food security · Livestock production · Ecosystem assessment · Land use change

Introduction

Land use change is essential for the provision of food, fiber, energy, and habitation for humans. However, land use change is a major driver of biodiversity loss (Díaz

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✉ Dolapo Enahoro
d.enahoro@cgiar.org

Marta Kozicka
kozicka@iiasa.ac.at

Catherine Pfeifer
catherine.pfeifer@fibl.org

Sarah K. Jones
s.jones@cgiar.org

Nhuong Tran
n.tran@cgiar.org

Chin Yee Chan
c.chan@cgiar.org

Timothy B. Sulser
t.sulser@cgiar.org

Elisabetta Gotor
e.gotor@cgiar.org

[1] International Livestock Research Institute, c/o, IWMI-Ghana, PMB CT 112, Cantonments, Accra, Ghana

[2] Bioversity International, Rome, Italy

[3] International Institute for Applied Systems Analysis, Vienna, Austria

[4] International Livestock Research Institute, Nairobi, Kenya

[5] Research Institute of Organic Agriculture (FIBL), Frick, Switzerland

[6] Bioversity International, Montpellier, France

[7] WorldFish, Penang, Malaysia

[8] International Food Policy Research Institute, Washington, D.C., USA

[9] Ferguson College of Agriculture, Oklahoma State University, Stillwater, OK, USA

et al. 2019), compromising food systems resilience, food security, sustainable development, and the supply of many vital ecosystem services (FAO 2019). Approximately 38 percent (%) of the Earth's total, ice-free land surface is used for agriculture with the majority supporting pasture used in livestock production (Foley et al. 2011). Major socioeconomic changes over several decades, including population growth, increased incomes, and urbanization, have resulted in higher global demand for animal-source foods (ASF) (Delgado et al. 2001; Gouel & Guimbard 2019; Popkin 2004). The higher demand for ASF has in turn accelerated land use change, with consequent higher demand for agricultural production potentially impacting negatively on underlying environmental systems (Delgado et al. 2012. The consumption of ASF products (fish, meat, milk, and eggs) however remains a major source of high-quality nutrients, playing a significant role in boosting the diets of nutritionally disadvantaged groups, including children, in low- and middle-income countries (Thilsted et al. 2016; Alonso et al. 2019). Coupling minimal consequences to ecosystems with increasing demand for ASF in low- and middle-income countries will be one of the major challenges for food systems in the future.

The nature of ongoing dietary transitions globally, i.e., where and in what ways demand for key food groups such as ASF will change, will have an important bearing on the evolution of environmental systems in the future (Willett et al. 2019). It becomes critical to better understand and anticipate emerging demand for food and its effects on capacities of production systems to continue supporting food production, including through the provision of ecosystem services over the long term. This will be useful for identifying practical solutions that can reduce potential negative externalities of more intensive use of natural resources, and move increasingly towards more sustainable, responsible, and efficient production of ASF (ILRI 2019). Until recently, little attention has been given to biodiversity-enhancing solutions (van Soesbergen et al. 2017). These are however of particular interest, as biodiversity plays a key role as regulator of underpinning ecosystem processes (Mace et al. 2012) from which ecosystem services are derived. Hence, biodiversity-enhancing solutions could potentially address the emerging trade-offs and offer multiple other benefits (Kremen et al. 2012; Kremen & Miles 2012; Rosa-Schleich et al. 2019; Kozicka et al. 2020).

Previous studies have tried to understand how higher demand for ASF will affect food security and human nutrition, as well as their socioeconomic and environmental impacts (Enahoro et al. 2018; Chan et al. 2019; Delgado et al. 2012). There however remain critical knowledge gaps in the understanding of the longer-term effects on the environment linked to rapid socioeconomic change occurring in some developing countries. Using an interdisciplinary analytical framework, van Soesbergen et al. (2017) assessed potential impacts of increased agricultural production on biodiversity in Uganda, Rwanda, and Burundi. Their integrated analysis framework, which linked scenarios from the global economic model (IMPACT) to a spatially explicit integrated land use model, provided a useful tool for exploring the role of conservation policies in maintaining biodiversity while meeting increased demands for food production. This study builds on van Soesbergen et al. (2017) by further associating ongoing dietary changes and their land use implications on local agricultural production, to the future provision of key ecosystem services. The provision of ecosystem services is considered an important measure of how much a change in the environment affects people, social benefits, or its value to society (Johnson et al. 2019).

This study presents a quantitative analysis of landscape-level environmental impacts related to the anticipated growth in the demand for ASF in Tanzania. The impacts of higher demand for ASF are traced first through their effects on international trade and local food production, then to their secondary effects on land use, agricultural land expansion, and the provision of ecosystem services. An associated study has analyzed the trade-offs between future higher demand for ASF in Tanzania and the contributions that ecosystem services make to various sustainable development goals (Kozicka et al. 2022). This study assesses if, and to what extent, increasing the diversity in agricultural production systems could mitigate losses to ecosystem services resulting from livestock-mediated agricultural land expansion. The analysis focuses on Tanzania as an example of a country facing the dual pressure to mitigate environmental stresses while expanding agricultural and livestock production to meet higher local demand for food (Wang et al. 2021). Many other developing countries find themselves in this category. The study has thus been designed to provide lessons in analytical tool building and evidence to support the design and implementation of multi-objective livestock policies in such countries. Emphasis is placed on demand and production related to terrestrial animals/livestock, i.e., aquatic animals/fish have not been included in the analysis. This is for analytical convenience and follows from livestock being the main focus of current debate on the associations of consumer-led food demand to environmental unsustainability (Willett et al. 2019; ILRI 2019).

Methodology

A three-level integrated modeling framework was developed consisting of the IMPACT, CLEANED-R, and MESH analytical tools (Fig. 1). IMPACT is a global

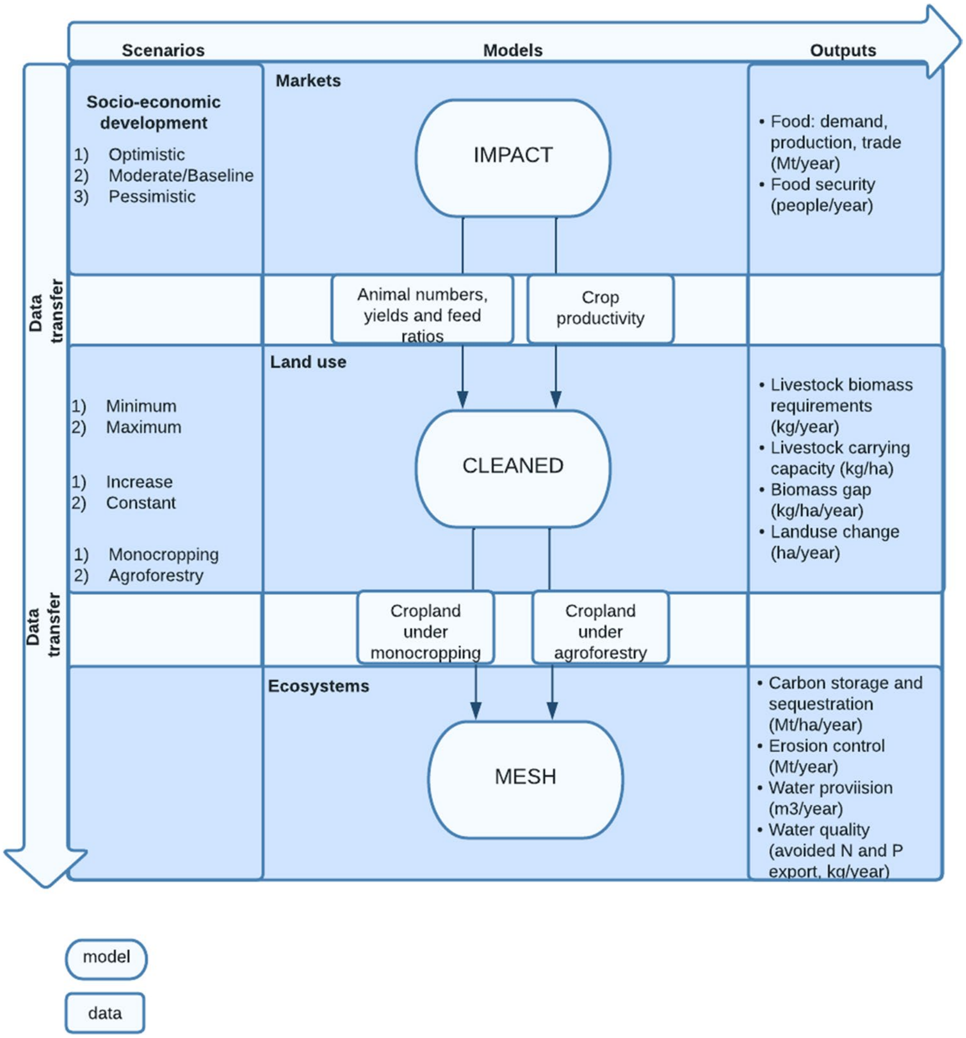

Fig. 1 Overview of the models, scenarios, and key outputs of the integrated assessment framework

economic simulation model used to assess international demand, supply, and trade of agricultural commodities (Robinson et al. 2015). CLEANED-R is an environmental impact assessment model that uses a regional biomass balance approach to compute land use and other environmental impacts of agricultural activity (Pfeifer et al. 2019). The Mapping Ecosystem Services to Human wellbeing (MESH) tool is a platform for simulation of expected changes in ecosystem services such as water provision and quality, resulting from alternative land management scenarios (Johnson et al. 2019). Three scenarios of plausible socioeconomic change affecting livestock demand and production were simulated using IMPACT. These scenarios set the overall context of the assessments. At the second level of the integrated assessment, three types of scenarios, i.e., an agricultural expansion scenario (minimal expansion versus maximal expansion), a crop productivity scenario (no change in productivity versus productivity gains), and a diversification of farming practices scenario (simplified agricultural expansion with crops planted in monocultures versus diversified expansion with crops planted in agroforestry systems) were introduced using CLEANED-R. These scenarios linked the socioeconomic scenarios from IMPACT to their land use change implications. No new scenarios were introduced at the third level of the integrated assessment, where MESH was used to calculate changes in ecosystem service provision associated with the land use change scenarios emerging from CLEANED-R. We report ecosystem service changes associated with six of these land use change scenarios, selected to capture the extremes of the combined socioeconomic, agricultural expansion, crop productivity, and diversification scenarios emerging from IMPACT and CLEANED-R.

This study employed an economic sectoral model approach to generate projections of potential futures under different combinations of economic and climate drivers (Robinson et al. 2015; Islam et al. 2016). The modeling approach (Wiebe et al. 2015; Nelson et al. 2014; Springmann et al. 2018) and specific drivers adopted (Nelson et al. 2010, van Zeist 2020) have previously been validated. The timeframe for this study focuses on a 20-year time horizon to allow for the evolution of underlying driver dynamics to generate a useful outlook for policy planning purposes. Data limitations that arise from a change in the methodology used to compile the FAO's Food Balance Sheet dataset (FAO 2020) restrict the latest available data for use in our modeling framework to the starting year of 2010. The projections generated from 2010 to 2030 are used to inform a 20-year scenario outlook for a "what if" policy analysis that addresses the broader scale magnitude and direction of changes in the future instead of generating precise predictions. Econometric modeling frameworks, for example, could provide more precise predictions but those are more limited in their application to the analysis of alternative future scenarios.

The integration of the models and scenarios was tested in a simulation of the effects of increased ASF demand and production in Tanzania. Given that the country has only a small share of the global market in agricultural and food commodities, the analytical framework adopted the assumption that demand, production, and trade of livestock in Tanzania, as well as policies guiding these outcomes, do not lead to significant impacts on the global market. As such, the analytical framework accounted for impacts in Tanzania of changes occurring at the global level, but not for feedbacks to the global economy from the dynamics of ASF demand and livestock production within Tanzania. In this sense, the model interlinkages went in one direction only. Global scenarios and outputs from the IMPACT model provided input data and scenarios for simulation of land use changes in CLEANED-R, results of which were passed on to MESH to calculate ecosystem services (ESS) provision associated with the land use changes and land management options. Full descriptions of the assumptions, structures, and input and output data of IMPACT, CLEANED-R, and MESH have been published previously (Robinson et al. 2015; Pfeifer et al. 2019; Johnson et al. 2019). Details relevant to this study are presented online in the Supplementary Information (SI) and summarized in the following sections.

IMPACT: simulating demand and production of livestock-derived food

The demand, supply, and international trade of ASF (excluding fish) were simulated for Tanzania using IMPACT, a multi-market model that can generate projections of the global trade of several agricultural commodities, including crops and livestock (Robinson et al. 2015). Demand for agricultural commodities in IMPACT derives from, mostly, assumptions about human population growth, changes in incomes, and consumer preferences (represented by income and price-responsive demand elasticities), while agricultural output responds to prices, technological change, and biophysical factors such as water and climate. IMPACT links information from climate, crop simulation, and hydrology models to a core economic model with a detailed representation of the agricultural sector. For each (crop or livestock) commodity, IMPACT assumes free markets, where prices are determined by relatively unrestricted competition between parties. As such, the model's outputs, including its crop land allocation between food, livestock feed, and other uses, reflect economic or market-based decisions and thus respect the competitiveness of different countries' agricultural production globally. In practice, countries could pursue food security strategies that are inconsistent with the equilibrium solutions that economic models will yield. For example, a country could impose import restrictions to spur its domestic ASF production, regardless of the competitiveness of its livestock sector.

Livestock production is simulated in IMPACT as the product of the numbers of producing (e.g., dairy) or slaughtered (e.g., beef) animals, and average production (e.g., of meat, milk) per animal. Four (4) main types of farm animals are included in the analysis, i.e., cattle, sheep and goats combined, pigs, and chickens. Livestock feed demand is influenced by the levels of livestock production and competes with other uses for harvested crops, such as human food, agro-processing input, and biofuel feedstock. Crop production is specified in the model by land areas allocated to crops, and crop productivity. Supply of crop-based livestock feeds was modeled as comprising of both domestically grown and imported components. Owing to a lack of data, feed sources such as crop residues and grasses are omitted from the IMPACT modeling, although these have been identified as important to include in the livestock sector specification of lower-income countries (Msangi et al. 2014). Demand and production of feed types that are traditionally not traded on international markets were thus simulated in a subsequent step of the integrated model framework (using CLEANED-R) but based on estimates of livestock numbers and production generated from IMPACT.

Scenario simulation using IMPACT

Country-specific and national-level projections of production, demand, and trade of agricultural commodities, including ASF, were generated for three alternative scenarios of global socioeconomic change in 2030. The three scenarios of socioeconomic change represented optimistic, moderate, and pessimistic global economic growth. Our analytical framework relied on scenarios of global economic change previously quantified for the Intergovernmental Panel on Climate Change, IPCC (Riahi et al. 2017). We utilized IPCC scenarios for 2030 that provide a plausible range of conditions for livestock sector transitions. As the primary focus is on changing food demand, this study took into consideration the key factors primarily driving demand for ASF in low- and middle-income countries, i.e., income and population growth (Gouel & Guimbard 2019). Of five narratives on future global trends, commonly referred to as shared socioeconomic pathways (Riahi et al. 2017), we assessed transitions in the demand for ASF in Tanzania under the high income and low population growth (also called optimistic), low income and high population growth (pessimistic), and moderate income and moderate population growth (moderate) scenarios This range of scenarios provides for a balanced view of possible futures for Tanzania.

Estimates of the key parameters of our study's socioeconomic scenarios are presented in SI Table A.1 Within IMPACT, global socioeconomic pathways can be intersected with climate change trajectories called Representative Concentration Pathways or RCPs (Robinson et al. 2015). In this study, the three socioeconomic scenarios, i.e., pessimistic, optimistic, and moderate economic growth, were simulated against the assumption of RCP 6.0 climate. This choice of climate trajectory was based on conditional climate probabilities presented in Engström et al. (2016), while the combinations of socioeconomic and climate change scenarios we used have been prior applied to livestock sector assessments (Enahoro et al. 2018; Springmann et al. 2018).

Outputs from the IMPACT scenarios provided input to the second stage of the integrated analysis, i.e., CLEANED-R, investigating livestock-related land use changes and their environmental impacts. Food security indicators simultaneously derived from IMPACT are described in the SI.

CLEANED-R: simulating livestock production-induced land use

The CLEANED-R tool was originally developed as a framework for assessing the environmental impacts of rapidly evolving livestock value chains in developing regions (Pfeifer et al. 2019). It is a spatially explicit tool for calculating impacts at landscape scale, such as districts or watersheds with user-defined livestock categories, i.e., context-specific animal species and breeds. It has previously been applied to a landscape in Tanzania (Notenbaert et al. 2020). The Tanzania landscape model was adjusted in this study to run at country scale, using livestock production and productivity parameters derived directly from IMPACT model simulation. For this, livestock categories in CLEANED-R (which are user-defined) were matched to the specification of the IMPACT model, namely, dairy cattle, beef cattle, sheep, and goats (combined), pigs, and chickens (for meat and eggs). Furthermore, the input parameters of CLEANED-R were defined to reflect animal numbers, productivity (e.g., kilograms of milk produced per dairy cow), livestock feed ratio (e.g., % planted fodder or agro-industrial by-product typically fed to livestock), and crop productivity (e.g., maize production in metric tons per hectare per year, MT/ha/year) associated with IMPACT's results.

Year 2015 land cover data for Tanzania, from the database of the European Space Agency (ESA) Climate Change Initiative (ESA CCI Land Cover project), was used as the baseline (ESA 2017). This was the most detailed land cover map available at the time of the analysis. The spatial allocation model assigns livestock impact associated to the land from which feed originates. It distinguishes between three feed categories: (1) feed and fodder from arable land (cereals, crop residue, planted fodder), (2) natural feed from grazing land and shrublands, and (3) agro-industrial by-products such as bran or oilseed cakes (concentrates). Whereas agro-industrial by-product is not assigned to any land use, the other two categories are assigned directly to land cover.

Not all of 48 land use classes available, among which are mosaic classes, i.e., classes with mixed crop, grassland, and forests, contribute to feed and fodder production. In addition, each one of the land classes assumed to produce livestock feeds was assumed to make a different level of contribution. As no historical data are available, estimates are typically used that derive from expert best guesses. In this study, all mosaic classes of the land use classes were assumed to contribute only half (of simulated) feed and fodder production. Also, shrubland was assumed to contribute less to grass production than grassland, because as its name will indicate, natural grass in this land class type is woody biomass that is not fully suitable as feed (Estell et al. 2012). Assumed productivity (in MT/ha/year) of biomass is spatially explicit and was taken from the Global Agro-Ecological Zones (GAEZ) data portal (Fischer et al. 2012). The agro-ecological potential productivity of grass for grassland and a weighted average on the feed ratio of actual productivity of cereal and planted fodder were used. The baseline land assigned to livestock and biomass productivity were initially set in the spatial allocation tool to reflect IMPACT's land use and production under the moderate growth scenario in 2010. This created a compatible and consistent land use map to link IMPACT with CLEANED-R and minimized data-related discrepancies in how the different components of the integrated assessment framework are specified.

CLEANED-R computes the livestock *carrying capacity* of an area by calculating the amount of grass, crop residue, and planted fodder that is grown for feed and fodder. This area level feed and fodder supply can be compared to the total biomass that will be required (e.g., to meet projected demand) from livestock production projected for that area. A negative biomass balance would suggest that feed demand surpasses the biomass-carrying capacity of the area. This is referred to as the biomass gap. The additional biomass that will be required to fill the gap, e.g., compared to a base run, can be computed in CLEANED-R. This is a measure indicating how much additional biomass needs to be allocated to livestock production in the area. Furthermore, land use dynamics are driven in CLEANED-R by livestock feed and fodder demand and are computed in a land use change module to generate future land use maps. Parameters of the land use change module can thus be adjusted to assess the environmental impacts of different scenarios of feed demand, production, and management.

Scenario simulation using CLEANED-R

Land use scenarios simulated in CLEANED-R allowed for the analysis to expand beyond the market solutions resulting from IMPACT (Fig. 1). This was made possible by simulating two extremes of land use change, i.e., minimum and maximum, in response to the need to grow additional biomass for livestock production. The maximum land use change scenario incorporates a restriction on imports of livestock products so that expanding domestic production is the only option for meeting national demand for ASF. This flexibility of the framework essentially enforces an objective of ASF self-reliance on the future projections of ASF and associated feed demand. Next, crop productivity scenarios introduced in CLEANED-R allowed for crop production per unit of land to either increase or remain constant relative to the trends underlying IMPACT's socioeconomic scenarios. This scenario accounts partly for the important role that improved feed production technology can play in the supply of feed biomass. It allowed us to explore what happens if crop productivity gains assumed in IMPACT (SI Eqn. A.9) cannot be achieved following, for example, non-adoption of seed or other technologies. Finally, a land management scenario relates to the level of diversity in the agricultural system, with a baseline assumption that new cropland comprises livestock feed (fodder) crops grown in monocropping systems tested against the assumption that these crops are grown in agroforestry systems.

In CLEANED-R, feed biomass demand was calculated for the optimistic economic growth scenario in IMPACT (and its associated implications for domestic production) of ASF, compared to the moderate growth scenario which was assumed the baseline or business-as-usual trend. An initial land use scenario was simulated to assess whether livestock feed biomass gaps generated from a substantially increased demand for ASF (under optimistic conditions) could be met using the current land allocation (i.e., using more of existing cropland to produce feed and fodder, hence at the cost of staple food production). The alternative to this was growing the needed feed biomass on converted land (i.e., converting other land uses to cropland for increased feed and fodder production) so that staple food production could be kept at current levels. These two options represent, respectively, the minimum and maximum rates of simulated livestock-driven land cover change. When restricting the conversion of new land to close the feed biomass gap, there is an implicit assumption that production on land currently under agriculture is adjusted to the need of livestock, and that land used for cereals and other food production can be converted to planted fodder. On the other hand, when all the additional biomass needed for livestock production comes from newly converted land (i.e., land not previously under agriculture), then the current mix of agricultural (crop) production can remain the same. This will lead to a calculation of the maximum amount of land that needs to be newly converted to cropping to support additional livestock production. To calculate these numbers, a *greedy* problem-solving algorithm (Vince 2002) was developed as an add-on to the CLEANED-R tool to solve mathematically for a local optimum. This algorithm defined how much additional land will be needed to meet livestock feed demand, accounting for spatially explicit yields, and for the fact that newly converted land generally has lower biomass productivity than existing croplands (i.e., the more productive lands are used up first).

For the productivity gain simulation, crop yield estimates could either be maintained as is into the future (i.e., no change in crop productivity over time), or they followed growth trends already simulated using IMPACT. As described in the SI (appendix B), technological growth affects agricultural yield in IMPACT and generally corresponds to the socioeconomic change scenarios, i.e., crop yields would increase under optimistic economic growth and are depressed under poor economic outcomes. The farming system scenario centered around the conversion of land for increased feed and fodder production. Selected land types were converted into two distinct types of production, i.e., under monocropping or agroforestry-based management. To do this, different land covers were classified into non-convertible land covers (this included urban area, bare areas, consolidated bare areas, unconsolidated area areas, water bodies, protected areas including in Tanzania forests), and convertible ones (the rest). Each convertible land cover cell on the map was then ranked in order of priority of conversion. Under this rule, areas near already existing cropland are considered more suitable and converted first. This ranking is based on GAEZ suitability layers for crops (Fischer et al. 2012). More details can be found in the SI.

The key difference between monocropping and agroforestry-based conversion was assumed to be in biomass yield for livestock. Although some studies point to positive yield gains of + 12 to + 62% from agroforestry relative to monocropped systems (Beillouin et al. 2021), others indicate yield disadvantages as varied as – 73 to – 3% for agroforestry systems, e.g., depending on shade cover (Blaser et al. 2018). While studies such as Beillouin et al. (2021) that have shown yield advantages of agroforestry systems considered production from all crops in agroforestry systems (i.e., annual crops and harvestable products from trees and shrubs), our own study focuses primarily on fodder crops and the change in yield when producing these in agroforestry versus monocropped systems. Fodder crop yields (primarily maize) under such conditions are likely lower (Sileshi et al. 2008; Musokwa et al. 2019). Given the prevailing uncertainty, our study has taken a precautionary approach, assuming the conservative estimate of a 50% decline in feed crop yields under agroforestry.

MESH: calculating changes in the provision of ecosystem services

In the three-model integration trialed in this study, maps of baseline and alternative scenarios of land use change generated using CLEANED-R were passed on to the integrative ecosystem service modeling tool. MESH is a modeling platform that calculates how ecosystem service supplies are expected to change under alternative land management scenarios (Johnson et al. 2019). The platform integrates Natural Capital Project Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST) ecosystem service models (Ruckelshaus et al. 2013; Tallis & Polasky 2009) and includes several functions that facilitate analysis of multiple scenarios across these models. MESH is an interface through which individual InVEST models can be easily accessed and the same land use scenarios tested across multiple models, but the models do not interact with each other.

Five InVEST ecosystem service models were utilized from MESH (version 0.9), i.e., carbon storage and sequestration, erosion control, water provision, nitrogen export, and phosphorus export (Fig. 1). InVEST models are spatially explicit, using mapped land use, topography, climatic data, erosivity, and other mapped environmental variables as information sources, and producing maps of ecosystem service provision as outputs. The spatial scale of the output maps is dependent on the resolution of the user-provided input maps, though use of pixel-level results is discouraged in favor of aggregation to watershed level to match model assumptions. The models are based on production functions that define how changes in an ecosystem's structure are likely to affect the flows and values of ecosystem services across a landscape or seascape.

MESH users must set parameters relevant to each land use class (and some independent of land use class) to calibrate the models to local conditions. MESH comes with a set of literature-based suggested parameter values for many land-use classes (SI section C). In ecosystem service modeling to date, the effects of cropland on ecosystem functions are commonly treated as uniform, while, in reality, environmental outcomes can vary significantly with farm management including level of farm diversity (Beillouin et al. 2019; Kremen et al. 2012; Kremen & Miles 2012). For this MESH application, we sought to distinguish between crops grown in monocropping systems and crops grown in agroforestry/silvopastoral systems. Details of InVEST and the parameter values of our study are presented in SI (appendix Table C.2).

Results

Throughout, results of the optimistic demand scenario, which leads to higher ASF demand and to substantial livestock-induced land use change, are discussed. These are compared to the moderate scenario. Results emerging from the pessimistic scenario in IMPACT have not been discussed, as this scenario proved redundant for the rest of our study. It does not lead to land use expansions that require land management practices to mitigate production-related losses to ecosystem services.

Animal-source food demand and food security

For the moderate economic growth scenario, human population in Tanzania was projected to increase by 63% in 2030, over 2010 figures, while per capita income increased by 133% over the same period. Projected annual income in 2030 was $2928 under the moderate scenario and 15% higher for the optimistic growth scenario (SI Table A.2). The resulting impacts of the socioeconomic changes on ASF demand (and production) were significant. The results on projected ASF demand are not discussed in detail here; the key points to note being that (1) projected estimates of milk and meat demand are close to 100% (or higher) under all three socioeconomic scenarios in 2030 compared to 2010, (2) the optimistic scenario leads to higher growth in ASF demand (than the moderate scenario) and, (3) compared to the baseline, the optimistic scenario has the highest positive impacts on the country's food security outlook to 2030.

Changes in ASF demand drive livestock-specific changes in production and have consequences for land use and environmental impacts. Under moderate growth, national production of milk and beef (as well as poultry) is projected to increase in 2030 compared to 2010, by 50% to more than 100%. This significant expansion in livestock production is accompanied by increases in animal numbers. The model's projections of technology-induced crop productivity gains as well as its market-driven specification led to the higher demand for ASF being met mainly through increased ASF imports. According to IMPACT's market equilibrium solution, the additional biomass quantities needed to support increased demand for ASF will not vary by much domestically, since most of the additional demand for ASF is satisfied through imports. This result holds under all scenarios such that 29% more milk and meat animals are projected for 2030 compared to 2010. Between them, projected estimates of animal numbers in 2030 differed by less than 2% under the alternative socioeconomic scenarios. Feed demand quantities thus increase substantially (for all three socioeconomic scenarios) between 2010 and 2030, but only minimally across the scenarios in 2030. We used the IMPACT estimates from the optimistic scenario in the subsequent assessments of biomass changes and land management.

Livestock-induced biomass balances

CLEANED-R simulation demonstrated that significantly higher production of biomass will be required for an alternative situation on imports, i.e., if increased demand for ASF is satisfied only through domestic production (Table 1). This scenario reflects an ASF self-reliance objective and corresponds to a maximum land expansion situation. In combination with a "no crop productivity gain" assumption, the optimistic scenario leads to a 21.4% increase in biomass production (compared to 20.3% under moderate growth). The amount of land that needs to be converted to produce this additional feed biomass was shown to depend on the level of diversification of new agricultural land, i.e., whether converted land was under monocropping or agroforestry. For example, with the assumption of maximum land expansion for ASF production, and no gains assumed in crop productivity, the land area needed will almost double under agroforestry (i.e., bringing an additional 15,178 km^2 of cropland into feed production) compared to an additional cropland of 7614 km^2 under monocropping. The results thus indicated a non-linear relationship in that effective land use expansion required to meet biomass needs under agroforestry was less than double for an assumption of 50% feed yield loss for agroforestry systems.

Simulations using CLEANED-R showed that, depending on the scenario (i.e., moderate, or optimistic) and the land management rule (i.e., monocropping or agroforestry), between 1254 and 2885 km^2 of additional land will need to be converted into cropland. This holds if there are no gains in crop productivity to 2030, and under the scenario of minimum land expansion that allows free inflow of ASF imports into Tanzania to meet increased ASF demand.

Provision of ecosystem services

With zero land expansion, highly productive, monocropped land will present the best option for preventing ecosystem service losses. This holds since no new cropland enters production, and ecosystem services are highest in natural ecosystems. With even minimal agricultural land expansion, however, future supplies of ecosystem services are shown to decrease, i.e., except for small increases in water provision nationally (Fig. 2). The severity of negative consequences of agricultural land expansion depends mainly on the role of ASF imports in meeting the domestic demand for ASF (i.e., minimum, or maximum land expansion), but also on whether there are gains in the unit production of biomass (i.e., crop productivity increases or is constant). The scenario denoting crop productivity gain and diversified farming is seen to represent the best scenario for reducing ecosystem service losses under agricultural land expansion. The scenario of maximum land expansion (to accommodate an

Table 1 Land use change in 2030 (compared to the base year) computed for three IMPACT scenarios

IMPACT Scenarios of socio-economic change	Crop productivity, land expansion and production system scenarios*	Productivity gain, maximum land expansion & mono culture	Productivity gain, maximum land expansion & agro forestry	No productivity gain, Minimum land expansion & monoculture	No productivity gain, Minimum land expansion & agro forestry	No productivity gain, Maximum land expansion & monoculture	No productivity gain, Maximum land expansion & agro forestry
Moderate	% biomass change	20.3%	20.3%	3.1%	3.1%	20.3%	20.3%
	new cropland (km^2)	6,362	12,708	1,254	2,380	7,614	15,178
Optimistic	% biomass change	21.4%	21.4%	3.7%	3.7%	21.4%	21.4%
	new cropland (km^2)	6,810	13,588	1,508	2,885	8,123	16,186
Pessimistic	% biomass change	19.2%	19.2%	2.2%	2.2%	19.2%	19.2%
	new cropland (km^2)	5,990	11,970	933	1,765	7,153	14,268

Source: Authors' derivations from the integrated model simulations

*The productivity gain, minimum land expansion & monoculture/agroforestry scenarios represent the baseline against which other land use or management scenarios are compared and are not included in the table

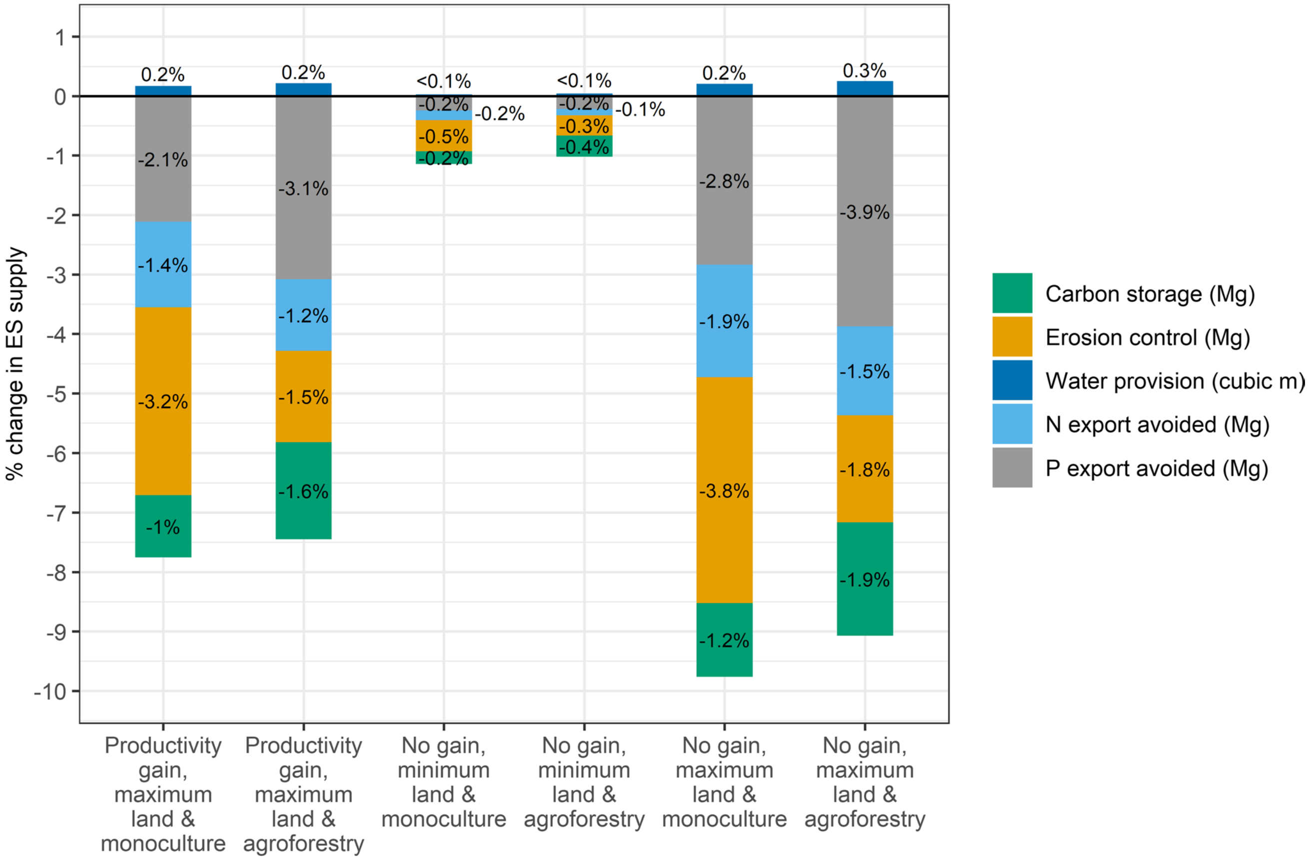

Fig. 2 Percentage changes in supply of five ecosystem services for six scenarios of combinations of crop productivity increase, land expansion, and crop production system in 2030

ASF self-reliance objective), constant/no crop productivity gain, and monoculture, appears to be the worst.

Across all scenarios, the greatest estimated losses to ecosystem services are with respect to phosphorus retention and erosion control, with 0.2–3.9% more phosphorus expected to be exported and 0.3–3.8% more sediment eroded into streamways across Tanzania. Compared to the baseline, an estimated 0.1–1.9% more nitrogen will be exported under the scenarios emanating from optimistic economic growth. The associated increase in phosphorus, nitrogen, and sediment in runoff would have a negative impact on water quality in areas downstream of the agricultural expansion.

Compared to the baseline, carbon storage is expected to decline, by 0.2 to 1.9%. This equates to 43.6 Mt less carbon storage under the maximum land expansion, and monocropping scenarios compared to the baseline, or 389.3 Mt less under maximum land expansion, and agroforestry. The anticipated loss in carbon storage, which will translate into higher net national carbon emissions in the absence of substantial mitigation actions, conflicts with Tanzania's pledge to be carbon neutral by 2050 (carbon–neutral-goals-by-country). An increase in water yield of less than 0.3% is expected across all scenarios. This reflects that most of the agricultural expansion occurs in mosaic cropland-natural vegetation class which is assumed to have levels of consumptive water use on par with agroforestry and a little lower than monocropping, effectively cancelling out the effects of land use change on consumptive water use.

Widescale adoption of agroforestry instead of monocropping drives a doubling of the agricultural expansion area with, relative to monocropping under each scenario pair, an increase of up to 0.5% in water provision, 2% in soil erosion control, and 0.4% nitrogen export avoided, but a decrease of up to 0.7% in carbon storage and 1% in phosphorus export avoided. The small differences between ecosystem service changes mean that adding trees to maize production in agroforestry systems effectively halves the impact of agricultural land on carbon storage, erosion control, water provision, and nutrient balances, compared to monocropping systems (the impacts on ecosystem services are similar under monocropping and agroforestry, despite the latter covering double the land area), with no losses to food provision (the same amount of food is provided in both systems under each scenario).

Discussion

Application of the integrated assessment to Tanzania indicated that population and income-based increases in the demand and supply of meat and milk will contribute to improved food security in the country in 2030, but with possible substantial losses in carbon storage, phosphorus and nutrient retention, soil erosion control, and water provision services. Increased livestock and crop productivity as well as higher imports to meet growth in demand dampen the localized effects of ASF demand expansion on land use and ecosystem services provision. Without reasonable gains in crop productivity, however, and in view of expected higher demand for cereals in the future, there will be competing claims on arable land and new land conversion into agriculture. Alternatively, depending on which one of cereals or ASF are more profitable to produce locally, increased importation of one or the other could take place. Increasing the imports of cereals could allow local farmers, the majority of whom currently are smallholders, to produce more ASF that are often more profitable. Importing livestock food products, on the other hand, will allow for a reduced environmental footprint of livestock production in Tanzania. Both cases raise the need for regulatory mechanisms that support the sustainable management of food production more globally.

Given that natural ecosystems have the highest supply of ecosystem services, a case of zero agricultural land expansion will lead to monocropping (contrary to expected) faring better than agroforestry for the supply of ecosystem services, i.e., if the monocropped land is highly productive for biomass production. In our study that assumes minimal to maximum land expansion will occur, this result is largely driven by the assumption that double the land area is needed to produce the same amount of fodder, when expanded feed production is undertaken in agroforestry compared to monoculture systems. In essence, the loss of ecosystem services provision per unit land area can be halved by incorporation of trees into maize and fodder production systems (agroforestry) but would require double the agricultural land expansion to meet future ASF demands. Traditional agroforestry systems have a long history in Tanzania where they imitate natural ecosystems with a mixture of annual and perennial plants (Kitalyi et al. 2010). The benefits of such systems over monocropping could be substantial if yields on agroforestry can be brought to levels comparable with monocropping systems, which the latest evidence suggests is feasible in many contexts (Beillouin et al. 2021). While arable crop yields are reported to decrease in African agroforestry systems (between − 100 and − 11%) (Félix et al. 2018; Staton et al. 2022), there is an expanding body of evidence showing that yields in agroforestry can be comparable or only slightly lower than those in monocropping and are generally higher when harvestable produce from tree products is included in the calculation (Niether et al. 2020; Castle et al. 2021). Future work could thus include fodder trees in the feed biomass and land management options. Policy interventions will likely be needed to incentivize and support farmers to adopt such diversified farming practices, as there may be institutional, social, and technical constraints to adoption (Schroth & Ruf 2014). Fodder trees are important feed sources but are currently not widely adopted by farmers (Franzel et al. 2014; Balehegn et al. 2020).

Under all agricultural expansion scenarios modeled, the largest expected losses in future ecosystem services related to increased ASF demand are to nutrient retention and soil erosion control services, but losses to carbon storage may also be substantial while there may be negligible gains in water provision. The differences between changes in phosphorus and nitrogen exports under each scenario are likely driven by the assumption that, while the retention efficiency of vegetation is the same across the two nutrients, 25% (under monocropping) or 50% (under agroforestry) nitrogen in runoff does not reach the streamway and is instead dissolved into groundwater. All phosphorus in runoff is assumed to reach the streamway (since phosphorus particles are less likely to dissolve and infiltrate subsurface flows). While agroforestry lessens the negative impact of agricultural expansion on ecosystem services, the results demonstrate that the most effective measure is to minimize expansion consistent with global studies (Zabel et al. 2019). Even under a low expansion scenario, without a shift in demand for ASF, the consequences of expansion are simply offset to another country, suggesting that dietary changes will need to be considered to minimize expansion while ensuring that all people everywhere have adequate nutrition (Tilman & Clark 2014; Willett et al. 2019).

Our assessment of ecosystem services was conducted using the MESH modeling interface which incorporates relatively simple biophysical models (InVEST models). While InVEST models are useful to gain insights on the direction of change and relative performance of different scenarios, they have some limitations. In particular, InVEST models are parameterized at the land cover level, and regional differences in ecological or agronomic factors are not considered. For example, fertilization rates have been assumed constant for each specific agricultural land cover class across the country, yet these can vary quite broadly across landscapes (Ricker-Gilbert 2020). It is more likely that inputs are not very accessible in areas recently converted to arable land. Also, potential benefits from rotational grazing of livestock in arid or semi-arid grassland in maintaining the C, N, and P cycles (Li et al. 2020; Teague & Kreuter 2020) are omitted. Some of these challenges could be overcome through local expert consultations in future research to develop robust actionable recommendations for policymakers, for example, to improve the agricultural expansion scenarios, productivity estimates, and model parametrization. It would also be beneficial to apply more complex hydrological and land systems models to improve the estimations for ecosystem services that are of most interest to decision makers in Tanzania.

In addition, quantitative models that account for the synergies between agriculture and biodiversity are still largely underdeveloped. This hampers the potential to understand how livestock can be a catalyst to closing ecological cycles (Dumont et al. 2013) and to enhancing ecosystem service provision. What the approach presented in this paper has allowed for is the exploring of the potential effects of livestock production systems on future provisioning of ecosystem services, within the context of narratives of intensification and efficiency. To support the development of livestock production systems that are more sustainable and resilient, there is also the need to simulate, explore, and assess the linkages of related industrial and agro-ecology practices to ecosystem services provision. This would require model suites that are ecological process–based rather than reliant on expert-generated parameters (Wolff et al. 2015).

Conclusions

This study presents a novel approach to integrating quantitative foresight and ex-ante impact modeling tools to assess the implications for food security, land use, and ecosystem services provision of an expanding demand for ASF. Its application to Tanzania that linked scenarios of global socioeconomic change to ASF demand, livestock production and their impacts on land use, has quantified important trade-offs between human nutrition and food security gains, and future losses in the provisioning of ecosystem services. Our results indicate there is high potential for strong trade-offs between objectives of food security, climate mitigation, land degradation, and freshwater conservation, from anticipated transitions in food and land use systems in Tanzania driven by increased demand for ASF. These trade-offs need to be better analyzed, anticipated, and managed to keep countries such as Tanzania on track to achieve Sustainable Development Goals and Paris Agreement targets. A key result emerging from this study is that additional interventions will be needed to incentivize or support farmers to adopt agroforestry practices, which have benefits over monoculture crop production for maintaining the sustainability of food production. Furthermore, increased productivity of crop and livestock can benefit ecosystem services provisions universally while higher imports of animal-source foods or livestock feed provide only localized benefits in the current context. While the insights and further research questions that emerge are interesting from both academic and policy perspectives, further methodological improvement will be required. There is in addition a dearth of observational data to inform more precise estimates of key parameters that drive outcomes in the models used, such as the contributions of different land use classes to feed and fodder production, and the yield gains/losses associated with monocropped compared with agroforestry systems. Future assessments could in addition seek to account for several other farm management factors such as tillage, agrochemical applications, irrigation management, and a diversity of livestock feed technologies, which can have significant effects on the provision of soil and water related ecosystem services.

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Data Availability Descriptions of the IMPACT, CLEANED-R, and MESH model versions and data used in this study are available in the Supplementary Information (https://doi.org/10.1007/s10113-023-02038-x). The model assumptions underlying IMPACT are available open access in GitHub (https://github.com/IFPRI/IMPACT) as are details of the CLEANED-R Model (https://github.com/ilri/CLEANED-R). MESH is free to download (https://naturalcapitalproject.stanford.edu/software/mesh) and comprehensive documentation on the InVEST models integrated into MESH and used in this analysis are available from the Natural Capital Project (https://naturalcapitalproject.stanford.edu/invest). The specific input and output data for the three-model integrated framework in this study are posted to a special studies folder on GitHub (IMPACT/DriverAssumptions/Special_Studies at master · IFPRI/IMPACT · GitHub).

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