# Diverging perspectives on diversification

A multi-objective Pareto-based optimisation for smallholder farmers under banana Xanthomonas wilt (BXW) pressure in Uganda


**MSc Thesis Farming Systems Ecology Group**

Droevendaalsesteeg 1 – 6708 PB Wageningen - The Netherlands

Author: T.I. (Tamar) de Jager


**July 2018**

# Diverging perspectives on diversification

## A multi-objective Pareto-based optimisation for smallholder farmers under banana Xanthomonas wilt (BXW) pressure in Uganda

| | |
|---|---|
| Name student: | T.I. (Tamar) de Jager |
| Registration number: | 930110387050 |
| Course code: | FSE-80436 |
| Period: | September 2017 – July 2018 |
| Supervisor(s): | dr. ir. J.C.J. (Jeroen) Groot and W. (Walter) Ocimati MSc |
| Examiner: | dr. ir. F.J.J.A. (Felix) Bianchi |

# Diverging perspectives on diversification

## *A multi-objective Pareto-based optimisation for smallholder farmers under banana Xanthomonas wilt (BXW) pressure in Uganda*

T.I. de Jager[1], W. Ocimati[1,2], E. Kikulwe[2], J.C.J. Groot[1]

[1]Farming Systems Ecology, Wageningen University and Research, P.O. Box 430, 6700 AK Wageningen, the Netherlands; [2] Bioversity International, P.O. Box 24384, Kampala, Uganda; Bioversity International, Rome.

## Highlights

- Minor changes in farm planning can result in major changes for revenues, nutrition and soil quality.
- Perennial fruits, vegetables and roots and tubers can improve farming systems in Central Uganda.
- Replacing banana by other crops is difficult for farmers, because of the numerous roles of bananas
- Semi-commercial farmers prefer redesigns optimised for profitability, subsistence farmers for nutritional value.
- FarmDESIGN modelling software can support farmers in making farm-management decisions.

## Abstract

In farm planning, smallholder farmers constantly have to consider the impact of their decisions on their revenues, household food production and soil quality. FarmDESIGN modelling software can support farmers in making these decisions at farm level by providing insight on the impact of decisions and exploring alternative farm configurations. In Uganda, due to Banana Xanthomonas Wilt (BXW) that causes the demise of entire banana plants and premature ripening and rotting of fruits, millions of households suffer from food and income insecurity. In this study we show that minor changes in crop choice and farm planning can result in major changes in farm performance for objectives related to revenues, nutrition and soil quality while working on the same area of land with crops locally grown. Our results demonstrate that farmers in Central Uganda can improve their revenues, food production and soil quality by replacing part of the maize, coffee, cooking bananas and beans by tomatoes, yam, mango, jackfruit, pawpaw, avocado, cassava, sweet potato and groundnuts. The integration of perennial fruits, vegetables and roots and tubers can improve farming systems for all objectives in Central Uganda. Furthermore, we found that larger, semi-commercial farmers prefer redesigns optimised for profitability while small, subsistence farmers prefer redesigns optimised for nutritional value. Redesigned farming systems provide farmers an alternative for traditional banana-based systems. Now that the model has been built, this research can be extended to other areas of Uganda and neighbouring countries with similar bio-physical and socio-economic characteristics and function as a starting point to instigate conversations with farmers about their future farming systems.

**Keywords:** *FarmDESIGN, farm planning, farm level, disease pressure, alternatives*

## List of tables



## List of figures

# Table of contents

# 1 Introduction

Banana Xanthomonas Wilt (BXW), a devastating bacterial disease caused by *Xanthomonas campestris* pv *musacearum*, causes the demise of entire banana plants and premature ripening and rotting of bananas. All banana cultivars and genome groups are susceptible to the disease (Biruma, et al., 2007). It spreads mainly through the use of contaminated garden tools, insect vector transmission and infected planting materials (Blomme, et al., 2014). In Uganda yields of cooking bananas in 2015 are 52% lower than before the outbreak of BXW in 2001 (Kikulwe, 2015). Because bananas are the staple food and an important source of income for many Ugandan farmers, due to BXW, millions of households suffer from food and income insecurity (Edmeades, et al., 2007; Tripathi, et al., 2009; Dowiya, et al., 2010). In addition, removing banana plants increases the risk of erosion. Bananas are a perennial crop with broad leaves that provide permanent soil cover to protect the soil against water erosion (Ocimati, et al., 2017).

Farmers have difficulties adapting their farming practices. Most of the banana plantations are still in use (68.2%) or are replanted with banana plants (21.7%). Only 6.6% of the farmers have planted other crops instead of bananas (Kikulwe, 2015). The remaining 3.6% of the plantations is left abandoned. Diversification could be an option to overcome disease pressure. Farmers would create new and more stable sources of food and income, increase nutritional diversity and spread the risk of losses. Furthermore, farmers would create an environment that is less attractive to BXW, since a monoculture of bananas is the ultimate habitat for BXW (Shepard, 2014).

In this study we explored diversification options for farmers in Uganda based on 29 interviews, 1217 household surveys, a farm typology, a trade-off analysis based on market research and literature study, and calculations with the FarmDESIGN farm-household model. FarmDESIGN is a computer model to simulate and redesign farming systems (Groot, et al., 2012). With FarmDESIGN a multi-objective optimisation was carried out, optimising the system towards increased revenues from sales, nutritional value and soil fertility, and reduced soil erosion. The ultimate aim was to design diversified farming systems that are Pareto-optimal, i.e. systems that cannot be improved for one of the objectives without compromising one of the others, thus being economically sound and ecologically sustainable, while improving diets. The redesigns were used to provide farmers insight in the consequences of their decisions and the trade-offs related to different crops.

The main research question is: *Which diversification options as alternatives for banana production under pressure of BXW are Pareto-optimal in terms of revenues, nutrition and soil quality for different types of farms?* The answers found to this question were discussed with farmers in focus-group discussions and used as a starting point for conversations with farmers about their future farming systems. This question was raised within the CGIAR Research Program on *Roots, Tubers and Bananas* and was addressed by Bioversity International.

The results presented in this paper are divided into two parts: (1) a crop level trade-off analysis and (2) an exploration of farming systems and possible improvements based on a trade-off analysis at farm level. In this paper first a trade-off analysis at the product level for 15 crops on revenues, nutrition and soil quality is presented (Section 3.1). After this an overview of current farming systems in Central and South-West Uganda is given (Section 3.2). This is followed by an analysis of farmers' ideas about diversification, exploring their objectives, preferences and constraints (Section 3.3). Using the preferences of the farmers as guidelines, finally the best-fit diversification prototypes were explored making use of the FarmDESIGN farm-household model (Section 3.4).

## 2 Materials and methods

The fieldwork was conducted in Uganda, in the districts Luwero (Central-Uganda) and Sheema (South-West Uganda). The central region is characterised by farmers who produce banana primarily for food, while in the South-Western region farmers have a more intensive market-oriented banana production system. In both regions banana crops suffer severely from BXW.

### 2.1 Crop level trade-off analysis

For the trade-off analysis at crop level the impact on revenues, nutrition and soil quality of 15 regularly cultivated crops in Uganda was calculated. First, revenues from sales per hectare were calculated by multiplying the average yield per hectare (see Appendix 1) by the farm gate price. Farm gate prices were based on 29 interviews with farmers. For crops of which farmers did not know the price, prices were collected on the local market and multiplied by 0.6. This correction factor was based on comparisons of prices of crops for which both the market price and the farm gate price were known. For the complete calculations see Appendix 2. In the economic part of the analysis, production costs were not taken into account.

Secondly, to measure the impact of crops on nutritional value, three possibly limiting micro-nutrients were selected: iron, zinc and vitamin A. These micronutrients were selected because these are often deficient in Eastern African diets (Talsma, 2017). The production of the macronutrients energy, carbohydrates and protein was calculated as well to complement the nutrient overview, although there is probably no shortage of these nutrients (Talsma, 2017). In a later stage of the research the most limiting nutrients were selected for further exploration of improvement options. Nutrients produced on one hectare of every crop were calculated using FarmDESIGN using the nutritional values of fresh products based on the food composition table for Central and Eastern Uganda (Hotz, et al., 2012) supplemented with data from the USDA food composition table (USDA, 2017). To compare crops, the nutritional yield – the number of adults who would be able to obtain 100% of the recommended daily reference intake (DRI) of nutrients for one year from the food item produced on one hectare (DeFries, et al., 2015) – was calculated.

Thirdly, to compare the impact of crops on soil quality, the impact on erosion and on the N-balance as an indicator of soil fertility was determined. For erosion, the C-score of the Revised Universal Soil Loss Equation (RUSLE) was used. The RUSLE equation is a mathematical model that describes soil erosion processes, consisting of the R (rainfall erosivity factor), K (soil erodibility factor), L (slope length factor), S (slope steepness factor), C (cover-management factor) and P (supporting practices factor) factors (Renard, et al., 1991;1997). The C-score, the ratio of soil loss from an area with specified cover and management to soil loss from an identical area in tilled continuous fallow, is the only factor that can be calculated per crop, independent of the environment it is growing in (Renard, et al., 1991;1997). Therefore, the C-factor was selected to compare the impact of different crops on erosion. Crops that cover well and prevent erosion received a low C-score. The C-factor per crop was based on literature research (see Appendix 3).

The N-balance was taken from FarmDESIGN, in which the N-balance was calculated by subtracting in N-outputs (N in crop products exported, N-crop product burning losses, N in animal products exported, N-volatilization, N lost through erosion, N-losses and N-accumulation) from the N-inputs (import of N through manure, crop N-fixation, non-symbiotic N-fixation and N-deposition). Input data related to the nitrogen content of crop products was derived from the HarvestPlus Food Composition Table (HarvestPlus, 2017) and the USDA food composition database (USDA, 2017). N-fixation numbers for legumes were based on standard values for the fraction of fixed N in above ground biomass N (0.5) and other N-fixation as a fraction of shoot N-fixation (0.25) (Farming Systems Ecology Group, 2018). A positive N-balance was perceived desirable, because this means that compared with the current state of low soil fertility the amount of nutrients (in this case nitrogen specifically) in the soil would increase and soils would become more fertile.

## 2.2 Farm level trade-off analysis

### *2.2.1 Farm typology and selection of participants*

To select participants for the study at farm level, farm types were determined using a farm typology. Farms were clustered into three groups with similar farm characteristics (Table 1) making use of multivariate statistics according to the guidelines for typology construction (Alvarez, et al., 2018), using the hierarchical cluster analysis (HCA) on the variables as listed in Table 1. The typology was based on a total of 978 famers for which all typology variables were known. Type small farms (SF) were subsistence farmers with the lowest number of crops and a relatively low percentage of bananas. Type MF were medium size farms, producing for both home consumption and the market, owning no cattle. Farms of type LF were the largest semi-commercial farms, with cattle, having the highest number of crops.

Table 1. Average farm characteristics of small farms (SF), medium farms (MF) and large farms (LF) in the whole of Uganda (total) and the sites Kabwohe and Nakaseke specifically. The typology is constructed based on the total sample of 978 farms.

| **Farm type** | | N | Farming objective | Farm size (ha) | Area used for bananas (%) | Number of crops | Owner of cattle (%) |
|---|---|---|---|---|---|---|---|
| **SF** | **Total** | **351** | **subsistence** | **3.6 ± 4.5** | **29.1 ± 24.6** | **7.6 ± 2.9** | **10 ± 30** |
| | Site 1 Kabwohe | 9 | subsistence | 2.8 ± 1.6 | 40.8 ± 19.2 | 6.2 ± 1.4 | 22 ± 44 |
| | Site 2 Nakaseke | 15 | subsistence | 4.5 ± 5.2 | 33.4 ± 23.5 | 7.8 ± 3.3 | 7 ± 26 |
| **MF** | **Total** | **457** | **semi-commercial** | **5.3 ± 8.1** | **41.0 ± 26.1** | **7.8 ± 3.0** | **0 ± 0** |
| | Site 1 Kabwohe | 10 | semi-commercial | 6.1 ± 5.2 | 43.1 ± 20.8 | 8.6 ± 1.8 | 0 ± 0 |
| | Site 2 Nakaseke | 21 | semi-commercial | 3.6 ± 3.2 | 39.4 ± 21.6 | 8.2 ± 2.4 | 0 ± 0 |
| **LF** | **Total** | **170** | **semi-commercial (80%), subsistence (20%)** | **8.0 ± 10.9** | **37.5 ± 24.8** | **8.4 ± 2.9** | **100 ± 0** |
| | Site 1 Kabwohe | 27 | semi-commercial | 16.3 ± 9.7 | 29.4 ± 21.6 | 7.4 ± 3.7 | 100 ± 0 |
| | Site 2 Nakaseke | 10 | semi-commercial | 19.1 ± 29.4 | 27.2 ± 22.3 | 9.4 ± 3.7 | 100 ± 0 |

In 2015 under supervision of Enoch Kikulwe (Bioversity International) 1217 household surveys were conducted in four regions of Uganda (Central, South-West, Mid-West and East) in 11 districts (Kikulwe, 2015). Participants for the household surveys were selected through purposive and simple random sampling. For our fieldwork out of this dataset, two districts were selected for interviews: Sheema (in South-West Uganda) and Luwero (in Central Uganda) (Figure 1). These districts were chosen because their data was of good quality and they come from two contrasting banana production zones. Within these districts 15 and 14 farmers respectively, representing three different farming types, were selected within two selected sub-counties: site 1 Kabwohe (in Sheema) and site 2 Nakaseke (in Luwero). Means for farm size, percentage of farm area occupied by bananas and number of crops in the selected sub-counties Kabwohe and Nakaseke sometimes deviate from the total mean (Table 1). For the interviews, farmers were selected as much as possible matching the means of the total group in the whole of Uganda.

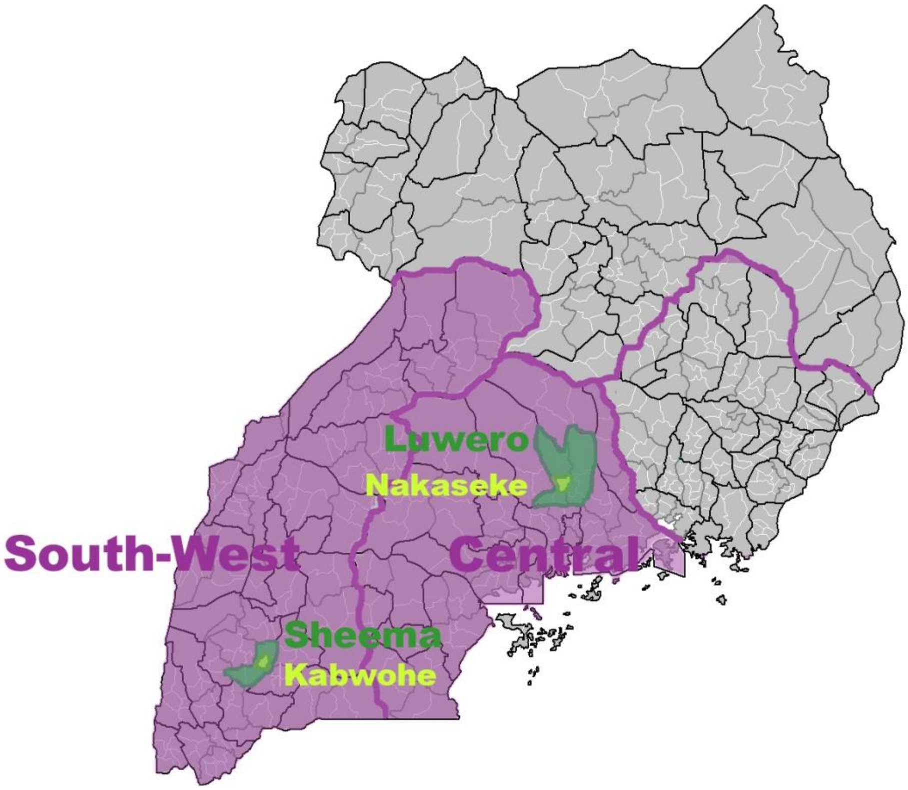


Figure 1 Locations selected for the fieldwork. In Kabwohe 15 interviews were conducted, in Nakaseke 14. In Kabwohe (site 1) interviews were conducted in the villages Rugasha, Mashojwa and Kiyagayaga in the parish Migina. In Nakaseke (site 2) interviews were conducted in the villages Bulwadda, Migguvula and Kifumbe in the parish Bulwadda.

### 2.2.2 Interviews

The interviews captured (1) input for the farm typology (Appendix 4), (2) input for FarmDESIGN (Appendix 5), and (3) information about farmers' objectives and preferences (Appendix 6). Via interview 1 we checked whether farmers were still matching the criteria of their farm type. In interview 2 data needed as input for FarmDESIGN was gathered. In interview 3 we discussed with farmers their future visions. These interviews were about farmers' motivations regarding diversification, what they see as the biggest advantages of diversification and what the most important obstacles for diversification are. Together with farmers objectives for the next phase were set. In addition, to the interviews farm size was measured using GeoMeasure, an mobile application to measure land area using GPS signals (Geomeasure, 2018), and estimations of land-use were made. This information was collected in one individual interview per farmer. From the interviews appeared that some farms changed and moved from one farm type to another in the period 2015-2018 (Table 2). Because in the end in Nakaseke hardly farms of LF were found, only SF and MF were taken into account.

Table 2. Number of farmers per farm type per site participating in the interviews and detailed farm analysis before and after the fieldwork. Farmers were equally distributed among the types, but during the fieldwork it appeared that some farms had changed and had shifted to another farm type.

| | Site 1 Kabwohe | | Site 2 Nakaseke | |
|---|---|---|---|---|
| **Farm type** | **Before (2015)** | **After (2018)** | **Before (2015)** | **After (2018)** |
| **SF** | 5 | 5 | 5 | 6 |
| **MF** | 5 | 4 | 5 | 7 |
| **LF** | 5 | 6 | *4*[1] | *1* |

### *2.2.3 Current farming systems*

Based on measurements and interviews, for every farm type at both sites an average farm was composed. These standard farms were modelled in FarmDESIGN modelling software, making use of the information from the interviews, review of relevant literature and expert knowledge of Jeroen Groot and Carl Timler. For these standard farms, the scores for the selected indicator set (see below) were calculated. Furthermore, to indicate the nutritional diversity of the crops and animal products produced at the moment, the Household Dietary Diversity Score (HDDS) and the Women Dietary Diversity score (WDDS) were calculated. Both are indicators of nutritional diversity based on the FAO guidelines for measuring household and individual dietary diversity, counting the number of food groups consumed in the household (FAO, 2013). Because consumption data was not available, the scores were based on what was produced instead.

### *2.2.4 Alternative farming systems*

The last step was performing a Pareto-based optimisation, consisting of a diversity of management alternatives and reflecting with farmers on the proposed options. Using the standard farm configurations and objectives set together with farmers, FarmDESIGN was run to explore Pareto optimal redesigns, i.e. systems that cannot be improved for one of the objectives without compromising one of the others. Objectives set were to maximize vitamin A yield, dietary energy yield, total N-losses as an indicator for soil fertility, WDDS-score and the household free budget. At the same time objectives were set to minimize the area used for bananas and the farm C-factor.

Redesigns could vary in land-use (area per crop), numbers of animals and amount of food used at home (decision variables). The new designs were rearrangements of existing practices on the same area of land plus the option to include some crops that were not cultivated by the majority of the farmers but that were found in the region. All crops, except from the fruit trees, could increase up to the total area of the farm. Increase of fruit trees was limited to five trees for SF (max 0.025 ha) and ten trees for MF (max 0.05 ha), based on farmers motivations. Constraints that were set were that the area used for bananas could not increase, no food and feed could be bought (self-supply rate is at least 1, where <1 indicates

[1] In this area there were no more than 4 farmers of LF available

imports and >1 is export of products), so there should be enough produced on-farm and the allowed deviations in the animal feed balance were between -5 and 8% for energy intake and between 0 and 30% for protein).

FarmDESIGN explored the trade-offs between the objectives with a multi-objective implementation of the evolutionary strategy of Differential Evolution (DE) developed by Storn and Price (1995, 1997). The DE parameters on amplitude (F) and crossover probability (Cr) were set on respectively 0.15 and 0.85. The number of iterations was set on 100. Out of 800 generated redesigns provided per standard farm by FarmDESIGN, three redesigns per farm type were selected. These alternatives were optimised towards different objectives. Redesign ECN scored very high in terms of revenues from sales. Redesign SOQ contributed as much as possible to improvement of the soil quality. Redesign NUT scored very good on nutritional value. The redesigns provided insight in the trade-offs between the different objectives set (Groot & Rossing, 2011). In Appendix 7 all redesigns created by FarmDESIGN are shown in scatterplots.

The redesigns were evaluated with farmers in focus group discussions. The impact of different crops on revenues, soil quality and nutrition was shared with farmers by placing pictures of crops on different scales from negative (-) to positive impact (+). In addition, the original and redesigned farms were drawn as maps with pictures of the crops linked to the corresponding fields. The most important changes in redesigns related to the original farms were presented next to the maps with pictures of crops which increase in area next to a plus, and pictures of crops that decrease in area next to a minus. Scores of the original and redesigned farms on different objectives were shown in bar charts. The selection of redesigns was explained using the cloud of alternatives generated by FarmDESIGN. Pictures of the posters used for these sessions can be found in Appendix 8. After explanation of the results farmers were asked to reflect on the proposed changes, choose a favourite redesign and explain their choice, and give their opinion on the modelling approach.

# 3 Results

## 3.1 Crop level trade-off analysis

In Table 3 an overview of the impact of regularly cultivated crops on profitability (revenues), soil quality (N-balance and erosion C-factor) and nutrition (energy and vitamin A yield) is presented. Fruit trees (mango, pawpaw, jackfruit), cooking and sweet banana scored generally high for all the objectives. These crops were especially better for erosion control and vitamin A production. Tomato and avocado were likewise doing well, except from two negative outliers (tomato scores low on energy production and avocado on N-balance). Because of the high scores of these crops on different objectives, they were expected to be selected by the model and appear in the redesigns.

Table 3. Trade-off analysis at the crop level: scores of all crops on different objectives. Colour marking from green (high score), via yellow (average score) to red (low score). Crops are ranked from crops with much positive impact (lots of green scores) to crops with not much positive impact (lots of red scores).

| Crop | Revenues (€/ha/year) | N-balance (kg/ha/year) | Erosion (C-factor/year) | Energy yield (pers/ha/year) | Vit A yield (pers/ha/year) |
|---|---|---|---|---|---|
| **avocado** | 2454 | -46 | 0.14 | 32.5 | 4.0 |
| **mango** | 777 | +13 | 0.14 | 9.0 | 15.0 |
| **pawpaw** | 1556 | +13 | 0.14 | 5.9 | 23.7 |
| **jackfruit** | 600 | +9 | 0.14 | 10.1 | 4.6 |
| **cooking banana** | 775 | +12 | 0.17 | 5.7 | 0.5 |
| **sweet banana** | 1062 | +13 | 0.17 | 4.6 | 0.4 |
| **tomato** | 810 | +15 | 0.25 | 1.2 | 8.0 |
| **groundnuts** | 566 | +15 | 0.31 | 3.2 | 0.0 |
| **yam** | 3807 | -2 | 0.34 | 21.0 | 3.5 |
| **coffee** | 594 | -6 | 0.20 | 0.0 | 0.0 |
| **Irish potato** | 1300 | +11 | 0.34 | 4.3 | 0.0 |
| **sweet potato** | 492 | -1 | 0.34 | 5.2 | 0.0 |
| **cassava** | 396 | +12 | 0.34 | 5.7 | 0.1 |
| **maize** | 280 | -13 | 0.34 | 4.0 | 0.0 |
| **beans** | 367 | -2 | 0.31 | 0.5 | 0.0 |

Maize, beans and cassava had the lowest (red) scores, performing poorly for at least two of the production objectives (i.e. more than two red scores) (Table 3). Although maize and beans were seen as cash crops by farmers, the revenues per hectare were low compared to other crops. Neither are beans and maize doing well in terms of erosion control nor nutritional value. Sweet potato, Irish potato, groundnuts and coffee also scored low, performing poorly for more than one objective. The roots and tubers and legumes had the lowest impact on erosion control and barely provide vitamin A. Coffee did not contribute to nutritional value, because it is not locally consumed. The model was not expected to select these crops in the redesigns in large proportions.

## 3.2 Current farming systems

### *3.2.1 Land-use in current farming systems*

A clear difference between the sites was the dominance of bananas in Kabwohe, while the land-use in Nakaseke was more evenly spread over a larger number of crops. However, the number of crops cultivated per farm was similar at both sites and the crops cultivated were more or less the same. Cattle and goats were prevalent in Kabwohe, while barely kept in Nakaseke.

For farmers in Kabwohe banana was by far the most important crop. Farms consisted largely of banana plantations with some other crops scattered or growing in between. From a distance the banana plantations appeared to be monocultures, but farms turned out to be quite diverse. On average 12 different crops were grown on a farm (varying from 5 to 21 crops). On average 65% of the land was used for banana production (Table 4). The small farmers used a relatively high proportion of their land to grow bananas. Next to plantations, the largest farms (LF) usually had grassland for cattle and goats grazing. On these large farms on average "only" 50% of the land was used for banana production. After bananas, the most important crops according to farmers were coffee, beans and sweet potato. An overview of the land-use in the original farming systems per farm type can be found in Figure 2.

Table 4. Characteristics of standardized small, medium and large farms (SF, MF and LF) in Kabwohe and Nakaseke. These standard farmers were based on averages found in the detailed farm analysis.

| | Site 1: Kabwohe | | | Site 2: Nakaseke | |
|---|---|---|---|---|---|
| | SF | MF | LF | SF | MF |
| **Farm size (ha)** | 0.6 | 1.88 | 9.14 | 0.5 | 3.44 |
| **Farming objective** | semi-commercial | semi-commercial | semi-commercial | semi-commercial | semi-commercial |
| **No. of crops** | 10 | 12 | 14 | 10 | 12 |
| **Land used for bananas (%)** | 80 | 70 | 50 | 30 | 20 |
| **Land used for bananas (ha)** | 0.48 | 0.3 | 4.6 | 0.15 | 0.7 |
| **Land used for other crops (ha)** | 0.12 | 0.58 | 4.54 | 0.35 | 2.74 |
| **Cows** | 0 | 0 | 9 | 0 | 0 |
| **Goats** | 0 | 0 | 8 | 1 | 2 |

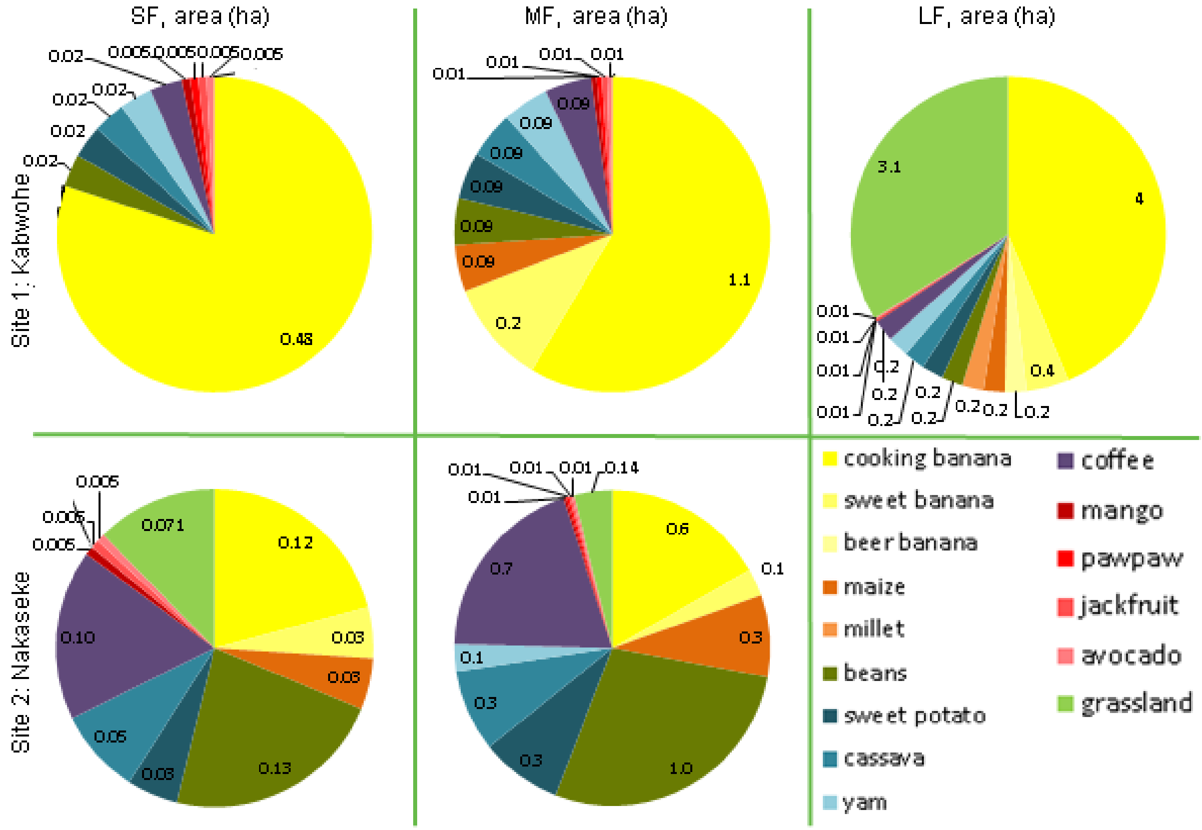


Figure 2. Original land-use in standardized farms in Kabwohe and Nakaseke of different farm types. In Kabwohe bananas were very dominant. In Nakaseke land area was divided more equally over a large number of crops. Total land area: 0.60 ha (site 1, SF), 1.88 ha (site 1, MF), 9.14 ha (site 1, LF), 0.50 ha (site 2, SF), 3.44 ha (site 2, MF).

For farmers in Nakaseke bananas, beans, coffee and cassava were the most important crops (Figure 2). These crops were intercropped with a small number of other crops, like sweet banana, maize, yam and some fruit trees like jackfruit, mango and avocado. Sweet potato was often grown on small, separate plots. Crops that provided farmers with income included cooking bananas, maize, coffee and beans. The other crops were consumed within the household. Ownership of cattle was rare and also having goats was not common. On average there were only two goats on MF farms and only one on SF farms (Table 4).

### 3.2.2 Nutrient production in the current farming systems

In the crops produced, the food groups ‘white tubers and roots’, ‘legumes’, ‘cereals’ and ‘fruits’ were strongly represented (Table 5). The starchy staples especially stood out. Vegetables, meat, dairy products and eggs were scarce. Of the Household Dietary Diversity Score (HDDS), 7 out of 12 food groups are produced while of the Women Dietary Diversity Score (WDDS) 7 out of 9 food groups are produced. To have a healthy diet according to the Women Dietary Diversity Score (WDDS) the food groups ‘dark green leafy vegetables’ and ‘milk and milk products’ should be added to the diet. Moreover, the consumption of other animal products like meat and eggs could be increased.

Table 5. Food items produced classified by food groups using the Household Dietary Diversity Score (HDDS) and Women Dietary Diversity Score (WDDS).

| HDDS | |
|---|---|
| **Cereals** | maize |
| **White tubers and roots** | cassava, sweet potato, yam |
| **Vegetables** | tomatoes |
| **Fruits** | mango, pawpaw, avocado, cooking banana, sweet banana, jackfruit |
| **Meat** | goat, cow |
| **Eggs** | eggs |
| **Fish and other seafood** | - |
| **Legumes, nuts and seeds** | beans |
| **Milk and milk products** | - |
| **Oils and fats** | - |
| **Sweets** | - |
| **Spices, condiments and beverages** | - |
| **Total** | 7/12 |

| WDDS | |
|---|---|
| **Starchy staples** | maize, cassava, sweet potato, yam |
| **Dark green leafy vegetables** | - |
| **Other vitamin A rich fruits and vegetables** | mango, pawpaw |
| **Other fruits and vegetables** | tomato, avocado, sweet banana, cooking banana, jackfruit |
| **Organ meat** | cow, goat |
| **Meat and fish** | cow, goat |
| **Eggs** | eggs |
| **Legumes, nuts and seeds** | beans |
| **Milk and milk products** | - |
| **Total** | 7/9 |

In terms of nutrients more than enough carbohydrates were produced across all farm types based on an average household size of 4.7 persons in Uganda (Table 6) (Uganda Bureau of Statistics, 2017). Although macronutrients in general scored higher than micronutrients, contrary to the expectation, the scores for energy and protein were not convincingly high. On small farms, energy and protein were limiting as well (<4.7 persons). Therefore, in the category macro-nutrients, energy was selected as an objective for optimization. In the category vitamins and minerals, the production of vitamin A was very low. Therefore, vitamin A was selected as the second objective for nutrition.

Table 6. Nutrient yields in original standardized farming systems expressed in persons potentially fed per farm per nutrient based on production. Yields are not corrected for storage, processing and preparation losses or utilization. The nutrients in the table are ranked based on their nutrient yield score from high to low.

| | Site 1 Kabwohe, nutrient yield (persons/farm) | | | Site 2 Nakaseke, nutrient yield (persons/farm) | |
|---|---|---|---|---|---|
| | SF | MF | LF | SF | MF |
| **Carbohydrates** | 17.5 | 52.7 | 170.4 | 7.6 | 53.2 |
| **Iron** | 4.2 | 13.2 | 43.2 | 2.1 | 15.6 |
| **Energy** | 3.7 | 11.0 | 36.8 | 1.7 | 11.5 |
| **Protein** | 2.1 | 6.5 | 27.8 | 1.1 | 7.5 |
| **Zinc** | 1.9 | 6.0 | 24.1 | 1.1 | 7.2 |
| **Vitamin A** | 0.6 | 1.5 | 6.0 | 0.2 | 1.3 |

### *3.2.3 Scores of current farming systems on objectives*

The original farms had low economic performance and nutritional value (Table 7). Three out of five farms had lower revenues than the estimated GDP per capita in Uganda (€1023), costs not taken into account (Nations Encyclopedia, 2018). The production of nutrients and revenues were especially very low on SF farms. Only LF produced enough vitamin A for an average household. On SF energy production was not enough for 4.7 people. The average C-factor for erosion was lower in Kabwohe than in Nakaseke. This was mainly due to large proportion of perennial crops. N-balances were higher in Kabwohe than in Nakaseke, because of the presence of livestock and manure that is brought into the system.

Table 7. Scores of original standardized farming systems on the objectives set for economic value, soil quality and nutritional value in Kabwohe and Nakaseke.

| | | Site 1 Kabwohe | | | Site 2 Nakaseke | |
|---|---|---|---|---|---|---|
| | | SF | MF | LF | SF | MF |
| **Economic value** | Revenues from sales (€) | 589 | 1745 | 6448 | 126 | 920 |
| **Soil quality** | Erosion (c-factor) | 0.1917 | 0.2101 | 0.1658 | 0.229 | 0.259 |
| | N-balance (kg) | -1 | 21 | 8 | 0.6 | 0.1 |
| **Nutritional value** | Energy (persons) | 3.7 | 11 | 36.8 | 1.7 | 11.5 |
| | Vitamin A (persons) | 0.6 | 1.5 | 6 | 0.2 | 1.3 |

## 3.3 Farmers' motivations and constraints

### *3.3.1 Visions on banana farming*

In both Kabwohe and Nakaseke farmers experienced major problems growing bananas. The largest problem was BXW (reported by 83% of the total farmers). In Kabwohe, farmers also reported shortage of labour (26.7%) and manure (13.3%). In addition, most of the farmers in Kabwohe (75%) perceived their soils to be infertile and unable to sustain production in the future while 53.3% experienced problems of soil erosion. Farmers in Nakaseke were somewhat more positive about soil quality than farmers in Kabwohe. Out of 14 farmers, only three farmers stated that the quality and fertility of the soil was insufficient. However, all farmers had problems with soil erosion. In addition, in Nakaseke prolonged dry seasons were a major problem.

Farmers, especially in Kabwohe were not willing to shift from production of bananas to other crops, mainly because bananas were their main source of food and income. Bananas being the staple food was mentioned by all farmers as the most important benefit of bananas. Other positive effects of banana that farmers agreed on were the production of mulch material (leaves and stems), all-year-around production, and use of leaves for cooking. In Kabwohe, farmers believed that banana plants would reduce erosion and could function as wind-breaks. Farmers in Nakaseke did not agree on this. They denied that banana plants help prevent erosion and function as windbreaks. They expected that for these purposes other, larger trees would be needed. In contrast to farmers in Kabwohe, farmers in Nakaseke used banana leaves to feed animals. By far the most important disadvantage of having bananas reported by farmers was the pest and disease pressure, followed by sensitivity to drought and high labour requirements. However, particularly in Kabwohe farmers strongly believed that the advantages overruled the disadvantages.

#### *3.3.2 An alternative for bananas?*

Diversification could offer an alternative for banana farming. However, most farmers were sceptical about replacing banana plants by other crops. In Nakaseke 57% of the farmers were not willing to do this whereas the other 43% were willing to consider replacing banana with other crops. In Kabwohe these ideas were even stronger, since 93.3% of the farmers were absolutely not willing to remove banana plants and grow other crops. Only one out of 15 farmers indicated to be willing to replace infected banana plants by for example cassava. Also the idea of having more different crops on the farm was rejected by the majority of the farmers in Kabwohe (73.3%). The other 26.5% farmers thought about growing more crops, but in between and not instead of the banana plants. In Nakaseke on the other hand, most of the farmers (79%) were open to the idea to grow more different crops in the future, strongly motivated by the extra income that could be gained from these crops. Crops that farmers considered as promising for the future are coffee, maize, beans and cassava. If there would be new crops that could provide farmers with more food and income, farmers in Nakaseke would be very willing to grow these and they would like to get advice on this.

The main motivator to grow other crops other than bananas was their value as food and for generating income (especially coffee, plus beans in Nakaseke). Beside this, almost all farmers agreed on the advantage of spreading risks and having fewer problems with pests and diseases than for bananas. Disadvantages of other crops mentioned by farmers in both Kabwohe and Nakaseke were shortage of space and lower prices for these crops. In Nakaseke the disadvantages of pests and diseases (although less than for banana), high labour requirements, competition with banana and lack of knowledge were added to this list. Although most farmers considered the prices for other crops lower, most of them did not expect a lack of demand.

#### *3.3.3 Ideas about future farming systems*

Both in Kabwohe and in Nakaseke farmers agreed on the objectives: dietary energy production (100%), economic profitability (97%), erosion reduction (97%), soil quality improvement (97%), and nutritional diversity (93%). In Kabwohe the most important driving factors for crop choice according to farmers were nutritional value (most important for 86.7%) – that can be split into nutritional diversity (40%) and a large amount of dietary energy produced (46.7%) - and in the second place economic value (even as important for 80%). In Nakaseke, the most important driving factor for crop choice according to farmers was economic value. All farmers mentioned this as the most important. In the second place nutritional value was even as important for 71% of the farmers.

Remarkable was that although all farmers in Nakaseke have experienced problems growing bananas, only 50% felt the need to change their farming approach. In Kabwohe this gap was even more extreme as 86.7% of the farmers experienced problems growing bananas, but only 20% felt the need to change. Farmers in Kabwohe were not interested at all in switching from bananas to other crops. This made the suggestion of useful diversification alternatives for these farmers problematic. It did not make sense to continue to the redesign phase for these farms. The last step of this research was therefore only executed for farms in Nakaseke.

## 3.4 Alternative farming systems

### *3.4.1 Crop areas in redesigns*

Table 8 shows the crop area changes in the redesigned farms. The most important increments in cultivated area were for tomato and yams for SF. Tomato and mango increased in every redesign. In SF farms sweet potato, yam, Irish potato and avocado increased in every redesign as well. In addition, pawpaw, jackfruit and groundnuts also markedly increased. These crops would partly replace maize, cooking banana, beans and coffee. New crops that appeared in the redesigns were groundnuts, Irish potato and tomato. For SF farmers, yam and pawpaw were new crops.

Table 8. Crop area changes in redesigns selected for highest benefits for economic performance (ECN; revenues), soil quality (SOQ; erosion C factor, N balance) and nutrition (NUT; energy and vitamin A yield) for SF and MF farms in Nakaseke compared to the original situation expressed in hectares. Green values are increasing crops (dark green = large increase), yellow values do not change and orange and red values decrease (red = large decrease). Crops are ranked from crops that mostly decrease (much red and orange scores) to crops that mostly increase (much green scores).

| | SF, area (ha) | | | | MF, area (ha) | | | |
|---|---|---|---|---|---|---|---|---|
| | Original | ECN | SOQ | NUT | Original | ECN | SOQ | NUT |
| **cooking banana** | 0.120 | -0.020 | -0.003 | -0.002 | 0.60 | -0.07 | 0.00 | -0.06 |
| **maize** | 0.030 | -0.005 | -0.015 | -0.015 | 0.30 | -0.60 | -0.17 | -0.12 |
| **coffee** | 0.100 | -0.012 | +0.006 | -0.030 | 0.70 | -0.01 | -0.09 | -0.09 |
| **beans** | 0.130 | -0.089 | -0.076 | -0.046 | 1.00 | 0.00 | -0.01 | 0.00 |
| **sweet banana** | 0.030 | 0.000 | 0.000 | 0.000 | 0.10 | 0.00 | 0.00 | 0.00 |
| **cassava** | 0.050 | +0.001 | 0.000 | +0.001 | 0.30 | 0.00 | 0.00 | 0.00 |
| **groundnuts** | 0.000 | 0.000 | 0.000 | +0.002 | 0.00 | +0.01 | 0.00 | +0.01 |
| **sweet potato** | 0.030 | +0.002 | +0.001 | +0.001 | 0.30 | 0.00 | +0.04 | 0.00 |
| **avocado** | 0.005 | +0.002 | +0.005 | +0.012 | 0.01 | 0.00 | 0.00 | +0.03 |
| **yam** | 0.000 | +0.017 | +0.001 | +0.017 | 0.10 | +0.16 | 0.00 | +0.13 |
| **Irish potato** | 0.000 | +0.001 | +0.001 | +0.004 | 0.00 | 0.00 | +0.03 | +0.04 |
| **tomato** | 0.000 | +0.102 | +0.059 | +0.004 | 0.00 | +0.02 | +0.15 | +0.11 |
| **mango** | 0.005 | +0.003 | +0.016 | +0.017 | 0.01 | +0.02 | +0.01 | +0.04 |
| **pawpaw** | 0.000 | +0.010 | +0.016 | +0.018 | 0.01 | +0.03 | +0.04 | 0.00 |
| **jackfruit** | 0.005 | +0.002 | 0.000 | +0.019 | 0.01 | +0.01 | +0.04 | +0.01 |
| **Total** | 0.505 | +0.014 | +0.011 | +0.002 | 3.44 | -0.43 | +0.04 | +0.10 |

To optimise for economic profit (redesign ECN) some of the crops that were seen as cash crops at the time of interviewing (cooking banana, maize and coffee and for SF also beans) would decrease in acreage, while alternative cash crops like yam, jackfruit, mango and pawpaw were added. In addition, larger parts of cooking bananas, sweet potato, cassava and yam would be sold, which were in the original situation only used for home consumption. In addition, crops that would increase in acreage were not consumed but all sold (Table 9**.** As a consequence, there would be less food left for home consumption.

Table 9 Changes in consumption in redesigns selected for highest benefits for economic performance (ECN; revenues), soil quality (SOQ; erosion C factor, N balance) and nutrition (NUT; energy and vitamin A yield) for SF and MF farms in Nakaseke compared to the original consumption patterns expressed in kilograms. Green values are crops for which the consumption increases (dark green = large increase), yellow values do not change a lot and orange and red values are crops for which the consumption decreases (red = large decrease). Crops are grouped in food groups (bananas, cereals, legumes, roots and tubers, cash crops, vegetables and fruits)

| | SF, consumption (kg) | | | | MF, consumption (kg) | | | |
|---|---|---|---|---|---|---|---|---|
| | Original | ECN | SOQ | NUT | Original | ECN | SOQ | NUT |
| **cooking banana** | 147 | -142 | -6 | +18 | 627 | -591 | +98 | +87 |
| **sweet banana** | 36 | -18 | -3 | -1 | 121 | -3 | -3 | -17 |
| **maize** | 30 | 0 | 0 | 0 | 200 | +15 | +30 | -1 |
| **beans** | 35 | +1 | -1 | +1 | 240 | +14 | +16 | +20 |
| **groundnuts** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **sweet potato** | 27 | 0 | 0 | -1 | 279 | -206 | -15 | -2 |
| **cassava** | 66 | +1 | 0 | -2 | 399 | -126 | -5 | -23 |
| **yam** | 0 | 0 | 0 | 0 | 503 | -496 | -464 | +46 |
| **Irish potato** | 0 | 0 | 0 | 0 | 0 | 0 | +5 | +7 |
| **coffee** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **tomato** | 0 | 0 | 0 | 0 | 0 | +1 | +8 | 0 |
| **mango** | 10 | 0 | 0 | 0 | 21 | 0 | 0 | 0 |
| **pawpaw** | 0 | 0 | 0 | 0 | 16 | +1 | 0 | 0 |
| **jackfruit** | 13 | 0 | 0 | -1 | 26 | 0 | 0 | 0 |
| **avocado** | 25 | 0 | 0 | 0 | 50 | 0 | 0 | 0 |
| **Total** | 389 | -158 | -10 | +14 | 2482 | -1391 | -330 | +117 |

To improve the N-balance and to reduce erosion, in redesign SOQ maize and beans cleared the way for tomatoes, fruit trees and for the second type of farms also root and tuber crops. Tomatoes did especially well in terms of the N-balance and the fruit trees had a high cover factor and strong root system to prevent erosion. Besides, the N-balance of the trees, excluding avocado, was quite positive. The increase of roots and tubers was remarkable because they were doing badly in terms of erosion and scored average on the N-balance.

For the sake of nutritional value (redesign NUT) maize, coffee and cooking banana – that contain relatively low concentrations of energy and vitamin A – would decrease. For SF farms also the acreage used for beans went down. These crops were replaced by fruit and vegetables: tomato, mango, pawpaw, jackfruit and avocado. Yam and groundnuts increased as well. The high yield of yam per hectare was an important reason for this increase. For SF farms also the roots and tubers increased in area. The fact that sweet bananas did not increase was due to the objective to decrease the acreage used for bananas because of BXW. The scores on the HDDS remained constant for all redesigns. Apparently, within the restrictions given, it was not possible to increase the HDDS-score. However, the spread of food production over the food groups was better in the redesigns than it was in the original situation. The overrepresented starchy staples and legumes groups decreased in size, while more vegetables were incorporated. Unfortunately, within the boundaries of the constraints set in FarmDESIGN and the crops available in the region, it was not possible to increase the production of nuts and seeds and animal products (meat and milk products).

### *3.4.2 Scores of redesigns on objectives*

These changes in crop areas and consumption and selling patterns resulted in positive changes for almost every objective in every redesign, because they were Pareto-optimal solutions (Table 10). Redesign ECN is optimised for economic value, but was at the same time doing well in terms of nutritional value. However, it appeared to be hard to improve soil quality – especially in terms of erosion – while optimising for economic value. Decreasing the erosion C-factor in general turned out to be difficult. Improving the N-balance was easier. Especially in redesign SOQ, the N-balance has improved a lot by increasing the acreage used for crops low in nitrogen demand. Combining this with production of vitamin A was no problem (fruit trees score well in terms of erosion, N-balance and vitamin A production), but the energy yield in redesign SOQ was clearly lower than in the other redesigns. The optimisation for nutritional value coincided well together with the other objectives, as redesign NUT showed.

Table 10. Scores of redesigns in Nakaseke on objectives set for economic value, soil quality and nutritional value. In the second column changes compared to the original situation are presented in percentages. Four out of six redesigns scores better on all objectives.

| | | Economic value | | Soil quality | | | | Nutritional value | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Scenario | Revenues from sales (€) | | Erosion (c-factor) | | N-balance (kg) | | Energy (persons) | | Vitamin A (persons) | |
| SF | Original | 126 | | 0.229 | | 0.6 | | 1.7 | | 0.2 | |
| | ECN | 333 | +165% | 0.224 | +2% | 3.4 | +422% | 2.2 | +29% | 1.4 | +552% |
| | SOQ | 204 | +62% | 0.213 | +7% | 2.9 | +350% | 2.1 | +23% | 1.3 | +537% |
| | NUT | 235 | +87% | 0.216 | +6% | 1.8 | +174% | 2.8 | +66% | 1.1 | +434% |
| MF | Original | 920 | | 0.259 | | 0.1 | | 11.5 | | 1.3 | |
| | ECN | 2384 | +159% | 0.261 | -1% | 0.5 | +217% | 14.8 | +29% | 3.2 | +148% |
| | SOQ | 1395 | +52% | 0.256 | +1% | 1.8 | +1110% | 12.3 | +7% | 3.7 | +190% |
| | NUT | 1488 | +62% | 0.261 | -1% | 0.8 | +419% | 15.4 | +34% | 3.4 | +167% |

In focus group discussion SF farmers were especially interested in redesign NUT, because of their focus on production for home consumption. Another possible factor for this outcome could have been the fact that this group of farmers consisted mainly of women. More than men, women emphasized the importance of feeding the family in a healthy manner. In response to the redesign, farmers discussed the nutritional value of different crops. Some farmers did not believe that the proposed crops could improve the diet, because they would not feel saturated after eating these crops. In the current diet the focus was on carbohydrate rich crops and not all farmers conceived the added value of vitamins and minerals. In addition to improved nutrition, farmers were attracted to the opportunity to sell more crops for income. However, they were not sure there would be enough demand for all crops in the village, especially fruits. Farmers liked the idea of adding more trees, but only on the boundaries of the farm because of competition for light with other crops. In the end, SF farmers were enthusiastic about increasing certain crops for nutritional value and income, but they were not very willing to reduce the acreage used for other crops, because they believed they needed these crops for food and income as well. The idea of replacement was difficult to accept for farmers.

MF farmers preferred redesign ECN. This group of farmers had a strong focus on earning money. They agreed together that a higher income would enable them to buy anything they need to improve soil quality and improve the diet. They discussed about degrading soils because every year products were harvested and exported from the farm, but no inputs are added. Extra income they would partly use for buying (chemical) fertilizers. Some farmers were sceptical about growing more trees because they cannot be rotated, some intercrop combinations are not possible because of light competition, and trees need much land. Similar to the SF farmers, for MF farmers it was difficult to imagine a different composition of their farm, without adding extra land.

Farmers agreed that the original design and the redesigns closely approached the reality of their farms. Explaining the trade-offs and showing the redesigns helped farmers to think about farm planning. Farmers stated that FarmDESIGN and associated exercises helped them to make decisions on which crops to grow, but that they would need more knowledge on farm planning. Farmers found it difficult to make their own decision based on trade-offs. They asked what they should do, instead of critically reflecting themselves on the impact of their decisions in farm management.

# 4 Discussion

Growing the same crops on the same amount of land, but distributing the land between the crops in a different way, could result in large changes of outputs in terms of revenues, dietary adequacy and soil quality (Groot, et al., 2012). For farmers in Nakaseke these three objectives could be improved by growing more fruits, vegetables, roots and tubers and groundnuts and less maize, coffee, cooking banana and beans. Farmers in Nakaseke reacted positively to these outcomes and were willing to adjust their farming practices, although they were sceptical about replacement of crops. The redesigns and the analysis of their composition provided the farmers in Nakaseke with an answer to the initial question of identifying alternatives for optimising their banana-based farming systems that are currently under pressure of the BXW disease. Small changes in the current orientation of the farms produced profound improvements in revenues, nutrient yield and soil quality.

## 4.1 Difficulties in the research process

A problem that appeared during the research was that farmers in Kabwohe were not willing to replant bananas by other crops and were therefore not interested in diversification redesigns. This once again underscored the importance of involving farmers early in the research process and paying attention to social aspects instead of purely focussing on the modelling approach. When this became clear we shifted the focus of the research from South-West to Central Uganda, where farmers were more interested in growing alternative crops. However, it must be said that farmers in Nakaseke as well had a strong preference for bananas. Only 43% of the farmers considered to plant other crops instead of bananas. This is a difficult issue when implementing the outcomes of FarmDESIGN.

Another difficulty in answering the research question was that the total acreage used for bananas did not increase as much as expected. Although FarmDESIGN was allowed to halve the acreage used for bananas, on average the area used for banana decreased with only 6% (Table 11). This probably happened because bananas scored high on other objectives. To provide an alternative for farmers with low banana yields, the acreage used for this should decrease more. Another factor that could have changed more is the number of animals on the farm that could have contributed to dietary diversity. Although this option was given to the model, this did not happen in any of the redesigns. Probably growing enough feed for animals would take so much area on these small-scale farms, that the negative impact of replacing crops for humans by fodder crops on objectives such human nutrition and profitability was too large. What is also disappointing from the nutritional point of view is that nuts, seeds and vegetables could not (much) increase, because for the redesigns only crops currently grown were used to increase the probability that farmers would be willing to grow more of these crops. Therefore, it was not possible to increase the WDDS.

Table 11. Total acreage used for banana production in original standardized farms and in redesigns for SF and MF farms in Nakaseke expressed in hectares. In the second column changes compared to the original situation are presented in percentages. In five out of six redesigns the area used for bananas decreases.

| Scenario | SF, area (ha) | | MF, area (ha) | |
|---|---|---|---|---|
| **Original** | 0.15 | | 0.7 | |
| **ECN** | 0.13 | -14% | 0.628 | -10% |
| **SOQ** | 0.147 | -2% | 0.698 | 0% |
| **NUT** | 0.148 | -1% | 0.636 | -9% |

Other difficulties to deal with during this project were that some expectations based on the household surveys, turned out to be different in reality. For example, lots of farmers called themselves subsistence farmers, but were selling some crops as well. In the end, almost all farmers turned out to be semi-commercial farmers. Another difference with the data from the survey was that the percentage of land used for bananas in reality was decreasing when the farm size increased. Based on the typology we were expecting that small farmers would grow relatively little bananas. Probably this happened due to mistakes in the estimations of land-use in the household survey. Farmers appeared to find it difficult to estimate how much land they own and how much land is used for particular crops. Measuring with the GeoMeasure application was much more precise. Often large differences between the measurements and farmers' estimations appeared.

Something that turned out to be different than expected based on the trade-off analysis was the increase of roots, tubers and legumes in the redesigns. This was unexpected, because of their very low scores for erosion and vitamin A as can be found in the crop trade-off analysis. Apparently, these crops compensated for other objectives. Groundnuts contributed to N-fixation and scored therefore high on the N-balance. Yam produced a lot of revenues and energy, because of the high yields. Irish potato, sweet potato and cassava were not doing very well on one of the objective, but scored not bad on the N-balance and energy production. Probably that is why FarmDESIGN selected these crops for redesigns.

### 4.2 Reflection on the modelling approach

The modelling mainly focused on using the resources more efficiently (Cortez-Arriola, et al., 2014). The main critique on design approaches has been that very few studies have addressed both biotechnical processes, farm management and advisory services (Gal, et al., 2011). This article revealed that using FarmDESIGN, these aspects can be perfectly integrated by involving participants in every stage, from setting the objectives to feedback on the outcomes of the model. Jones' et al. (2017) main critique that there were no knowledge systems that efficiently communicate model results to society has been addressed by the reflections with the involved farmers through focus-group discussions and their positive reactions. In this article the outcomes from the model were translated to farmers' reality and communicated and discussed with farmers. Because redesigns were made for a representative farm of a certain type, outcomes are widely applicable for a group of farmers instead of only for one farmer.

However, the modelling approach needs some critical reflection. The most fundamental bottleneck that was found was the question whether the trade-off analysis that is underlying FarmDESIGN fits the way farmers in Uganda make decisions. The problem in this case was not that farmers were not engaged enough in the process, as Klapwijk et al. (2014) suggested. Farmers' ideas have been leading throughout the research process. However, there seems to be another problem. Max Weber observed the rationalisation of the society in Europe in the beginning of the 20$^{th}$ century: the historical change from tradition to rationality as the dominant mode of human thought (Macionis & Plummer, 2012). Current scientific approaches, including computer-based modelling and optimisation, were based on rationality: deliberate, matter-of-fact calculation of the most efficient means to accomplish a particular goal (Macionis & Plummer, 2012). However, it is questionable whether these ideas are universal. Observations in Uganda showed that decision making of smallholder farmers was strongly based on tradition: sentiments and beliefs passed from generation to generation (Macionis & Plummer, 2012). An indicator of this was the fact that farmers experienced difficulty in answering the question: "Why do you do this?" and often responded with an answer similar to "That is the way we do it". In the focus group discussions farmers were very interested in the redesigns, but rarely in the trade-off analysis and the explanation of the considerations made. More in depth sociological research would be needed, but at least critical reflection is needed on whether the way FarmDESIGN generates alternatives for farmers, matches the manner in which farmers would make decisions.

### 4.3 Possibilities to amplify the input data

To make it possible to run FarmDESIGN, much data was required. To come to the redesign and reflection phase, assumptions were made and some parts were simplified. Broadening the data the research is based on would improve the research. For example the yield data can be studied in more detail and could be adapted more to the specific context of the redesign site. In addition, market prices could be studied in more detail, and demand should be taken into account. Some farmers doubted whether there would be a market for fruits and other crops that are currently not perceived as cash crops. Nutritional aspects could be improved by studying the current diet (based on production instead of consumption patterns) and the corresponding nutrient deficiencies. At the same time the social aspect of eating behaviour should be taken into account, because from the interviews the it was eminent that farmers do not perceive the current nutritional situation as a problem. If this would be the case, farmers would probably not be motivated to change practices based nutritional advices.

## 4.4 Practical applicability

Despite the bottlenecks, the results have already yielded practical recommendations. Together with farmers the impact of decisions made in farm planning and choosing certain crops were discussed. Redesigns provided a good starting point for conversations with farmers about the implications of their decisions. In these discussions, recommendations to increase certain crops and decrease others were made. Farmers were enthusiastic about the results presented and seemed willing to implement some of the outcomes on their farms. Reflecting on the production objectives was interesting for farmers and provided them with new insights in their farming strategies. Now that the trade-off analysis is completed and much data is collected, the outcomes should be brought to practice to see whether the predictions of the model are in line with reality. Also this research could easily be scaled up and executed in other regions of Uganda.

## 5 Conclusion

Ugandan farmers face major problems growing bananas. Based on the trade-of analysis of 15 crops regularly grown in Uganda using FarmDESIGN modelling software, we have exposed that minor changes in crop choice and farm planning can result in major changes for revenues, nutrition and soil quality while working on the same area of land with crops locally grown. We found that farmers in Central Uganda can improve their revenues, food production and soil quality – objectives set in consultation with farmers - by replacing part of the maize, coffee, cooking bananas and beans by tomatoes, yam, mango, jackfruit, pawpaw, avocado, cassava, sweet potato and groundnuts. Perennial fruits, vegetables and roots and tubers would improve farming systems in every aspect. Especially the benefits of fruit trees for all objectives stood out. Redesigns could offer farmers an alternative for banana-based systems under pressure of BXW. Furthermore, we found that larger, semi-commercial farmers preferred redesigns optimised for profitability and that small, subsistence farmers preferred redesigns optimised for nutritional value.

Farmers were enthusiastic about the outcomes and acknowledged the advantages of diversification, although they had difficulties with the idea of replacing bananas by other crops. Now that the model has been built, this research could be extended to other parts of Uganda and possibly neighbouring countries, and function as a starting point to initiate conversations with farmers about their future farming systems, as we did in focus group discussions in Nakaseke. FarmDESIGN was a useful tool to calculate the impact of crop choice, generate alternative farming systems and start conversations with farmers about the way they use the land and what could be the impact of changing practices. It supported farmers in decision making regarding land-use.

## Acknowledgements

First I would like to thank my thesis supervisors Jeroen Groot of Farming Systems Ecology group at Wageningen University and Walter Ocimati from Bioversity International in Kampala who assisted me all the way through the thesis process, from formulating the right questions, up to reviewing the article in the end. Special thanks goes to Walter for helping me organise the fieldwork in Uganda and introducing me to key actors in the field. I would also like to thank Enoch Kikulwe for providing a comprehensive dataset about BXW in Uganda that functioned as the starting point for my thesis. Subsequently, I would like to thank Carl Timler for helping me through FarmDESIGN and providing me with lots of useful data to make the program run.

I would also like to acknowledge Charles Kwarakunde, Jesca Nambi and Liora Nuwasiima for assisting me in the field, helping to contact farmers, interpreting and organising focus group discussions. Finally, I must express my gratitude to the 29 farmers from Nakaseke and Kabwohe who were willing to participate in this research and reflect on the outcomes.

This study was supported by the CGIAR Research Program on Roots, Tubers and Banana (RTB), funds of Bioversity International and the strategic funds of Wageningen University & Research under the program 'Global One Health'. We thank the CGIAR Fund Donors who support RTB (www.cgiar.org/who-we-are/cgiar-fund/fund-donors-2).

## References


Alvarez, S., Timler, C., Michalscheck, M., Paas, W., Descheemaeker, K., Tittonell, P., & Groot, J. (2018). Capturing farm diversity with hypothesis-based typologies. An innovative methodological framework for farming systems typology development. *PLoS ONE, 13*(5).

Angima, S., Stott, D., O'Neill, M., Ong, C., & Weesies, G. (2003). Soil erosion prediction using RUSLE for central Kenyan highland conditions. *Agriculture Ecosystems & Environment*(97), 295-308.

Biruma, M., Pillay, M., Tripathi, L., Blomme, G., Abele, S., Mwangi, M., . . . Eden-Green, S. (2007). Banana Xanthomonas wilt. A review of the disiease, management strategies and future research directions. *African Journal of Biotechnology, 6*(8), 953-962.

Blomme, G., Jacobsen, K., Ocimati, W., Beed, F., Ntamwira, J., Sivirihauma, C., . . . Karamura, E. (2014). Fine-tuning banana Xanthomonas wilt control options over the past decade is East and Central Africa. *European Journal of Plant Pathology, 139*, 271-287. doi:10.1007/s10658-014-0402-0

Borrelli, P. (2018). *Crop groups and their corresponding base C-factors*. Retrieved February 17, 2018, from Springer: https://static-content.springer.com/esm/art%3A10.1038%2Fs41467-017-02142-7/MediaObjects/41467_2017_2142_MOESM1_ESM.pdf

Cortez-Arriola, J., Groot, J., Amendola-Massiotti, R., Scholberg, J., Mariscal-Aguayo, V., Tittonell, P., & Rossing, W. (2014). Resource use efficiency and farm productivity gaps of smallholder diary farming in North-west Michoacan, Mexico. *Agricultural Systems*(126), 15-24.

Cropreview. (2018). *Jackfruit, a promising cash crop*. Retrieved February 1, 2018, from Cropreview: http://www.cropsreview.com/jackfruit.html

DeFries, R., Fanzo, J., Remans, R., Palm, C., Wood, S., & Anderman, T. (2015). Metrics for land-scarce agriculture. Nutrient content must be better integrated into planning. *Science, 349*(6245), 238-240.

Dowiya, N., Blomme, G., Dheda, D., Rweyemamu, C., Vellly, D., Vigheri, N., . . . Maerere, A. (2010). The alarming spread of Banana Xanthomonas Wilt in Eastern Democratic Republic of Congo and its impact on food security and income. *Tree and Forestry Science and Biotechnology, 4*(2), 56-59.

Drzewiecki, W., Wezyk, P., Pierzchalski, M., & Szafranska, B. (2014). Quantitative and Qualitative Assessment of Soil Erosion Risk in Małopolska (Poland), Supported by an Object-Based Analysis of High-Resolution Satellite Images. *Pure and Applied Geophysics*(171), 867-895.

EarthStat. (2018). *Data download*. Retrieved February 1, 2018, from EarthStat: http://www.earthstat.org/data-download/

Edmeades, S., Smale, M., Kikulwe, E. M., Nkuba, J., & Byabachwezi, M. (2007). Characteristics of banana-growing households and banana cultivars in Uganda and

Tanzania. In M. Smale, & W. Tushermereirwe (Eds.), *An Economic Assessment of Banana Genetic Improvement and Innovation in the Lake Victoria Region of Uganda and Tanzania* (pp. 49-74). Washinton, DC: IFPRI.

FAO. (2013). *Guidelines for measuring household and individual dietary diversity.* Rome: FAO.

Farming Systems Ecology Group. (2018). *Farm DESIGN manual.* Wageningen: Wageningen University and Research.

FOASTAT. (2018). *Data production crops*. Retrieved February 1, 2018, from FOASTAT: http://www.fao.org/faostat/en/#data/QC

Fugazza, M. (2018). *L'erosione del suolo. Appunti alle lezioni.* Retrieved January 17, 2018, from http://www-3.unipv.it/webidra/materialeDidattico/fugazza/sistBacini/Erosione.pdf

Gal, P. L., Dugue, P., Faure, G., & Novak, S. (2011). How does research adress the design of innovative agricultural production systems at the farm level. A review. *Agricultural Systems*(104), 714-728.

Geomeasure. (2018). *Geo measure are calculator app*. Retrieved March 1, 2018, from geomeasure: http://geomeasure.in/

Groot, J., & Rossing, W. (2011). Model-aided learning for adaptive management of natural resources. An evolutionary design perspective. *Methods in Ecology and Evolution*(2), 643-650.

Groot, J., Oomen, G., & Rossing, W. (2012). Multi-objective optimization and design of farming systems. *Agricultural Systems*(110), 63-77.

HarvestPlus. (2017). Food composition table Uganda. Kampala.

Hotz, C., Abdelrahman, L., Sison, C., Moursi, M., & Loechl, C. (2012). *A food composition table for Central and Eastern Uganda.* Washington DC: HarvestPlus.

Jones, J., Antle, J., Basso, B., Boote, K., Richard, T., Foster, I., . . . Herrero, M. (2017). Towards a new generation of agricultural system data, model, and knowledge products. State of agricultural systems sciency. *Agricultural Systems*(155), 269-288.

Kikulwe, E. (2015). BXW baseline data - Uganda. Kampala: Bioversity International.

Klapwijk, C., Wijk, M. v., Rosenstock, T., Asten, P. v., Thornton, P., & K.E., G. (2014). Analysis of trade-offs in agricultural systems. Current status and way forward. *Environmental Sustainability*(6), 110-115.

Macionis, J., & Plummer, K. (2012). Societies. In J. Macionis, & K. Plummer, *Sociology. A global introduction* (pp. 104-141). Harlow: Pearson Education Limited.

Mari, F. (2015). The evaluation of soil erosion C factor. *International Journal of Applied Science and Technology, 5*(6), 30-38.

Nations Encyclopedia. (2018). *Uganda - Income*. Retrieved June 4, 2018, from Nations Encyclopedia: http://www.nationsencyclopedia.com/Africa/Uganda-INCOME.html

NRCS-USDA. (2018). *C Factor.* Retrieved January 10, 2018, from RUSLE. Online soil erosion assessment tool: http://www.iwr.msu.edu/rusle/cfactor.htm

Ocimati, W., Groot, J., Titonell, P., Taulya, G., & Blomme, G. (2017). Effects of Xanthomonas wilt and other banana diseases on ecosystem services in banana-based agroecosystems. *Acta Horticulture*(1196), 19-32.

Ocimati, W., Ntamwira, J., Groot, J., Taulya, G., Titonell, P., Dhed'a, B., . . . Blomme, G. (2018). Banana leaf pruning to integrate annual crops: a trade-off between farm income and land use efficiency. *Unpublished*.

Panagos, P., Borrelli, P., Meusburger, K., Alewell, C., Lugato, E., & Montanarella, L. (2015). Estimating the soil erosion cover-management factor at the European scale. *Land Use Policy*(48), 38-50.

Renard, K., Foster, G., Weesies, G., & Porter, J. (1991). RUSLE. Revised universal soil loss equation. *Journal of Soil and Water Conservation, 46*(1), 30-33.

Renard, K., Foster, G., Weesies, G., McCool, D., & Yoder, D. (1997). *Predicting soil erosion by water. A guide to conservation planning with the revised universal soil loss equation (RUSLE).* U.S. Department of Agriculture (USDA).

Shepard, M. (2014). *Restoration agriculture. Real-world permaculture for farmers* (Vols. Chapter 15 How to keep an agro-ecosystem healthy). (M. Spoor, & L. Brouns, Trans.) Meppel: Uitgeverij Jan van Arkel.

Storn, R., & Price, K. (1995). *Differential evolution. A simple and efficient adaptive scheme for global optimization over continuous spaces.* Berkeley, USA: International Computer Science Institute.

Storn, R., & Price, K. (1997). Differential evolution. A simple and efficient heuristic for global optimization over continuous spaces. *Journal of global optimization*(11), 341-359.

Talsma, E. (2017, December 8). Nutrient deficiencies. (T. de Jager, Interviewer)

Tripathi, L., Mwangi, M., Aritua, V., Tushemereirwe, W., Abele, S., & R., B. (2009). Xanthomonas Wilt. A threat to banana production in East and Central Africa. *Plant Disease, 93*(5), 440-451.

Uganda Bureau of Statistics. (2010). *Uganda census of agriculture 2008/2009. Volume IV: crop area and production report.* Kampala: Uganda Bureau of Statistics.

Uganda Bureau of Statistics. (2017). *The Uganda national household survey 2016/17.* Kampala: UBOS.

USDA. (2017). *USDA Food Composition Databases*. Retrieved December 13, 2017, from https://ndb.nal.usda.gov/ndb/search/list

Wall, G., Coote, D., Pringle, E., & Shelton, I. (2002). *Revised Universal Soil Loss Equation for Application in Canada (RUSLEFAC). A handbook for estimating soil loss from water erosion in Canada.* Ottawa: Research Branch, Agriculture and Agri-Food Canada.

# Appendices

## Appendix 1 Calculations yields

Table 12. Data used for the calculations of yields (kg/ha). Average yields that are used in the research are based on as much as possible available resources. When on FAOSTAT there was no data from Uganda available, data from Kenya is used (*).Crops are grouped in food groups (bananas, cereals, legumes, roots and tubers, cash crops, vegetables and fruits).

| | (FOASTAT, 2018) | (Uganda Bureau of Statistics, 2010) | (EarthStat, 2018) | (Ocimati, et al., 2018) | (Cropreview, 2018) | Average yield |
|---|---|---|---|---|---|---|
| **cooking bananas** | 4196 | 5000 | 8680 | | | **5959** |
| **sweet bananas** | 4196 | 1600 | 8689 | | | **4828** |
| **maize** | 2501 | 2300 | 1650 | | | **2150** |
| **beans** | 1301 | 1500 | 590 | 923 | | **1078** |
| **groundnuts** | 700 | 700 | 670 | | | **690** |
| **sweet potato** | 4104 | 4100 | 4100 | | | **4101** |
| **cassava** | 3301 | 3300 | | | | **3300** |
| **yam** | 16552* | | | | | **16552** |
| **Irish potato** | | 5200 | 6810 | | | **5200** |
| **coffee** | | 1600 | 730 | | | **1165** |
| **tomato** | 5951 | | 6510 | | | **6231** |
| **mango** | 12945* | | | | | **12945** |
| **pawpaw** | 14147* | | | | | **14147** |
| **jackfruit** | | | | | 10000 | **10000** |
| **avocado** | 18880* | | | | | **18880** |

## Appendix 2 Calculations revenues from sales

Table 13. Calculations of the revenues from sales (€/ha). Farm gate prices either originate from interviews with farmers (then the market price column is empty), and if not available based on market prices collected during the fieldwork on local markets. Ugandan shillings are converted to euros. Crops are grouped in food groups (bananas, cereals, legumes, roots and tubers, cash crops, vegetables and fruits).

| | Yield (kg/ha) | Market price (UGX/kg) | Farm gate price (UGX/kg) | Price (€/kg) | Revenues from sales (€/ha) |
|---|---|---|---|---|---|
| **cooking banana** | 5959 | | 561 | 0.13 | **775** |
| **sweet banana** | 4825 | 1643 | 986 | 0.22 | **1062** |
| **maize** | 2150 | | 594 | 0.13 | **280** |
| **beans** | 1078 | | 1486 | 0.34 | **367** |
| **groundnuts** | 690 | 6000 | 3600 | 0.82 | **566** |
| **sweet potato** | 4101 | 870 | 522 | 0.12 | **492** |
| **cassava** | 3300 | | 531 | 0.12 | **396** |
| **yam** | 16552 | 1667 | 1000 | 0.23 | **3807** |
| **Irish potato** | 5200 | 1818 | 1091 | 0.25 | **1300** |
| **coffee** | 1165 | | 2235 | 0.51 | **594** |
| **tomato** | 6231 | 948 | 569 | 0.13 | **810** |
| **mango** | 12945 | 400 | 240 | 0.06 | **777** |
| **pawpaw** | 14147 | 790 | 474 | 0.11 | **1556** |
| **jackfruit** | 10000 | 477 | 286 | 0.06 | **600** |
| **avocado** | 18880 | 923 | 554 | 0.13 | **2454** |

## Appendix 3 Calculations erosion C-factor

Table 14. Calculations of the erosion C-factor per crop. Average values are based on as much as possible different resources *Average 0.14: changed to 0.17 to make it higher than real trees (more leaves = higher cover factor). **Average 0.32: changed to 0.31 to make it the same as beans (similar crop). ***Average 0.31: changed to 0.34 to make all root and tubers crops the same. ****Average 0.38: changed to 0.34 to make all root and tubers crops the same. The final C-values correspond with the order of the C-factors for crop group that Borelli developed (Borrelli, 2018). Crops are grouped in food groups (bananas, cereals, legumes, roots and tubers, cash crops, vegetables and fruits).

| | (Borrelli, 2018) | (Panagos, et al., 2015) | (Wall, et al., 2012) | (NRCS - USDA, 2018) | (Angima, et al., 2003) | (Fugazza, 2018) | (Drzewiecki, et al., 2014) | (Mari, 2015) | Average |
|---|---|---|---|---|---|---|---|---|---|
| **cooking bananas** | 0.15 | 0.22 | 0.05 | | | | | | 0.17* |
| **sweet bananas** | 0.15 | 0.22 | 0.05 | | | | | | 0.17* |
| **maize** | 0.38 | 0.38 | 0.39 | | | | | | 0.38 |
| **beans** | 0.32 | 0.32 | | 0.29 | 0.31 | | | | 0.31 |
| **groundnuts** | 0.32 | | | | | | | | 0.31** |
| **sweet potato** | 0.34 | 0.34 | 0.35 | 0.23 | | 0.30 | 0.22 | 0.39 | 0.34*** |
| **cassava** | 0.34 | | 0.42 | | | | | | 0.34**** |
| **yam** | 0.34 | | 0.42 | | | | | | 0.34*** |
| **Irish potato** | 0.34 | 0.34 | 0.35 | 0.23 | | 0.30 | 0.22 | 0.39 | 0.34**** |
| **coffee** | 0.2 | | | | | | | | 0.20 |
| **tomato** | 0.25 | | | 0.25 | | | | | 0.25 |
| **mangoes** | 0.15 | 0.22 | 0.05 | | | | | | 0.14 |
| **jackfruit** | 0.15 | 0.22 | 0.05 | | | | | | 0.14 |
| **pawpaw** | 0.15 | 0.22 | 0.05 | | | | | | 0.14 |
| **avocado** | 0.15 | 0.22 | 0.05 | | | | | | 0.14 |

## Appendix 4 Interview 1 Typology[2]

### *1.1 Introduction*

| | |
|---|---|
| *BXW Identification (household ID)* | |
| Date | |
| Village | |

| | *2015* | 2018 |
|---|---|---|
| Name respondent | | |
| Age, gender | | |
| Farm size farmer (acre) | | |
| Farm size GPS measurement | - | |
| Acres used for bananas (farmer) | | |
| *%bananas farmer* | | |
| % bananas own estimation | | |
| Farming objective | *Subsistence /semi-commercial* | Subsistence /semi-commercial |
| No. of different crops (sum 1.2) | | |

### *1.2 Crops cultivated*

| Q1.2.1 Which crops have you grown on your farm in the last 12 months? | | | | | |
|---|---|---|---|---|---|
| | Cooking bananas | | Sweet potato | | Mangoes |
| | Sweet bananas | | Irish potato | | Jackfruit |
| | Beer bananas | | Yam | | Pawpaw |
| | | | Cassava | | Passion fruit |

[2] Questions in italics to be filled in by the recorder (not asked to the respondent)

| | | | | | |
|---|---|---|---|---|---|
| | Maize | | | | Oranges |
| | Millet | | Coffee | | Avocado |
| | Sorghum | | Sugar cane | | Guava |
| | | | Tomato | | |
| | Beans | | Pumpkin | | |
| | Groundnuts | | Eggplant | | |

*Q1.2.2 How much (%) of the land is used for growing which crops (estimation)?*

………………………………………………………………………………………………………………

………………………………………………………………………………………………………………

……………………………………………………………………………………………………………….

### *1.3 Animal ownership and products*

Q1.3.1 How many of the following animals did you keep on your farm in the last 12 months?

- Cow: ……………………
- Goat: …………………...
- Sheep: ……………………
- Chicken: …………….…………
- Pig: …………….............
- Other: ……………….………

Q1.3.2 Information cattle

| Total (no.) | Breed | Male (no.) | Femal e (no.) | Giving milk (no.) | Not giving milk (no.) | *% producing milk* |
|---|---|---|---|---|---|---|
| | | | | | | |
| | | | | | | |

| | ***2015*** | **2018** |
|---|---|---|
| *Q1.3.3 Production of milk on the farm?* | *yes / no* | yes / no |

## Appendix 5 Interview 2 Input for FarmDESIGN

### *2.1 Products prices*

| | | 2.1.1. (1) con, (2) sold, (3) both (+%) | 2.1.1 Price per unit | 2.1.2 Unit | 2.1.3 Weight of a unit (kg) |
|---|---|---|---|---|---|
| bananas | Cooking banana | | | | |
| | Sweet banana | | | | |
| | Beer banana | | | | |
| cereals | Maize | | | | |
| | Millet | | | | |
| | Sorghum | | | | |
| legu | Beans | | | | |
| | Groundnuts | | | | |
| roots/tubers | Sweet potato | | | | |
| | Irish potato | | | | |
| | Yam | | | | |
| | Cassava | | | | |
| cash | Coffee | | | | |
| | Sugar cane | | | | |
| vegetable | Tomato | | | | |
| | Pumpkin | | | | |
| | Eggplant | | | | |
| fruits | Mango | | | | |
| | Jackfruit | | | | |
| | Pawpaw | | | | |
| | Passion fruit | | | | |
| | oranges | | | | |
| | Avocado | | | | |
| | Guava | | | | |
| an | Milk (cow) | | | | |

| | | | | | |
|---|---|---|---|---|---|
| | Meat (cow) | | | | |
| | Meat (goat) | | | | |

### *2.2 Chemical fertilizers*

Q2.2.1 Have you used chemical fertilizers last 12 months? Yes / no

| Q2.2.2 Which fertilizer have you used? | Q2.2.3 How much have you used last 12 months? | Q2.2.4 To which crops have you applied the fertilizer? | Q2.2.5 Costs |
|---|---|---|---|
| | | | |
| | | | |

### *2.3 Use of manure*

Q2.3.1 Have you brought animal manure on your land last 12 months? Yes / no

| Q2.3.2 Manure from which animal did you used? | Q2.3.3 How much have you used last 12 months? | Q2.3.4 To which crops have you applied the manure? | Q2.3.5 Costs |
|---|---|---|---|
| | | | |
| | | | |
| | | | |

### *2.4 Animals*

Q2.4.1. Where do you keep cattle and goats?

| | Cattle | Goats |
|---|---|---|
| Shed | | |
| Farm yard | | |
| Crop field | | |
| Pasture field | | |
| Off farm | | |

Q2.4.2 At what age do you on average slaughter cows? …………………………….……………..

Q2.4.3 At what age do you on average slaughter goats? ……………………...............................

Q2.4.4 How often do cows give birth? …………………………….……………..

Q2.4.5 How often do goats give birth? …………………………….……………..

Q.2.4.6 Do you own grassland where your animals graze? Yes / no

Q.2.4.7 If yes, what is the size of this grassland? …………………………….………… acres

| | Q2.4.8 What do you feed to cattle? | Q2.4.9 What do you feed to goats? | Q2.4.10 Where do you get the animal feed from? (own farm / collected / bought) |
|---|---|---|---|
| Grassland | | | |
| Napier grass | | | |
| Caliandra | | | |
| Gliricidia sepium | | | |
| Leucaena | | | |
| Banana leaves | | | |
| Banana stems | | | |
| Beans | | | |
| Bean residues | | | |
| Cassava leaves | | | |
| Maize stalks | | | |
| Groundnut residues | | | |
| Sorghum residues | | | |
| Sweet potato residues | | | |

| | | | |
|---|---|---|---|
| | | | |
| | | | |
| | | | |

### *2.5 Use of residues*

Q2.5.1 What do you do with the crop residues?

| | There are no residues | Back on the land / green manure | Feed for animals | Bedding material | Burned | Other (out of farming system) |
|---|---|---|---|---|---|---|
| Avocado | | | | | | |
| Beans | | | | | | |
| Banana leaves | | | | | | |
| Banana stems | | | | | | |
| Cassava | | | | | | |
| Coffee | | | | | | |
| Groundnuts | | | | | | |
| Irish potato | | | | | | |
| Jackfruit | | | | | | |
| Maize | | | | | | |
| Mangoes | | | | | | |
| Millet | | | | | | |
| Oranges | | | | | | |
| Passion fruit | | | | | | |
| Pawpaw | | | | | | |
| Sorghum | | | | | | |
| Sugar cane | | | | | | |
| Sweet potato | | | | | | |
| Tomato | | | | | | |
| Yam | | | | | | |

### *2.6 Farm type*

| | **2015** | **2018** |
|---|---|---|
| *Q1.4.1 What type of farm is this?* | *1 / 2 / 3* | *1 / 2 / 3* |
| *Q1.4.2 Does the farmer match the criteria of his type?* | *Yes / no* | *Yes / no* |

## Appendix 6 Interview 3 Farmers' objectives and preferences

### *3.1 Problems with banana farming*

| | | |
|---|---|---|
| Q3.1.1 Do you experience problems with bananas on your farm? | | Yes / no |
| Q3.1.2 If yes: what kind of problems? | | |
| Q3.1.3 Do you have BXW on your farm at the moment? | | Yes / no |
| Q3.1.4 Do you feel the need to change anything at your farm at the moment? | | Yes / no |
| Q3.1.5 Please explain why (not) | | |

### *3.2 Possible alternatives for bananas*

| | |
|---|---|
| Q3.2.1 Are you willing to / open to replace banana plants by other crops or | Yes / no |

| | |
|---|---|
| animals? | |
| Q3.2.2 Please explain why (not) | |
| Q3.2.3 Would you like to have more different crops in the future? | Yes / no |
| Q3.2.4 Please explain why (not) | |
| Q3.2.5 What do you see as promising crops for the future? | 1. ………………………………………………………………………<br>2. ………………………………………………………………………<br>3. ……………………………………………………………………… |
| Q3.2.6 Please explain why | |
| Q3.2.7 What are now the most important crops at the moment? | 1. ………………………………………………………………………<br>2. ………………………………………………………………………<br>3. ……………………………………………………………………… |

### *3.3 Underlying motivation crops choice*

| | |
|---|---|
| Q3.3.1 What is the most important driving factor to choose a certain crop or animal? | o Economic value<br>o Nutritional diversity<br>o Nutritional value<br>o Impact on erosion<br>o Soil quality |
| Q3.3.2 If new/other crops than bananas would have a high market value and are healthy, would you plant these crops? | Yes / no |
| Q3.3.3 Please explain why (not) | |

| | |
|---|---|
| Q3.3.4 Do think objective (1) ‘maximizing economic profit’? is a good objective? | Yes / no |
| Q3.3.5 Please explain why (not) | |
| Q3.3.6 Do you earn enough at the moment? | Yes / no |
| Q3.3.7 Do you think objective (2) ‘maximizing (nutritional) diversity’ is a good objective? | Yes / no |
| Q3.3.8 Please explain why (not) | |
| Q3.3.9 Do you produce diverse enough at the moment to eat healthy? | Yes / no |
| Q3.3.10 Do you think objective (3) ‘maximizing energy production (nutritional value)’ is a good objective? | Yes / no |
| Q3.3.11 Please explain why (not) | |
| Q3.3.12 Do you produce enough energy at the moment? | Yes / no |
| Q3.3.13 Do you think objective (4) ‘minimizing erosion’ is a good objective? | Yes / no |

| | | |
|---|---|---|
| Q3.3.14 Please explain why (not) | | |
| Q3.3.15 Do you have problems with erosion at the moment? | | Yes / no |
| Q3.3.16 Do think objective (5) ‘minimizing N losses (improving soil quality) is a good objective? | | Yes / no |
| Q3.3.17 Please explain why (not) | | |
| Q3.3.18 Do you have problems with soil quality at the moment? | | Yes / no |

### *3.4 Advantages and disadvantages of bananas vs. diversification*

| yes | no | ! | **3.4.1 Advantages of bananas** | yes | no | ! | **3.4.2 Disadvantages of bananas** |
|---|---|---|---|---|---|---|---|
| | | | Food production | | | | Disease pressure |
| | | | Source of income | | | | High labour requirements |
| | | | Mulching material | | | | Shortage of manure |
| | | | Produce all-year around | | | | Drought |
| | | | Cooking/wrapping material | | | | Thieves |
| | | | Aesthetic value | | | | Storm damage |
| | | | Erosion regulation | | | | |
| | | | Windbreaks | | | | |
| | | | Construction material | | | | |
| | | | Low labour investments | | | | |
| | | | Fodder | | | | |
| | | | Medicines | | | | |
| | | | Fuel | | | | |

| yes | no | ! | **3.4.3 Advantages of other crops** | yes | no | ! | **3.4.4 Disadvantages of other crops** |
|---|---|---|---|---|---|---|---|
| | | | Food production | | | | Not enough space |
| | | | Source of income | | | | Low price |
| | | | Risk spreading | | | | High labour requirements |
| | | | No diseases | | | | Access to seeds |
| | | | Lowering BXW pressure | | | | Not willing to change |
| | | | | | | | Low demand |
| | | | | | | | Shortage of manure |
| | | | | | | | Competition |
| | | | | | | | Lack of knowledge |

## Appendix 7 Selection of redesigns

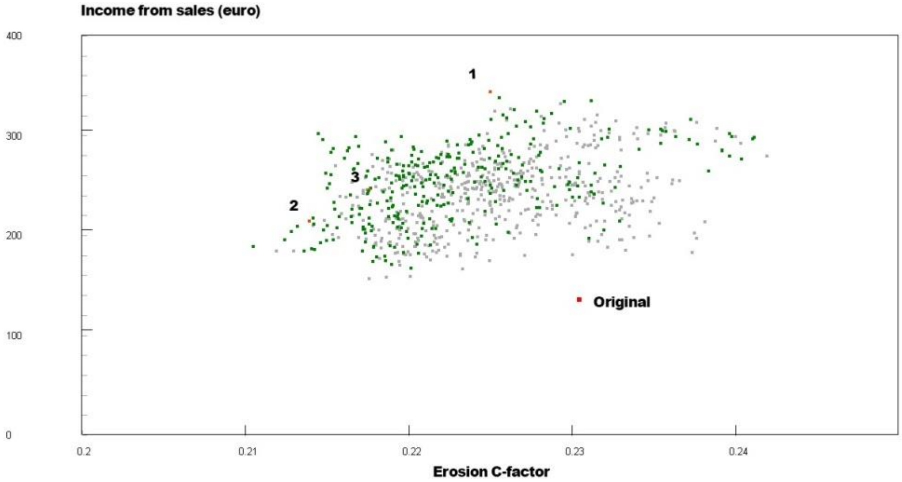


Figure 3. Selection of redesign ECN for SF farms. Out of the cloud of redesigns, a farm is chosen that scores very high on profitability.

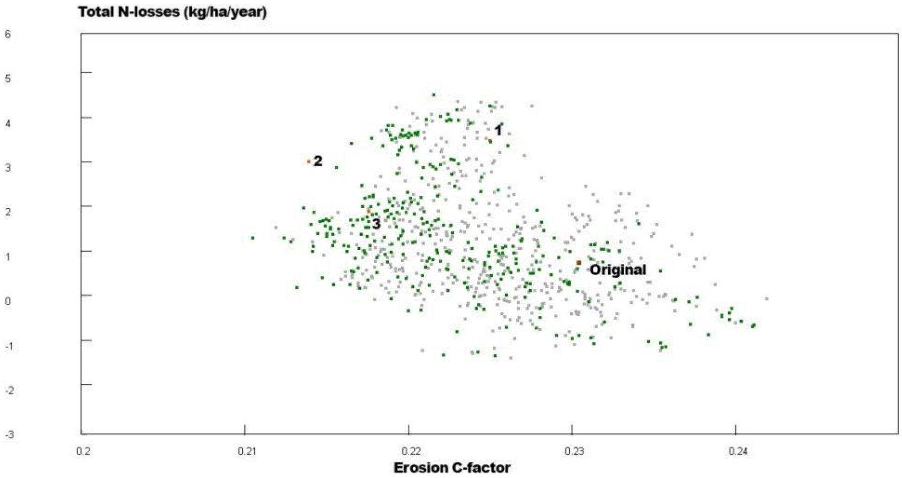


Figure 4. Selection of redesign SOQ for SF farms. Out of the cloud of redesigns, a farm is chosen that scores very high on soil quality.

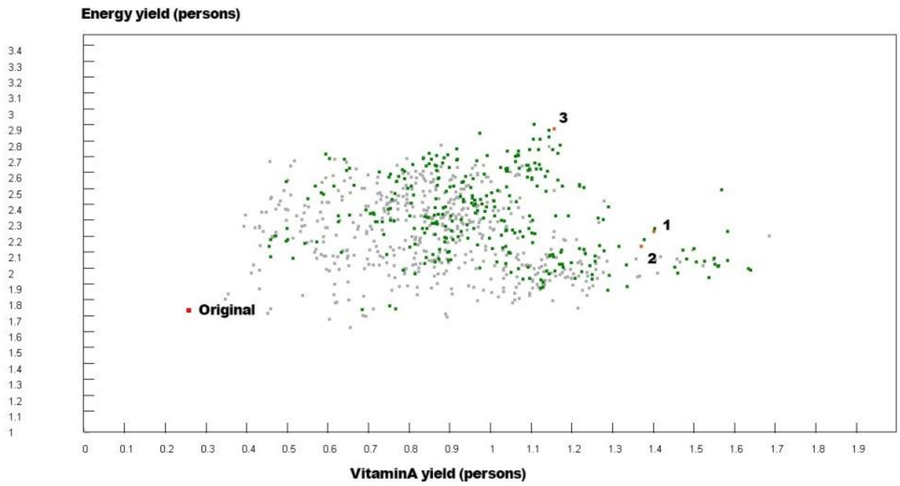


Figure 5. Selection of redesign NUT for SF farms. Out of the cloud of redesigns, a farm is chosen that scores very high on nutritional value.

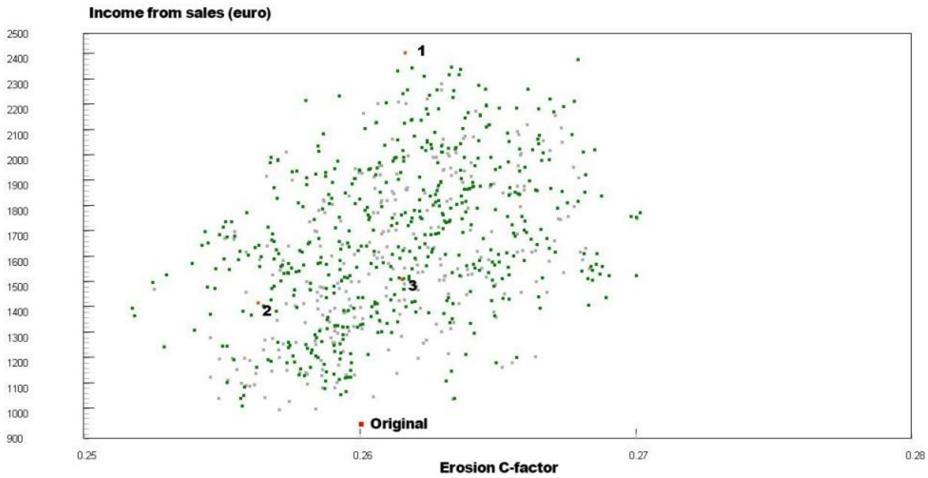


Figure 6. Selection of redesign ECN for MF farms. Out of the cloud of redesigns, a farm is chosen that scores very high on profitability.

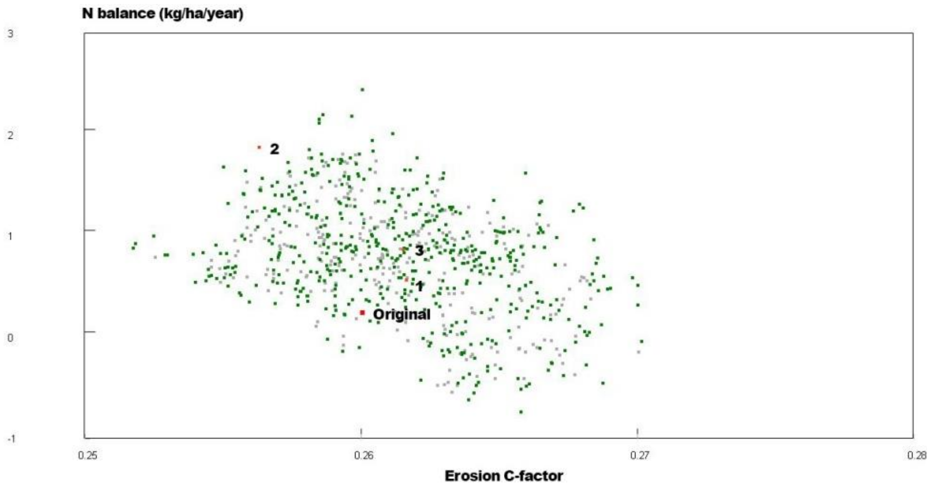


Figure 7. Selection of redesign SOQ for MF farms. Out of the cloud of redesigns, a farm is chosen that scores very high on soil quality.

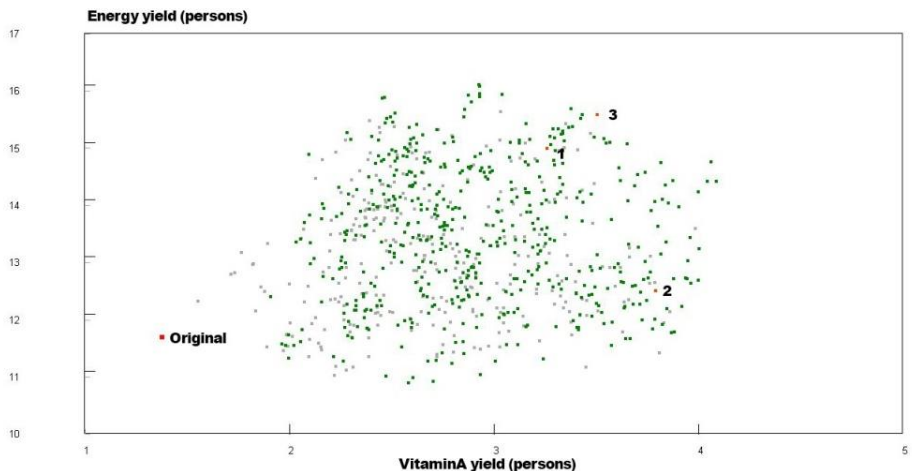


Figure 8. Selection of redesign NUT for MF farms. Out of the cloud of redesigns, a farm is chosen that scores very high on nutritional value.

## Appendix 8 Posters focus-group discussions

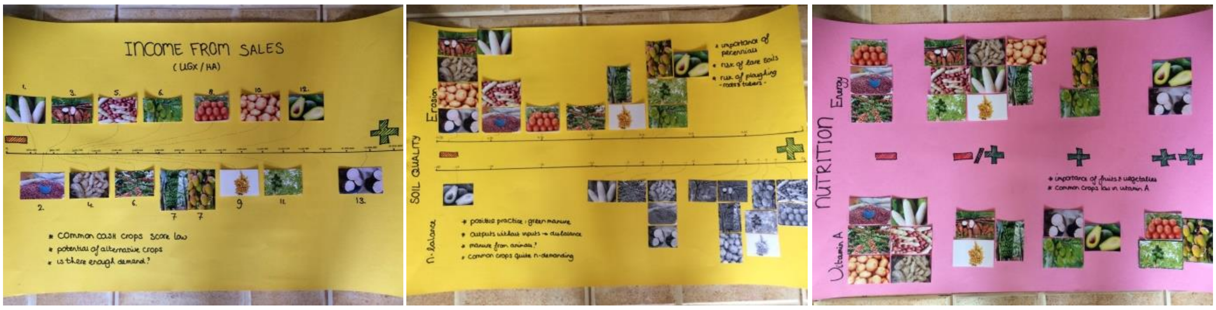


Figure 9. Posters used for the explanation of the trade-off analysis to farmers in focus group discussions. The impact of different crops on revenues, soil quality and nutrition is showed by placing pictures of crops on different scales from negative (-) to positive impact (+).

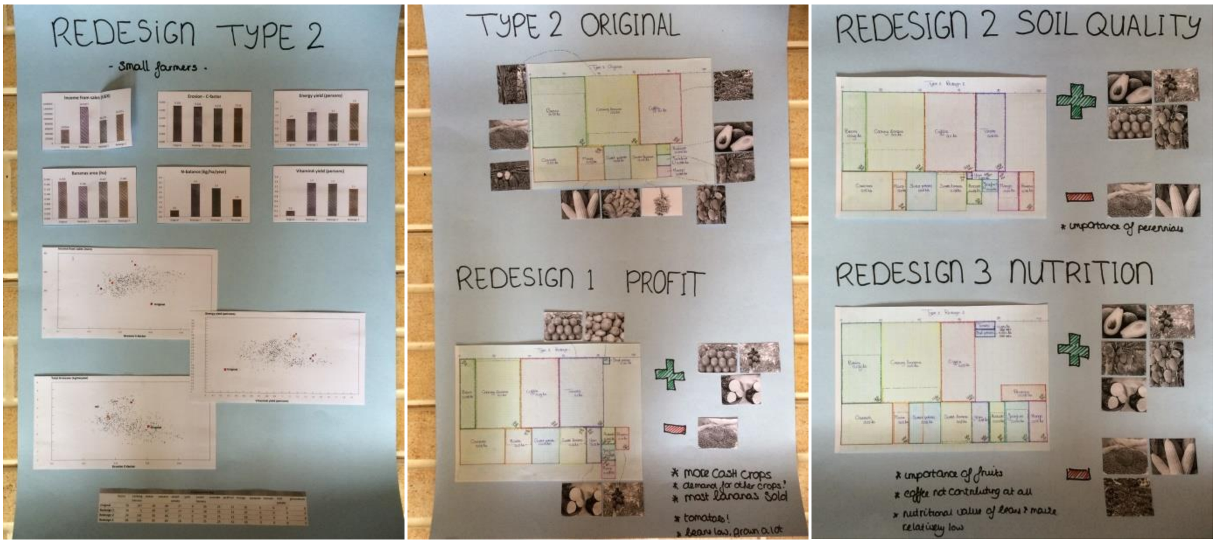


Figure 10. Posters used for the explanation of redesigns to SF farmers in focus-group discussions. The original and redesigned farms are drawn as maps with pictures of the crops linked to the corresponding fields. The most important changes in redesigns relative to the original farms are presented next to the maps with pictures of crops which increase in area next to a plus, and pictures of crops that decrease in area next to a minus. Scores of the original and redesigned farms on different objectives are shown in bar charts. The selection of redesigns was explained using the cloud of alternatives generated by FarmDESIGN.

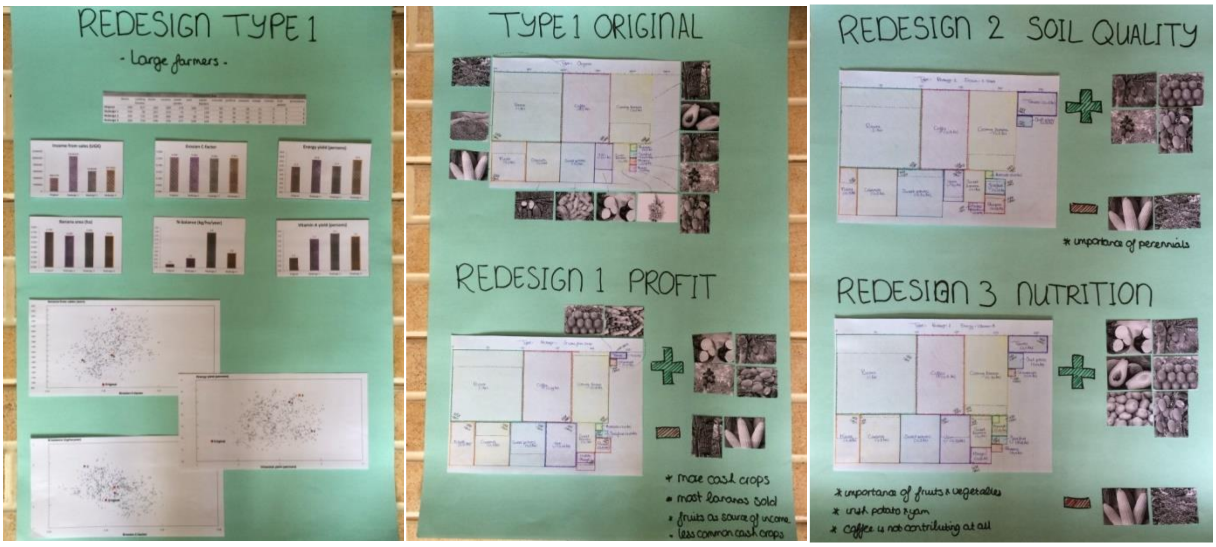

Figure 11. Posters used for the explanation of redesigns to MF farmers in focus-group discussions. The original and redesigned farms are drawn as maps with pictures of the crops  linked to the corresponding fields. The most important changes in redesigns relative to the original farms are presented next to the maps with pictures of crops which increase in area next to a plus, and pictures of crops that decrease in area next to a minus. Scores of the original and redesigned farms on different objectives are shown in bar charts. The selection of redesigns was explained using the cloud of alternatives generated by FarmDESIGN.