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Can crop diversity strengthen small-scale farmers' resilience?

Modelling future global biophysical and economic trends to understand individual farmers' resilience options

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KEY MESSAGES:

- When making decisions about which crops to plant, farmers consider both how to maximize profits, and to minimize risks. They also have other goals in mind: diversifying crops to improve diets or selecting crop combinations that improve soil health, for example.
- Not only do farmers look at farm level but also at trends in their environment. Which crops are in demand? Which are more vulnerable to disease? Which command higher prices?
- In this paper, we explore options for a typical smallholder farmer making decisions on their farm in the context of different global trends with the aim of optimizing a variety of goals.
- One objective is to see how crop diversity can help the farmer reach their goals even when confronting different disturbances. The second is to quantify possible trade-offs and synergies between different goals, depending on the planting decisions.

Introduction

All human societies comprise a complex interaction of people and nature. Our choices as consumers and producers of food have a direct impact on the ecological world, and in turn the natural world of crops, soils, trees, air, water, insects and so on provides services to us, such as food, clean air, clean water and income. These interactions between people and nature are often called socioecological systems and the services called ecosystem services. Studies into vulnerability and resilience assess the human and natural characteristics of socioecological systems and their interactions (1).

Agricultural biodiversity consists of crops and their wild relatives, trees, animals, microbes and other species that contribute to agricultural production. It is a key element of healthy and stable socioecological ecosystems and a major driver of ecosystem services (2–5). It is important for diversified and nutritious diets, as well as for the genetic resources that allow farmers and plant breeders to adapt a crop to diverse and changing environments, for example under climate change (6). Biodiversity is a key asset of the rural poor in lower-income countries, who depend on agriculture for their livelihoods and well-being (7). Farm households and rural communities have long used agricultural biodiversity to manage pests, diseases and weather-related stress, provide soil health and water conservation, and to diversify their diets (8–13).

Different levels of agrobiodiversity on farm can realize different sets of farm goals (e.g. income, food and nutrition security, soil health and natural environment) that shape the vulnerability and resilience of socioecological systems. Resilience is the capacity of the system to 'bounce back' from a disturbance.

Climate change is one of the largest global challenges to agriculture and food security, with agricultural productivity set to decline and prices set to increase as a result. This effect will, however, be unequally distributed across regions and crops, with some areas actually benefiting from new climatic conditions, and some crop yields being more affected than others. Climate change is expected to increase crop vulnerability to pest and disease outbreaks (15). The impact of pests and diseases on agricultural production can vary from minor to completely devastating (16, 17). The real prices of all agricultural commodities will increase until the year 2050, with the prices of maize, rice and wheat projected to increase by up to 30% in the most extreme climate scenario. The impact on food security will be worst in sub-Saharan Africa (18).

Farmers manage vulnerability and resilience on their farms by dynamically adjusting the practices they use and the crops they plant. The initial management choices, for instance cropping pattern, animals kept and resources used, generate certain outcomes, like income or nutrition. Following a disturbance, like a drought or a decline in the price of a product, the outcomes deteriorate and the farmer can respond by reconfiguring the farm through changing the space she allocates to her existing crops, or she can try new crops, farming practices or inputs, in order to get the farm system's performance back to the pre-disturbance level.

When making decisions about which crops to plant, farmers consider how to maximize yield, but minimize risks. They also have other goals in mind: diversifying crops to improve diets, selecting crop combinations that improve soil health, among many others. Not only do they look at farm level but also at trends in their environment: Which crops are in demand? Which are more vulnerable to diseases? Which command higher prices?

In this paper, we explore the options for a typical smallholder farmer making decisions on his farm in the context of different global trends with the aim of optimizing a variety of goals. One objective is to see how crop diversity in particular can help the farmer reach his goals even when confronting different disturbances. A second objective is to quantify possible trade-offs and synergies among different goals depending on the planting decisions the farmer makes.

For modelling purposes, we imagined a small-scale banana-growing farm in Uganda facing challenges of a banana disease outbreak and climate change over the coming 30 years. The farmer grows nine (basic) crops: banana, plantain, maize, cassava, sweet potato, beans, coffee, yam and grassland. We considered seven additional (intervention) crops, which the farmer could potentially add to the farm. These are avocado, mango, pawpaw, groundnut, jackfruit, Irish potato and tomato.

Setting the context

In Uganda, bananas and plantains are among the most important staple food crops, contributing to rural populations' household food security, revenues and culture. Additionally, bananas play an important role in environmental conservation, because they provide a good, permanent soil cover that reduces soil erosion on steep slopes, and are a principal source of mulching material for maintaining and improving soil fertility (19). Smallholder banana systems dominate banana-farming systems in Uganda (20). These systems are perennial, low input and rural based. The first purpose of these systems is food security, but commercial interests have become increasingly important as of recent years.

Banana production is affected by fungal, bacterial and viral diseases, like Panama disease, black Sigatoka or banana Xanthomonas wilt (21–23), as well as by other environmental issues due to climate variability, including floods and droughts (15). Bananas are particularly vulnerable to disease as a result of very low genetic diversity – cultivated bananas are practically seedless and so are reproduced by using tissue culture (like cuttings), making them essentially clones of the original plant (24). Panama disease (Fusarium wilt), which in the 1900s wiped out production worth at least US$2.3 billion (in 2000 prices) and caused major socioeconomic crises in affected regions, is a prime example of the risks that are inherent in the use of crop monocultures and bananas in particular (25).

Modelling concept

In order to assess the potential role of crop diversity in reducing vulnerability and improving resilience, we combined two existing modelling tools.

IMPACT stands for the International Model for Policy Analysis of Agricultural Commodities and Trade. It is used to support scenario analysis of long-term opportunities and challenges related to food security, climate change and economic development facing the global food and agricultural sector. It is set up in annual time steps and currently runs scenarios covering years 2005 to 2050. A multimarket model of the global economy links agricultural commodity markets for around 62 internationally traded (primary and processed crop and livestock) commodities and 159 countries or country groupings.

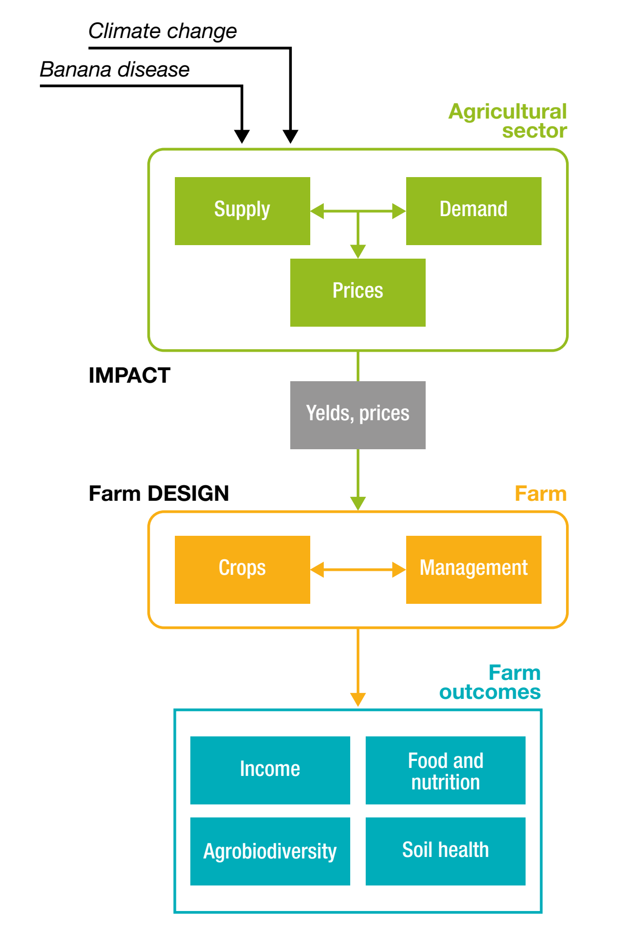
FarmDESIGN shows the consequences of decisions at farm and field level, and explores relations between different productive, socioeconomic, nutritional and environmental farm goals (26, 27). We set the model to reflect the conditions of a banana-producing farm in Uganda that produces for both home consumption and market. It owns no cattle and the size is 5.3ha with around 40% dedicated to bananas. We collected data for the model by conducting interviews with 1,217 randomly selected households in 11 districts in 2015.

We combine the two models – of global agricultural markets and of farmer management decisions on the farm – so that we can assess the implications of climate change or a banana disease outbreak for four important farm goals (income, food and nutrition, agrobiodiversity and soil health), and trade-offs and synergies between the goals until the year 2050 (Figure 1). We considered three different future scenarios (baseline, climate change, disease incidence), and two sets of crops available for cultivation (nine basic plus seven intervention crops) (28). We modelled how farm resilience would be affected by stress disturbances resulting from disease incidence or climate change, and associated price changes until 2050.

We answer three main questions using the integrated models:

1. Under the three future scenarios, what is the potential for crop diversity to increase resilience and in what ways might climate change or disease outbreak increase vulnerability?
2. What are the trade-offs and synergies between different farm goals ?
3. How does the cultivation of different individual crops influence the farm goals?

FIGURE 1 – Conceptual framework for linking global scale to farm scale with IMPACT and FarmDESIGN models



Three global future scenarios

In the model, we consider three scenarios representing possible global futures, built around climate change, socioeconomic trends and a banana disease outbreak.[i]

Baseline scenario: assumes the status quo of the socioecological system. In this scenario, there is no climate change, meaning that climate-related variables are constant until 2050. When it comes to socioeconomic development, we assume similar growth as observed in the past – uneven demographic and economic growth globally.

Bad climate scenario: assumes severe climate change coupled with high unsustainable socioeconomic growth, producing high greenhouse gas emissions. The other factors are the same as in the baseline scenario.

Banana -50% scenario: assumes a banana disease outbreak that reduces banana and plantain yields annually by 50% in East Africa until 2050. The other factors are the same as in the baseline scenario.

The first step is to analyze these three scenarios with the IMPACT model to draw implications for the food sector, in particular crop productivity and food prices. The resulting sets of output levels and prices until 2050 are then introduced into the FarmDESIGN model to assess the consequences of possible farm configurations for revenues and allow calculation of trade-offs between various farm goals.

Farm outcomes and goals

We linked possible distributions of the farmland among crops (different farm configurations) to four desirable farm outcomes: high and stable income, food and nutrition, agrobiodiversity and soil health. We selected six indicators to measure (some aspects of) these outcomes that we considered to be important in the context of a small farm in Uganda (Table 1). Through modelling with FarmDESIGN we explored trade-offs and synergies between these goals.[ii]

TABLE 1 – Farm goals and indicators to measure them used in modelling with FarmDESIGN.

Farm goals	Indicators
High and stable income	Maximize revenues from crops
	Minimize variance of crop revenues
Nutrition security	Maximize vitamin A yield
Crop diversity	Maximize crop diversity measurement (Shannon index)
Soil health	Maximize farm nitrogen balance
	Minimize erosion potential

High and stable income: We chose to maximize revenues from crops, and also to minimize variance of crop revenues because excessive food price volatility has broad negative consequences, primarily affecting poor producers and consumers, by elevating risks of future prices (29, 30). As a result of high volatility, net food producers, especially in low-income countries where financial markets do not function well, may lower their input use and consequently their agricultural output (31–33).

Nutrition security: We chose vitamin A yield as the nutrition security indicator. Vitamin A deficiency is considered one of the most prevalent micronutrient deficiencies worldwide, mainly affecting children in low-income countries (34). In East and Central Africa, the prevalence of vitamin A deficiency significantly exceeds the World Health Organization threshold of 15% (35). Vitamin A deficiency can be addressed through supplementation programmes (administering concentrated doses of vitamin A to at-risk populations), food fortification (adding micronutrients to food), and dietary diversification (adding naturally vitamin A-rich foods to diets). While all of these are valid approaches (36), the first two have generally proven difficult to implement in low-income countries such as Uganda. Dietary diversification is considered to be an intervention strategy that is sustainable without external support and can simultaneously combat multiple micronutrient deficiencies (37).

Crop diversity: We aim to maximize crop diversity on farm, because it is one strategy farmers use to strengthen resilience to climate change and pests. The contribution may arise from the choice of crop (climate- or pest-resistant, for example), the portfolio effect of having different crops which react differently to different disturbances, increasing the chances that not all crops are equally vulnerable, or from synergies between different crops (for example, growing nitrogen-fixing legumes like beans alongside pumpkins).

Soil health: When it comes to soil health, we focus on minimizing soil erosion while maximizing nitrogen balance. Soil erosion affects productivity negatively due to loss of nutrients, and has negative environmental consequences due to pollution of natural waters or adverse effects on air quality due to dust and emissions of gases (38). Soil nutrient depletion is one of the major causes of declining per capita food production in sub-Saharan Africa. Adequate soil management will be required to sustain food security in the light of increasing population densities (39).

Vulnerability and resilience of smallholder farmers under different scenarios

A farmer's room to manoeuvre is determined by the farm configuration and management options she has available. The more opportunities a farmer has to recover system performance after a disturbance to get her farm goals back to or beyond original performance, the more resilient the farm is.

The potential for crop diversity to reduce vulnerability and increase resilience

We analyzed the consequences of cultivating only the nine basic crops versus adding seven intervention crops to the farmer's portfolio. Adding intervention crops improved the farmer's possibilities of achieving all her goals. This means that the farmer has more opportunities to respond to future disturbances related to climate change or banana disease outbreak. Higher species diversity increases farm resilience.

Through comparing the options under the three different global scenario results, we see that climate change will create more income opportunities – potential and average crop revenues are the highest under the climate change scenario. However, this comes with higher uncertainty of income – the highest average and potential revenue variance are also under this scenario. These results suggest that climate change can increase vulnerability of smallholder farmers in Uganda with respect to their income. Banana disease significantly decreases the potential for achieving vitamin A yield and slightly increases soil erosion potential. Implications are that banana disease can put pressure on nutrition and sustainability of production.

The trade-offs and synergies among different farm goals

Analysis of trade-offs and synergies between the selected farm goals reveals intuitive patterns. For instance, increasing revenues from cropping comes with a trade-off of slightly more erosion potential (Table 2). The biggest trade-off was between the economic indicators of revenues and their variance. A focus on a small number of profitable crops means higher revenue in good years, but more risk of crop failure. Adding more crops to the farm has a significant positive impact on soil health (especially soil erosion) and nutrition (vitamin A yield). Although on average crop diversity slightly increases revenue variance, the lowest variance of revenue was found at the highest levels of crop diversity.

TABLE 2 – Trade-offs and synergies among indicators for the 'Business as usual' scenario. Positive numbers indicate a synergy (marked in yellow and green), negative numbers a trade-off (marked in orange and red).

	Crop diversity	High and stable income		Nutrition security	Soil health	
	Shannon index	Crop revenues	Revenue variance	Vitamin A yield	Erosion potential	Nitrogen balance
Shannon index		0.177	-0.361	0.399	0.627	0.240
Crop revenues			-0.958	0.791	-0.082	-0.052
Revenue variance				-0.911	-0.154	-0.148
Vitamin A yield					0.278	0.498
Erosion potential						0.307
Nitrogen balance						

Influence of different crops on the farm goals?

Finally, we analyze how each crop impacts the farm goals (Table 3). Correlations between areas of specific crops and the performance indicators can be used to inform farmers about the consequences of their planting choices. The production of yam was strongly correlated with crop revenues, but would also lead to higher erosion potential and variance of revenues, hence more economic and environmental risks for farmers. Tomato cultivation could contribute strongly to vitamin A yield and the nitrogen balance of the farm, while generating significant but volatile revenues. The worst performing crops from an economic, environmental and nutritional perspective were groundnut, beans and coffee. Introduction of the new, intervention crops (marked in grey), would positively influence crop diversity (increase Shannon index).

TABLE 3 – Correlations between the area of different crops and the performance indicators (sorted by declining correlation with crop revenues) for the 'Business as usual' scenario.

The intensity of a colour indicates the strength of correlation between a crop area and a performance indicator. Shades of green are assigned to positive (desirable) impacts and shades of red to negative (disadvantageous) impacts.

Crop	Crop diversity	High and stable income		Nutrition security	Soil health	
	Shannon index	Crop revenues	Revenue variance	Vitamin A yield	Erosion potential	Nitrogen balance
Yam	-0.151	0.861	0.684	0.408	0.496	-0.380
Tomato	0.288	0.560	0.717	0.923	-0.302	0.696
Avocado	0.568	0.519	0.605	0.424	-0.348	-0.162
Pawpaw	0.598	0.459	0.629	0.729	-0.517	0.387
Mango	0.585	0.337	0.511	0.639	-0.548	0.449
Jackfruit	0.741	0.134	0.298	0.344	-0.627	0.228
Grassland	-0.066	0.102	0.080	0.074	0.085	-0.013
Cassava	-0.024	0.025	0.022	0.047	0.115	0.115
Irish potato	0.387	-0.022	0.045	0.075	-0.132	0.115
Maize	-0.100	-0.150	-0.295	-0.485	0.484	-0.638
Plantain	0.253	-0.159	-0.009	0.054	-0.683	0.295
Sweet potato	-0.027	-0.169	-0.161	-0.109	-0.059	0.031
Sweet bananas	0.639	-0.179	0.029	0.192	-0.739	0.517
Coffee	0.143	-0.309	-0.281	-0.388	-0.540	-0.519
Beans	-0.656	-0.487	-0.674	-0.747	0.617	-0.450
Groundnut	-0.128	-0.634	-0.571	-0.328	0.207	0.532

Conclusions: What does this mean for farmers and policymakers?

This study contributes to an important discussion on trade-offs between various objectives related to agricultural production, keeping in mind the complexity of a farm as an agroecological system and the complexity of human needs, going beyond calories and income. We analyze farm-level goals in the light of global challenges to agricultural production of the future. We show that crop diversity can significantly improve resilience to climate change and banana disease of a small farm in Uganda over the next 30 years.

Modelling different scenarios, different crop configurations and different goals is important for farmers and policymakers when making decisions to achieve short- and long-term goals in dynamic situations of change. This kind of exercise can be used at a national or regional level by those designing policies to reach multiple goals (nutrition, soil health, revenue etc). It can also be useful for farmers to help design their farms to better meet their complex needs.

The models indicate that increasing crop diversity is generally a good strategy – it leads to more resilience, better soil health, more stable income and better nutrition. However, decision-makers need to be mindful of the trade-offs between different objectives. Increasing the number of cultivated crops will improve most farm-level goals, but will not achieve the highest potential income. On the other hand, growing a small selection of the most profitable crops maximizes potential revenues, but also increases risk, due to their volatility. Since banana disease and climate change can have a negative impact on nutrition and soil productivity, diversity-maximizing polices supporting these outcomes will be very relevant.

This example of modelling a smallholder banana farm in Uganda is relevant elsewhere. In the framework of Agenda 2030, in which the Sustainable Development Goals are "an indivisible whole" policymakers need solutions which combine economic prosperity, social justice and environmental protection. Integrating models that combine on-farm decision-making with global agricultural market trends is an approach that can be used in low-, middle- and high-income countries to understand how to generate synergies and manage trade-offs so that global goals of crop diversity conservation, nutrition, environmental protection and human nutrition can be considered and managed together. For smallholders and actors working with them, analyses of trade-offs and synergies open spaces for increasing resilience at a farm-household level that link up to strengthen resilience at regional and global levels.

Notes

[i] This methodology is called scenario analysis. It is different from forecasting, which should take into account all important factors that will affect food supply, demand and governance in the future. These factors are very difficult or impossible to predict over the next decades. On the contrary, scenario analysis uses information about the current dynamics of the food system to understand how possible future changes of the major drivers, grouped into scenarios, could affect the food system. Scenarios are different, internally consistent narratives about the future (40).

[ii] Crop revenues were calculated based on the market prices generated in IMPACT. Production costs were not taken into account. Nutrients produced on 1ha of every crop were calculated based on the food composition table for Central and Eastern Uganda (41). Soil erosion was calculated based on the crop cover factor (C-factor) of the Revised Universal Soil Loss Equation (RUSLE). The C-factor links soil loss to land cover and land management and is independent of the environmental conditions (42, 43). Nitrogen balance was calculated based on data on the nitrogen content of farm inputs and crop products using food composition tables of HarvestPlus and USDA (41, 44). The Shannon diversity index (H) was used as an indicator of crop diversity. It quantifies the ecological diversity and 'evenness' of distribution of species in a farm (measured as a farm's frequency distribution). H = 0 if there is only one species on the farm and H reaches its maximum when each species occupies the same area on the farm. Thus, a monoculture results in a low value for the Shannon index (38).

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Cleaning and drying grains in the Tigray region, Ethiopia. Credit: Chiara Mancini

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