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Responding to future regime shifts with agrobiodiversity: A multi-level perspective on small-scale farming in Uganda

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ABSTRACT

We analyse the impact of two large-scale regime shifts caused by disease incidence or climate change, and associated crop productivity and price changes, on banana-based smallholders in Uganda. We evaluate these farmers' vulnerability and assess the potential of using increased crop diversity to improve their resilience. We further explore trade-offs and synergies between environmental, economic and nutritional outcomes faced by the farmers in their decision making when a regime shift occurs. We simulate the large-scale scenarios with the IMPACT model and use the results obtained to assess their effect at the local level using the bio-economic farm-household model, FarmDESIGN.

Our results indicate that climate change can lead to a regime shift that expands revenue variance, increases soil erosion and reduces vitamin A yield for farmers. Banana disease can negatively impact income levels and species diversity. We show that under both scenarios farmers have scope to reconfigure their farms and recover farm performance. Specifically, we discuss the benefits of species diversity; increasing agrobiodiversity by adding new crops increases the farm's adaptive capacity and resilience, allowing for much higher revenues, on-farm crop diversity and vitamin A production.

The conceptual approach and the method we developed can be applied to assess the local synergies and trade-offs between crop diversity conservation, nutrition, environmental protection and human nutrition that farmers face as a result of global drivers. Our results offer a further understanding of how biodiverse systems respond to regime shifts, which can inform effective policy design. Our method can be also useful to help farmers manage their farms in a way to better meet their complex needs.

1. Introduction

The purpose of this study is to determine to what extent large-scale regime shifts may affect the livelihoods of smallholder farmers in sub-Saharan Africa, and to assess the potential of agrobiodiversity interventions in supporting smallholders' agricultural adaptation and recovery from climate-related events. Past methods mostly focused on improved crop varieties as the solution to future challenges, primarily assessing their agronomic performance through a narrow lens of intensification (Adams et al., 1998; Kaiser et al., 1993). To address the complexity of external and internal factors shaping farmers' vulnerability and resilience, however, there is growing consensus that a systems approach and multi-scale analyses are necessary (Campbell et al., 2014; Dixon et al., 2014; Donatelli et al., 2017; Lipper et al., 2014). This approach is particularly important for resource-poor farming systems that have little access to markets and formal seed systems.

Agrobiodiversity (or agricultural biodiversity) refers to the diversity of living organisms (plants, animals, bacteria, etc.) that underpin agricultural systems (Wood and Lenné, 1999). It provides numerous, critical benefits that include income opportunities and diversified, nutritious diets (Love and Spaner, 2007). Agrobiodiversity is particularly important for supplying the genetic resources that allow farmers and plant breeders to adapt crops to changing environments under pressure from climate change (Fowler and Hodgkin, 2004). Another important benefit is the provision of ecosystem services such as disease and pest resistance, soil health and water conservation (Hajjar et al., 2008).

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Agrobiodiversity is a key asset for the rural poor in developing countries who depend on agriculture for their income and well-being (Jarvis et al., 2000). Conserving agrobiodiversity on a farm, however, is not without its costs. These costs and benefits impact outcomes such as income, food security and soil health, which in turn affect the vulnerability and resilience of socio-ecological systems (SESs). Consequently, one of the key topics for sustainable development research is to understand the role that agrobiodiversity plays in shaping the vulnerability and resilience of SESs at the local, regional and global levels (Groot et al., 2016).

Regime shifts occur when gradual changes in the SES pass a tipping point so that the system undergoes a large shift that is often difficult to reverse (Figueiredo and Pereira, 2011). A persistent stressor, like climate change or a long-lasting disease outbreak, may lead to a regime shift challenging the resilience of SESs and their continued ability to function (Lin and Petersen, 2013). Agrobiodiversity influences how SESs respond to these shifts, while vulnerability and resilience studies jointly assess the human and biophysical characteristics of SESs and their interactions (Gallopín, 2006; Lin and Petersen, 2013). To design better interventions that facilitate increased agrobiodiversity, it is crucial to understand and quantify the effect of farm management choices on agrobiodiversity and impacts on ecosystem services at different scales. Furthermore, it is necessary to analyse associated trade-offs and synergies in light of challenges such as climate change or disease outbreaks that are expected to have increasingly devastating effects on agriculture and food security (Kang et al., 2009; Wheeler and von Braun, 2013).

Climate change is expected to have a strong impact on agricultural production and prices as a result of changes in temperatures, crop water requirements, and water quality and availability (Fronzek et al., 2018; Srivastava et al., 2018). This effect will be unequally distributed across the world (Ericksen et al., 2011), with some areas actually benefiting from adjusted climatic conditions and, across crops, with some crop yields changing more than others (Knox et al., 2012; Roudier et al., 2011). Furthermore, the real prices of all agricultural commodities are expected to increase by the year 2050 (Ignaciuk and Mason-D'Croz, 2014). This price effect is anticipated to be crop-specific, with the prices of maize, rice and wheat (the three major globally-consumed crops) projected to increase by up to 30% in the most extreme climate scenario. The impact on food security would be strongest in Sub-Saharan Africa (ibid).

It is expected that climate change will compound the frequency and severity of pest and disease outbreaks (Donatelli et al., 2017; Rosenzweig et al., 2001). Pests and diseases devastate agricultural production (Oerke, 2006; Strange and Scott, 2005). For instance, bananas are mostly grown by smallholder farmers in the tropics and are particularly vulnerable to disease as a result of very low genetic diversity, due to the domination of genetically identical plants (Ordonez et al., 2015). In the 1900s, Panama disease (Fusarium wilt) wiped out production worth at least $2.3 billion (the equivalent of 2020 prices) and caused major socio-economic crises in the affected regions. It is a prime example of the risks that are inherent in the use of banana monocultures (Ploetz, 2005). Despite major efforts to control banana diseases, farms are continuously under critical attack by diseases like Panama disease, Black sigatoka, or Banana Xanthomonas wilt (BXW) (Butler, 2013; Jesus de Jesus Júnior et al., 2008; Smith et al., 2008).

Banana (here, plantain, dessert and cooking banana) is a key staple food crop in Uganda, contributing to rural populations' household food security, revenues and culture. Banana also plays an important role in environmental conservation by providing a dense and permanent soil cover, reducing soil erosion on steep slopes and by supplying large quantities of mulching material for maintaining and improving soil fertility (Kalyebara et al., 2006). Smallholder banana systems dominate banana farming systems in Uganda (Kikulwe et al., 2018). A smallholder farm system is "...a decision-making unit comprising the farm household, cropping and livestock systems, that transform land, capital (external inputs) and labour (including genetic resources and knowledge) into useful products that can be consumed or sold" (Fresco and Westphal, 1988). Smallholder banana systems are perennial, low-input, and rural-based systems. The primary purpose of these systems is to provide food security, but commercial interests have become increasingly important. Consequently, banana systems in Uganda have attracted a good deal of technical attention, particularly regarding pest and disease management. Despite such focused efforts, Ugandan banana production is still affected by fungal, bacterial and viral diseases, as well as by other environmental issues due to climate variability, including floods and droughts (Sabiiti et al., 2016).

Crop diversity is an element of agrobiodiversity and is often used as its measure. In relation to food security, crop diversity is the most valuable components of agrobiodiversity (Lenné and Wood, 2011, p. 64). Therefore, this study focuses on crop diversity, understood as the number of crop species and the "evenness" of their distribution. We assess the vulnerability and adaptive capacity of small farms that may face regime shifts caused by significant climate change and crop disease disturbances, and we quantify possible trade-offs and synergies among different outcomes at the farm level. The focus of our analysis is on small banana-growing farms in Uganda facing a banana disease outbreak coupled with climate change, and the related consequences for the agricultural sector. First, we present our theoretical approach and our multi-level modelling methodology. We simulate the changes in markets and technical development at the global level as affected by these drivers through 2050 and evaluate the impact of the resulting changes at the local, farm level.

2. Methods

2.1. Analytical framework

A variety of theoretical and practical approaches have been used to assess the vulnerability and resilience of agricultural systems at different levels (Hahn et al., 2009; Luers et al., 2003; Pandey et al., 2016; Smit and Wandel, 2006; Tambo and Wünscher, 2017). We build on the method developed by Groot et al. (2016), which is based on an assessment of the adaptive capacity and demonstrated recovery of the system. We augment this approach by introducing global regime shifts and analysing their impact through an agrobiodiversity lens. Our goal is to assess the potential of agrobiodiversity in decreasing vulnerability and improving resilience, while quantifying the related trade-offs. We quantify these properties at the farm level in relation to the agroecosystem's buffer capacity and adaptive capacity, as described below.

The initial farm management, in terms of cropping pattern (characterized by crop variety and land area allocated to them), livestock husbandry, and resources used to generate certain socio-economic, environmental and nutritional outcomes. A disturbance, such as a drought or a drop in prices, negatively impacts upon these outcomes, with the extent of the change reflecting the farm's vulnerability level. In order to mitigate the impact of the disturbance, the farmer can change the cropping pattern or can change management practices or inputs. Existing crops and resources available when making such adjustments comprise the 'buffer capacity'. The farmer can also decide to innovate and introduce new crops and management practices. The resulting new set of configurations constitute the 'adaptive capacity' of the farm system. The system's resilience is measured by the recovery of the farm's performance as a result of the farmer's reconfiguration.

We analyse the vulnerability and resilience of a banana-based smallholder in Uganda as affected by a regime change resulting from a banana disease incidence or climate change, and the associated changes in crop productivity and prices. This simulation is conducted over the time period of 2015 to 2050. The situations with modelled impacts of climate change or banana disease are considered regime shifts and are compared to the baseline scenario in 2050. To connect a farm-level analysis to national and global levels of evaluation, we combine two simulation models (Fig. 1): a global economic model called the 'International Model for Policy Analysis of Agricultural Commodities and Trade (IMPACT)' (Robinson et al., 2015), and a bio-economic farm-household optimisation model called FarmDESIGN (Groot et al., 2012). We analyse implications for the food sector of global scenarios assuming climate change or a banana disease outbreak. This macro-level analysis provides information about changes in crop productivity and market prices in temporal and relative terms, as affected by both socio-economic and biophysical factors, and their interactions within the selected scenarios. In the next step we link them to potential responses at the farm-household level and resulting outcomes concerning income, food and nutrition, agrobiodiversity and soil health. Further, we quantify the trade-offs and synergies among these different objectives linked to various farm use arrangements.

2.2. Models

The IMPACT modelling suite is an integrated modelling system that has a partial equilibrium economic model as its core, linked to climate, crop simulation and water models (Robinson et al., 2015) IMPACT has been used to support scenario analyses of long-term opportunities and challenges facing the global food and agricultural sector in regard to food security, climate change and economic development (Enahoro et al., 2018; Mason-D'Croz et al., 2019; De Pinto et al., 2017; Springmann et al., 2018). It is set up in annual time steps and currently runs scenarios covering years 2005 to 2050. A multi-market model of the global economy links agricultural commodity markets (primary and processed crops and livestock) for 62 internationally-traded commodities and 159 countries and political units. Food consumption is determined by income and food prices, summarized by functions describing how they affect demand. Producer behaviour is determined similarly by commodity prices and input costs, while crop production is modelled as a product of cropped areas and yields. Crop yields are a function of commodity prices, prices of inputs, available water, climatic conditions and exogenous trends.

Demographic development, economic growth and climate change are defined outside of the model (i.e. exogenous) and can constitute elements of scenarios. They draw on the work developed for the IPCC AR5 report. Climate data (temperature and precipitation) are used as inputs to the water and crop simulation models. Demographic and economic growth data determine total food demand.

Because countries are linked by trade, IMPACT finds global prices that clear commodity markets (demand equals supply); these global prices equalise supply and demand in domestic and world markets for all commodities, causing net trade to equal zero. As a result, one of the major outputs of the model are sets of crop yields, total outputs and prices of all 62 agricultural commodities. As a result of the scenario analysis, IMPACT defines the external environment in which a farm operates.

A farm is conceived as a management unit consisting of a large array of interrelated components of various types, including biophysical components, the socio-economic setting, and crops and crop products. FarmDESIGN (Ditzler et al., 2019; Groot et al., 2012) therefore combines a bio-economic farm-household model with a multi-objective optimization algorithm to generate a large set of Pareto-optimal alternative farm arrangements largely based on yields and market prices of agricultural commodities. On an annual basis, a static farm balance model calculates flows of organic matter, carbon, nitrogen, phosphorus and potassium to, through and from a farm, with the resulting material balances, the feed balance, the amount and composition of manure, the labour balance and the economic results. The model has been parametrized to reflect the conditions of a banana-producing smallholder farm in Uganda producing both for home consumption and the market. Typically, a farm-household owns two goats and 3.57 ha of land, with 20% dedicated to bananas. Data for the model were collected via farm interviews and a survey ($n = 1217$) in 11 districts in 2015, with a focus on the Nakaseke district in central Uganda. We modelled a typical farm in the Nakaseke district to demonstrate the multi-level modelling framework and the impact of different model scenarios on outcomes at the national and local levels. To keep the data presented in this paper manageable, we did not address the diversity within the farmer population captured by the survey; these aspects will be addressed in a subsequent analysis. FarmDESIGN uses the IMPACT outputs on crop productivity and prices and explores solution spaces that represent the farmers' room to manoeuvre. The FarmDESIGN model shows the consequences of decisions at the field and farm levels, thereby exploring relationships among the different productive, socio-economic, nutrition and environmental farm objectives.

2.3. Scenarios modelled

We consider three different, future scenarios for socio-economic and climatic developments at the regional level:

1. Baseline scenario (BAU) – depicts the status quo of an SES, without climate change, thus allowing the impact of climate change and other regime shifts to be isolated by comparing the results with counterfactual scenarios. Climate-related variables are constant until 2050 and a 'middle of the road' socioeconomic growth (SSP2[1]) is employed, which follows historical trends and has uneven growth.
2. 'Bad climate' scenario (BCL) – a major climate change would occur (we use the IPCC scenario RCP 8.5 —see Riahi et al. (2011) for details about climate change scenarios), coupled with high unsustainable socio-economic growth (SSP5[2]) and high greenhouse gas (GHG) emissions. This scenario combines assumptions about fast population growth and relatively slow income growth, with modest rates of technological change and energy intensity improvements. In the long term, this leads to a high energy demand and GHG emissions in the absence of climate change policies. All the remaining factors are those of the baseline scenario.
3. 'Reduced banana productivity' scenario (RBP) – depicts permanent banana and plantain yield reductions. The rest of the factors are the same as in the baseline scenario. This scenario models a banana disease outbreak that would gradually reduce banana and plantain yields in East Africa over time until 2050. In Uganda, the average yields in 2050 are assumed to be lower by around 40% for bananas and 50% for plantains (and cooking bananas), as compared to the baseline scenario. This degree of productivity reduction due to banana disease outbreaks has been recorded in the past; independent of region and production system, pests and diseases are among the main constraints to banana production, responsible for yield losses of up to 100% (Blomme et al., 2017). In Uganda, the total banana yield loss between 2001 and 2004, strictly due to BXW infection, is estimated at 30–52% (Karamura et al., 2010). Current banana production in Uganda is less than half of the pre-BXW levels (FAO, 2019). Though other factors such as declining soil fertility play a role, pests and diseases seem to be the primary cause of this decline (Jackson et al., 2015).

These three scenarios are analysed with the IMPACT model and conclusions for the food sector (in particular food prices and crop productivity) are drawn. The resulting sets of crop yields and product prices are considered as external drivers, which are subsequently

[1] Shared Socio-Economic Pathways (SSPs) are socio-economic scenarios used to derive emissions scenarios. They consist of a narrative outlining the broad characteristics of the global future and country-level population, GDP and urbanisation projections. SSP2 assumes continuation of historical trends, with uneven growth and environmental degradation.

[2] Rapid growth focused on carbon fuels, ultimately leading to large increases in carbon emissions.

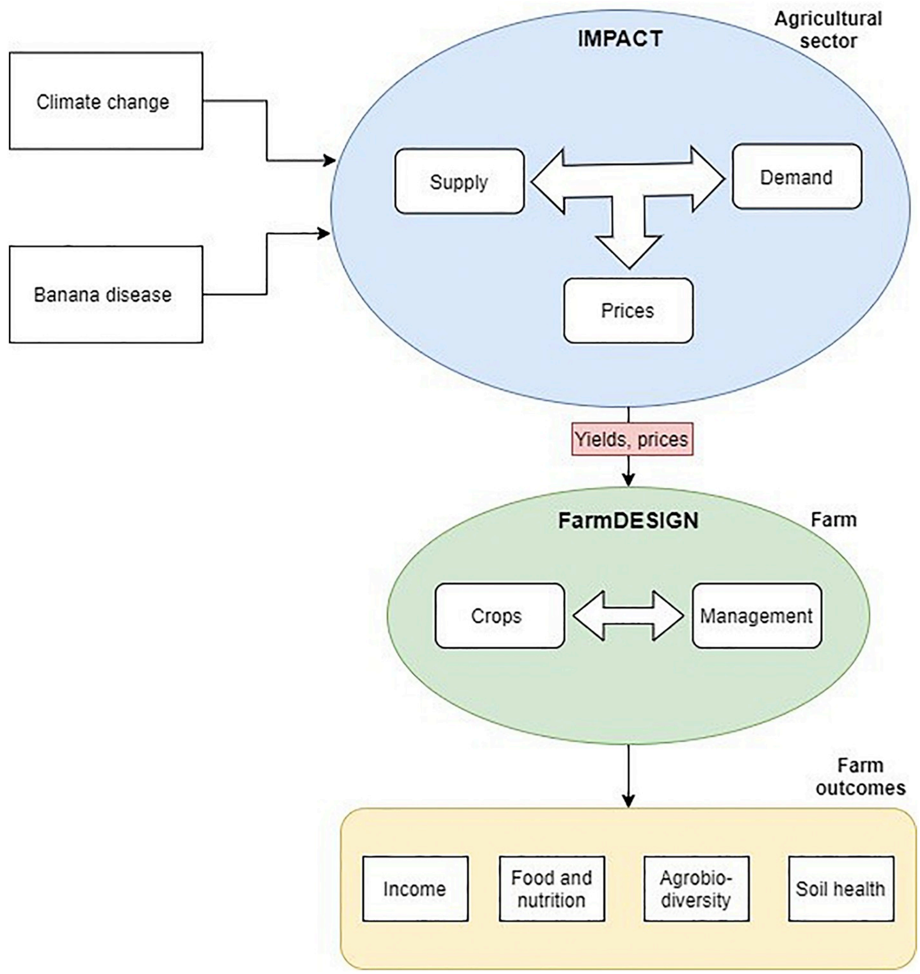

Fig. 1. Analytical framework for linking global scale and farm-scale level analyses with IMPACT and FarmDESIGN models. Adapted from (Bioversity International, 2019, p. 137).

introduced into the FarmDESIGN model to assess the consequences of possible farm arrangements on revenues and to allow for calculations of trade-offs between economic and other farm objectives.

2.4. Farm outcomes and objectives

This analysis considers a representative, small banana-growing farm in Uganda. It grows nine crops: banana, plantain, maize, cassava, sweet potato, beans, coffee, yam and grasses. We also considered seven crops that could potentially be cultivated in addition to the current cropping portfolio, given environmental conditions: avocado, groundnut, jackfruit, Irish potato, mango, pawpaw and tomato.

We linked different farm configurations (various possible distributions of the farmland among crops and the number of goats and dairy cattle) to a number of outcomes, related to four broad goals: high and stable income; food and nutrition security; agrobiodiversity; and soil health. This set of goals allows different aspects of sustainability in agriculture (productivity, socio-economic, environmental and ecological dimensions) and a broad spectrum of farmers' preferences to be considered. By presenting all Pareto-optimal solutions with respect to these goals, we refrain from value judgements in relation to them and allow individuals to prioritise as they see fit.

Crop productivity and revenues were calculated based on the yields and the market prices generated in IMPACT. The production costs were not considered, which is consistent with the IMPACT model's assumption of stable production costs across scenarios. Nutrients produced on one hectare for every crop planted were calculated based on the food composition tables for central and eastern Uganda (Hotz et al., 2012). Potential for soil erosion was quantified in terms of the crop cover factor (C-factor) in Revised Universal Soil Loss Equation (RUSLE). It links soil loss to land cover and land management, and is applicable irrespective of the biophysical environment (Renard et al., 1997; Renard et al., 1991). The C-factor varies between 0 and 1, with a lower score meaning a lower amount of soil erosion. Production of dietary nutrients, particularly vitamin A, was expressed in consumer units that can be eaten given the farm production level, after having corrected for average losses during processing and preparation and for bio-availability (adapted from DeFries et al., 2015). The total nutrient demand for a reference person (male, 30 years of age) was based on individual Dietary Required Intakes (DRI), specifically the Recommended Dietary Allowance (RDA) (Otten et al., 2006).

We selected five indicators as proxies to measure the outcomes that we consider to be important in the context of a small farm in Uganda. We linked them to the farm goals by assigning the desirable direction of change to the indicators (minimizing or maximising), and in this way defined the farm objectives used in the FarmDESIGN model. Through modelling we explored trade-offs and synergies between these objectives:

1 Maximise revenues from crops (USD per farm)
Ending poverty in all its forms is the first of the Sustainable Development Goals (SDGs). Poverty, however, is interlinked with many other challenges to achieving sustainable livelihoods. Poor households are usually more food insecure (Maitra and Rao, 2015)

and vulnerable to different shocks (Akter and Basher, 2014; Lohmann and Lechtenfeld, 2015). Even though Uganda has reduced monetary poverty at a very rapid rate in the past few years, 34.4% of its population still lived on $1.90 PPP per day or less in 2013 (The World Bank, 2016). Importantly, poverty reduction was mainly attributed to increased income derived from agriculture, which highlights the role of agricultural revenues in achieving the SDGs and sustainable livelihoods.

2 Minimise variance of crop revenues (USD)
Excessive food price volatility can have broad, negative consequences, primarily affecting poor producers and consumers by elevating uncertainty and risks associated with future price fluctuations (Kalkuhl et al., 2013; von Braun and Tadesse, 2012). Net food producers may lower their input use and production as a result of high risk levels, especially in developing countries where financial markets do not function well (Binswanger and Rosenzweig, 1986; Donato and Carraro, 2015; Haile et al., 2014)

3 Minimise erosion potential (erosion C-factor, between 0 and 1)
Soil erosion negatively impacts productivity due to direct effects on crops, and has negative environmental consequences due to pollution of natural waters or adverse effects on air quality due to dust and emissions of radiatively active gases (Lal, 1998).

4 Maximise vitamin A production (vitamin A yield, by persons fed per annum)
Vitamin A deficiency (VAD) is considered one of the most prevalent micronutrient deficiencies worldwide, mainly affecting children in developing countries (Wirth et al., 2017). In East and Central Africa, the prevalence of VAD significantly exceeds the World Health Organization (WHO) threshold point of 15% (WHO, 2009). VAD can be addressed through supplementation programmes (administering concentrated doses of vitamin A to at-risk populations), food fortification (the process of adding micronutrients to food), and dietary diversification (horticultural interventions or management of proper distribution and availability of vitamin A-rich foods). While all of these are valid approaches (Chakravarty, 2000), the first two have generally proven difficult to implement in developing countries such as Uganda. Dietary diversification is considered to be an intervention strategy that is sustainable, without requiring external support, and that can simultaneously combat multiple micronutrient deficiencies (Tontisirin et al., 2002).

5 Maximise crop diversity (evenness, as per the Shannon diversity index)
One of most frequently used measures of diversity is the Shannon index (H) (Morris et al., 2014). It quantifies ecological diversity and the "evenness" of distribution of species on a farm, measured by the frequency distribution of crop areas. $H = 0$ if there is only one species in the farm and $H = 1$ when each species occupies the same area on the farm. Thus a monoculture or situations where a few crops occupy large areas of a farm result in a low H value (Oyarzun et al., 2013).

We explored interrelations among the five objectives using the Pareto-based multi-objective optimization in FarmDESIGN (Groot et al., 2012) based on the evolutionary algorithm of Differential Evolution (DE) (Storn and Price, 1997).

To assess the effects of macro trends on farm performance in 2050 as simulated by IMPACT in accordance with the three scenarios, we followed three steps:

a. Multi-objective optimization with the yields and prices in 2050 as simulated in the BAU scenario, resulting in a set of Pareto-optimal farm configurations.
b. Assessing the effect of a regime change on crop productivity and prices due to bad climatic conditions (BCL scenario) or lower banana productivity due to a disease (RBP scenario), by imposing scenario yields and prices on the BAU farm configurations from step a.
c. Multi-objective optimization with BCL and RBP scenario yields and prices, using either the original or expanded crop portfolio (9 and 16 crops, respectively) to assess the buffer and adaptive capacities.

Optimizations were run for 2000 iterations to generate a solution set of 1500 alternative farm configurations, with DE parameters for the crossover probability of 0.85 and amplitude of 0.15. The 'solution space' for the farm system is constituted by combinations of values of the objectives corresponding with configurations derived from the multi-objective optimization. The solution space is delimited by the Pareto frontier, and the size of a solution space dictates the options for adjusting the system. To assess the resilience of the farm we only consider options that perform at least as well as the existing system. The size and shape of the solution space change as a result of system changes and the environment, for example due to technological innovations or disease outbreaks.

3. Results

The crop productivity, prices and resulting revenues per hectare in 2050 for the three scenarios simulated by the IMPACT model are presented in Fig. 2. Climate change (BCL scenario) is projected to have a negative impact on the productivity of all crops currently cultivated (Fig. 2a). However, due to price increases for those crops (Fig. 2b), their revenues are expected to slightly increase compared to the baseline (BAU) scenario (Fig. 2c). Many of the potential intervention crops, such as avocado, jackfruit, mango and papaw are expected to have higher yields under climate change while also fetching higher market prices. As a result, these crops might generate significantly higher revenues than in the baseline scenario.

These differences in price and yield change between the scenarios. For example simultaneous increases in yields and prices are possible because the yields are determined locally, while the prices result from global supply and demand shifts. Also, as a result of expected changes in biophysical conditions, due to climate change predictions, some of the yields in Uganda are expected to grow while others will decline. Prices are expected to increase globally when compared to the scenario without climate change factors. This presents new opportunities for Ugandan farmers to increase their revenues by redesigning their farms and reviewing the crop diversity they plant.

In the case of a banana disease (RBP scenario), all of East Africa, including Uganda, would see lower yields for banana and plantain compared to the baseline scenario. Due to the region's high share in the global trade, this would lead to significantly higher market prices for these two commodities. The rest of the yields and prices in this scenario only change slightly when compared to the BAU scenario (Fig. 2).

Fig. 3 presents the impact of climate change in 2050 on realizations of the four farm objectives resulting from the multi-objective optimization and the interactions between them, scaled between 0 and 1. Overall they form solution spaces and the lines ("hulls") around them indicate the boundaries of the total solution set. The dashed blue line delineates the solution space in 2050 with the nine original crops according to the BAU scenario. The dashed red line delineates the solution space after regime shift due to climate change and without any adaptation measures, while the dashed green line corresponds with the optimized farm, still growing the same set of crops. The solid green line represents a larger solution space due to the introduction of seven new crops to the farm under the BCL scenario. For objectives that are maximized (in this two-dimensional presentation), a shift of the solution space to lower values means that the farm household is worse off in respect to the objective, and has not improved the other objective under consideration. Conversely, a shift to the right means that there are new configurations available, which result in the improvement of at least one of the objectives without compromising another one. For objectives that are minimized, such as the erosion C-factor, the opposite is true.

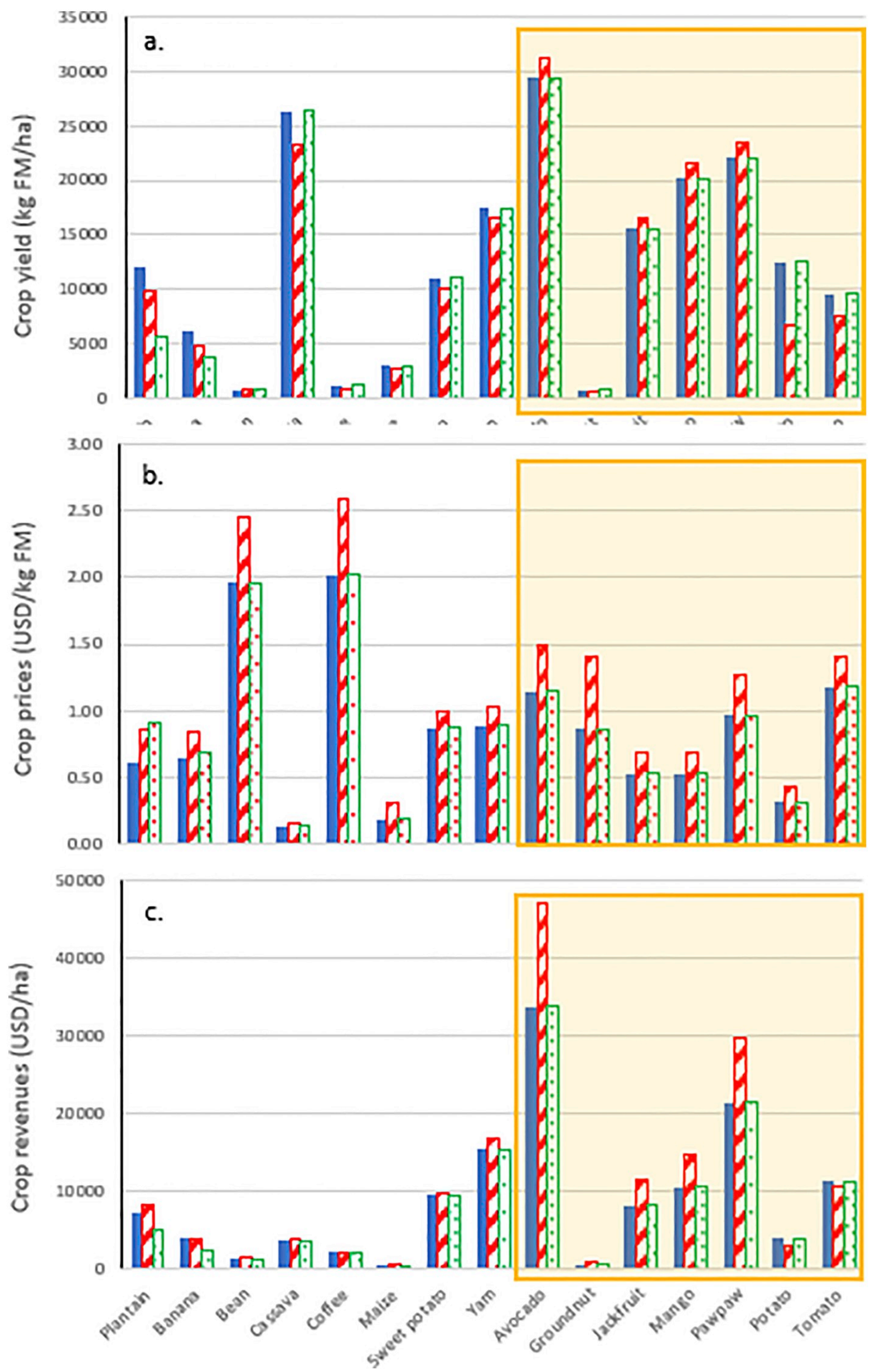

Fig. 2. (a) Crop fresh matter (FM) productivity; (b) Product price in United States Dollars (USD); and (c) crop revenues in US$ in 2050 according to the baseline (BAU), bad climate (BCL) and reduced banana production (RBP) scenarios, as simulated by the IMPACT model. The crops in the box on the right are the potential additional intervention crops.

The shift from the initial BAU optimization towards the disturbed situation (the shift from the dashed blue to dashed red line) can be associated with the farm's vulnerability to climate change, showing the farm's outcomes in the case without adaptation in the farm's configuration. Finally, the shift towards the optimized solution spaces under the BCL scenario (solid green line) can be associated with the farm's resilience level.

The regime shift due to climate change did not affect the erosion C-factor or the Shannon index (Fig. 3f). Due to this shift farm revenues increased somewhat, but vitamin A yields were lower and the variance in revenue levels increased, indicating the vulnerability of these two indicators. A reconfiguration in response to the BCL scenario would reduce most indicators only slightly, while large improvements could be reached by introducing the seven intervention crops, indicating a large adaptive capacity. Most prominently, the intervention crops enable much higher farm revenues and on-farm diversity, while vitamin A yield could be restored to the level of the BAU scenario (Figs. 3g-3j).

Fig. 3 also provides information about correlations between

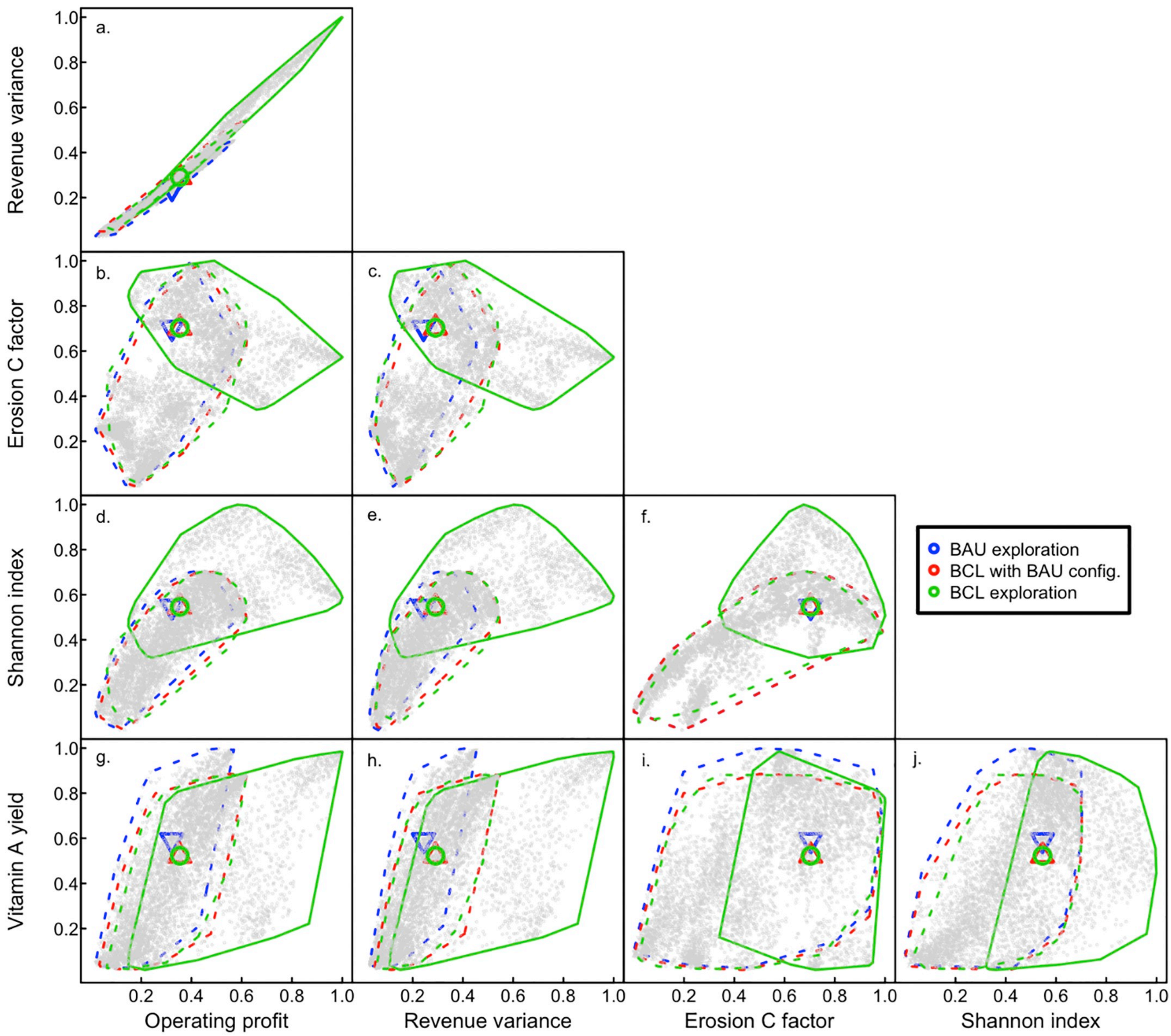

Fig. 3. Solution spaces in 2050 showing the relationship among the five objectives included in the optimization, scaled between 0 and 1. The erosion C-factor was minimized, other objectives were maximized. The dashed lines indicate the solution spaces with the nine original crops, the solid green lines represent the results with introduction of seven new crops into the farm. The hulls are drawn around solution sets, as indicated by the grey symbols. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

different farm outcomes, allowing an analysis of trade-offs and synergies among the selected objectives. For instance, increasing revenues would come with a strong trade-off of increased revenue variance (Fig. 3a), indicating that farmers would be more vulnerable to yield and price fluctuations. This trade-off can be linked to a stronger focus on a small number of profitable crops —the highest levels of revenues and revenue variance are achieved with intermediate values of the Shannon Index (Fig. 3d and e). Concerning crop diversification, low erosion levels and high vitamin A yields would be obtainable at high values of the Shannon index.

Actual (non-scaled) indicator values for extremes of the solution spaces for both BCL and RBP scenarios are presented in Table 1. Again, the results indicate that climate change can create opportunities to significantly increase revenues, however, with larger variance in revenue levels. Alternatively, banana disease can significantly reduce revenues (and their variance) —halving average and maximum farm revenues. Adding intervention crops would enable recovery almost to the level of the baseline revenues while improving on-farm species diversity, which demonstrates the importance of having a diverse production when reconfiguring the farm to respond to shocks and regime shifts. As a result of adding new crops, average erosion C-factor increases slightly under both scenarios, but the maximums (worst-case results) are close to or even below the original values. The Shannon index could increase with additional crops under both scenarios. Vitamin A yield could be significantly reduced as a result of climate change if no measures are taken. After adding the intervention crops, the farmer has a possibility to recover most but not all of the vitamin A yield. Banana disease creates much less pressure on this outcome, leaving space for even higher maximum Vitamin A yields after the introduction of the new crops. Overall, these results suggest that banana disease can increase vulnerability to revenue loss, whereas climate change can make farmers more vulnerable to both revenue fluctuations

Table 1
Average, worst and best outcomes for indicators in 2050 under the 'Baseline' scenario and after regime shifts before (impact) and after adaptation measures (recovery).

Scenario	Revenues	Revenue variance	Erosion C-factor	Shannon index	Vitamin A yield
BAU Original (9)	12,368 (1670; 22,832)	3783 (6817; 1202)	0.213 (0.312; 0.136)	1.68 (1.01; 2.2)	75.9 (6.7; 142.4)
BCL Impact (9)	13,548 (2242; 24,778)	4487 (8031; 1477)	0.213 (0.312; 0.136)	1.68 (1.01; 2.2)	67.6 (5.5; 126.6)
BCL Recovery (16)	22,380 (6686; 39,421)	7767 (14,031; 2246)	0.255 (0.313; 0.197)	2.14 (1.55; 2.7)	70.4 (5.5; 140.4)
RBP Impact (9)	10,662 (950; 19,884)	3047 (5585; 813)	0.213 (0.312; 0.136)	1.68 (1.01; 2.2)	70.1 (3.3; 131.3)
RBP Recovery (16)	20,058 (5328; 35,074)	6554 (12,011; 1539)	0.249 (0.308; 0.198)	2.17 (1.54; 2.7)	73.9 (4.1; 149.2)

Note: In the scenario column, there are three parameters – IMPACT model scenario: BAU, BCL, and RBP; farm configuration; and the number of crops cultivated on the farm. Thus, Original (initial configuration with 9 crops under BAU scenario in 2050), Impact (initial configuration with 9 crops after regime shift), and Recovery (configuration after adaptation by adding 7 intervention crops, resulting in the total of 16 crops, after regime shift). The outcomes are reported with their mean values, followed by worst and best possible outcomes in parentheses.

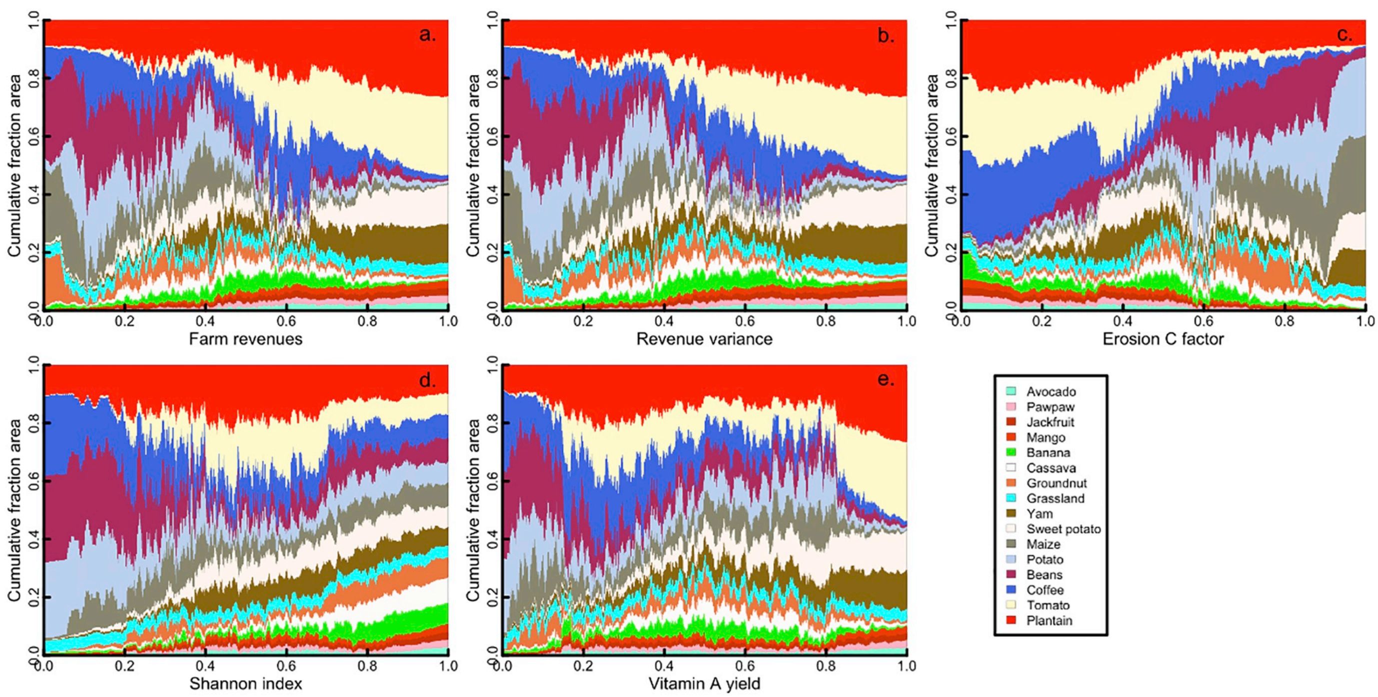

Fig. 4. Changes in crop areas as related to indicator performance in the multi-objective optimization under the climate change scenario in 2050. The indicators are scaled between 0 and 1.

and vitamin A loss.

Results presented in Fig. 4 allow as analysis of the contribution of individual crops to the objectives. Fig. 4a and b show that the crops contributing to higher farm revenues also increase revenue variance. Under the climate change scenario, plantain, tomato, sweet potato and yam bring the highest and most volatile revenues. These four crops also generate large vitamin A yields (Fig. 4e). Interestingly, plantain and tomato, alongside coffee, are the top three crops to for minimizing erosion (Fig. 4c). Fig. 4d provides an illustration of the Shannon index design —the highest levels are obtained via an approximately equal allocation of land to all crops.

4. Discussion and conclusions

Farm households and rural communities have long used agricultural biodiversity to manage pests, diseases and weather-related stresses, as well as to diversify their diets. During the last 60 years, however, policymakers and researchers have considered these approaches to be economically uncompetitive. During the Green Revolution, improved varieties and other new technologies benefitted many poor consumers in developing countries by providing significantly cheaper sources of calories, while simultaneously generating higher incomes for many farmers (Evenson and Gollin, 2003). However, they did not manage to equally benefit farmers in "marginal" environments (ibid), and neglected nutritional aspects of food security, as dietary diversity in fact decreased for many poor people (Pingali, 2012). Moreover, the new technologies and higher input levels often resulted in environmental damage —leading to high water use, soil degradation and chemical runoff (ibid), while genetic diversity of cultivated crops (and animals kept) was also reduced considerably. The complexity of issues related to sustainable intensification is being increasingly recognized (Musumba et al., 2017). Furthermore, scientific evidence has demonstrated that agricultural biodiversity, in combination with innovative technologies and approaches, has much to offer in addressing these challenges (Bélanger and Johns, 2008; Bellon, 2004; Di Falco and Chavas, 2009; Jarvis et al., 2008; Johns and Sthapit, 2004). However, there is still a limited understanding of the spatial and temporal relationships between the elements of this complex puzzle.

Our study contributes to this important discussion on trade-offs among various objectives related to agricultural production, keeping in mind the complexity of a farm as an agroecological system, as well as the complexity of human needs, that go beyond calories and income. We focus on farm-level objectives and analyse them in the light of future global challenges and drivers of agricultural production. We show that a typical smallholder farm in Uganda can use crop diversity to improve the farm's capacity to adapt after regime shifts associated with climate change and banana disease. We expose trade-offs for socio-economic and environmental outcomes and provide a detailed analysis of trade-offs between available crops. It is an important step towards better understanding the opportunities available to farmers managing mono-cropped systems versus biodiverse systems, and how to design adequate and supportive policies. Our results can also help farmers design their farms in such a way that would better meet their complex needs. Our conceptual and modelling framework linking global trends and regime shifts to farm outcomes can also serve when considering potential future challenges and their implications for farmers and policymakers around the world.

In our case study, we demonstrate that it is a good strategy for a farmer to increase the farm's agricultural biodiversity in order to improve its resilience to shocks, soil health and nutrition. However, the farmer should be aware of the potential trade-offs among different objectives. For example, by increasing the number of cultivated crops, they will not achieve the highest income; by growing a small selection of the most profitable crops, they can increase their potential revenues, but will also increase the volatility of revenue levels. This type of analysis provides information about farmers' potential room to manoeuvre and it can identify incentives for farmers to maintain a broader on-farm agrobiodiversity, eventually leading to greater ecosystem services at larger scales and increased public benefits (Carmona-Torres et al., 2011; Parra-López et al., 2009).

We further identify potential areas for interventions that can reduce Ugandan farmers' vulnerability to future regime shifts. For example, under climate change we find that a farm's revenue volatility will increase and hence we stress that providing income-smoothing solutions for farmers will be increasingly important. These could be in the form of agricultural insurance or credit (Wik, 1999). A banana disease can have a negative impact on revenue levels and nutrition, hence policies focusing on these outcomes will be needed.

It is important to emphasize that our methodology is based on scenario analysis and is fundamentally different from forecasting, which should take into account all the key factors that will affect future food supply, demand and governance in smallholder agricultural farming. These factors are very difficult or even impossible to predict over the coming decades. On the contrary, simulation analysis uses information about the current food system's dynamics in order to understand how possible future changes in the major drivers, grouped into scenarios, could affect the food system. These scenarios are varied, internally consistent narratives about the future (Wilkinson and Kupers, 2014). With our study we intend to estimate potential future trends and provide insights into changes in windows of opportunity, given these likely future scenarios. Furthermore, we focus on a single representative farm and do not address the diversity in smallholder farming systems or implications at the landscape level. With this study, instead, we provide a conceptual approach to illustrate the effective integration of two models operating at different hierarchical levels and on temporal and spatial scales. This approach can be applied to a variety of sites in order to inform decision-makers on how to benefit from synergies and manage trade-offs between crop diversity conservation, nutrition, environmental protection and human nutrition, considering possible future scenarios.

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Declaration of Competing Interest

None.

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