



Systems methods for analyzing trade-offs between food security and conserving biodiversity

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Abstract

The endeavor for greater food security has caused trade-offs between increasing agricultural production and conserving habitat of threatened species. We take a novel approach to analyze these trade-offs by applying and comparing three systems methods (systems diagrams, influence matrices, and land use modeling) in a case study of Uganda. The first two methods were used to scope out the trade-off system and identify the most important variables influencing trade-offs. These variables were agricultural yield, land governance processes, and change in land use and land cover. The third method was used to quantify trade-offs and evaluate policy scenarios to alleviate them. A reference scenario indicated that increasing agricultural production by expanding agricultural land provided food for 79% more people in 2050 (compared to 2005) but with a 48% loss of habitat of threatened species. A scenario assuming strong investments to augment agricultural yield increased the number of people fed in 2050 up to 157%, while reducing the loss of habitat down to 27%. We use a novel “trade-off coefficient” for a consistent comparison of scenario results. A scenario assuming yield improvement and ring-fencing protected areas reduced the trade-off coefficient from -0.62 in the reference case to -0.15 . This coefficient can be used as a common basis to compare results from different trade-off studies. It was found that the three systems methods are useful, but have limitations as stand-alone tools. Combining the methods into a single methodology increases their collective utility by maximizing the transparency and comprehensiveness and potential stakeholder engagement of a trade-off analysis.

Keywords Systems approach · Systems diagram · Influence matrix · Land use modeling · Trade-off coefficient · Trade-offs between SDGs

1 Introduction

The goal of alleviating hunger and providing adequate and nutritious food to billions frequently comes into conflict with conserving the diversity, viability, and extent of natural ecosystems. The main cause of this conflict—the expansion of agricultural land onto habitat of threatened species—is documented in an extensive literature from both a global

perspective (Alcamo et al. 1994; Foley et al. 2011; Meyfroidt et al. 2013; Newbold et al. 2015; Oakley und Bicknell 2022; Schwarzmüller und Kastner 2022) and regional perspective (van Soesbergen et al. 2017; Mwanjalolo et al. 2018; Sharma et al. 2018; Göpel et al. 2020; Guerrero-Pineda et al. 2022). Among other implications, this trade-off is making it difficult, in principle, to simultaneously achieve Target 2.1 of the Sustainable Development Goals (“end hunger and ensure access by all people ... to safe, nutritious and sufficient food all year round”) and Target 15.5 (“take urgent ... action to ... prevent the extinction of threatened species”).

Various methods have been used to analyze trade-offs between food security and biodiversity conservation. Hanspach et al. (2017) used expert surveys to collect data about trade-offs on the farming landscape level, and analyzed the collected data with non-linear principal component analysis. Delzeit et al. (2017) used a coupled modeling exercise consisting of a global economic model for calculating future food production, a crop suitability model for assessing likely

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locations of new cropland, and a statistical analysis relating land use with species endemism. Gabriel et al. (2013) used statistical analysis to understand the relationship between species abundance/density and crop yield for different types of agriculture in a region of England. Schwarzmüller und Kastner (2022) used bilateral trade statistics to assess consumption-based impacts of agricultural trade on national Species Habitat Indices. These examples illustrate the wide variety of approaches that have been taken to investigate trade-offs. But a gap in this research has been the use of a systems approach to identify and understand the underlying factors that influence trade-offs. By “systems approach” we mean the methodologies developed by Churchman (1968) and others for investigating the functioning of a system by identifying its components and how they interact. In this paper we show that the systems approach provides a vehicle for systematically analyzing the contributing factors to a trade-off and their relative influence. Understanding these factors, in turn, enables analysts to identify policies and measures to minimize or avoid trade-offs.

The objective of this paper is to investigate the utility of a systems approach to analyze trade-offs, using the example of trade-offs between food security and conserving biodiversity.

Several methods fall under the rubric of a systems approach. In this paper we take a novel approach and apply and compare three different systems methods: systems diagrams, influence matrices and land use modeling. These are selected because they represent a variety of complexities and approaches. By using and comparing these three different methods we identify their potentials and limitations. This work will provide insights into the utility of these methods for understanding trade-offs between food security and conserving biodiversity, and will conceivably have applications to the analysis of other large-scale and complex trade-offs. We note that one of these methods, land use modeling, has already been used in various trade-off studies (Fohrer et al. 2002; Lapola et al. 2010; Asadolahi et al. 2018; Hinz et al. 2020; Ji et al. 2021). However, the utility of land use modeling has not been compared to the utility of other systems methods as is done in this paper.

What exactly is a trade-off? In the context of the SDGs, a “trade-off” has been defined as a condition by which an action to achieve one goal or target makes it more difficult to achieve one or more other goals or their underlying targets (Alcamo et al. 2020). From the perspective of systems science, we propose that a “trade-off” is a positive change in one variable that leads to a negative change in another. “Positive” and “negative” are normative in this context, and must be clarified before a trade-off can be assessed. For example, in this paper we are concerned with trade-offs between providing food for people (positive) and losing habitat of threatened species (negative).

2 Methods

2.1 The case study

We select Uganda as a case study because its economic and ecological conditions already leads to strong competition for land and a trade-off between achieving food security and conserving biodiversity. Food insecurity related to poverty is endemic. Data show that around 37.8% of the population live on less than US\$1.25 per day, and 14.1% of children under the age of five are malnourished (World Bank 2015). Uganda, as many other nations, aims for food security by increasing its own agricultural production. Currently this production is dominated by smallholders, of which only 2% use mineral fertilizers (Kaizzi et al. 2012). Because of the low fertilizer application rates, Uganda has one of the highest average soil N depletion rates and lowest crop yields in the world (Namazzi 2008). Low yield and increasing food demand from a rapidly growing population (3.3% per annum in year 2013; World Bank (2015)) have driven a continuous expansion of agricultural land onto natural habitats (World Bank 2015). This expansion is the most important threat to natural ecosystems and biodiversity in Uganda (Mwanjalolo et al. 2018). Nevertheless, Uganda still ranks among the top 10 most biodiverse countries (CBD 2015). On its relatively small territory, it supports the highest species richness per unit area of all African countries (Plumptre et al. 2019).

Vervoort et al. (2013) estimate that national food demand in Uganda will continue to grow over the coming decades. This is likely to cause further expansion and intensification of agriculture in the country and further threats to natural ecosystems (van Soesbergen et al. 2017) and habitat of threatened species. Hence, minimizing trade-offs between increasing food security and conserving biodiversity is a key challenge for the country.

2.2 Metrics for food security and conservation of biodiversity

In the context of a trade-off analysis, we propose the following metrics to describe food security and conservation of biodiversity: For food security we use “number of people fed with an adequate diet from domestic agricultural production.” This metric addresses the issue of “food availability” which is one of four dimensions of food security articulated by (FAO 2006) and the World Food Conference (FAO 2009). The other dimensions are “access,” “utilization,” and “stability.” Although all four dimensions are important, we argue that “food availability” is a prerequisite of the other three and will have a particular impact

on biodiversity conservation. The mentioned references define food availability as “the availability of sufficient quantities of food of appropriate quality, supplied through domestic production or imports (including food aid).” This paper focuses on “domestic agricultural production” rather than food imports because it is expected that local production will have the largest direct impact on biodiversity in Uganda (an exception might be some hunting practices that endanger species). Food imports to Uganda may have an impact on biodiversity in the food exporting country, but these are not accounted for in this paper.

The metric used here for conservation of biodiversity is “cumulative habitat of threatened species.” This is calculated by summing up the areas occupied by particular species, including overlapping areas. For example, if two threatened species occupy the same hectare of habitat, then the cumulative habitat of threatened species is two hectares. Hence, this metric assigns greater biodiversity importance to areas containing several threatened species. This metric emphasizes the importance of habitat area in ensuring conservation of species which is consistent with current thinking in conservation. For example, the IUCN Red List of Threatened Species uses habitat area as an essential criterion for estimating species extinction risk (Gupta et al. 2020).

These metrics are used by all systems methods presented below to evaluate the trade-offs between food security and conservation of biodiversity.

2.3 Systems diagram

A systems diagram is a technique for visualizing the content, structure, and working of a system. The elements of a system are expressed with words and/or a box or other graphical symbol, and connections between elements with lines and/or arrows. Among the earliest and best known systems diagrams were those used to depict multi-sector global systems (Forrester 1969; Meadows et al. 1972). These or similar diagrams have had numerous applications in various fields of inquiry under the names of “cognitive maps,” “causal loop diagrams,” and “digraphs” (Jeffries 1974; Klein und Cooper 1982; Morecroft 1982).

In this study, we apply a “stock and flow diagram,” which is a specific type within the more general systems diagram methodology. The main steps in drawing such a systems diagram are to specify the stocks (state variables), flows (rates of change), and influencing variables of the system. In the example in Fig. 1, we enclose key stock and influencing variables in boxes. Other influencing variables are associated with arrows which indicate the direction of their impact. Arrows indicate either a positive or negative influence. Arrows are also used to specify the direction of impact of stock variables. The hourglass symbolizes the flow rate of a variable, and double arrows with an hourglass symbol

are used to depict particularly significant flows. Variables near clouds represent either sources or sinks of the adjacent variables. (In Fig. 1 clouds are only used to represent sinks.)

2.4 Influence matrix

An influence matrix expresses the influence of each member of a set of variables on each member of another set of variables, or the cross influence of each member of a set of variables on all other members of the set. An early example of the first kind is given by (Leopold 1971) who used a matrix to evaluate the impacts of different aspects of a project (e.g., building sites, building materials, transportation corridors) on different aspects of the local environment (e.g., water quality, soil quality, and vegetation). An early example of the second kind is from Gordon und Hayward (1968) who proposed a general method for using an influence matrix to depict the influence of one set of events on the same set of events and applied it to both Cold War military events and to developments in the transportation industry. In the literature influence matrices are also called “cross-impact matrices” (Gordon und Hayward 1968) or “cross-impact balances” (Weimer-Jehle 2006).

A typical influence matrix lists a set of variables in its first column and a duplicate or second set in its first row. The boxes between them are used to score the influence of one variable on another. The variables and scores are selected by experts and/or stakeholders.

Different approaches have been used in the literature to score the influence of one variable on another. Sometimes a minus or plus are used to indicate the direction of influence. A zero or one are sometimes used to indicate an insignificant or significant influence, respectively. Numerical grading systems are also common; Fig. 2 uses a three point grading system, from 0 to +3. Zero indicates no influence, and three the largest influence.

One way to make the specification of variables more transparent and consistent is to use variables from a systems map. For example, Fig. 2 uses many of the state variables from the systems diagram in Fig. 1.

2.5 Land use modeling

Land use models present dynamic representations of the social, economic, and ecological subsystems that influence land use changes and explore the interactions and feedbacks among them (Voigt und Troy 2008).

In our application we use the LandSHIFT land use/cover change model (Schaldach et al. 2011) to compute land use changes stemming from assumptions about the future agricultural system in Uganda. LandSHIFT is dynamic, spatially explicit, and rule-based, and has been used to simulate various aspects of land use change in West Africa (Heubes et al.

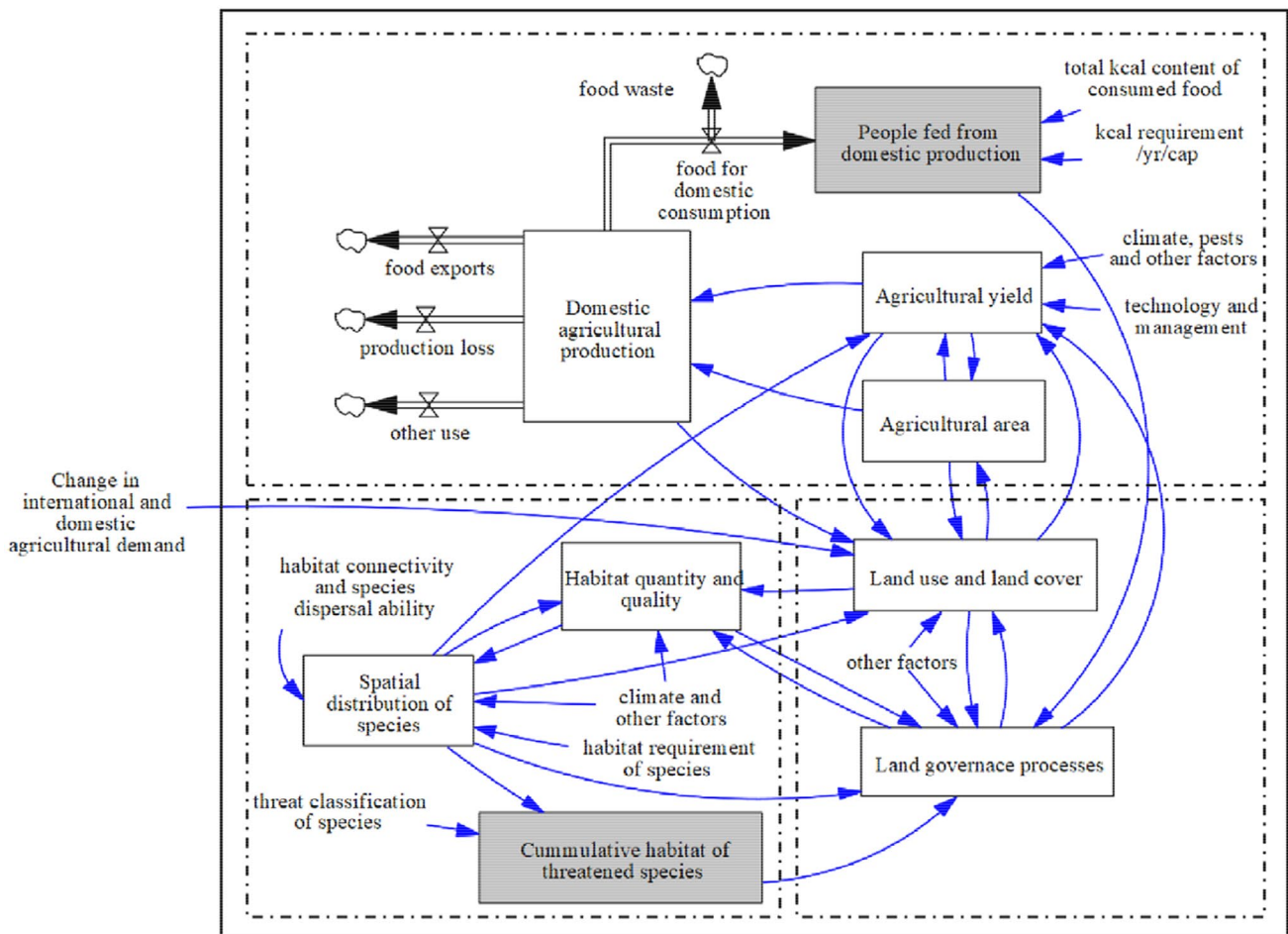


Fig. 1 Simplified systems diagram (i.e., stock and flow diagram) of trade-offs between food security and conservation of biodiversity for the Uganda case study. The dashed lines delineate the following sub-systems: (i) Food (upper half), Biodiversity (lower left) and (iii)

Land (lower right). Key stock and influencing variables are enclosed in boxes. The two boxes with gray shading are the two main trade-off variables. Double arrows indicate the physical flows associated with domestic agricultural production. Used software: Vensim PLE×32

2013), East Africa (van Soesbergen et al. 2017), and over the entire African continent (Alcamo et al. 2011), as well globally (Schüngel et al. 2022) and in other world regions (Göpel et al. 2020; Hinz et al. 2020). Information about LandSHIFT is given in Supplementary Information and in the previously mentioned references. The present modeling analysis builds on an earlier analysis of East Africa (van Soesbergen et al. 2017) co-authored by one of the present authors (Stuch). In the present study LandSHIFT parameter inputs and other settings are adjusted to match Ugandan characteristics, e.g., the mosaic character of cropland (see Supplementary Information).

LandSHIFT is used to calculate the change in land use due to increases in domestic food production for 2030 and 2050, and for a base year, 2005. Four scenarios are investigated—a reference case plus three policy scenarios (Fig. 3).

Scenario A is a reference case in which neither policy is implemented. Nevertheless the agricultural system

continues to evolve due to population growth, trading arrangements, and other socio-economic factors. Assumptions for domestic food production and yield used to compute this scenario are given in Supplementary Information. These data come from food scenarios for eastern African countries developed jointly by the climate change agriculture and food security programme (CCAFS) and the international food policy institute (IFPRI) (Vervoort et al. 2013). (Referred to hereafter as the “IFPRI” scenarios.) The IFPRI scenarios were developed in two steps. First, qualitative versions of the scenarios were derived by eastern African stakeholders and CCAFS experts at a series of workshops. Next, the qualitative scenarios were quantified using a partial equilibrium multi-market economic model (Rosegrant et al. 2012). The economic model takes into account both national and global aspects of agricultural markets including food trade and the interaction between supply and demand under climate change conditions. The

Fig. 2 Example of an influence matrix containing key variables influencing the trade-offs between food security and conservation of biodiversity in the case study

Key variables	1	2	3	4	5	6	7	8	9	Active sum
1 People fed from domestic production	-	0	0	0	0	0	2	0	0	2
2 Cumulative habitat of threatened species	0	-	0	0	0	0	2	0	0	2
3 Domestic agriculture production	3	0	-	0	0	1	0	0	0	4
4 Agricultural yield	0	0	3	-	3	2	0	0	0	8
5 Agricultural area	0	0	3	1	-	3	0	0	0	7
6 Land use and land cover change	0	0	0	3	3	-	1	3	0	10
7 Land governance processes	0	0	0	2	0	3	-	2	0	7
8 Habitat quantity and quality	0	0	0	0	0	0	1	-	3	4
9 Spatial distribution of species	0	3	0	1	0	2	1	1	-	8
Passive sum	3	3	6	7	6	11	7	6	3	

IFPRI scenarios are country-scale and are converted to grid-scale information by the LandSHIFT model. We apply the IFPRI “industrial ants” scenario to include the respective future agricultural market conditions for investigating the four policy options of scenarios A-D (Fig. 3). The IFPRI scenario assumes population growth based on projections from (UN 2015). Key scenario characteristics to drive the LandSHIFT land use change simulation from 2005 to 2050 (in 5 year time-steps) are population growth (+167%), increase in total agriculture production (+181%) and crop yield changes due to technology and management improvements (e.g., +71% for cassava, +100% for maize, and +127% for sorghum). Further information about the IFPRI scenarios is given in Supplementary Information and Vervoort et al. (2013).

To convert domestic agricultural production (crop and livestock) from the policy scenarios to “number of people fed with an adequate diet from domestic agricultural production” we assume an average dietary consumption of 2238 kcal per person in Sub-Saharan Africa based on (FAO 2015). We do not take into account the unfortunate fact that the unequal distribution of food may still result in some people being malnourished.

To compute the biodiversity conservation metric—“cumulative habitat of threatened species”—we take habitat area data from the IUCN Red List (IUCN 2013)

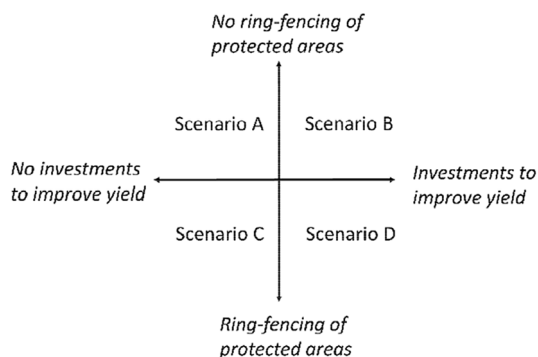


Fig. 3 Sketch of policy assumptions of scenarios

for *aves* (birds), *amphibia* (amphibians), and *mammalia* (mammals). These areas are filtered to include only those listed as extant or probably extant, and native or reintroduced. For each of these species, IUCN habitat preferences (IUCN 2013) are compiled. These compiled habitat preferences are linked to suitable land cover categories (LCC) used in LandSHIFT using a crosswalk table. This table links the standard global land cover database (GLC2000; Bartholomé und Belward 2005) with the IUCN habitat classification scheme based on Foden et al. (2013). A species is counted as present in a given grid cell if its range encompasses any part of that grid cell and if the LCC is suitable for that species.

Scenarios B, C, and D have the same agricultural assumptions as Scenario A, but also assume that one or both policies—increasing crop yield or ring-fencing protected areas—are implemented (see Fig. 3).

To provide a consistent basis for comparing trade-offs of different scenarios we introduce a “trade-off coefficient,” *toff*, defined as:

$$toff = \frac{A'_t}{P'_t} \tag{1}$$

where A'_t = normalized deviation of habitat area at time t from its value in the base year t_0 , i.e.,

$$A'_t = \frac{A_t - A_{t_0}}{A_{t_0}}$$

and P'_t = the normalized deviation of number of people fed, i.e.,

$$P'_t = \frac{P_t - P_{t_0}}{P_{t_0}}$$

In this particular application A'_t is put into the numerator of (1) in order to estimate the trade-off in habitat that stems from an increase in number of people fed. Since P'_t is always positive in the present analysis, a negative value of A'_t gives a negative value of *toff*, with the more negative the number, the greater the trade-off.

Note, that A'_i can also, in principle, take a positive value, in which case $toff$ is positive, indicating a synergy rather than a trade-off between food security and conservation of biodiversity. The larger this positive number, the larger the synergy between increasing habitat relative to increasing number of people fed. However, in our particular application all computed values of A'_i are negative, indicating that (for these particular scenarios) the increase in agricultural production causes a decrease in habitat area, and therefore, a trade-off.

Numerically, a negative value of $toff$ indicates the percentage decrease in habitat per 100% increase in people fed. For example the value of -0.62 for Scenario A in 2050 indicates a proportional 62% decrease in habitat for every 100% increase in people fed. (In this particular example the number of people fed under Scenario A increased by only 78.8% which corresponded to a decrease in habitat of 48.5%.)

We note that expressing trade-offs in the form of coefficients assumes that they occur linearly over time. This, however, is not necessarily the case. In reality, changes in food production and loss of habitat are likely to occur at different tempos over time.

3 Results

3.1 Systems diagram

An example of a simplified systems diagram for the trade-offs between food security and conserving biodiversity is shown in Fig. 1. Such a diagram facilitates understanding of trade-offs in a number of ways. First, the process of deciding which variables to include, or not, in the diagram is equivalent to deciding on the boundaries of a system. Likewise, this selection process is a method for collecting factors that may influence trade-offs. Secondly, it depicts connections between variables and therefore has the potential to provide insights into the pathways of cause and effect that lead to trade-offs. For example, Fig. 1 implies that increasing domestic food production makes more food available and more people can be fed from this production (all other factors being equal). At the same time, however, the increase in domestic production increases land requirements for agriculture, which drives land use and land cover change and reduces habitat quantity and quality. Furthermore, depending on the spatial distribution of species, the new agricultural land could encroach on the habitat of threatened species. Thirdly, a systems diagram is a tool that can be interactively developed by a group of stakeholders and experts and therefore can represent a transparent and shared understanding of the factors influencing trade-offs.

A drawback to a systems diagram is that it has to incorporate many different elements and connections and therefore can become very complicated and difficult to understand. Another disadvantage is that it presents only a static, rather than dynamic, view of a system's operation. (An exception is the field of *systems dynamics* which uses systems diagrams as a first step in formulating dynamic models). Although systems diagrams can be jointly constructed by experts and/or stakeholders, the knowledge behind the diagram itself is not obvious nor reproducible. A final disadvantage is that a systems diagram depicts connections between variables, but not their importance, and therefore has limited use in identifying the most important combination of factors affecting a trade-off.

3.2 Influence matrix

To address the inability of a systems diagram in identifying the significance of different variables we can use instead an influence matrix. The key question here is, how can an influence matrix provide information about the importance of particular variables? The aggregate influence of a particular variable as compared to other variables can be assessed by adding up their scores in the rows or columns of the matrix (Priester et al. 2014; Kunze et al. 2016). Summing the row of a particular variable gives its “active sum,” a measure of its impact on the rest of the variables in the influence matrix. Summing its column provides its “passive sum,” indicating the degree to which it is influenced by other variables in the diagram.

In Fig. 2, land use and land cover change, the spatial distribution of species, and agricultural yield have the largest active sums which implies that they have the largest influence on the trade-off system as a whole. However, this does not ensure that they have the largest influence on the two main metrics of the trade-off. This is because an influence matrix only visualizes the impacts of a particular variable on one other (usually adjacent) variable, rather than the impacts exerted through a chain of variables. To address this limitation, and to identify the important linkages in the system that influence the main trade-off metrics, we use a novel (to our knowledge) “critical chains” approach. Beginning with each of the main trade-off metrics, a pathway is followed backward that traces the linkage of all variables with a significant influence, where “significant” is defined here as an influence score of 2 or 3 (out of a maximum of 3).

This can best be explained by example. Starting with the food security metric “people fed from domestic production” (Variable 1) we note in Fig. 2 in the column below this variable that “domestic food production” (Variable 3) received a score of 3. This indicates a strong direct linkage between Variables 1 and 3. We continue with this procedure and observe that in the column below Variable 3, the

variables “agricultural yield” (Variable 4) and “agricultural area” (Variable 5) received a score of 3, and so on. Following this procedure, we obtain the critical chains of important variables (Fig. 4) which influence directly (adjacent) and indirectly (non-adjacent) the two main trade-off metrics (Variables 1 and 2).

To assess the importance of particular variables, we note that some variables in Fig. 4 occur more frequently than others. We propose that the frequency of occurrence of a variable in the critical chains diagram is a measure of its importance in influencing the main metrics of a trade-off. The most frequently occurring are land governance processes (Variable 7) and agricultural yield (Variable 4). This approach is useful for the first four levels of linkage depicted in Fig. 4. Afterward the linkages proliferate and the diagram simply shows that everything in a system is eventually connected to everything else.

We have now presented two ways of assessing the importance of variables—with their frequency of appearance in critical chains and with their active sums. Considering the results from these two methods we conclude that the most significant variables for the current application are agricultural yield and land governance processes (which have the largest influence on the two main metrics of the trade-off) and land use and land cover change (which has the largest influence on the trade-off system as a whole). We propose that these are the variables with the greatest influence on the trade-offs between food security and biodiversity conservation consistent with the analysis and set of conditions in the case study. We stress that this conclusion only follows from the subjective judgements reflected in the systems diagram and influence matrix. To ensure that this subjectivity reflects

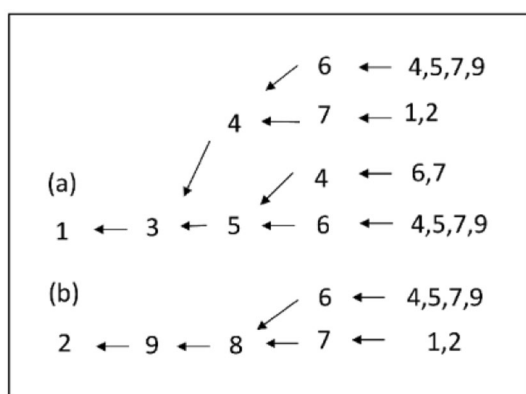


Fig. 4 Critical chains built from results in the influence matrix (Fig. 2). Numbers refer to the variable numbers in the influence matrix (Fig. 2). Only variables with a score of 2 or 3 are included in the critical chains because they are assumed to have a significant influence on adjacent variables because of their high score. **a** Critical chain of main metric for food security. **b** The same but for conservation of biodiversity

a wider range of views, and to make this methodology more useful to policymaking, it is strongly recommended that the systems diagram and influence matrix are co-designed with groups of experts and stakeholders.

In sum, we have seen that an influence matrix has the advantage of providing a transparent method for assessing the relative importance of different factors influencing trade-offs and identifying critical causal chains. It is also feasible to co-develop a matrix with a group of stakeholders and experts and thereby promote a shared understanding of trade-offs. Some disadvantages are noted in the next section.

3.3 Land use modeling

Although systems diagrams and influence matrices provide important insights about trade-offs, they do not generate quantitative information about these trade-offs. Neither do they describe the temporal or spatial aspects of trade-offs nor of their influencing factors. To address these limitations and to obtain a finer-grain view of trade-offs we apply a third systems method—land use modeling.

It was noted previously that the influence matrix and critical chain analysis indicate three variables with the greatest influence on trade-offs. LandSHIFT is now used to investigate policies that are related to two of these variables—agricultural yield and land governance. The policy having to do with agricultural yield, termed “investing to improve yield,” assumes that additional agricultural inputs (e.g., additional fertilizer and advanced seeds) are used to increase agricultural yield. The policy having to do with land governance, termed “ring-fencing protected natural areas,” assumes that agricultural development is not allowed on protected natural areas. These policies are elaborated in the following paragraphs.

Selected results from the scenarios are given in Table 1 and an example of the simulated land use and land cover change maps is provided in Supplementary Information. The computed trade-offs between food security and conservation of biodiversity are depicted in Table 2 and Fig. 5. Trade-offs are expressed as normalized percentage deviations from the base year. The metrics are the same as used elsewhere in the text, i.e., “number of people fed with an adequate diet from domestic agricultural production” and the related loss of “cumulative habitat of threatened species.”

Under the reference case (Scenario A) the number of people fed increases by 85% in 2030 and 79% in 2050 relative to the base year (2005). The smaller figure in 2050 reflects a decline in yield in some parts of the country due to climate change and shortages of land for agricultural expansion. To meet future food requirements for the growing population (+174%), agricultural land expands onto natural land, decreasing it by 89% in 2030, and depleting it entirely by

Table 1 Selected results from land use modeling

Scenario	Year	Agricultural land (km ²)	Natural land (km ²)	Crop yield (t/ha)	Agricultural production (kt)	Agricultural production (M kcal)	Biodiversity (Number of threatened species remaining)	Food security, Number of people fed with an adequate diet from domestic agricultural production (M people)	Conservation of biodiversity, Cumulative habitat of threatened species (km ²)
Baseline	2005	114,791	86,722	3.1	27,565	26,964,900	53	33.0	1,297,682
A	2030	190,343	9,448	3.0	50,036	49,639,790	42	60.8	822,033
	2050	198,229	0	2.7	54,064	48,532,590	11	59.4	669,634
B	2030	136,526	63,265	4.5	50,036	49,639,790	53	60.8	1,135,364
	2050	165,278	32,951	5.7	77,376	69,282,270	53	84.8	950,990
C	2030	171,872	27,920	3.0	49,273	49,032,112	53	60.0	919,471
	2050	170,641	27,588	2.7	47,294	42,455,147	53	52.0	871,712
D	2030	135,138	64,654	4.6	50,036	49,639,790	53	60.8	1,141,224
	2050	166,489	31,740	5.7	77,376	69,282,270	53	84.8	996,335

Table 2 Trade-off coefficients (*toff*) for the land use modeling scenarios investigated

Scenario		Year 2030	Year 2050
A	Reference case	− 0.43	− 0.62
B	Investments to improve yield	− 0.15	− 0.17
C	Ring-fencing protected areas	− 0.36	− 0.57
D	Both policies	− 0.14	− 0.15

Coefficient is computed with Eq. (1). The larger the negative number, the larger the trade-off

2050. Under the assumptions of Scenario A, more land is needed for agriculture in 2050 than is available.

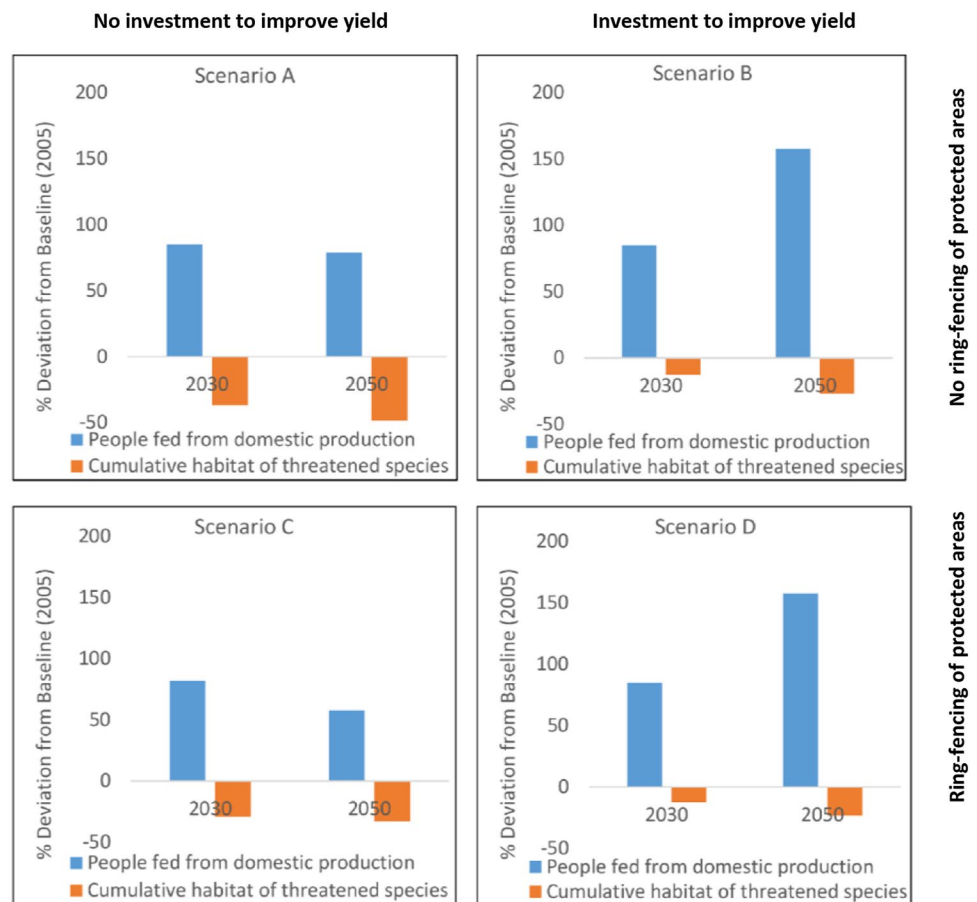
Because of the depletion of natural land, the cumulative habitat of threatened species decreases by 48% by 2050. Habitat exists for only 11 of the original 53 species threatened in 2005. These are the 11 species that can exist on agricultural and/or settlement areas accordingly to IUCN (2013). The trade-off coefficient for Scenario A is − 0.62 in 2050 (Table 2) indicating that the loss of habitat is 62% for every 100% increase in people fed from domestic production, or 6.2% per 10% increase.

Scenario B assumes that substantial investments are made to increase crop yields by increasing access of farmers to modern production technologies, knowledge, affordable credit and market information. The yield increase due to these investments compensates for declines due to climate change, resulting in an 84% net increase of national average yields by 2050. In 2030, the number of people fed is approximately the same as in Scenario A. However, by 2050 it is twice as large (157%) because of the steady, long term increase in yield. Since the additional food produced

under this scenario is mostly achieved by increasing yield and intensifying production per hectare (up to a national average of 5.7 t/ha), the expansion of agricultural land is much smaller (+ 44%) in 2050 than in Scenario A (+ 73%). A smaller expansion of agricultural land in turn causes a much smaller decline in habitat of threatened species by 2050 (− 27% as compared to − 48% in Scenario A). With more people fed and less habitat exploited, the trade-off coefficient in 2050 drops substantially from − 0.62 under Scenario A to − 0.17 in Scenario B.

We can understand this effect by examining the systems diagram (Fig. 1) and critical chains diagram (Fig. 4). An increase in agricultural yield (assuming all other factors are constant) leads to an increase in domestic food production and an increase in food availability from domestic production, and therefore an increase in the number of people fed with an adequate diet from domestic agricultural production. At the same time, the increase in yield decreases agricultural land requirements for the same amount of domestic production, which reduces land use and land cover change and finally leads to a lower loss in habitat area (again, assuming all else is constant). Hence, increasing yield allows more food to be produced on the same land, reducing the pressure to expand agricultural land onto natural land. Likewise, producing more food on the same amount of land produces more food for people. Therefore, increasing yield per hectare significantly enhances food security while minimizing the loss of natural land and habitat of threatened species. In this case, the insights gathered from the systems and influence diagrams have been quantified by the land use modeling, and in turn these diagrams provide an explanation for land use modeling results.

Fig. 5 Trade-offs between food security and conservation of biodiversity for the four scenarios shown in Fig. 3. Food security and conservation of biodiversity are represented by metrics of “people adequately fed from agriculture production,” and “cumulative habitat of threatened species,” respectively. Shown are the deviations of these metrics in 2030 and 2050 relative to a baseline year (2005)



While the conservation of habitat on natural land is clearly beneficial to biodiversity conservation, the habitat of species on agricultural land could be threatened by the methods used to boost agricultural yield. According to IUCN (2013) 9 threatened species in Uganda are likely to occupy agricultural land. This is because much of this land is mosaic cropland which provides suitable habitat for some threatened and other species because of its mix of arable land and natural vegetation (see Supplementary Information). Additionally, farmers use a relatively low amount of pesticides and other ecologically-damaging inputs on this land. However, increasing crop yield in the future could increase the threat to these threatened species if it is achieved by converting mosaic cropland into homogenous cropland, by increasing mechanization, and/or by boosting fertilizer and pesticide inputs (Tschardt et al. 2012; Jeliakov et al. 2016; Egli et al. 2018). The present study assumes that the mosaic characteristics of cropland are conserved and does not include possible negative effects due to increases in mechanization or inputs of fertilizer and pesticide. However, these negative effects may be relatively small compared to the beneficial effect of conserving natural land because natural land provides the main habitat for threatened species in Uganda (IUCN 2013). Some researchers also argue that it is feasible

to both increase yield and conserve biodiversity through “sustainable”/“agroecological” intensification and achieving landscape heterogeneity (Tschardt et al. 2012) or by replacing exotic tree species with indigenous tree species in agroforest systems (Graham et al. 2022).

Scenario C examines the impact of ring-fencing protected areas. This policy was represented in the modeling by assuming that agricultural land is not allowed to expand onto protected areas as they stood according to IUCN and UNEP-WCMC (2014). Ring-fencing is expected to be an effective policy for conserving biodiversity because protected areas tend to contain a disproportionately large number of threatened species (MTWA 2018). As anticipated, the loss of habitat of threatened species is much lower than in Scenario A (–29% and –33% in 2030 and 2050, respectively) and just slightly greater than the losses under Scenario B. At the same time, fewer people are fed from domestic production as compared to Scenarios A and B (Fig. 5). This is because ring-fencing restricts agriculture from expanding onto potentially productive agricultural land and thereby limits the quantity of land that is potentially available for agricultural production. Accordingly, this scenario’s trade-off coefficient (*toff*) is more negative than in Scenario B, and only slightly smaller than the reference case Scenario A (Table 3).

Scenario D examines the combined effects of both investing in yield increases and ring-fencing protected areas. Scenario D, together with Scenario B, has the largest increase in people fed up to 2050 (157%). (Because of assumed yield increases.) Meanwhile the loss in habitat of threatened species is the lowest of all scenarios (− 23%) because of the ring-fencing of protected areas. The combined effect yields the lowest *toff* of all four scenarios.

However, the habitat loss in Scenario D is not substantially below that of Scenario B (− 28%). This is because of compensating causal relationships that can be seen in the systems diagram (Fig. 1). On one hand, the increase in yield in this scenario tends to reduce the natural land needed for agricultural production, saving habitat. On the other hand, the policy of ring-fencing diverts some agricultural land onto less productive natural land which increases the total land needed for agriculture and reduces the total area of natural land in scenario D (compared to scenario B). Because protected areas tend to overlap with natural land disproportionately rich in threatened species, the net result of ring fencing protected areas is a slightly lower loss of habitat as compared to Scenario B.

Summing up, the reference case, Scenario A, aims to increase the number of people fed which leads to substantial loss of habitat area due to the expansion of agriculture onto natural land. Scenario B, which investigates a policy

of improving yield, has substantial benefits in increasing the number of people fed while significantly lessening the loss of habitat area. A small trade-off, nevertheless, still occurs between food security and biodiversity conservation. Scenario C investigates a policy of ring-fencing protected areas and finds substantially lower habitat loss than in the reference scenario, but also a smaller number of people fed, resulting in a large trade-off. Scenario D combines the two policies and reduces the trade-off to its lowest level of the four scenarios.

As in all modeling, some pertinent factors were not taken into account. For example, it was noted earlier that the modeling did not account for the potential risk to sensitive species on agricultural land posed by increasing yield.

We note that land use modeling, as compared to systems diagrams and influence diagrams, provides quantitative data for assessing trade-offs, for including spatial factors, and for investigating the relative influence of specific factors on trade-offs. However, the assumptions and data behind land use (and most) models are difficult for the non-expert to grasp and therefore more difficult to use than systems diagrams and influence matrices as part of an assessment process with stakeholders and experts.

An exception is that stakeholders can be very effectively engaged in developing and analyzing scenarios from the models (Voigt und Troy 2008). As an example, we

Table 3 Summary of advantages/disadvantages of using different systems methods to assess the trade-offs between food security and conservation of biodiversity as framed in this paper

Systems method	Advantages	Disadvantages
Systems diagram	<p>An efficient method for collecting potential factors influencing trade-offs. The procedure for selecting the variables to include or exclude in the diagram also sets the boundaries of the trade-off system</p> <p>Depicts connections between variables and hence helps identify causal chains that might have an important influence on trade-offs</p> <p>Suitable for being co-developed with a group of stakeholders and experts and therefore has the potential to represent a shared understanding of the factors influencing trade-offs</p>	<p>A snapshot of a dynamic system rather than an illustration of the evolution of a system over time</p> <p>Does not show magnitude of influence of variables</p> <p>Does not take into account spatial variation of variables</p> <p>Cannot quantify trade-offs</p> <p>Because of above limitations, of limited use in evaluating policies</p>
Influence matrix	<p>Indicates relative importance of different factors affecting trade-offs</p> <p>Identifies a critical causal chain of factors that influence a trade-off</p> <p>Suitable for being co-developed with a group of stakeholders and experts and therefore has the potential to represent a shared understanding of the factors influencing trade-offs</p>	<p>A snapshot of a dynamic system. Therefore does not depict the evolution of a system over time</p> <p>Does not take into account spatial variation of variables</p> <p>Cannot quantify trade-offs</p> <p>Because of above limitations, of limited use in evaluating policies</p>
Land use model	<p>Takes into account spatial variation of important variables</p> <p>Depicts temporal changes in the trade-off system and can therefore represent a dynamic system</p> <p>Provides quantitative basis for assessing the importance of trade-offs</p> <p>Provides quantitative basis for assessing the relative influence of different factors on trade-offs</p> <p>Because of above advantages, can be used to quantify trade-offs and evaluate policies for reducing trade-offs</p>	<p>Requires substantially more inputs than a systems diagram or influence matrix</p> <p>Expensive to develop and use as compared to a systems diagram or influence matrix</p> <p>Requires special training in modeling and digital skills</p> <p>Although model inputs and outputs can be specified by stakeholders, land use models themselves are usually too complicated and time-demanding to be co-developed with stakeholders</p>

previously noted that stakeholder workshops were used to develop the IFPRI scenarios and these scenarios were used as a source of input data for the LandSHIFT land use modeling. Moreover, models are frequently used as part of a policy development process.

4 Discussion

Each of the methods for analyzing trade-offs has its advantages and disadvantages as explained in the text and summarized in Table 3. In short, each of these methods are useful individually for analyzing trade-offs, but in a limited way. A systems diagram is useful for scoping out the variables leading to trade-offs and their interrelationships. It does not, however, indicate the relative importance of the variables or yield spatial or quantitative information about trade-offs. Meanwhile, an influence matrix can be used to identify the most important variables from the systems diagram that influence the trade-off under study. Yet it also does not provide spatial or quantitative information and therefore has limited application for evaluating policies. A land use model can be used to quantify the trade-off and evaluate policy scenarios to alleviate it. But the complexity of developing and using this tool compared to the previous two methods means it is more difficult to engage stakeholders in its development and use.

The different methods can also be combined as shown in Fig. 6. Coupling a systems diagram with an influence matrix strengthens both. Firstly, the systems diagram can be used as a transparent basis for selecting the variables in the influence matrix. The matrix, in turn, provides information on importance of the relationships depicted in the systems diagram. Because they are relatively easy to use, a systems diagram and influence matrix can be co-designed with a variety of stakeholders and experts and can be used to gain a shared understanding of the trade-off system. (Examples are Sedlacko et al. (2014) and Cole et al. (2007)). We see that the combination of systems diagram and influence matrix with the novel “critical chain approach” helps us elaborate the system leading to trade-offs, and identify variables with the greatest influence on these trade-offs.

Linking a land use model with the other two methods brings additional advantages. The important variables identified by the influence matrix can be used to analyze policies with the land use model, as was done in this paper (assuming these variables are contained in the model). Stakeholders and experts can also provide input to model scenario assumptions as we saw in the case study. Information from the land use modeling provides dynamic, spatial and quantitative information on the variables contained in the systems diagram and influence matrix. Results from the model can also be further processed in a policy-friendly way (e.g.,

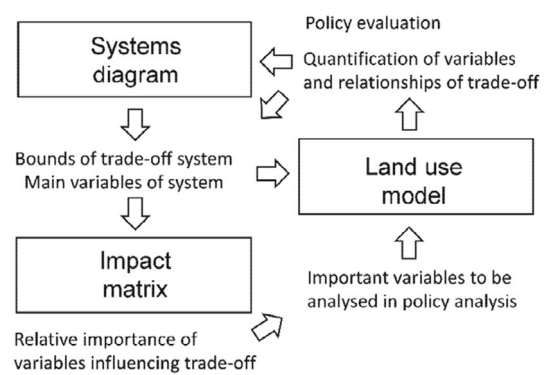


Fig. 6 Combining systems methods for analyzing trade-offs between food security and biodiversity conservations

as results from the land use modeling were converted into trade-off coefficients) to inform stakeholders and experts as part of a policy process.

5 Conclusion

Among the greatest challenges facing the international community as it implements the Sustainable Development Goals is how to deal with trade-offs between and among the goals. Herein we have addressed one of these important trade-offs – between food security (SDG 2) and conservation of biodiversity (SDG 15). The aim of the current study was methodological, and we have shown how three different systems methods are individually useful for illuminating these trade-offs.

The simpler methods, systems diagrams and influence matrices, can help frame and scope a trade-off situation and provide insight into the main factors influencing a trade-off. Using these methods we identified agricultural yield, land governance processes, and change in land use and land cover as highly influential factors in the context of the case study in Uganda.

A third method, land use modeling, is more difficult to apply because it has considerable data and computational requirements. But it is also better suited than the other two methods for quantifying trade-offs and evaluating policies. In this study, land use modeling was used to investigate the impact of two policies on trade-off scenarios. One of the policies, “ring-fencing protected natural areas,” is very beneficial for protecting threatened species, but surprisingly did not substantially reduce the trade-off between food security and biodiversity conservation. This is because ring-fencing restricts agriculture from expanding onto potentially productive land and thereby limits the area for future food production. Ring-fencing has this effect only because potentially arable land is becoming increasingly scarce in Uganda.

However, if productive land become less scarce in the future (e.g., due to changed management practices) then ring fencing will also make a stronger contribution to reducing the trade-off.

By contrast, the policy of “investing to improve yield” significantly reduces the trade-off compared to a reference scenario. Improving yield decreases the amount of new agricultural land needed for food production, and subsequently reduces the habitat area exploited for new agricultural land (relative to a reference scenario, and all other factors being equal). The higher yield also means that more food can be produced from the same amount of land. The combination of increased food production and smaller decline in biodiverse habitats leads to a smaller trade-off.

It is important to note that conclusions from the systems diagram, influence matrix and land use modeling only pertain to the particular framing of trade-offs in this paper. We have also noted that these methods have limitations when they are used as stand-alone tools. Systems diagrams and influence matrices are unable to provide spatial or temporal detail, while the complexity of land use modeling makes it less than ideal for engaging stakeholders. The solution to these limitations is to combine the methods into a single methodology. The systems diagram and influence matrix can be used to scope the system, identify important relationships between variables, and identify influential variables, while the land use modeling can build on this information and provide important quantitative spatial and temporal details about the trade-offs, and evaluate policy scenarios to alleviate them.

While the current study had a methodological focus, future practical applications of the methodology should directly engage with the stakeholders who may be affected by the conclusions of a trade-off analysis. For example, the policies investigated in the current study—investing in increased yield and ring fencing protected areas—will have an impact on the practices of farmers in agricultural areas and on the livelihoods of inhabitants in the ring-fenced areas. Moreover, the application of systems methods involves subjective judgements, for example in selecting the variables to be included in an analysis. To ensure that this subjectivity reflects a wider range of views it is recommended that stakeholders be involved in the co-design and use of the systems diagram and influence matrix. For example, stakeholders can provide advice on the variables to include in the systems diagram and thereby help determine the scope of the analysis; they can advise on the connections between variables and elaborate the cause-and-effect involved with trade-offs; they can provide input to the scoring of interactions in the influence matrix.

Although it is more difficult to engage stakeholders in the land use modeling as compared to the other

two methods, some level of involvement is encouraged. For example, stakeholders can provide input to scenario assumptions to be used in the land use modeling. They can also be involved in the interpretation of modeling results. As a general rule, engaging stakeholders in trade-off analysis is worthwhile because it increases the range of views represented in the analysis and the likelihood of equitable outcomes.

A particular deficiency of the literature on trade-offs is the lack of comparability between studies. This arises from the fact that the magnitude of trade-offs are usually reported in the units and magnitudes pertinent to a particular study, making comparisons between studies difficult. A solution would be to calculate a trade-off coefficient that can be used across studies, such as the coefficient *toff* proposed in this paper. The basic idea of such a coefficient is simple—expressing the main trade-offs as a ratio of normalized changes. This simple approach has the advantage of providing a unit less metric reflecting the intensity of trade-offs. In using this metric for the present study we found that it provides a useful way to compare trade-offs for different scenarios in which the magnitudes of change are very different.

In conclusion, while being mindful of their limitations, systems methods can provide a useful and transparent methodology to assess the important trade-offs between food security and conservation of biodiversity.

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Declarations

Conflict of interest With an exception of the funding statement above, the authors have no additional competing interests to declare that are relevant to the content of this article.

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References

- Alcamo J, van den Born GJ, Bouwman AF, de Haan BJ, Goldewijk KK, Klepper O, Krabec J, Leemans R, Olivier JGJ, Toet AMC, de Vries HJM, van der Woerd HJ (1994) Modeling the global society-biosphere-climate system: Part 2: computed scenarios. *Water Air Soil Pollut* 76:37–78. <https://doi.org/10.1007/BF00478336>
- Alcamo J, Schaldach R, Koch J, Kölling C, Lapola D, Priess J (2011) Evaluation of an integrated land use change model including a scenario analysis of land use change for continental Africa. *Environ Model Softw* 26:1017–1027. <https://doi.org/10.1016/j.envsoft.2011.03.002>
- Alcamo J, Thompson J, Alexander A, Antoniadis A, Delabre I, Dolley J, Marshall F, Menton M, Middleton J, Scharlemann JPW (2020) Analysing interactions among the sustainable development goals: findings and emerging issues from local and global studies. *Sustain Sci* 15:1561–1572. <https://doi.org/10.1007/s11625-020-00875-x>
- Asadolahi Z, Salmanmahiny A, Sakieh Y, Mirkarimi SH, Baral H, Azimi M (2018) Dynamic trade-off analysis of multiple ecosystem services under land use change scenarios: towards putting ecosystem services into planning in Iran. *Ecol Complex* 36:250–260. <https://doi.org/10.1016/j.ecocom.2018.09.003>
- Bartholomé E, Belward AS (2005) GLC2000: a new approach to global land cover mapping from Earth observation data. *Int J Remote Sens* 26:1959–1977. <https://doi.org/10.1080/01431160412331291297>
- CBD (2015) Countries profiles. <http://www.cbd.int/countries/profile/?country=ug>
- Churchman (1968) *The systems approach*. Delacorte Press, New York
- Cole A, Allen W, Kilvington M, Fenemor A, Bowden B (2007) Participatory modelling with an influence matrix and the calculation of whole-of-system sustainability values. *IJSD* 10:382. <https://doi.org/10.1504/IJSD.2007.017911>
- Delzeit R, Zabel F, Meyer C, Václavík T (2017) Addressing future trade-offs between biodiversity and cropland expansion to improve food security. *Reg Environ Change* 17:1429–1441. <https://doi.org/10.1007/s10113-016-0927-1>
- Egli L, Meyer C, Scherber C, Kreft H, Tschardt T (2018) Winners and losers of national and global efforts to reconcile agricultural intensification and biodiversity conservation. *Glob Chang Biol* 24:2212–2228. <https://doi.org/10.1111/gcb.14076>
- FAO (2006) Food security. Policy brief. <https://reliefweb.int/report/world/policy-brief-food-security-issue-2-june-2006>
- FAO (2009) Declaration of the world summit on food security. FAO, Rome
- FAO (2015) Achieving zero hunger: the critical role of investments in social protection and agriculture. Food and Agriculture Organization of the United Nations, Rome
- Foden WB, Butchart SHM, Stuart SN, Vié JC, Akçakaya HR, Angulo A, DeVantier LM, Gutsche A, Turak E, Cao L, Donner SD, Katariya V, Bernard R, Holland RA, Hughes AF, O'Hanlon SE, Garnett ST, Sekercioğlu CH, Mace GM (2013) Identifying the world's most climate change vulnerable species: a systematic trait-based assessment of all birds, amphibians and corals. *PLoS ONE* 8:e65427. <https://doi.org/10.1371/journal.pone.0065427>
- Fohrer N, Möller D, Steiner N (2002) An interdisciplinary modelling approach to evaluate the effects of land use change. *Phys Chem Earth Parts a/b/c* 27:655–662. [https://doi.org/10.1016/S1474-7065\(02\)00050-5](https://doi.org/10.1016/S1474-7065(02)00050-5)
- Foley JA, Ramankutty N, Brauman KA, Cassidy ES, Gerber JS, Johnston M, Mueller ND, O'Connell C, Ray DK, West PC, Balzer C, Bennett EM, Carpenter SR, Hill J, Monfreda C, Polasky S, Rockström J, Sheehan J, Siebert S, Tilman D, Zaks DPM (2011) Solutions for a cultivated planet. *Nature* 478:337–342. <https://doi.org/10.1038/nature10452>
- Forrester J (1969) *Urban dynamics*. MIT Press, Cambridge
- Gabriel D, Sait SM, Kunin WE, Benton TG (2013) Food production vs. biodiversity: comparing organic and conventional agriculture. *J Appl Ecol* 50:355–364. <https://doi.org/10.1111/1365-2664.12035>
- Göpel J, Schüngel J, Stuch B, Schaldach R (2020) Assessing the effects of agricultural intensification on natural habitats and biodiversity in Southern Amazonia. *PLoS ONE* 15:e0225914. <https://doi.org/10.1371/journal.pone.0225914>
- Gordon TJ, Hayward H (1968) Initial experiments with the cross impact matrix method of forecasting. *Futures* 1:100–116. [https://doi.org/10.1016/S0016-3287\(68\)80003-5](https://doi.org/10.1016/S0016-3287(68)80003-5)
- Graham S, Ihli HJ, Gassner A (2022) Agroforestry, indigenous tree cover and biodiversity conservation: a case study of Mount Elgon in Uganda. *Eur J Dev Res* 34:1893–1911. <https://doi.org/10.1057/s41287-021-00446-5>
- Guerrero-Pineda C, Iacona GD, Mair L, Hawkins F, Siikamäki J, Miller D, Gerber LR (2022) An investment strategy to address biodiversity loss from agricultural expansion. *Nat Sustain* 5:610–618. <https://doi.org/10.1038/s41893-022-00871-2>
- Gupta G, Dunn J, Sanderson R, Fuller R, McGowan P (2020) A simple method for assessing the completeness of a geographic range size estimate. *Global Ecol Conserv* 21:e00788. <https://doi.org/10.1016/j.gecco.2019.e00788>
- Hanspach J, Abson DJ, French Collier N, Dorresteijn I, Schultner J, Fischer J (2017) From trade-offs to synergies in food security and biodiversity conservation. *Front Ecol Environ* 15:489–494. <https://doi.org/10.1002/fee.1632>
- Heubes J, Schmidt M, Stuch B, García Márquez JR, Wittig R, Zizka G, Thiombiano A, Sinsin B, Schaldach R, Hahn K (2013) The projected impact of climate and land use change on plant diversity: an example from West Africa. *J Arid Environ* 96:48–54. <https://doi.org/10.1016/j.jaridenv.2013.04.008>
- Hinz R, Sulser TB, Huefner R, Mason-D' Croz D, Dunston S, Nautiyal S, Ringler C, Schuengel J, Tikhile P, Wimmer F, Schaldach R (2020) Agricultural development and land use change in India: a scenario analysis of trade-offs between UN sustainable development goals (SDGs). *Earth's Future*. <https://doi.org/10.1029/2019E001287>
- IUCN (2013) The IUCN red list of threatened species: V 2013.1. IUCN
- IUCN, UNEP-WCMC (2014) The world database on protected areas (WDPA)
- Jeffries C (1974) Qualitative stability and digraphs in model ecosystems. *Ecology* 1974:1415–1419
- Jeliazkov A, Mimet A, Chargé R, Jiguet F, Devictor V, Chiron F (2016) Impacts of agricultural intensification on bird communities: New insights from a multi-level and multi-facet approach of biodiversity. *Agr Ecosyst Environ* 216:9–22. <https://doi.org/10.1016/j.agee.2015.09.017>

- Ji Z, Wei H, Xue D, Liu M, Cai E, Chen W, Feng X, Li J, Lu J, Guo Y (2021) Trade-off and projecting effects of land use change on ecosystem services under different policies scenarios: a case study in central China. *Int J Environ Res Public Health*. <https://doi.org/10.3390/ijerph18073552>
- Kaizzi KC, Byalebeka J, Semalulu O, Alou I, Zimwanguyizza W, Nansamba A, Musinguzi P, Ebanyat P, Hyuha T, Wortmann CS (2012) Maize response to fertilizer and nitrogen use efficiency in Uganda. *Agron J* 104:73–82. <https://doi.org/10.2134/agronj2011.0181>
- Klein JH, Cooper DF (1982) Cognitive maps of decision-makers in a complex game. *J Oper Res Soc* 33:63. <https://doi.org/10.2307/2581872>
- Kunze O, Wulffhorst G, Minner S (2016) Applying systems thinking to city logistics: a qualitative (and quantitative) approach to model interdependencies of decisions by various stakeholders and their impact on city logistics. *Transp Res Proc* 12:692–706. <https://doi.org/10.1016/j.trpro.2016.02.022>
- Lapola DM, Schaldach R, Alcamo J, Bondeau A, Koch J, Koelking C, Priess JA (2010) Indirect land-use changes can overcome carbon savings from biofuels in Brazil. *Proc Natl Acad Sci U S A* 107:3388–3393. <https://doi.org/10.1073/pnas.0907318107>
- Leopold LB (1971) Geological survey a: procedure for evaluating environmental impact. U.S Department of the Interior
- Meadows DH, Meadows DL, Randers J, Behrens W (1972) *The limits to growth*. Universe Books, New York
- Meyfroidt P, Lambin EF, Erb KH, Hertel TW (2013) Globalization of land use: distant drivers of land change and geographic displacement of land use. *Curr Opin Environ Sustain* 5:438–444. <https://doi.org/10.1016/j.cosust.2013.04.003>
- Morecroft J (1982) A critical review of diagramming tools for conceptualizing feedback system models. *Dynamica* 8(1):20–29
- MTWA (2018) Red list of threatened species of Uganda 2018. MTWA
- Mwanjalolo M, Bernard B, Paul M, Joshua W, Sophie K, Cotilda N, Bob N, John D, Edward S, Barbara N (2018) Assessing the extent of historical, current, and future land use systems in Uganda. *Land* 7:132. <https://doi.org/10.3390/land7040132>
- Namazzi J (2008) Use of inorganic fertilizers in Uganda. Uganda strategy support program
- Newbold T, Hudson LN, Hill SLL, Contu S, Lysenko I, Senior RA, Börger L, Bennett DJ, Choimes A, Collen B, Day J, de Palma A, Díaz S, Echeverria-Londoño S, Edgar MJ, Feldman A, Garon M, Harrison MLK, Alhousseini T, Ingram DJ, Itescu Y, Kattge J, Kemp V, Kirkpatrick L, Kleyer M, Correia DLP, Martin CD, Meiri S, Novosolov M, Pan Y, Phillips HRP, Purves DW, Robinson A, Simpson J, Tuck SL, Weiher E, White HJ, Ewers RM, Mace GM, Scharlemann JPW, Purvis A (2015) Global effects of land use on local terrestrial biodiversity. *Nature* 520:45–50. <https://doi.org/10.1038/nature14324>
- Oakley JL, Bicknell JE (2022) The impacts of tropical agriculture on biodiversity: a meta-analysis. *J Appl Ecol* 59:3072–3082. <https://doi.org/10.1111/1365-2664.14303>
- Plumptre AJ, Ayebare S, Behangana M, Forrest TG, Hatanga P, Kabuye C, Kirunda B, Kityo R, Mugabe H, Namaganda M, Nampindo S, Nangendo G, Nkuutu DN, Pomeroy D, Tushabe H, Prinsloo S (2019) Conservation of vertebrates and plants in Uganda: identifying key biodiversity areas and other sites of national importance. *Conserv Sci Pract*. <https://doi.org/10.1111/csp2.7>
- Priester R, Miramontes M, Wulffhorst G (2014) A Generic code of urban mobility: how can cities drive future sustainable development? *Transp Res Proc* 4:90–102. <https://doi.org/10.1016/j.trpro.2014.11.008>
- Rosegrant MW et al. (2012) International model for policy analysis of agricultural commodities and trade (IMPACT): model description. <https://www.technicalconsortium.org/wp-content/uploads/2014/05/International-model-for-policy-analysis.pdf>
- Schaldach R, Alcamo J, Koch J, Kölling C, Lapola DM, Schüngel J, Priess JA (2011) An integrated approach to modelling land-use change on continental and global scales. *Environ Model Softw* 26:1041–1051. <https://doi.org/10.1016/j.envsoft.2011.02.013>
- Schüngel J, Stuch B, Fohry C, Schaldach R (2022) Effects of initialization of a global land-use model on simulated land change and loss of natural vegetation. *Environ Model Softw* 148:105287. <https://doi.org/10.1016/j.envsoft.2021.105287>
- Schwarzmueller F, Kastner T (2022) Agricultural trade and its impacts on cropland use and the global loss of species habitat. *Sustain Sci* 17:2363–2377. <https://doi.org/10.1007/s11625-022-01138-7>
- Sedlacko M, Martinuzzi A, Röpke I, Videira N, Antunes P (2014) Participatory systems mapping for sustainable consumption: discussion of a method promoting systemic insights. *Ecol Econ* 106:33–43. <https://doi.org/10.1016/j.ecolecon.2014.07.002>
- Sharma R, Nehren U, Rahman S, Meyer M, Rimal B, Aria Seta G, Baral H (2018) Modeling land use and land cover changes and their effects on biodiversity in Central Kalimantan. *Indonesia Land* 7:57. <https://doi.org/10.3390/land7020057>
- Tscharntke T, Clough Y, Wanger TC, Jackson L, Motzke I, Perfecto I, Vandermeer J, Whitbread A (2012) Global food security, biodiversity conservation and the future of agricultural intensification. *Biol Cons* 151:53–59. <https://doi.org/10.1016/j.biocon.2012.01.068>
- UN (2015) World population prospects: the 2015 revision. <http://esa.un.org/unpd/wpp/DVD>
- van Soesbergen A, Arnell AP, Sassen M, Stuch B, Schaldach R, Göpel J, Vervoort J, Mason-D’Croz D, Islam S, Palazzo A (2017) Exploring future agricultural development and biodiversity in Uganda, Rwanda and Burundi: a spatially explicit scenario-based assessment. *Reg Environ Change* 17:1409–1420. <https://doi.org/10.1007/s10113-016-0983-6>
- Vervoort JM, Palazzo A, Mason-D’Croz D, Ericksen PJ, Thornton PK, Kristjanson PM, Förch W, Herrero MT, Havlík P, Jost C, Rowlands H (2013) The future of food security, environments and livelihoods in Eastern Africa: four socio-economic scenarios. CGIAR
- Voigt B, Troy A (2008) Land-use modeling. *Encyclopedia of ecology*. Elsevier, pp 2126–2132
- Weimer-Jehle W (2006) Cross-impact balances: a system-theoretical approach to cross-impact analysis. *Technol Forecast Soc Chang* 73:334–361. <https://doi.org/10.1016/j.techfore.2005.06.005>
- World Bank (2015) Data indicators. <https://data.worldbank.org/indicator>