Trajectories of agricultural change in southern Mali

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This research was conducted under the auspices of the *C.T. de Wit* Graduate School of Production Ecology and Resource Conservation

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Thesis
submitted in fulfilment of the requirements
for the degree of doctor
at Wageningen University
by the authority of the Rector Magnificus
Prof. Dr A.P.J. Mol,
in the presence of the
Thesis Committee appointed by the Academic Board
to be defended in public
on Monday 13 June 2016
at 4:00 pm in the Aula

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Trajectories of agricultural change in southern Mali.
209 pages.

PhD thesis, Wageningen University, Wageningen, NL (2016)
With references, with summary in English.

ISBN: 978-94-6257-759-6

Pour Léo

Abstract

Smallholder agriculture in sub-Saharan Africa provides basis of rural livelihoods and food security, yet farmers have to cope with land constraints, variable rainfall and unstable institutional support. This study integrates a diversity of approaches (household typology and understanding of farm trajectories, on-farm trials, participatory *ex-ante* trade-off analysis) to design innovative farming systems to confront these challenges. We explored farm trajectories during two decades (1994 to 2010) in the Koutiala district in southern Mali, an area experiencing the land constraints that exert pressure in many other parts of sub-Saharan Africa. We classified farms into four types differing in land and labour productivity and food self-sufficiency status. During the past two decades, 17% of the farms stepped up to a farm type with greater productivity, while 70% of the farms remained in the same type, and only 13% of the farms experienced deteriorating farming conditions. Crop yields did not change significantly over time for any farm type and labour productivity decreased. Together with 132 farmers in the Koutiala district, we tested a range of options for sustainable intensification, including intensification of cereal (maize and sorghum) and legume (groundnut, soyabean and cowpea) sole crops and cereal-legume intercropping over three years and cropping seasons (2012-2014) through on-farm trials. Experiments were located across three soil types that farmers identified – namely black, sandy and gravelly soils. Enhanced agronomic performance was achieved when targeting legumes to a given soil type and/or place in the rotation: the biomass production of the cowpea fodder variety was doubled on black soils compared with gravelly soils and the additive maize/cowpea intercropping option after cotton or maize resulted in no maize grain penalty, and 1.38 t ha^{-1} more cowpea fodder production compared with sole maize. Farm systems were re-designed together with the farmers involved in the trials. A cyclical learning model combining the on-farm testing and participatory *ex-ante* analysis was used during four years (2012-2015). In the first cycle of 2012-2014, farmers were disappointed by the results of the *ex-ante* trade-off analysis, i.e marginal improvement in gross margin when replacing sorghum with soybean and food self-sufficiency trade-offs when intercropping maize with cowpea. In a second cycle in 2014-2015 the farm systems were re-designed using the niche-specific (soil type/previous crop combinations) information on yield and gross margin, which solved the concerns voiced by farmers during the first cycle. Farmers highlighted the saliency of the niches and the re-designed farm systems that increased farm gross margin by 9 to 29% (depending on farm type and options considered) without compromising food self-sufficiency. The involvement of farmers in the co-learning cycles allowed establishment of legitimate, credible and salient farm reconfiguration guidelines that could be scaled-out to other communities within the “old cotton basin”. Five medium-term contrasting socio-economic scenarios were built towards the year 2027, including hypothetical trends in policy interventions and change towards agricultural intensification. A simulation framework was built to account for household demographic dynamics and crop/livestock production variability. In the current situation, 45% of the 99 households of the study village were food self-sufficient and above the 1.25 US$ day^{-1} poverty line. Without change in farmer practices and additional policy intervention, only 16% of the farms would be both food self-sufficient and above the poverty line in 2027. In the case of diversification with legumes combined with intensification of livestock production and support to the milk sector, 27% of farms would be food self-sufficient and above the poverty line. Additional broader policy interventions to favour out-migration would be needed to lift 69% of the farms out of poverty. Other additional subsidies to favour yield gap narrowing of the main crops would lift 92% of the farm population out of poverty. Whilst sustainable intensification of farming clearly has a key role to play in ensuring food self-sufficiency, and is of great interest to local farmers, in the face of increasing population pressure other approaches are required to address rural poverty. These require strategic and multi-sectoral approaches that address employment within and beyond agriculture, in both rural and urban areas.

Key words: *longitudinal study, farm typology, food self-sufficiency, income, legumes, ex-ante analysis, participatory research, scenario.*

Contents

Chapter 1

General Introduction

1. Current challenges for smallholder farmers in sub-Saharan Africa

Agriculture is the main livelihood strategy for the majority of smallholders in sub-Saharan Africa (Davis et al., 2010; Loison, 2015). Agricultural productivity in this region is low, due to poor inherent soil fertility and high cost of agricultural inputs (Sanchez, 2002; Vanlauwe et al., 2010). Millet and maize grain yields averaged for West, East and Southern Africa were 0.8 and 1.6 t ha^{-1} for the period 2009-2013 and average annual milk production was below 1 kg cow^{-1} day^{-1} (FAOSTAT, 2015). About half the population of sub-Saharan Africa is below the 1.25 \$ day^{-1} poverty line (Dzanku et al., 2015).

On top of that, farmers face diverse risks and have to cope with an uncertain production context. Inter-annual rainfall variability and seasonal rainfall distribution result in high crop yield variability: short rainfall seasons and/or high number of dry spells lead to strong crop yield decrease (Barron et al., 2003; Ripoche et al., 2015; Rurinda et al., 2013; Traore et al., 2013). Socio-economic and institutional factors, such as the institutional support for crop production, political stability and law enforcement are also heavily fluctuating. For example, in Uganda, cassava overtook cotton as a result of the collapse of cotton marketing institutions (Ebanyat et al., 2010a), while coffee producers diversified into other cash crops due to dysfunctional buying cooperatives (Sassen et al., 2013). These changing factors cause unstable income and household food security situations (Franke et al., 2014; Luan et al., 2013). Africa's population is growing faster than in any other continent (United Nations, 2015) and population pressure leads to cropland expansion at the expense of grazing land (De Ridder et al., 2004; Ebanyat et al., 2010a; Hiernaux et al., 2009). This disturbs the traditional role of manure and nutrient transfers from rangelands to cropland (Powell et al., 1996), hence threatening the sustainability of farming systems.

Households are highly diverse in terms of resource endowment and production objective (Giller et al., 2011) and respond in different ways to their changing environment (Dorward et al., 2009). Understanding farm diversity, past farm trajectories and their drivers is therefore crucial when addressing the problem of low food security and income in sub-Saharan Africa.

2. Opportunities for sustainable intensification

How can smallholder farmers cope with the challenging characteristics of their environment? Sustainable intensification offers an avenue to intensify food production, resilience to climate stresses and maintenance of healthy soils (Vanlauwe et al., 2014). Locally adapted practices based on improved crop varieties, combined fertilizer and organic resource management, crop diversification through cereal-legume rotations or cereal-legume intercropping all offer potential to contribute to sustainable intensification (Franke et al., 2014; Snapp et al., 2010; Vanlauwe et al., 2015). Improvement of feed quality with production of forage legume and use of concentrates (e.g. cotton seed cake) allows intensifying livestock production and mitigate negative environmental impacts (De Ridder et al., 2015; Tarawali et al., 2011). More broadly, the increasing urban population and rising demand for high value products create new markets. Farmers can diversify to higher-value products like meat and milk and thus offset the decline in prices for traditional exports like cotton, coffee and tobacco (Herrero et al., 2012; Tiffen, 2006).

How can these opportunities be incorporated into innovative farming systems? The diversity of soil type and farmers' past management creates a large spatial and temporal heterogeneity in soil fertility and responsiveness to intensification options (Zingore et al., 2007a). Tailoring options to the local context of farmers therefore requires extensive on-farm trials (Baudron et al., 2012; Naudin et al., 2010; Ronner et al., 2016). Integration of options within a farm also entails the understanding of potential trade-offs associated with land, labour and nutrient allocation: e.g. the trade-off between different uses of crop residues (Andrieu et al., 2015) and trade-offs in nutrients and labour allocation (Tittonell et al., 2007). Farm models have been developed to explore *ex-ante* the trade-offs associated with alternative farming systems combining different options like improved mineral fertilizer use, fodder production and crop residues management (Bontkes and Keulen, 2003; Rufino et al., 2011). However, the lack of involvement of farmers in the conception and evaluation of the designed farming system was also reported (Bontkes and Keulen, 2003; Rufino et al., 2011). Considering farmers' knowledge and their 'expert capacity' is indeed a promising way for designing and assessing new systems (Doré et al., 2011). Based on participatory modelling with farmers of Burkina Faso, Andrieu et al. (2012) stressed the ability of farmers to design alternative farm activities and make use of modelling outputs for their own activity planning. However, this study also revealed the will of farmers to test different technologies in their field (on-farm trials) in addition to the simulation exercise. The NUANCES approach and methodology (Giller et al., 2011) has proven useful and robust in combining on-farm trials with *ex-ante* analysis and farm modelling, but with a less strong focus on participatory approaches. There is thus a great need for an approach combining on-farm testing and participatory modelling of new options at farm and farming system scale.

3. Study area

Mali has the second highest birth rate in the world after Niger (http://www.indexmundi.com/g/r.aspx?v=25, last accessed 10/02/2016). This study was carried-out in the Koutiala district in the 'old cotton basin' of Southern Mali (Soumaré et al., 2008) (Figure 1), an area currently facing challenges that are exerting pressure on many land constrained regions across sub-Saharan Africa. The area is characterized by high population pressure (reaching 70 people km^{-2}) compared with the rest of the country (Soumaré et al., 2008). Annual rainfall is highly variable, with maximum of 1200 mm and minimum of 500 mm and an average of 850 mm for the period 1965-2005 (Traore et al., 2013). Agriculture is the major source of income, with off-farm activities providing only a small (12%) share (Losch et al., 2012). A central farmers' objective is to achieve food self-sufficiency (Bosma et al., 1999) with the cultivation of maize, sorghum and millet. Cotton is the main cash crop and the production is bought by the Compagnie Malienne pour le Developpement des Textiles (CMDT).

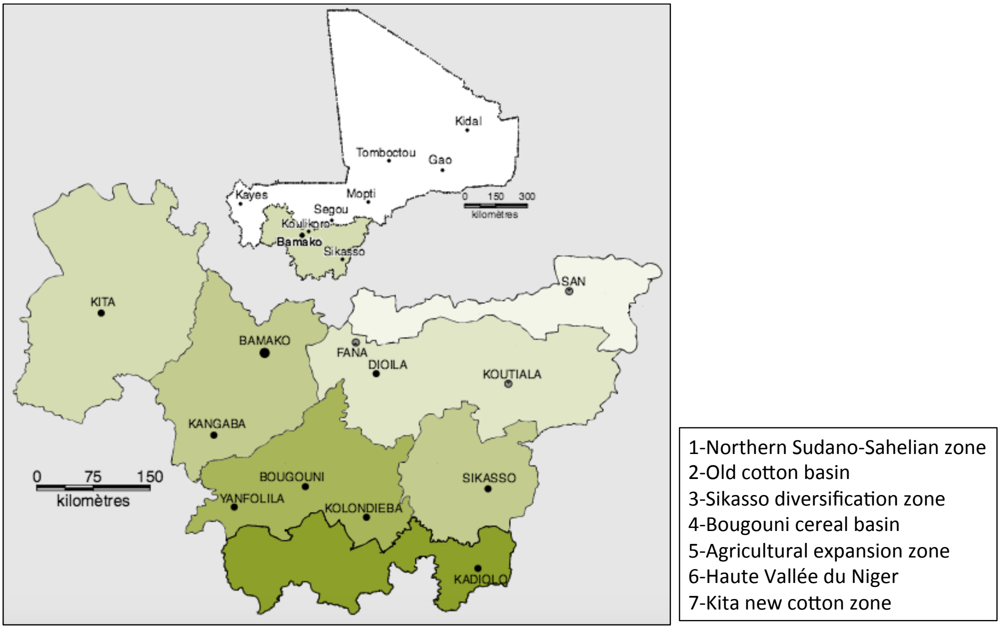

Figure 1: Agricultural regions in southern Mali. Regions are defined as homogenous geographical entities in term of cropping and farming systems. Adapted from Soumaré et al. (2008).

The CMDT provides farmers with credit facilities for fertiliser on cotton and maize. Historically, The region has shown promising agricultural intensification pathways linked to cotton production (Benjaminsen et al., 2010; Falconnier et al., 2015b) and cotton earnings have been re-invested in livestock (Dufumier and Bainville, 2006). Livestock contributes to enhanced land productivity and food self-sufficiency (Tefft, 2010), thanks to draught power and manure provision. Over the past years, the cotton sector has been highly uncertain, due to the volatility of world prices that has challenged the efficiency of the CMDT (Tumusiime et al., 2014). Expansion of cropland and increase in livestock number create grazing pressure and degradation of rangelands (De Ridder et al., 2004; van Keulen and Breman, 1990).

Previous agricultural research has identified a range of options for sustainable intensification that are specific to the context of Southern Mali: improved cereal varieties (Rattunde et al., 2013) and cereal/legume intercropping (Bengaly, 1998; Struif Bontkes, 1999) with the use of improved legume varieties (Dugje et al., 2009). Stall feeding of cows and use of on-farm produced legume forage and concentrates (cotton seed cake) can increase dairy cattle productivity (De Ridder et al., 2015). Furthermore, maize, sorghum, and dairy products are becoming important income generators thanks to increasing outlets in nearby expanding cities (Corniaux et al., 2012; Kaminski et al., 2013). However, the agronomic performance of these different options for sustainable intensification in farmers' contexts (soil types, rotations and seasons) is still poorly documented.

4. Study objectives and methods

Household typologies have proven successful in linking resource endowment (land, labour) with soil fertility status and land productivity (Senthilkumar et al., 2012; Tittonell et al., 2010). However, there are still few longitudinal studies in the smallholder context analysing how, at which speed and under which socio-economic conditions households can increase their resource endowment. Furthermore, though promising sustainable options for crop and livestock intensification exist, studies of their effective tailoring to the highly diverse smallholders' contexts remain rare. Participatory research, i.e. on-farm participatory trials, participatory *ex-ante* analysis and farm modelling have proven useful to generate practical recommendations for farmers. But their integration in a single and reflexive framework is still needed.

The overall objective of this study is to integrate this diversity of approaches (household typology and understanding of farm trajectories, on-farm trials, *ex-ante* trade-off analysis, scenario building and participatory research) in order to design innovative farming system to confront the current and expected challenges faced by farmers.

Specific objectives were to:

(1) Explore farm trajectories during two decades (1994 to 2010) and their link with farm resource endowment and governmental support in Southern Mali.

(2) Assess the agronomic performance of a range of options for sustainable intensification across a wide range of farmers' fields, explore the causes of the wide variability in farmers' yields and in the effects of the options on productivity, and define simple rules on where and when the intensification options perform best.

(3) Develop and test a cyclic and adaptive combination of participatory on-farm trials and *ex-ante* analysis to generate innovative and relevant farm systems that improve farmer income without compromising food self-sufficiency.

4) Assess the contribution of agricultural intensification, rural to urban migration and human net fertility reduction in lifting rural people out of poverty for contrasting plausible mid-term futures (fifteen years ahead) in a case study village of 99 households in Southern Mali.

5. Outline of the thesis

Chapter 2 analyses how different types of households of three villages of the Koutiala district responded to a fluctuation in the political context during the period 1994-2010 (Objective 1). In Chapter 3, a set of options for sustainable intensification is tested with farmers from nine villages of the Koutiala district. The aim was to understand causes of yield variability and define simple rules on where and when the options performed best (Objective 2). Chapter 4 presents the usefulness of co-learning cycles to design innovative farming system, building on the participatory work carried-out during three years in nine villages of the Koutiala district. Emphasis is on the adaptive nature of the approach and the effective coupling of on-farm trials and whole farm modelling (Objective 3). Chapter 5 explores how some of the options tested in Chapter 3 and

Chapter 4 can contribute in reducing poverty in a fifteen-year timeframe, for contrasting plausible futures that take into account broader socio-economic changes (Objective 4). In a final chapter, opportunities for scaling-out and diffusion of the outputs of participatory research are discussed and a framework is proposed. Issues of insider and outsider perspectives in participatory research are also discussed.

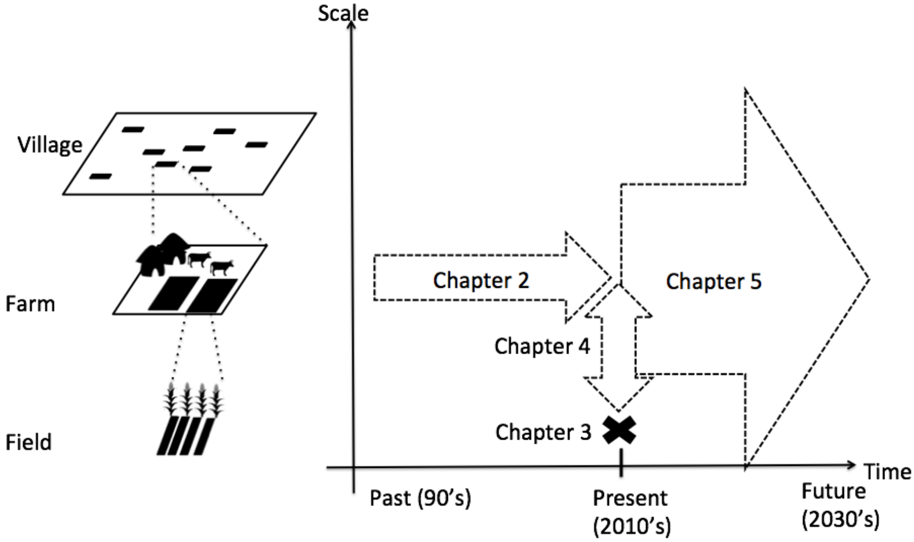

Figure 2: Outline of the thesis. Each chapter encompasses a given dimension of analysis in terms of scale (field, farm, village) and time (from past to present to future).

Chapter 2

Understanding farm trajectories and development pathways: Two decades of change in southern Mali

This chapter is published as:
Falconnier, G.N., Descheemaeker, K., Van Mourik, T.A., Sanogo, O.M., Giller, K.E., 2015. Understanding farm trajectories and development pathways: Two decades of change in southern Mali. Agric. Syst. 139, 210–222.

Abstract

Institutional support for smallholders has been the motor for the expanding cotton production sector in southern Mali since the 1970s. Smallholder farms exhibit diverse resource endowments and little is known on how they benefit from and cope with changes in this institutional support. In this paper we explore farm trajectories during two decades (1994 to 2010) and their link with farm resource endowment and government support. We distinguished a favourable period for cotton production and an unfavourable period during which institutional support collapsed. A panel survey that monitored 30 farms in the Koutiala district in southern Mali over this period was analysed. Based on indicators of resource endowment and using Ascending Hierarchical Classification (AHC), farms were grouped into four types: High Resource Endowed farms with Large Herds (HRE-LH), High Resource Endowed farms (HRE), Medium Resource Endowed farms (MRE) and Low Resource Endowed farms (LRE). Farms remaining in the same type were classified as 'hanging in', while farms moving to a type of higher yields, labour productivity and food self-sufficiency status were classified as 'stepping up', and farms following the opposite trajectory of deteriorating farming conditions were classified as 'falling down'. The LRE farms differed from all other farm types due to lower yields, while both LRE and HRE farms differed from the MRE and HRE-LH farm types due to a combination of less labour productivity and less food self-sufficiency. During those two decades, 17 % of the farms 'stepped up', while 70% of the farms remained 'hanging in', and only 13% of the farms 'fell down'. We found no obvious negative impact of the collapse of government support on farm trajectories. Crop yields did not change significantly over time for any farm type and labour productivity decreased. We discuss how technical options specific for different farm types (increase in farm equipment, sale of cereals, incorporation of legumes and intensification of milk production) and broader institutional change (improvement in finance system and infrastructure, tariffs) can enhance 'step up' trajectories for farming households and avoid stagnation ('hanging in') of the whole agricultural sector.

Key words: longitudinal study, farm typology, land productivity, labour productivity, food self-sufficiency

1. introduction

Cotton production and export from West Africa grew rapidly over the last four decades and government support provided inputs for more than one million cotton-producing smallholder farm families (Gabre-Madhin and Haggblade, 2004). In Southern Mali, cotton earnings have been used to invest in livestock, providing animal traction (Dufumier and Bainville, 2006) and contributing to enhanced land and labour productivity and food self-sufficiency (Tefft, 2010). Smallholder farms are diverse in their resource endowment and production objectives (Giller et al., 2011), and respond differently to changing conditions, with the poorest often left behind (Hazell et al., 2010; Valbuena et al., 2014). In West Africa, fluctuating cotton world prices and restructuring or privatization of state-owned companies intensifies uncertainties for farmers (Fok, 2010). Little is known of what types of farm households benefited most from institutional support for cotton production, nor of how farmers cope with changing production conditions. Farm typologies can help in understanding farmer diversity and allow analysis of the impact of development interventions (Iraizoz et al., 2007). Typology studies have revealed links between current farm resource endowment and soil fertility status (Tittonell et al., 2010; Zingore et al., 2007a), adaptation strategy (Zorom et al., 2013), land productivity, profitability and labour productivity (Senthilkumar et al., 2012). Yet most studies depend on single snapshots in time from one-off household surveys (Senthilkumar et al., 2012; Tittonell et al., 2010; Zorom et al., 2013) and do not allow analysis of how farms cope in response to fluctuating external forces. In a developed country context, based on detailed agricultural censuses and land use monitoring datasets, (Mignolet et al., 2007) showed the link between European Common Agricultural Policy and specialisation of farms towards cash crops and disappearance of livestock at regional scale. Landscape spatial organization dynamics in link with farmers decisions, market conditions and public policies has also been well documented in various European countries (Schaller et al., 2011; Stoate et al., 2009). Dynamic farm typologies in Guadeloupe (Chopin et al., 2014) showed how access to irrigation schemes can trigger diversification of farm systems. In the African smallholder context, studies explaining trends in agricultural systems are rare. Some explored the long-term impact on land use change of political context, demography and markets at village or regional scale (Benjaminsen et al., 2010; Ebanyat et al., 2010a; Sassen et al., 2013). Other relied on individual recall of household heads to understand how they cope in response to changing production conditions (Dufumier and Bainville, 2006).

A longitudinal survey (i.e. repeated observations of the same variables over time) monitored 30 farms in the cotton zone of Southern Mali from 1994 until 2010 (Djouara et al., 2005; Sanogo et al., 2010). This dataset provides a rich basis to explore the trajectories of farm development in terms of land and labour productivity and food self-sufficiency over two decades in relation to the influence of external factors. We explored two hypotheses, namely that: (i) stratification according to farm resource endowment explains heterogeneity in land and labour productivity and food self-sufficiency and (ii) favourable cotton prices stimulated farm development while unfavourable cotton prices had the opposite impact. We use this analysis to propose options for sustainable intensification that may be suitable to the different types of smallholder farms in Southern Mali.

2. Materials and methods

2.1. Description of the different steps of the method

The methodology for this longitudinal study includes five steps: (i) the building of a farm typology using a set of key resource endowment variables in the first year of the monitoring (ii) the generation of fixed thresholds for the classification of farms in the remaining years (iii) the computation of indicators of land productivity (crop yields), labour productivity and food self-sufficiency for each farm for each year iv) the assessment and quantification of farm trajectories i.e. change from a type to another v) a focus group discussion with farmer in order to validate the typology and add insights in the different trajectories. Variables explaining yield variability between farms and farm type can be collected/computed and include agro-ecological conditions, input use (e.g. mineral and organic fertiliser), land investment (e.g soil bunds, trees) (Gigou et al., 2006), access to information (extension services), services (e.g. credit) and markets for inputs and outputs. Food self-sufficiency can be assessed either by measuring the number of months per year when the household is food self-sufficient (Tittonell et al., 2010; Valbuena et al., 2014) or by comparing the sum of basic energy requirements of the different members of the household to on-farm cereal production (Andrieu et al., 2015; Paassen et al., 2011; Tittonell et al., 2009).

2.2. Study area

The study area is located in Koutiala district in the cotton zone of Southern Mali, between the 800 mm and 1000 mm isohyets. Yearly rainfall fluctuates from 600 to 1400 mm (Figure 1a). The population pressure is relatively high compared with the rest of the country, reaching 70 people km^{-2} (Soumaré et al., 2008). The dominant crops are cotton, maize, sorghum, millet and groundnut where organic fertiliser is applied on cotton, and mineral fertiliser solely on cotton and maize (Kanté, 2001). Farmers rely largely on cotton, maize and livestock for income and on maize, sorghum and millet as staple foods. Crop-livestock interactions are a key element of the farming systems of the area, accounting for good cotton and cereal yields, food self-sufficiency and income generation. Draught power allows for improved timeliness of farming operations to cope with the erratic distribution of rainfall, while application of livestock manure has positive feedbacks on crop productivity (Kanté, 2001).

2.3. Dataset

We analysed a dataset collected by the 'Equipe Système de Production et Gestion des Resources Naturelles (ESPGRN)' of the Malian Institut d'Economie Rural (IER). This dataset contains 17 years (1994-2010) of data on household resource endowment (total cropped land and area of the different crops, composition of the household, animals owned, number of tools), input use (mineral fertiliser, herbicides, pesticides and manure) and farmer-estimated yields (cotton, maize, sorghum and millet) for 32 farms from three villages of the Koutiala area. Of this sample, 12 farms were located in the village Try (12° 16' N and 5° 23' W), 8 farms in M'Peresso (12° 17' N and 5° 20' W) and 10 farms in N’Goukan (12° 21’ N and 5° 19’ W). The farms were selected purposively according to a typology established by IER (IER, 1988) that distinguished four farm types (A, B, C, D) according to oxen endowment. In 1994, A, B, C and D farm types constituted 31, 53, 6, and 9% of the sample respectively. These shares correspond to the relative frequency of the farm types found in the broader cotton zone at that period (Tefft, 2010). Two farms were excluded from our analysis because of incomplete data and consequently, our analysis was carried out on 30 farms from 1994 to 2010. Surveys were conducted on an annual basis between 1994 and 2010 by an IER extension worker based at each site. Absolute values of production need to be interpreted cautiously as they were based on farmers’ estimates. However thanks to frequent interactions with the CMDT, farmers usually accurately know the size of their different fields (ha). Cotton is weighed by the CMDT so for this crop the measurement is precise. Finally, because the same farmers were interviewed over all these years, trends over time and the relative differences between farms can be interpreted with confidence.

We characterized the economic and institutional cotton context over the past three decades based on an analysis of changes in Malian cotton production (*US Department of Agriculture PSD database ,http://www.indexmundi.com/agriculture/?country=ml&commodity=cotton&graph=production, last accessed 01/27/ 2014*), cotton world prices (National Cotton Council of America, *http://www.cotton.org/econ/prices/monthly.cfm, last accessed 01/27/ 2014)* and prices paid to farmers (sourced from CMDT). Prices were expressed in CFA francs using historical rates. Trends of average cotton yield were derived from (Blanchard, 2010) and records of annual rainfall were acquired from Meteo Mali.

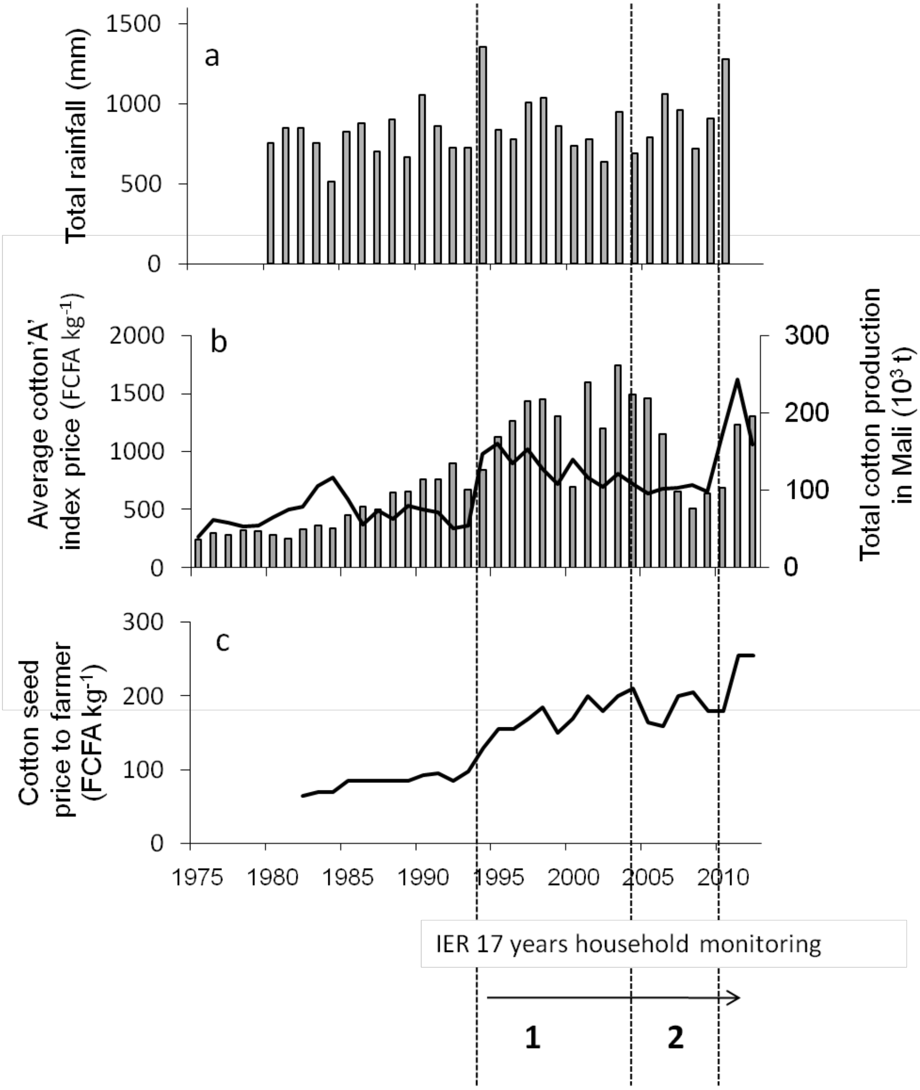

Figure 1: The context of rainfall and cotton price in the Koutiala area, showing two distinct periods within the household monitoring period (1994-2010). (a) Annual rainfall. (b) Average cotton'A' index price (line) and total cotton production in Mali (bars). (c) Cotton seed price paid to the farmer. Period 1= the favourable context for cotton production, Period 2 = the unfavourable period when support from CMDT collapsed

2.4. Establishment of a farm typology

In order to define farm types based on resource endowment, we used the farm data of the first year (1994) of the monitoring period as the baseline. The farm types were derived from a cluster analysis, for which six variables describing basic farm resources and defining potential land and labour productivity were retained (Dufumier and Bainville, 2006; IER, 1988). Those included (1) total cropped land (ha), (2) number of workers, (3) total household size, (4) herd size, expressed in Tropical Livestock Units (TLU) of 250 kg, (5) number of oxen and (6) number of draught tools (ploughs, weeders and sowing machines). Number of workers was calculated by counting 1 worker for adult men and women (15-60 years old), and 0.5 for young people (7-15 years old) and the elderly (>60 years). Though total household size and cropped land were strongly correlated, they represented different attributes of the household and were both retained. The number of workers, oxen and draught tools are good indicators for timeliness of cropping operations and planting in particular, while the herd size is an indicator of the potential transfer of fertility from rangeland to cropland as well as the recycling of fertility within cropland. The distribution of each variable among the 30 farms in 1994 was analysed to identify outliers. Excluding those outliers, cluster analysis using Ascending Hierarchical Classification (AHC) (Köbrich et al., 2003) was carried out. Following Pacini et al. (2014) we normalized the data ((initial value – mean of the variable) / standard deviation of the variable) before the AHC to avoid the influence of different levels of variation due to the unit of measurement. In order to define cut-off values for the classification of farms, we used boxplots for the identification of variables with distinctive power. For each variable and each group of two farm types, we analysed the maximum of the variable for the farm type with the lowest median, and the minimum of the variable for the farm type with the highest median. When there was no overlap between the maximum and the minimum, we took the maximum as the cut-off between the two farm types. When there was an overlap, we did not define any cut-off. Considering the cut-offs, we developed a simple decision tree to classify each farm into a type for the remaining years of the monitoring period (1995-2010).

2.5. Calculation of indicators of farm productivity and food self-sufficiency

Crop yields were used as indicators of land productivity. In our study, all the farms were situated in a similar agro-ecological zone (i.e. they originated from three villages not more than 10 km apart) so we did not consider it as an explaining factor of farm productivity. Indicators of soil fertility like soil nutrient content and soil type were not available in the panel dataset. The lack of information on land investment and institutional factors in the dataset precluded an analysis of the effects on yields of these explaining factors. However, services provided by CMDT, i.e. access to credit for fertiliser, advice from village-based field agents and the offtake of all cotton production, were similar in all the villages (Degnbol, 2001). Hence, cotton production (share of cotton in the cropped land) was used as a key indicator of access to information, service and market and its influence on farm productivity was assessed.

In our dataset, total cropped land, crop area, crop production and input use were recorded based on farmers' estimates during the 17 years of the monitoring period. We calculated average input use (for nitrogen, phosphorus, potassium, and organic fertilizer), land and labour productivity (for cotton, maize, sorghum and millet), grain production per household member, and percent fulfilment of household calorific need for each farm type and year, using arithmetic means (Appendix 1, Table A1). As crop area and household size did not vary widely within a type, it was assumed that each farm contributed equally to the type average. Labour productivity was assessed as the total crop production per worker. Hired labour was not included in the computation of the number of workers, as it represents a minor part of the total on-farm available labour (Coulibaly, 2011). Production of calories was computed based on household cereal production, considering an average supply of 3500 kcal kg^{-1} maize, sorghum and millet grain (Muhammad-Lawal and Omotesho, 2008; FAO: *http://www.fao.org/docrep/t0818e/T0818E0b.htm, last accessed 23/06/2015)*. For household calorific needs, we considered specific daily needs for different age and sex groups following Britten et al. (2006) data. Percent fulfilment of household calorific need is further referred as food self-sufficiency. We did not take into account livestock products in the food self-sufficiency computation, as the data was not available in the panel data and the frequency of meat and milk consumption is low in the rural setting of southern Mali (Generoso, 2015). Our computation of food self-sufficiency further deliberately ignored food purchases, as it would then become a measure of 'food security' rather than food self-sufficiency. This choice was motivated by (i) the absence of data on food purchase in the panel dataset, (ii) knowledge that the farmers' main objective in the area is to achieve food self-sufficiency (Paassen et al., 2011) given the few off-farm opportunities to generate cash to buy food.

Given the skewness of the data, the non-parametric Kruskal Wallis test was used to test for differences between indicator means for each farm type. When significant differences were found, post hoc pairwise comparisons were performed using a probability of <0.05.

2.6. Analysis of farm trajectories

The trajectory of each farm was analysed during three periods of six years each: a) 1994-1999, b) 1999-2004, c) 2004-2009 and for those three periods combined (1994-2009). For each period and farm, we compared the farm type at the beginning and at the end of the period. Farms remaining in the same type were classified as 'hanging in' (Dorward et al., 2009), implying no change in farm structure. Farms moving to a type of higher land and labour productivity and food self-sufficiency status were classified as 'stepping up' (Dorward et al., 2009), as their farming and living conditions had improved. Farms following the opposite trajectory of deteriorating farming conditions such as decreased labour productivity and food self-sufficiency were classified as 'falling down'.

2.7 Focus group discussion with farmers

We discussed the results of the farm typology and the analyses of trajectories with farmers. In total 22 farmers from neighbouring villages participated in the discussion. A survey prior to the group discussion allowed for the selection and invitation of farmers who were distributed equally among farm types. Before the discussion, a poster for each farm type was presented with drawings of the average resources. After presentation of the posters, in order to validate the farm typology, farmers were asked if they could recognize themselves and their households in the farm types (i.e. determine to which farm type they belong). Eventually farmers were asked to comment on possible explanations for the different farm trajectories.

3. Results

3.1 Cotton context

Two main periods characterizing the economic and institutional context for cotton production were distinguished (Figure 1b,c). The first period, from 1975 to 2004, we refer to as the “favourable context for cotton production”. During this period, Malian cotton production increased. This was mainly due to the increasing number of cotton producers under the supervision of the Compagnie Malienne pour le Développement des Textiles (CMDT), the state-owned company. The CMDT offered a guaranteed and subsidized price for cotton, credit for fertilizers and equipment (ploughs, carts and oxen), and improved varieties. Average cotton yield continuously increased from 1975 to 1990, reaching 1.2 t ha^{-1}. From 1990 to 2004, cotton yields declined slightly to 1 t ha^{-1} in 2004.

During the 2004-2010 period, cotton production fell when CMDT went bankrupt. We refer to this period (2004-2010) as the “unfavourable period when support from CMDT collapsed”. From 1984 until 2010, the cotton world price decreased steadily (in 1994, the local currency (FCFA) was devalued, which artificially raised the local cotton price). CMDT subsidized the price given to Malian farmers to offset the decrease in the world price and to sustain production, but this led to the bankruptcy of CMDT in 2004. The bankruptcy led to cessation of the price subsidy, delays in payment and fertilizer delivery in 2005, resulting in farmers’ distrust of CMDT and a decline of cotton production in the subsequent years. During this unfavourable period cotton yield stagnated at around 0.9 t ha^{-1}.

During the past few years (2011-2012), the world market cotton price has increased sharply due to a drought in China, the largest cotton producing country in the world. Cotton production in Southern Mali has again increased and the CMDT has been offering good prices to regain the trust of the farmers.

3.2 Farm typology

The distribution of the six variables describing farm resources among the 30 farms in 1994 showed three farms with outlier values for herd size (Appendix 1, Figure A2). The cluster analysis carried out on the 27 remaining farms resulted in three clusters (Appendix 1, Figure A3): Low Resource Endowed farms (LRE), Medium Resource Endowed farms (MRE), and High Resource Endowed Farms (HRE). The three farms with outlier values for herd size were classified as High Resource Endowed farms with Large Herds (HRE-LH). The boxplot analysis showed that the cut-off value discriminating HRE-LH from HRE farms was a herd size of 22.4 TLU. Farms were classified as HRE rather than MRE if the number of workers was higher than 9.5. Herd size >2.2 TLU, total cropped land >5.8 ha and draft tools>2 together discriminated MRE farms from LRE farms (Appendix 1, Figure A4, A5). Farms were classified as MRE when they fulfilled at least 2 of the 3 criteria distinguishing MRE from LRE.

The MRE farms constituted the majority of the farms (50% of the sample) in 1994, followed by the HRE farms (23% of the sample), while LRE and HRE-LH constituted 17% and 10% of the sample respectively (Table 1). Analysis of farm type distribution in 4 villages in the Koutiala district that were exhaustively sampled in 2006 showed that these villages were composed on average of 19, 40, 28, and 13% of LRE, MRE, HRE and HRE-LH farms respectively, a share that is similar to the share of the SEP survey (13, 40, 30, 17%).

3.3 Yields, labour productivity and food self-sufficiency

From 1994 to 2010, the number of MRE farms fell by six (40%), whereas the number of HRE farms increased by four (57%). Over the same period, the number of LRE farms increased by two (40%), whereas the number of HRE-LH remained constant. From 1994 to 2010 and for the entire sample, the household size and average number of workers per household increased (33% and 52% respectively), while the total cropped land area remained constant. Consequently, the average number of workers per ha almost doubled (Table 1).

There was a strong link between resource endowment and land productivity (Table 2). Average input use intensity (mineral and organic fertilizer) was significantly less for LRE compared with the other farm types. LRE farms achieved lower land productivity for all crops than the other farm types. Both MRE and HRE farms used similar amounts of mineral and organic fertilizer inputs and had higher land productivity than LRE farms. The best land productivity for all crops was obtained by HRE-LH farms.

The lower labour productivity of LRE and HRE farms coincided with a smaller oxen worker^{-1} ratio (Table 2). HRE farms had a larger number of workers compared with MRE farms, but less investment in oxen and lower labour productivity compared to MRE farms. In contrast, the large cattle herd of HRE-LH farms, providing sufficient oxen to complete farming operations in a timely manner, corresponded with a better labour productivity of this type over the monitoring period.

All farm types were able to fulfil their household calorific needs most of the time (Figure 2). However, LRE farms and HRE farms were more often close to or below the self-sufficiency threshold compared with MRE and HRE-LH farm types. When considering only on-farm cereal production during the monitoring period, LRE farms were unable to achieve food self-sufficiency in three years and HRE farms in two years, compared with one year for MRE. HRE-LH farms were food self-sufficient throughout. LRE farms showed much higher year-to-year fluctuations in food self-sufficiency as compared with the other farm types (Figure 2), and HRE had the least average grain production per capita over the monitoring period (Table 2).

Table 1: Characteristics of the four farm types (average with standard deviation in brackets) in 1994 and 2010 (TLU = Tropical Livestock Unit of 250 kg)

Year	Farm type		Number of farms	total cropped land (ha)	number of workers	number of household members	oxen	herd size (TLU)	draught tools[1]	workers ha^{-1}	oxen ha^{-1}	TLU ha^{-1}	TLU $worker^{-1}$	tools $worker^{-1}$
1994	Low Resource Endowed farms	LRE	5	3.8	3.0	5.0	0.8	1.5	1.2	1.0	0.2	0.4	0.5	0.4
				(2.1)	(1.0)	(1.6)	(1.1)	(0.8)	(1.1)	(0.5)	(0.2)	(0.3)	(0.3)	(0.4)
	Medium Resource Endowed farms	MRE	15	9.1	6.1	11.2	2.9	7.1	4.2	0.7	0.3	0.8	1.3	0.8
				(2.3)	(2.3)	(4.1)	(0.9)	(3.4)	(0.9)	(0.2)	(0.1)	(0.4)	(0.9)	(0.3)
	High Resource Endowed farms	HRE	7	15.8	14.4	25.9	4.7	12.2	5.3	0.9	0.3	0.8	0.8	0.4
				(3.7)	(4.1)	(7.4)	(0.8)	(5.0)	(0.8)	(0.1)	(0.1)	(0.2)	(0.3)	(0.1)
	High Resource Endowed farms with Large Herds	HRE-LH	3	19.8	13.8	26.7	7.3	52.6	7.0	0.7	0.4	3.1	4.6	0.5
				(6.4)	(5.0)	(11.0)	(3.1)	(24.5)	(1.0)	(0.0)	(0.1)	(2.5)	(3.7)	(0.1)
	Average		30	10.9	8.3	15.1	3.4	11.9	4.2	0.8	0.3	1.0	1.4	0.6
				(5.8)	(5.2)	(9.8)	(2.2)	(15.9)	(1.9)	(0.3)	(0.1)	(1.0)	(1.6)	(0.3)
2010	Low Resource Endowed farms	LRE	7	3.2	5.0	7.9	1.3	1.7	1.1	1.8	0.6	0.9	0.7	0.3
				(2.0)	(3.0)	(4.9)	(1.0)	(0.9)	(1.5)	(1.1)	(0.7)	(1.1)	(1.0)	(0.4)
	Medium Resource Endowed farms	MRE	9	7.5	7.3	12.6	4.1	6.2	5.3	1.1	0.6	0.9	0.8	0.8
				(2.4)	(1.6)	(1.7)	(6.5)	(4.7)	(2.9)	(0.5)	(1.0)	(0.6)	(0.6)	(0.6)
	High Resource Endowed farms	HRE	11	11.8	17.5	27.3	2.7	8.4	4.2	1.7	0.2	0.7	0.5	0.3
				(6.0)	(4.8)	(6.6)	(1.6)	(6.1)	(2.9)	(0.7)	(0.1)	(0.5)	(0.3)	(0.2)
	High Resource Endowed farms with Large Herds	HRE-LH	3	16.6	28.3	45.3	5.7	46.1	4.3	1.7	0.4	3.2	1.9	0.2
				(8.3)	(15.6)	(18.0)	(1.5)	(8.6)	(4.5)	(0.2)	(0.1)	(1.3)	(0.7)	(0.1)
	Average		30	9.0	12.6	20.1	3.1	9.9	3.8	1.5	0.4	1	0.8	0.4
				(6.1)	(9.2)	(13.5)	(3.8)	(13.5)	(3.1)	(0.8)	(0.6)	(1.0)	(0.7)	(0.5)

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[1] Ploughs, weeders and sowing machines

Table 2: Indicators of farm productivity and food self-sufficiency for four farm types in southern Mali. Means for the 1994- 2010 period are presented. Means with no letter in common are significantly different.

	Low Resource Endowed farms (LRE)	**Medium Resource Endowed farms (MRE)**	**High Resource Endowed farms (HRE)**	**High Resource Endowed farms with Large Herds (HRE-LH)**
% of farms growing cotton	35 *b*	94 *a*	96 *a*	99 *a*
% of farms growing maize	33 *b*	88 *a*	88 *a*	85 *a*
% cotton in total cropped land	10 *c*	34 *b*	32 *b*	39 *a*
% of maize in total cropped land	5 *b*	9 *a*	9 *a*	10 *a*
oxen worker^{-1}	0.1 *d*	0.5 *a*	0.3 *c*	0.4 *b*
Input use intensity (kg ha^{-1} year^{-1})				
nitrogen	7 *c*	21 *a*	19 *b*	20 *ab*
phosphorus	2 *b*	5 *a*	5 *a*	5 a
organic fertilizer	521 *d*	1872 *b*	1551 *c*	2614 *a*
Land productivity (kg ha^{-1} year^{-1})				
cotton	754 *b*	912 *a*	944 *a*	1051 *a*
maize	1298 *c*	1888 *b*	2081 *ab*	2427 a
sorghum	650 *c*	907 *b*	871 *b*	1107 *a*
millet	524 *c*	697 *b*	668 *b*	884 *a*
Labour productivity (kg worker^{-1} year^{-1})				
cotton	234 *b*	490 *a*	285 *b*	427 *a*
all cereals	626 *bc*	852 *a*	567 *c*	682 *b*
maize	143 *b*	243 *a*	179 *ab*	241 *a*
sorghum and millet	510 *ab*	571 *a*	364 *c*	440 *b*
Grain/capita (kg person^{-1}year^{-1})	455 ab	493 a	327 c	379 bc
% fulfillment of household calorific need	164 *b*	195 *a*	132 *c*	154 *bc*

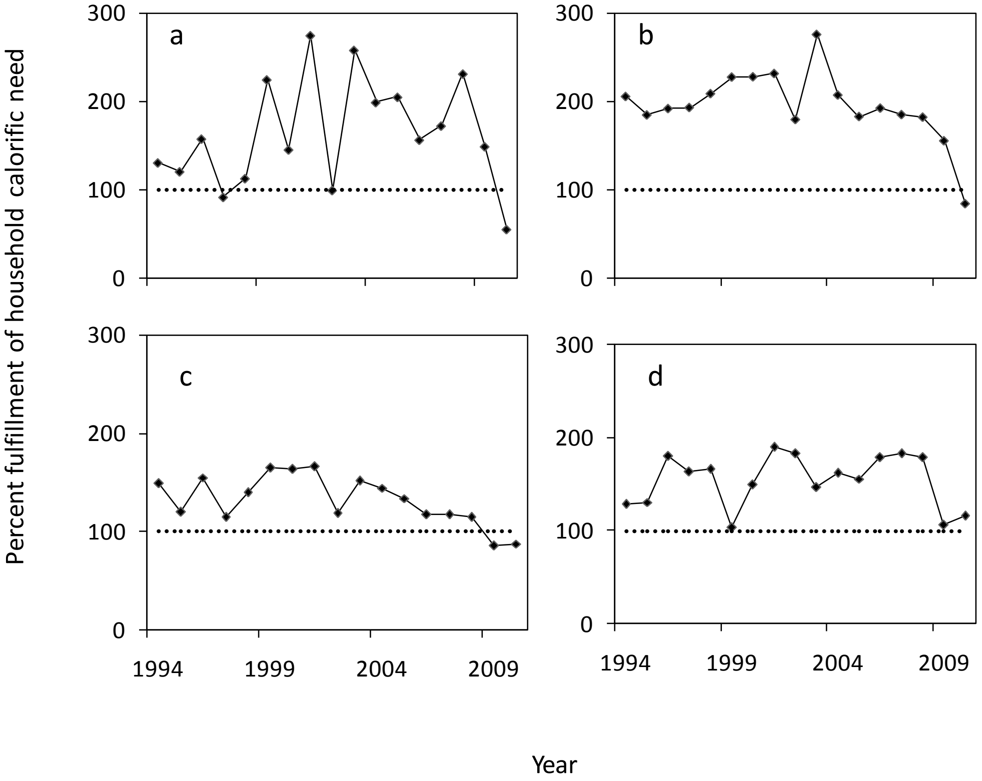


Figure 2: Fulfillment of household calorific needs (%) for (a) LRE farms, (b) MRE farms, (c) HRE farms and (d) HRE-LH farms during the monitoring period from 1994 to 2010. See Table 1 for a description of the main characteristics of the farm types.

Logically, the two farm types with low labour productivity (LRE, HRE) also were less food self-sufficient (they more often fell below the 100% fulfilment threshold), as the number of workers is closely related to the number of household members.

As a result, the LRE farms differ from all other farm types due to their lower land productivity, while both LRE and HRE farms differ from the MRE and HRE-LH farm types due to a combination of less labour productivity and less food self-sufficiency (Figure 3). In other words, whereas higher resource endowment goes hand in hand with greater land productivity, it does not correlate directly with labour productivity and food self-sufficiency.

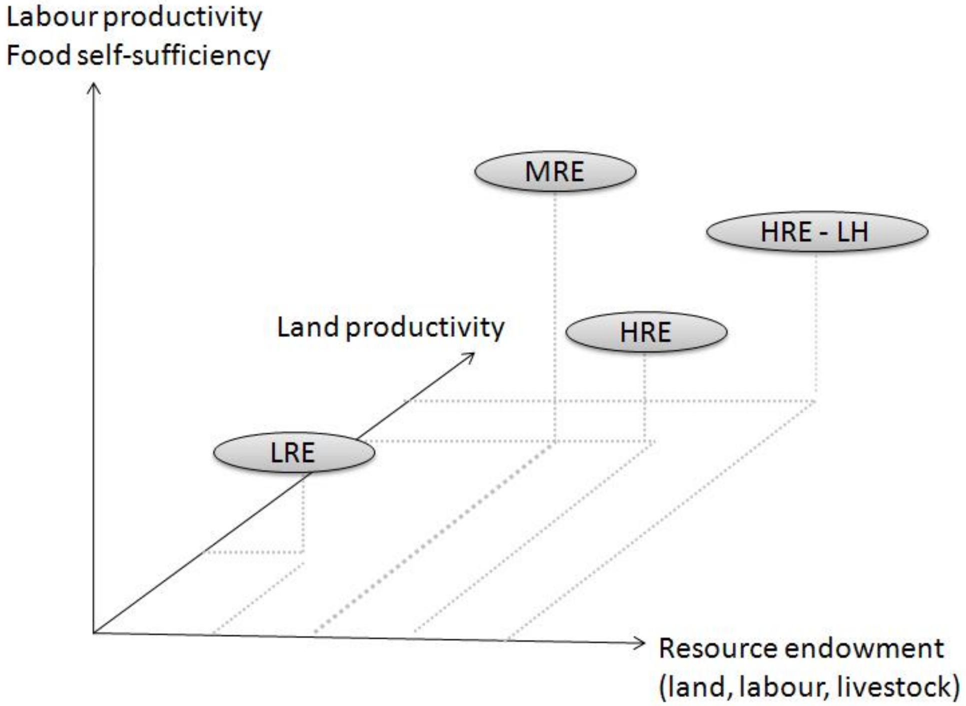


Figure 3: Conceptual representation of four farm types in a three-dimensional space of resource endowment, land productivity and combined labour productivity and food self-sufficiency. See Table 1 for a description of the main characteristics of the farm types.

3.4 Farm trajectories: transition from a type to another

Overall, one third of the farms transitioned from one type to another during the monitoring period, either ‘stepping up’ or ‘falling down’ (Table 3). Almost two thirds of the farms remained ‘hanging in’ or ‘stepped up’ to higher land and labour productivity, whereas a third of the farms experienced lower land and labour productivity while ‘hanging in’ or ‘falling down’. There was no obvious negative impact of the collapse of CMDT on farm trajectories: more farms ‘stepped up’ and fewer farms ‘fell down’ during the unfavourable period than in the previous period.

Analysis of specific farms allowed us to better understand the various trajectories for a given farm type. We found evidence that HRE farms and LRE farms had 'stepped up' to a more productive farm type by increasing their herd size (Figure 4a, b). Some MRE farms 'fell down' due to a decrease in available livestock for traction (decreased oxen worker^{-1}) (Figure 4c) and one HRE farm 'fell down' due to a decrease in total cropped land, number of workers, number of oxen and herd size (Figure 4d). Other farms remained 'hanging in' the same farm type (Figure 4a, b, c).

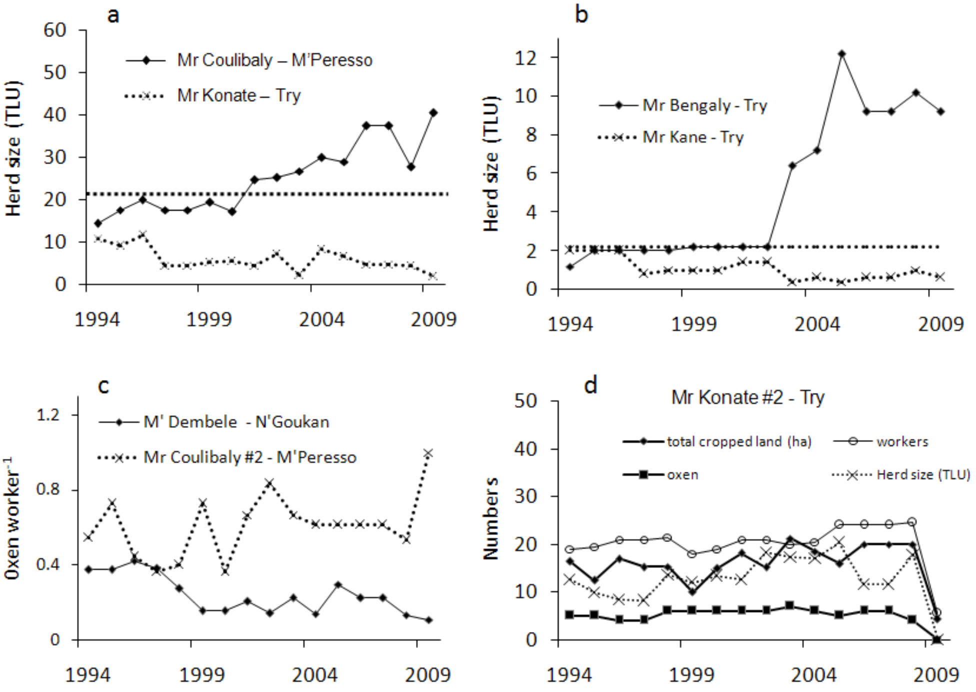


Figure 4: Examples of farm trajectories. (a) A farm 'stepping up' from HRE to HRE-LH compared to a farm 'hanging in'. (b) A farm 'stepping up' from LRE to MRE compared to a farm 'hanging in'. (c) A farm 'falling down' from MRE to HRE compared to a farm 'hanging in'. (d) A farm 'falling down' from HRE to LRE. For (a) and (b) the horizontal dotted line indicates the threshold herd size that discriminates two farm types. Names of household heads are fictitious. See Table 1 for a description of the main characteristics of the farm types.

Table 3: Importance of different farm trajectories for distinct periods according to the context of the cotton market.

Period		**% of farms**					
		(a) 'Hanging in' with high land and labour productivity[1]	**(b) 'Stepping up'[2]**	**(a)+(b)**	**(c)'Hanging in' with low land and labour productivity[3]**	**(d) 'Falling down'[4]**	**(c)+(d)**
Period 1 : Favourable context	1994 - 1999	47	7	54	33	13	46
	1999 - 2004	43	10	53	37	10	47
Period 2 : Unfavourable period when CMDT support collapsed	2004 - 2009	47	17	63	27	10	37
Whole period	1994 - 2009	47	17	64	23	13	36

[1] 'Hanging in' with high productivity = farms that stayed in MRE or HRE-LH.
[2] 'Stepping up' = farms that transitioned from HRE to HRE-LH, or from LRE to MRE, or from HRE to MRE.
[3] 'Hanging in' with low productivity = farms that stayed in HRE or LRE.
[4] 'Falling down' = farms that transitioned from MRE to HRE, or from HRE to LRE, or from HRE-LH to HRE

3.5 Farm trajectories: change in land and labour productivity

For MRE, HRE and HRE-LH farms, average nitrogen and phosphorus use intensity increased from 1994 to 2004 (Figure 5), along with an increase in the share of maize in the total cropped land (Figure 6). During the following cotton crisis, the share of cotton decreased (Figure 6), explaining the downward trend in mineral fertilizer application rates (Figure 5). This illustrates the fact that farmers rely on the cotton sector for credit to purchase fertilizer. On the other hand, organic fertilizer use intensity significantly increased over the entire monitoring period for MRE and HRE-LH farms ($P<0.01$, $R^2=0.47$ and 0.45 respectively) (Figure 5).

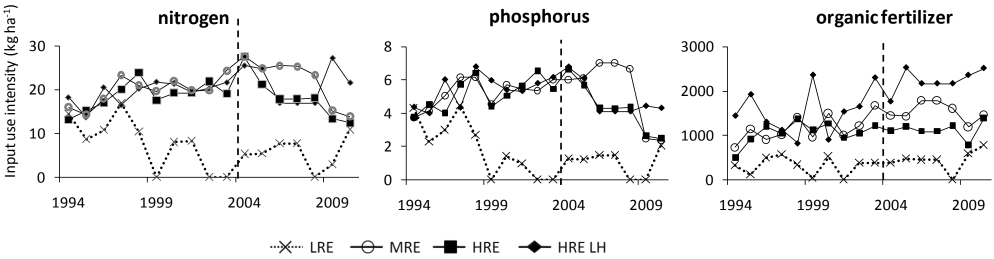


Figure 5: Average input use intensity per farm type over the 17 years of household monitoring. The vertical dotted line separates the period of favourable economic context for cotton production (1994-2004) from the unfavourable period during which support from CMDT collapsed (2004-2010). See Table 1 for a description of the main characteristics of the farm types.

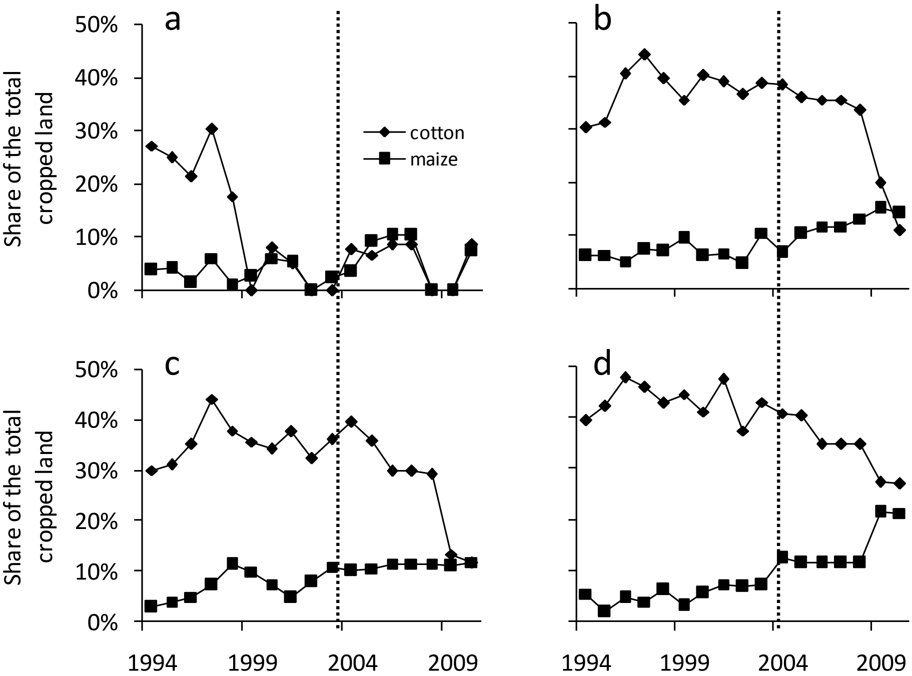


Figure 6: Share of maize and cotton in the total cropped land of (a) LRE farms, (b) MRE farms, (c) HRE farms and (d) HRE-LH farms during the monitoring period. The vertical dotted line separates the favorable context for cotton production (1994-2004) from the period when support from CMDT collapsed (2004-2010). See Table 1 for a description of the main characteristics of the farm types

We found no significant change in crop yield over time for any farm type and any crop. However, maize yields have decreased since the period when CMDT collapsed (Figure 7). Crop yields of LRE farms were more variable, especially for maize (CV=72%), compared with the other farm types. For MRE, HRE and HRE-LH farms, cotton and maize yields fluctuated more than sorghum and millet yields (Figure 7). Labour productivity for both cotton and cereals drastically decreased since the beginning of the unfavourable period when CMDT collapsed (Figure 8) as a result of stagnating yields and increased number of workers per farm (Table 1).

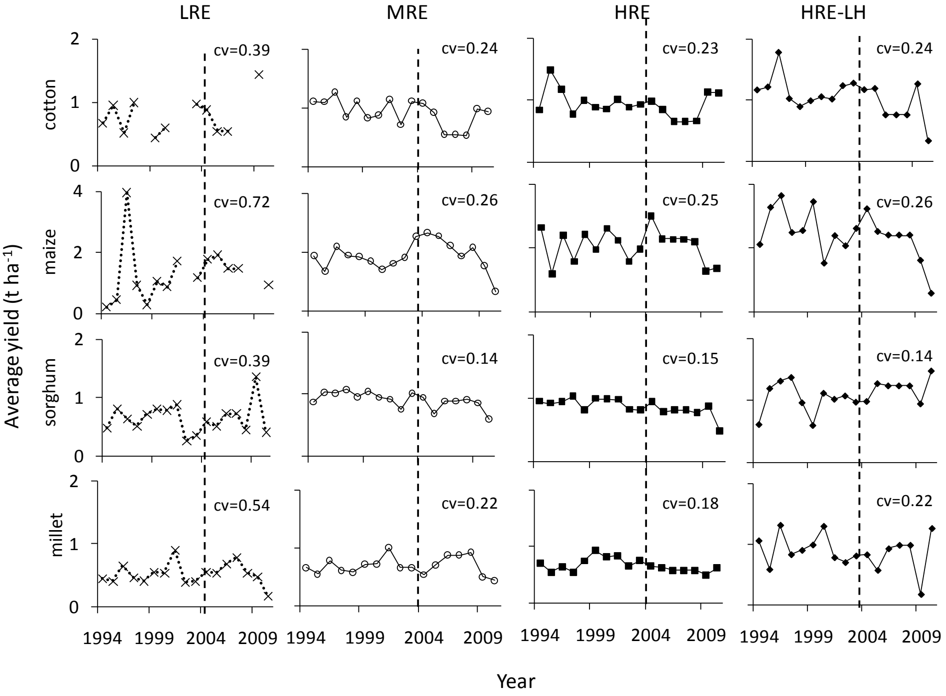


Figure 7: Average land productivity for cotton, maize, sorghum and millet for LRE farms, MRE farms, HRE farms and HRE-LH farms over the 17 years of household monitoring with indication of the coefficient of variation (cv). The vertical dotted line separates the favourable context for cotton production (1994-2004) from unfavourable period when support from CMDT collapsed (2004-2010). In some years, LRE did not grow cotton and/or maize. See Table 1 for a description of the main characteristics of the farm types.

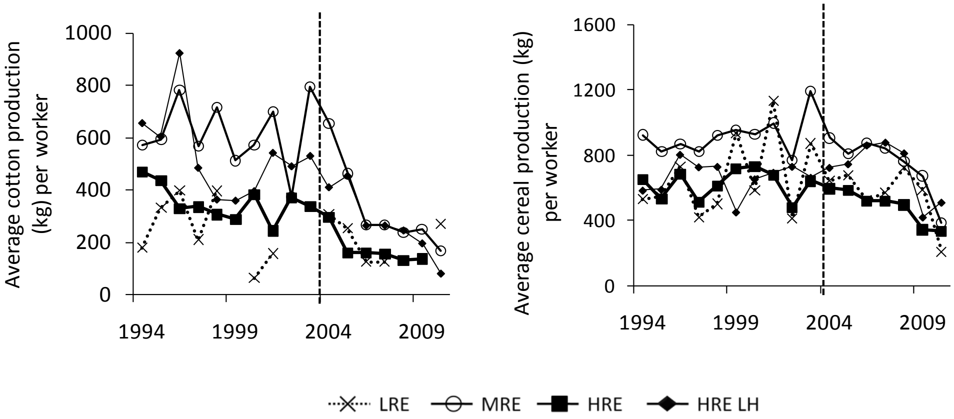


Figure 8: Average labour productivity for cotton (left) and cereals (right) for each farm type (see Table 1) over the 17 years of household monitoring. The vertical dotted line separates the favourable context for cotton production (1994-2004) from the period when support from CMDT collapsed (2004-2010).

3.6 Focus group discussion with farmers

During the focus group discussion, all farmers recognized themselves in the typology, and mentioned to which type they belong. The presentation of the different trajectories: ‘stepping up’, ’falling down’ or ‘hanging in’ led to fruitful debates, adding insight in the different trajectories. Farmer explanations for the trajectories were mostly related to intra-household organization, fodder production, off-farm opportunities and sharing of income.

4. Discussion

4.1. Discussion of the method for understanding farm trajectories

Studies using static typologies and assessing change over time by a new farm typology each year (Iraizoz et al., 2007; Mignolet et al., 2007; Sanogo et al., 2010) may confound trajectories and change in farm type definition. Our study builds on the body of evidence that fixed thresholds need to be defined, ensuring invariability in the definition of types and relevance of the trajectories depicted (Chopin et al., 2014).

The determined cut-off values allowed an easy classification of the farm and determination of their trajectories. When there was no overlap between two resource endowment variables, we arbitrarily defined the cut-off as the maximum of the variable with the lowest median. One could also have taken the minimum of the variable with the highest median or the average of the maximum and the minimum (see Appendix 1, figure A4). A sensitivity analysis showed that changing the cut-off determination method led to a marginal change in land and labour productivity of the different types (see Appendix 1, Table A2) and to slight changes in the quantification of trajectories (see Appendix 1, Table A3). Therefore, the latter need to be interpreted cautiously. However, as the same cut-offs were used throughout the monitoring period, the relative quantification of trajectories between periods can be interpreted with confidence. In other datasets, if all variables overlap, an interpretative value resulting in the least overlap can be chosen or classification and regression tree (CART) analysis may be used (Chopin et al., 2014).

Mushongah and Scoones (2012) and Valbuena et al. (2014) similarly described a rich diversity of individual storylines and conceptualized possible trajectories in link with socio-economic drivers. Their studies were based on two snapshots at the beginning and the end of a ten and twenty years period respectively. This type of longitudinal study does not allow tracing back non-linearity in trends. For example, in our study the year-to-year monitoring indicated that fertilizer use intensity increased from 1994 to 2004 and decreased thereafter, a trend that would not have been revealed if only the start year 1994 and the end year 2010 had been considered. The year-to-year monitoring also allowed for a detailed analysis of inter-year food self-sufficiency variability, and therefore the risk of food insufficiency. Furthermore, the trajectories we described are clearly linked to easy-to-identify farm types (see Appendix 1, Figure A5), making it easy to scale up recommendations in the Koutiala district.

4.2. Resource endowment and farm trajectories

Our study provides a comprehensive picture of farm trajectories over two decades in the Koutiala district. 17 % of the farms ‘stepped up’ to a type of higher land and labour productivity and food self-sufficiency status while 70% of the farms remained 'hanging in', and only 13% of the farms 'fell down' (Table 3). Hence the majority of farm households have been able to avoid falling down, notwithstanding a decrease in the available fodder resources (van Keulen and Breman, 1990) and the unfavourable economic-institutional context during the period when support from CMDT collapsed. Farmers have been able to do so by transhumance, conducting off-farm work (Abdulai and CroleRees, 2001) and increasing the number of traction animals (Table 1). Even though the use of mineral fertilizer and organic materials did not increase for all types, farmers have been able to counteract soil fertility decline to some extent thanks to these practices (Benjaminsen et al., 2010; De Ridder et al., 2004).

However, for 70% of the farms, which remained 'hanging in', neither has land productivity nor food self-sufficiency improved over the last two decades (Figures 2 and 7). Indeed, labour productivity decreased since the beginning of the unfavourable period when support from CMDT collapsed (Figure 8). This lack of productivity improvement is in line with stagnating crop yields in many countries of sub-Saharan Africa (Tittonell and Giller, 2013). Decreasing labour productivity suggests that farming is less able to meet the needs of a rapidly growing population. Farms already fail to achieve food self-sufficiency in some years and this may increase in frequency if crop yields do not improve. The decrease in cotton area initiated in 2004 for MRE, HRE and HRE-LH (see Figure 6) was compensated by a significant increase in average cereals share (maize, sorghum and millet) since 2004 for MRE, HRE and HRE-LH ($P<0.05$, R-sq = 0.66, 0.87 and 0.86 respectively, data not shown). Therefore although cereal yields did not increase, total cereal production was able to cope with increase in population, thanks to the increase of cereal share in the total cropped land.

Our study confirmed the strong relationship between resource endowment and land productivity (Table 2), which was described earlier (Djouara et al., 2005). During the monitoring period only 35% of LRE farms grew cotton, which provided access to credit for mineral fertilizers through the CMDT. LRE farms applied on average only 7 kg of N $ha^{-1}$and 1 kg of P ha^{-1}. With very small livestock herds and seldom a cart to transport organic fertilizer, LRE farms used on average only 0.56 t DM ha^{-1} organic fertiliser across the farm. LRE farms also did not have access to a complete oxen span, which negatively impacted their ability to sow and weed in a timely fashion, impairing yields. With smaller cotton yields (750 kg ha^{-1}) on small areas the LRE farms struggle to pay back credit for fertilizers, consequently losing the possibility for future contracts from the CMDT. This risk discouraged LRE farmers from growing cotton, explaining the rapid decline in the share of cotton in their cropped land (Figure 6a). On the other hand, MRE farms obtained better cotton (910 kg ha^{-1}) and maize (1300 kg ha^{-1}) yields due to more mineral fertilizer inputs (20 kg N ha^{-1} and 5 kg P ha^{-1}), financed through credit from cotton cultivation, and a small herd and a cart to handle organic fertilizer. Yields of sorghum and millet were also 40 and 33% larger on MRE than LRE farms (Table 2), thanks to the positive residual effect of fertilizer applied to cotton and maize earlier in the rotation. This crucial role of cotton for soil fertility maintenance and improved food crop productivity was described in another study (Ripoche et al., 2015). HRE farms achieved similar land productivity as MRE farms, because of their similar mineral and organic fertilizer inputs. The greatest land productivity for all crops was obtained by HRE-LH farms (exceeding 1000 kg ha^{-1} for cotton and sorghum and 2400 kg ha^{-1} for maize), explained by the largest rates of organic manure inputs allowed by the largest animal to land ratio of all farm types (Table 1). In addition, our study clarified the more complex link between resource endowment, labour productivity and food self-sufficiency (Table 2 and Figure 2). Some ‘large farms’ achieved larger crop yields, and yet had poor labour productivity and food self-sufficiency (see HRE farms). The expected correlation between larger farm size (more family members, land and labour) and betterment of the household situation (Figure 9a), concealed a ‘falling down’ trajectory in which the labour productivity and food self-sufficiency declined as the farm increases in size (Figure 9b).

4.3. Farm trajectories illustrated by farmers’ reality

The ‘Stepping up’ trajectories recorded illustrate the scope for improving farm performance in the area. For example, Mr Coulibaly in M’Peresso ‘stepped up’ from HRE to HRE-LH in 2001 as a result of enlarging his herd size, compared with Mr Konate in Try who did not increase his herd size and remained in the HRE type (Figure 4a). During focus group discussions, farmers indicated that increasing the herd size depends on a good intra-household work organisation for crop and livestock activities. Livestock feeding and watering are time-consuming activities, for which labour is often lacking, as the household members are primarily occupied with cropping activities. As a result, when these activities are handed over to an unmotivated child, they are not carried out properly, thus compromising the animal health status and herd growth. Fodder production, e.g. cowpea, was mentioned as another strategy for increasing the herd size. Also low resource endowed farmers, like Mr Bengaly from Try, can step up to a more productive farm type by increasing herd size (Figure 4b). As indicated by the farmers, LRE farms are small farms with little cotton production and cash income from crop cultivation, so that a step up is possible only through the investment of income gained off-farm into the farm. Farmers indicated that seasonal migration of young people to gold mines can offer the cash needed for such farm investments (cf Pijpers (2014)).

Some farms fell down during the monitoring period. For example, the number of workers in Mr Dembele's farm in N'Goukan doubled, leading to a decrease in the oxen worker^{-1} ratio (Figure 4c). The increasing number of workers is a natural development in the typical Malian extended families characterized by polygamy and high birth rates (with 45 births per 1000 people, Mali is the third country in the world according to the Index Mundi Data portal, http://www.indexmundi.com/g/r.aspx?v=25, last accessed 03/06/2015). While Mr Dembele transitioned from MRE to HRE, his land productivity remained equal, thus decreasing labour productivity and food self-sufficiency, which is interpreted as 'falling down' (Figure 9b). 'Falling down' trajectories also involve farms moving from HRE to LRE, like Mr Konate #2 from Try in 2009 (Figure 4d). Farmers explained this trajectory by a household split because of a disagreement among household members over income sharing from cotton. In the typical Malian extended family, the head of the household is in charge of the share of the income obtained from cotton production among the younger brothers and/or married sons. In some cases, an inequitable share of this income can lead to tensions between members of the household and lead to the split of the household. Our analysis showed that only 13% of the 30 farms followed 'falling down trajectories', and that those were not influenced by the unfavourable period when support from CMDT collapsed (Table 3). However, due to the shorter monitoring period of the 'unfavourable context' (2004-2009) as compared with the 'favourable context' (1994-2004), effects of the cotton crisis might still be observed in the future if the uncertainties concerning cotton production persist. For some farms, "hanging in" masked transitions up and down at various times during the monitoring period. For example, Mr Kane #2 in Try, remained a HRE farm, but with strong fluctuations in the herd size, illustrating a common trend in West African livestock keeping: farmers use livestock as a hedge against risk, decapitalizing to get the cash needed to face an unexpected event (Appendix 1, Figure A6a). Mr Coulibaly #3 in M'Peresso is a MRE farm with oscillating worker numbers, as explained by the dynamics of the young people entering and leaving the farm (Appendix 1, Figure A6b) as a result of rural migration (Hertrich and Lesclingand, 2013).

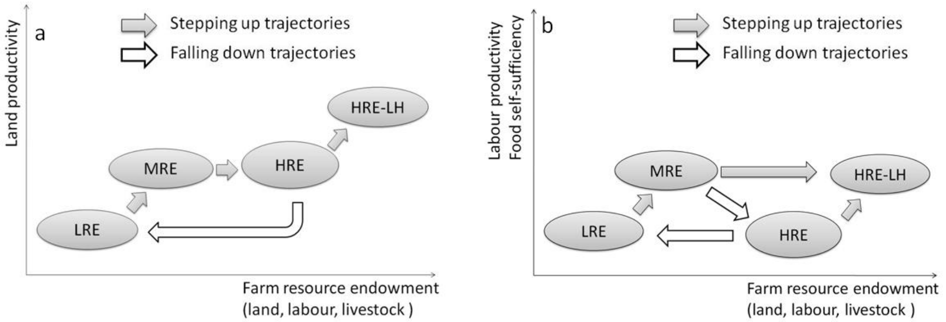


Figure 9: Possible farm trajectories when considering land productivity (a) or labour productivity and food self-sufficiency (b). Labour productivity and food self-sufficiency are shown on the same axis as they follow the same behaviour.

4.4. Two decades, a change in farm practices?

Mineral fertilizer use has decreased since the beginning of the cotton crisis in 2004 (Figure 5). This decrease was linked to a change in cropping patterns: a decrease in the share of cotton in the total cropped land since 2004, which was not offset by an increase in the share of maize (Figure 6). This highlights the crucial role of the parastatal company CMDT with respect to agricultural input supply in Mali. There is a strong need for increased input use to underpin crop yield improvement. The CMDT is the only institution that guarantees access to fertiliser for cotton and maize. The decision to split CMDT in four local units owned by private societies, together with the creation of one national union of farmer cooperatives in 2007 to take over some of the organisation of the value-chain (access to credit, capacity building and information of producers, market share), raises some uncertainties on the future of the cotton sector (Bélières et al., 2008). So far the privatisation has not been operationalized, and the challenge of regaining farmers' trust in cotton production remains. Another remaining challenge is farmer empowerment in the price negotiation process (Nubukpo, 2011). However, the recent investment in fertiliser subsidy of Malian state for rice, cotton and maize, raising from 13.4 billion CFA in 2008 to 21.2 billion CFA in 2010 offers scope for an increase of fertiliser use intensity (Aparisi et al., 2013). Furthermore, farmer cooperatives working on cereal commercialization and providing credit for fertilizer also offer potential (Kaminski et al., 2013).

All of the farms with cattle (MRE, HRE, HRE-LH) used substantial amounts of organic manure with HRE-LH using 2.5 t DM ha^{-1} on average across the farm in 2010 (Figure 5). For a typical HRE-LH farm, Blanchard (2010) measured a lower organic fertilizer use intensity of 1.6 t DM ha^{-1}. Our database contains farmers' estimates of the number of cartloads, from which the amount of organic fertilizer was derived using a conversion of 200 kg per cartload and 70% of dry matter (Kanté, 2001). The larger amounts presented in this study might thus be related to farmers overestimating the number of cartloads or to an overestimate of the cartload weight. However, focusing on the trends and the relative differences, HRE-LH and MRE farm types increased their organic fertilizer use intensity by 74 and 100% respectively over the last two decades. (Bodnar, 2005) also found that organic fertilizer use intensity in Koutiala region went from 0.7t DM ha^{-1} in 1993 to 1.2 t DM ha^{-1} in 2003; a 71% increase. This promising trend is the result of the efforts of the extension services in the district, who have been training farmers intensively to pen animals at night to collect animal droppings and to recycle more biomass by adding crop residues to cattle beds and digging composting pits (Blanchard, 2010). Considering an average nutrient content of 1.1% N and 0.2% P (Bodnar, 2005), the organic fertilizer applied by HRE-LH farms (2.5 t DM ha^{-1}), contained 28 kg of N and 5 kg of P per ha, which is similar to the N and P input rate from mineral fertilizer. In reality, farmers concentrate 80 % of the organic fertilizer on cotton (data not shown), which in 2010 covered 5.6 ha on HRE-LH farms. This results in a nutrient input from manure of 65 kg of N ha^{-1} and 12 kg of P ha^{-1}.

4.5 Development pathways and options for sustainable intensification

Enhancing productivity through sustainable intensification is essential for agricultural development. Interventions should improve the farming situation of farms 'hanging in' with low productivity. Credit for investment in farm equipment (oxen, ploughs) is the lever for 'stepping up' of LRE farms and improvement of HRE labour productivity. Increased oxen endowment improves the timeliness of sowing, which positively impacts cotton, maize and sorghum yields (Traore et al., 2014). The Asian example of credit systems financing one-quarter of farm equipment assets (Mellor, 2014) serves as an inspiration for facilitating the 'stepping up' of LRE farms. Nevertheless, we did not capture the complete livelihood strategies of households as data on off-farm activities were not available in the panel dataset. However existing literature shows that cash-oriented non-farm activities provide only 6% of total household income per capita in the Koutiala region (Abdulai and CroleRees, 2001), indicating that farming remains the major livelihood strategy for farms in the Koutiala region. Future analyses would also benefit from including information on livestock productivity (milk, meat consumption and animal sales) and inputs (purchased feed, veterinary care).

For HRE farms with relatively large cattle herds, improved livestock productivity through shorter calving intervals and increased calving rates for faster oxen turn-over can be achieved through better herd management, feeding practices and veterinary care (Sanogo, 2011).

For farms with large herds, land productivity can be improved by increasing manure availability and its nutrient cycling efficiency through proper collection and storage procedures (Rufino et al., 2007). Furthermore, with maize/legume intercropping, fodder can be produced with a small penalty to maize yields (Rusinamhodzi et al., 2012), hence providing opportunities to keep part of the cattle herd that would otherwise move in transhumance and benefit from its manure. The growing urban population increases the demand for dairy products (meat, milk) and processed cereals. This creates opportunities to intensify milk production through stable feeding of cows (Sanogo, 2011; Tarawali et al., 2002), or to intensify cereal production through improved varieties and increased organic and mineral fertilizers use. As MRE farms usually surpass food self-sufficiency, they can be net sellers of their cereal surpluses. Emerging farmer cooperatives are organizing the storage of cereal grains and facilitating contracts with buyers at local and national scale (Kaminski et al., 2013). Increasing off season productivity with irrigation is another option that can increase land and labour productivity, income, and food self-sufficiency (Pachpute, 2010). These farm type specific technical options must be discussed with the head of the household, but also with young people and women who participate in farming activities, to ensure the intra-household cohesion that was pointed out by farmers as a prerequisite to stepping-up trajectories.

To underpin those positive changes in agriculture, broader socio-economic and politic change is needed. Subsidized imported products (meat, milk powder) compete with local products and artificially lower prices. International trade agreements give African states some leeway to raise their agricultural trade protection level and thus raise domestic prices (Laroche Dupraz and Postolle, 2013). Improved roads could also increase farm gate prices (Obare et al., 2003). Apart from intensification of agriculture, investment in family planning and the associated fertility reduction can also be an important means of responding to the increasing land constraints (Headey and Jayne, 2014).

Conclusion

Longitudinal studies of smallholder farming systems in Africa are rare but provide important insights that may help to guide future interventions for rural development. The study area, the Koutiala district, is representative of the 'cotton zone' of the Sudano-Sahel of West Africa where the income from cotton has allowed farmers to accumulate cattle (Dufumier and Bainville, 2006). Our study shows that this general impression of an increase in wealth and numbers of cattle in the Koutiala region masks a rich diversity of dynamics for different households. Over the two decades, 17% of the farms were able to achieve better land and labour productivity and more food self-sufficiency, but 70% remained in the same type and 13 % 'fell down' to a type with less land and labour productivity and less food self-sufficiency.

Nor have the underlying changes been unidirectional – the changing policy and economic environment has exerted a strong influence. Although changes in governmental support did not appear to impact farm trajectories, they strongly impacted the intensity of fertilizer use within each farm type. We found no change in crop yields over the two decades, and yet labour productivity decreased, a worrying trend given the increasing population.

The options available for farmers to achieve a 'sustainable intensification' of their farming systems are several. Farm equipment can still be increased; the cereal crops, maize, sorghum and millet, have emerged as cash crops (Kaminski et al., 2013); there are opportunities for intensification of milk production (Sanogo, 2011), and it is likely that cotton will remain important. There are also options to enhance food self-sufficiency and fodder availability through the incorporation of legumes such as cowpea. Yet fundamental improvements to the general policy and institutional environment will be needed (such as the finance system, investment in infrastructure, tariffs to increase farm gate prices) as a prerequisite for such technical options to be viable interventions. Our current work is focused on exploring such options together with farmers in the Koutiala region.

Acknowledgment

Funding for this research was provided by the McKnight Foundation through the project 'Pathways to Agro-ecological Intensification of Sorghum and Millet Cropping Systems of Southern Mali' and by the CGIAR Research Program on Dryland Systems. We thank the Institut d'Economie Rurale (IER) for making available the panel dataset. Thanks also to three reviewers for their detailed comments that helped us to improve the manuscript.

Chapter 3

Unravelling the causes of variability in crop yields and treatment responses for better tailoring of options for sustainable intensification in southern Mali

This chapter is published as:
Falconnier, G.N., Descheemaeker, K., Van Mourik, T.A., Giller, K., 2016. Unravelling the causes of variability in crop yields and treatment responses for better tailoring of options for sustainable intensification in southern Mali. Field Crops Res. 187, 113–126.

Abstract:

Options that contribute to sustainable intensification offer an avenue to improve crop yields and farmers' livelihoods. However, insufficient knowledge on the performance of various options in the context of smallholder farm systems impedes local adaptation and adoption. Therefore, together with farmers in southern Mali we tested a range of options for sustainable intensification including intensification of cereal (maize and sorghum) and legume (groundnut, soyabean and cowpea) sole crops and cereal-legume intercropping during three years on on-farm trials. There was huge variability among fields in crop yields of unamended control plots: maize yielded from 0.20 to 5.24 t ha^{-1}, sorghum from 0 to 3.53 t ha^{-1}, groundnut from 0.10 to 1.16 t ha^{-1}, soyabean from 0 to 2.48 t ha^{-1} and cowpea from 0 to 1.02 t ha^{-1}. This variability was partly explained by (i) soil type and water holding capacity, (ii) previous crop, its management and the nutrient carry-over and (iii) inter-annual weather variability. Farmers recognized three soil types: gravelly soils, sandy soils and black soils. Yields were very poor on gravelly soils and two to three times greater (depending on the crop) on black soils. Yields were also poor at the end of the typical crop rotation, i.e. after sorghum and millet, and 1.3 to 1.7 times greater (depending on the crop) after the fertilized crops maize and cotton. We diagnosed a number of cases of technology failure where no improvement in yield was observed with hybrid varieties of maize and sorghum and rhizobial inoculation of soyabean. Regardless of soil type and previous crop, mineral fertilizer improved yields by 34 to 126 % depending on the crop. Targeting options to a given soil type and/or place in the rotation enhanced their agronomic performance: (i) the biomass production of the cowpea fodder variety was doubled on black soils compared with gravelly soils, (ii) the additive maize/cowpea intercropping option after cotton or maize resulted in an average overall LER of 1.47, no maize grain penalty, and 1.38 t ha^{-1} more cowpea fodder production compared with sole maize. Soil type and position in the rotation, two indicators easy to assess by farmers and extension workers, allowed the identification of specific niches for enhanced agronomic performance of legume sole cropping and/or intercropping.

Keywords: intercropping; cereals; legumes; soil type; rotation

1. Introduction

Farmers in Southern Mali grow cotton for income generation, cereals for food self-sufficiency and keep livestock for a wide variety of reasons, including draught power, manure, meat, milk and buffer against risk (Falconnier et al., 2015b; Kanté, 2001). Due to market uncertainty and increasing land pressure, agriculture needs to adapt to the decline in cotton profitability (Coulibaly et al., 2015) and reduced availability of fodder for livestock (Breman, 1992; De Ridder et al., 2004; Leloup, 1994). Sustainable intensification offers an avenue to improve farmers' livelihood and is based on three principles (Vanlauwe et al., 2014): i) production of more food, feed and/or fuel from the same amount of land, labour and/or capital ii) maintenance of healthy soils and reduction of negative environmental impacts and iii) resilience to climate shocks and stresses. Two strategies are often mentioned to contribute to sustainable intensification. Firstly, Integrated Soil Fertility Management (ISFM), which assembles locally-adapted practices based on the use of improved crop varieties together with combined fertilizer, organic resource management and other soil amendments (e.g. lime) can enhance crop productivity and contribute to maintenance of healthy soils (Vanlauwe et al., 2015). Secondly, crop diversification through cereal-legume rotations or cereal-legume intercropping can reduce yield variability and improve overall farm productivity (Franke et al., 2014; Snapp et al., 2010). The options we tested all fall under one of these two strategies and can thus contribute to sustainable intensification. Although many studies report increased crop productivity in trials with such practices (Kaizzi et al., 2012; Otinga et al., 2013; Pitan and Odebiyi, 2001; Rurinda et al., 2013), local adaptation to diverse smallholder farm systems and conditions has received less attention. Indeed smallholder farming in SSA exhibits wide variability in household resource endowment and in soil fertility (Giller et al., 2011), resulting in huge ranges in yields within the same agro-ecological zone or even within individual farms (Baudron et al., 2012; Ronner et al., 2016; Zingore et al., 2007b). Large numbers of on-farm trials are required to unravel the relationships between the farmers' socio-ecological context and the performance of interventions. For example, 63 on-farm trials in semi-arid Zimbabwe showed that no tillage and insufficient mulch favoured crusting of sandy soils, thereby reducing water infiltration and decreasing cotton yields compared with ploughing (Baudron et al., 2012). Ojiem et al. (2007) used 27 trials to demonstrate that soil fertility status impacted the contribution of forage and grain legumes species to soil fertility improvement through biological nitrogen fixation.

In southern Mali, past research has identified a range of options for sustainable intensification including (i) maize-legume intercropping in which leguminous fodder is produced without penalizing maize grain yields (Bengaly, 1998), (ii) hybrid sorghum varieties that yield more than local landraces under fertilized conditions (Rattunde et al., 2013) and (iii) improved varieties of cowpea that allow grain production whilst also providing good quality fodder (Dugje et al., 2009). Yet little is known of the agronomic performance of these different options across the wide array of soil types, rotations and seasons that are encountered in the prevailing crop-livestock farming system. Hence, for better advice to farmers, information is needed on the niches where these options perform best. Such information needs to be easy to use and to assess by local farmers and farm advisors. Furthermore, numerous papers report on specific crop (maize, cowpea, soyabean) experiments, but very few studies encompass the complete set of farmers' crops in multi-year on-farm trials. However, such experimental setup is required to produce relevant information for farmer decision-making, which takes into account the management of the entire cropping system and the risk and trade-offs associated with certain decisions. Together with local farmers we therefore experimented with five crops (maize, sorghum, soyabean, cowpea and groundnut), two intercrops (maize/cowpea and sorghum/cowpea) and a whole range of options including hybrid varieties, combined additions of mineral fertilizer and manure, rhizobial inoculation of soyabean, improved varieties of cowpea and groundnut and intercropping patterns. After a series of participatory rural appraisals to understand and define farmers' constraints and opportunities, experiments to test these options were co-designed by researchers and farmers. Farmers tested the options in their fields over three consecutive seasons. The on-farm trials formed part of a larger participatory farming system re-design process (Falconnier et al., 2015a), which for example accommodated for annual adjustments in the set of trials.

In this paper we (i) assess the agronomic performance of a range of intensification options across a range of farmers' fields; (ii) explore the causes of the variability in farmers' yields and in the effects of the options on productivity; and (iii) define simple rules on where and when the intensification options perform best. In doing this, we explored the hypotheses that (i) soil type and characteristics, previous crop and its management, and seasonal rainfall variability explain the variability in farmers' yields and treatment effects; and (ii) better matching of intensification options with the environment (previous crop, soil type) increases the likelihood of increased crop yield.

2. Material and methods

2.1. Study area

The study area is located in Koutiala district in the cotton zone of Southern Mali, between the 800 mm and 1000 mm isohyets. The region is characterised by a uni-modal rainy season that starts in May and ends in October, with total rainfall fluctuating from 600 to 1400 mm. The population is relatively dense compared with the rest of the country, reaching 70 people km^{-2} (Soumaré et al., 2008). Farmers distinguish three main soil types with a vernacular name related to landscape position and texture (Blanchard, 2010; Kanté, 2001): "gravelly soils" at higher elevation, "sandy soils" in the middle and "black soils" in the lowest part of the catena. All soils are classified as Lixisols (FAO, 2006). Dominant crops are cotton, maize, sorghum, millet and groundnut. Farmers rely largely on cotton, maize and livestock for income and on maize, sorghum and millet as staple foods. The most common rotations are: (i) cotton and maize rotations, (ii) cotton and maize followed by sorghum and/or millet and (iii) sorghum and millet rotations. In all cases, organic and mineral fertilizers are applied solely on cotton and maize (Blanchard, 2010). The major livestock are cattle, sheep and goats. On average, farmers own 10 Tropical Livestock Units (TLU) of 250 kg with a wide range from 0-54 TLU (Falconnier et al., 2015b). Besides milk and meat, animals provide draught power for timely farming operations to cope with the erratic distribution of rainfall, while application of livestock manure in the fields has positive feedbacks on crop productivity (Kanté, 2001).

2.2. On-farm trials

We carried out on-farm trials during three consecutive cropping seasons (2012-2014). Participating farmers originated from nine neighbouring villages of the Koutiala district: M'Peresso, Nitabougouro, Nampossela, Finkoloni, Try, Koumbri, Kaniko and Kani. A total of 372 trials were planted by 12, 111 and 132 farmers in 2012, 2013 and 2014 respectively. Trials were not repeated in the same location. The first season was an inception year with only 12 participating farmers, while in the second and third season the network of participating farmers expanded. Seven different trials on options with sole crops and intercrops were co-designed by researchers and farmers to explore the opportunities discussed in participatory rural appraisals. Treatments included: (i) a maize and (ii) a sorghum hybrid and local variety, with and without combined mineral fertilizer and manure application (iii) soyabean without any amendments, with rhizobial inoculation and/or P fertilizer with manure, (iv) a grain variety and a fodder variety of cowpea with and without P fertilizer (v) an improved and a local groundnut variety, (vi) the cowpea grain and fodder varieties intercropped with maize or (vii) sorghum, with an additive and a substitutive intercropping pattern. Farmers indicated which improved varieties for maize and sorghum they were interested in for testing. As farmers were eager to test groundnut options, the groundnut trial was added in the third year.

Each sole crop trial was comprised of four plots of 6 × 8 m each: a control plot, two plots to test the effect of the first and second factor and a plot to test the combination of the two factors (Table 3). The control was the current farmer practice for maize, sorghum and groundnut, i.e. the local variety of the crop without fertilizer for sorghum and groundnut and with the mineral fertilizer dose recommended by the Compagnie Malienne pour le Développement du Textile (CMDT) for maize (as farmers do not grow maize without fertilizer), i.e. 80, 7, 12 kg ha^{-1} for N, P and K respectively. For soyabean and cowpea, the control was an improved variety (as cowpea is grown by only 16% of farmers and soyabean is seldom grown) with no fertilizer inputs. Seed of the local varieties was purchased from one resource farmer and used in all the trials. Manure was bought at the abattoir in Koutiala and was a mix of cattle droppings and sand from the pen. This manure was similar to that which farmers commonly collect in their cattle pen (Blanchard, 2010). Manure analysis at ICRISAT Sadore lab (Niger) indicated a nutrient content of 0.88 % N, 0.28% P, 0.65% K, 16 % organic carbon (OC) and 72 % ash in 2013 and 1.19% N, 0.33% P, 0.49% K, 15 % OC and 69 % ash in 2014. The rate of manure application used in the trials (9 t ha^{-1}) was in the range of the reported application rates by farmers (7-18 t ha^{-1}) (Blanchard et al., 2013).

Sun-dried manure (86% DM) was broadcasted before ploughing in plots established with a manure treatment. Farmers ploughed the fields and farmers and technicians planted the trials together. Seed was sown at a spacing of 75 cm between rows for maize, sorghum, cowpea and soyabean and 60 cm for groundnut. Within row spacing was 40 cm for maize, sorghum and cowpea, 30 cm for groundnut and 5 cm for soyabean, with one seed per station for soyabean, two for groundnut, three for maize and cowpea, and four for sorghum. Crops were thinned at 15 days after planting: one plant per station for groundnut and two plants per station for maize, cowpea, and sorghum were retained. Sorghum, cowpea and soyabean were weeded 15 days after sowing and ridged 45 days after sowing. Maize was weeded twice (15 days and 30 days after sowing) and ridged 45 days after sowing. Cowpea was sprayed with neem oil (from the tree *Azadirachta indica* A. Juss.) every two weeks after the first weeding and every week during flowering and pod filling.

For the intercropping trials, farmer chose cowpea as the companion crop for maize and sorghum. The intercropping arrangement proposed by farmers was an additive pattern where the cereal (maize or sorghum) was sown with the same density as the sole crop (67 000 plants ha^{-1}) and cowpea was added every other row between cereal planting stations two weeks after the cereal (giving a cowpea density of 33 500 plants ha^{-1}). The substitutive pattern designed by researchers was a substitutive pattern where one out of three rows of the cereal was replaced by cowpea, leading to a pattern of two rows of the cereal and one row of cowpea (giving a density of 45 000 and 22 000 plants ha^{-1} for maize and cowpea respectively). In the substitutive pattern, both the cereal and cowpea were sown the same day. The intercropping trials consisted of four intercropping plots for the cowpea variety and pattern combinations, and three additional plots for the sole cereal (maize or sorghum), the sole cowpea fodder variety and the sole cowpea grain variety.

Participating farmers managed the trials with the help of technicians to ensure that operations were conducted in a timely manner. Each farmer hosted one single, non-replicated trial with the four treatments, each trial forming a replicate. Further details of treatments are given in Table 3. In 2012, only the maize/cowpea intercropping trials were conducted.

2.3. Surveys and measurements

A number of factors were recorded at the plot or farm level to help understand the reasons for differences in crop yields. The factors recorded were (i) soil type as defined by farmers (three levels: gravelly soil; sandy soil; black soil); (ii) previous crop in the field where the trial was implemented (three levels: cotton or maize; millet or sorghum; groundnut or cowpea further referred to as legume); and (iii) cropping season (three years: 2012, 2013 and 2014).

In each village, one farmer collected daily rainfall data with a manual rain gauge. We geo-referenced each trial and recorded the soil type as defined by the farmer. Farmers also described the field history based on the previous crops and the amount of mineral and organic fertilizer applied in the three years prior to the trial.

In May of 2012, 2013 and 2014, soil was sampled in each trial (a composite sample bulked from 9 cores at 0-15 cm depth following a W in the trial) before the start of the rainy season and before plots were established with different treatments. Samples were weighed, air-dried, ground and passed through a 2 mm sieve. Gravel was separated and weighed and fine earth was analysed for organic C, total N, extractable P, K, Ca and Mg and pH. Organic C and total N were determined with the Walkley-Black and Kjeldhal procedures respectively; total N, K Ca and Mg were determined from

H_2SO_4 extracts; P was determined from $NaHCO_3$ extracts according to the Olsen method. Proportions of clay, silt and sand were determined through sedimentation. Carbon and nutrient content and % clay, silt and sand were expressed per total weight (fine earth and gravel).

Timing of the different operations (weeding, harvest) was recorded by field agents. At crop maturity, farmers and researchers jointly harvested the central area of the plot discarding two border rows. Mature sorghum and maize plants were harvested following the local practice of cutting the panicles and cobs. Legume pods were harvested when mature. Stover of all crops was weighed at the plot and a stover sub-sample was taken and weighed. Sorghum panicles, maize cobs and legume pods were dried on a clean floor at the homestead. Sorghum panicle and maize cobs were threshed and hand-winnowed and legume pods were shelled by hand. Grains were weighed and grain sub-samples were taken and weighed. All sub-samples (grain and stover) were oven-dried at the ICRISAT Research Station in Samanko, and re-weighed to determine dry weights. All grain and stover yields were expressed in t DM ha^{-1}.

After the 2014 harvest, a profile pit was dug in each major local soil unit within farmers' fields (one on a gravelly soil, one on a sandy soil and one on a black soil). Morphological characteristics were described using the FAO guidelines (FAO, 2006) and soil samples of each horizon were weighed, air-dried, ground and passed through a 2 mm sieve. The fine earth and gravels were weighed and fine earth was analysed for organic C, sand, silt and clay content. Plant available water in each horizon was estimated using pedo-transfer functions (Saxton and Rawls, 2006).

2.4. Statistical analysis

The two experimental units of our design were (i) the plot within a trial and (ii) the trial (blocking factor). Treatments were plot attributes, while covariates such as soil type, previous crop, season and soil characteristics were trial attributes. Linear mixed effects models (Coe, 2002; Parsad et al., 2009) were used to explain variability in sole crop yields and partial Land Equivalent Ratio (pLER) of intercrops (Willey, 1979). pLERs were calculated as follows:

$$(1)\,\text{pLER} = I/S$$

Where I is the intercrop yield, S is the sole crop yield. We considered fodder and grain yield for cowpea and grain yield for maize.

A trial was a given experimental unit on a particular soil type, with a particular previous crop, for a particular farm during a particular cropping season. Each trial was thus randomly chosen from a wider population of possible experimental units on the same soil type, and following the same previous crop. Therefore, the factor 'trial' was treated as a random effect in the models below (Allan and Rowlands, 2001). The attributes of the experimental units were fixed effects (Allan and Rowlands, 2001) and included (i) the experimental treatments, i.e. fertilization, pattern, variety or inoculation and (ii) covariates to explain the variability, i.e. soil type, cropping season, previous crop in the field where the trial was implemented and topsoil characteristics (i.e. pH, C, N, P, Mg, Ca, K and clay+silt).

Mixed linear models were constructed as follows:

(Model 1) $Y_{il} = \alpha F_i + \varepsilon NT_l + R$

(Model 2) $Y_{jl} = \beta V_j + \varepsilon NT_l + R$

(Model 3) $Y_{ijl} = \alpha F_i + \beta V_j + \varepsilon NT_l + R$

(Model 4) $Y_{ijl} = \alpha F_i + \beta V_j + \delta FV_{ij} + \varepsilon NT_l + R$

(Model 5) $Y_{ijkl} = \alpha F_i + \beta V_j + \gamma C_k + \varepsilon NT_l + R$

(Model 6) $Y_{ijkl} = \alpha F_i + \beta V_j + \gamma C_k + \delta FC_{ik} + \varepsilon NT_l + R$

(Model 7) $Y_{ijkl} = \alpha F_i + \beta V_j + \gamma C_k + \delta VC_{jk} + \varepsilon NT_l + R$

where Y_{ijkl} represents the square-root transformed yields for sole crops and pLER for intercrops, F_i is the ith level of the fertilization treatment (or pattern in the intercropping trials), V_j is the jth level of the variety treatment (or inoculum in the soyabean trial), C_k is the kth level of the covariate (soil type, previous crop, season and continuous topsoil characteristics for which levels are irrelevant and k can be ignored), $FV_{ij,}$ FC_{ik} and VC_{jk} are the interactions between F_i and V_j, F_i and C_k, and V_j an C_k respectively, NT_l the lth trial and R is the residual, and α, β, γ, δ, ε represent fixed and random effects coefficients.

Visual inspection of plots of residuals did not reveal heteroscedasticity or deviations from normality. *P*-values to test the significance of effects were obtained by likelihood ratio tests of the full model with the effect tested against the model without the effect. Concretely this was done for treatments effects by testing model 3 against model 1 or 2, for covariates effect by testing Model 5 against Model 3, for interaction effects between treatments by testing Model 4 against Model 3 and for interaction effects of treatments with covariates by testing model 6 or 7 against Model 5. Trials that suffered crop damage by animals (roaming cattle, rabbits) were excluded from the analysis (2, 4, 16, 6, and 2 trials for maize, sorghum, soyabean, cowpea and maize/cowpea respectively). The analysis was done using R (R Development Core Team, 2005; http://www.R-project.org, last accessed 13/07/2014) and the linear mixed-effect model was developed and tested with the R package *lme4* (http://cran.r-project.org/web/packages/lme4/index.html, last accessed 13/07/2015). We performed the likelihood ratio test using the *anova* function.

The coefficients of determination (R^2) of final models (containing all significant treatments and covariates) were calculated as the squared Pearson correlation between predicted and observed values. Predicted values were calculated using the estimated fixed effects coefficients for treatments and covariates.

3. Results

3.1. Season and soil characteristics

The seasons started earlier and received more total rainfall in 2012 and 2014 compared with 2013 (Figure 1). 2013 was a “bad” season with an average of 723 mm across all villages, i.e. a value below the first quartile of rainfall in Koutiala for the period 1980-2010 (data not shown). On the contrary, 2012 and 2014 were “good” seasons with average annual rainfall of 1023 and 883 mm respectively, i.e. values above the third quartile and above the median rainfall in Koutiala for the period 1980-2010 respectively.

Gravel content and texture differed among the farmer-defined soil types. Gravelly soils contained more gravel than black and sandy soils, while black soils had higher silt+clay content compared with the other soils (Table 1). Gravelly and sandy soils had a loamy sand texture, while the texture of black soil was sandy loam. Soil organic carbon (SOC) and nutrient content (N, P, K, Ca, Mg) also differed among the soil types (Table 1). Black soils had larger SOC and nutrient content than the other soil types. Cotton and maize received more manure and mineral fertilizer than other crops, regardless of the soil type (Appendix 2, Table A1). SOC and nutrient (N, P and K) content was larger after cotton and maize compared with after sorghum and millet (Table 1). SOC and nutrient (N, P, Ca, K) content was smaller after legumes compared with after cotton and maize on gravelly and sandy soils, but larger on black soils (Table 1).

Roots were observed up to 160, 100 and 50 cm in the soil pits in black soil, sandy soil and gravelly soil respectively (Table 2). We could not sample deeper than 50 cm in the gravelly soil pit due to the presence of concretions. The estimated cumulative plant available water (in the zone where roots were observed) was greater in black soils (189 mm) compared with sandy soils (166 mm) and gravelly soils (33 mm) (Table 2).

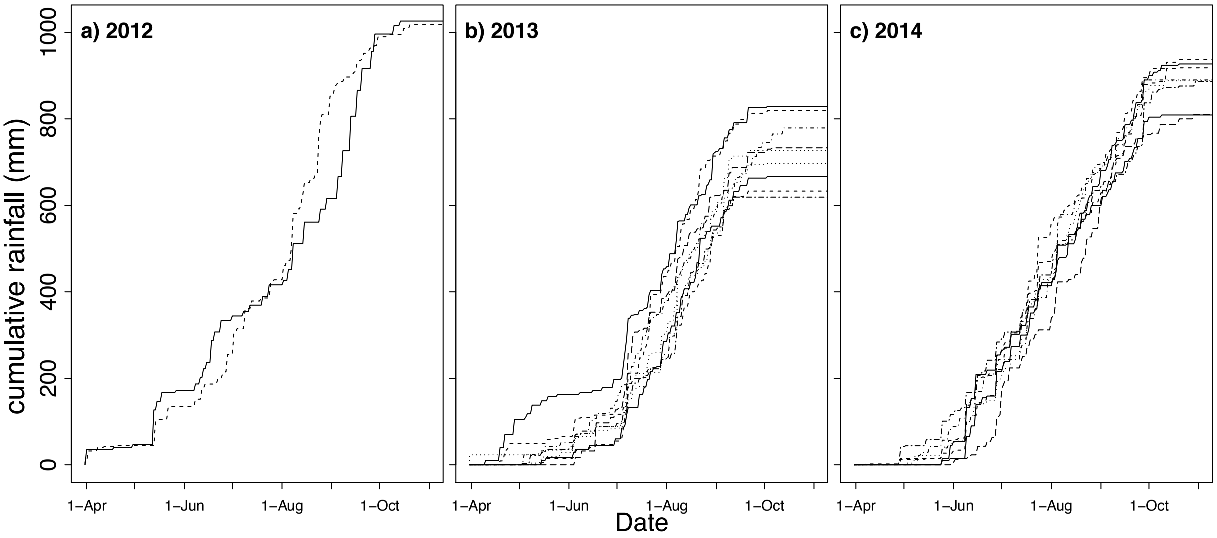


Figure 1: Cumulative rainfall during the 2012 (a), 2013 (b) and 2014 (c) seasons measured in 2, 9 and 8 villages in the Koutiala district (represented by the different line types) respectively. Total rainfall ranged from 1019 to 1026 mm in 2012, from 619 to 829 mm in 2013, and from 809 to 927 mm in 2014.

Table 1: Characteristics of the three farmer-defined soil types for different previous crops, derived from topsoil (0-15 cm) samples from the on-farm trials in 2012, 2013 and 2014 (SOC: soil organic carbon; N: total nitrogen; P: available phosphorus, K: exchangeable potassium, Mg: exchangeable magnesium, Ca: exchangeable calcium, SE = standard error of the mean). Carbon, nutrient and clay+silt content were expressed per total weight (fine earth and gravel). Significant effects ($P < 0.05$) are highlighted in bold.

			pH		SOC (g/kg)		N (g/kg)		P (mg/kg)		Ca (cmol(+)/kg)		Mg (cmol(+)/kg)		K (cmol(+)/kg)		Clay + silt (g/kg)		Gravel (g/kg)	
Farmer-defined soil type	Previous crop	n	mean	SE	mean	SE	mean	SE	mean	SE	mean	SE	mean	SE	mean	SE	mean	SE	mean	SE
Gravelly soils	Cotton/maize	26	5.3	0.49	3.4	0.27	0.28	0.019	4.7	0.85	0.86	0.128	0.33	0.038	0.16	0.017	162	16.2	432	37.7
	Sorghum/millet	28	4.9	0.25	3.1	0.28	0.25	0.018	3.4	0.30	0.96	0.126	0.32	0.027	0.12	0.013	156	7.8	416	44.4
	Legume	6	5.1	0.32	2.6	0.22	0.20	0.023	2.8	0.38	0.76	0.166	0.35	0.029	0.11	0.008	175	23.5	323	61.8
Sandy soils	Cotton/maize	65	5.0	0.38	2.8	0.11	0.24	0.008	5.7	0.22	1.43	0.112	0.47	0.034	0.23	0.010	192	10.7	45	5.1
	Sorghum/millet	131	5.0	0.24	2.7	0.11	0.23	0.007	4.3	0.17	1.43	0.072	0.54	0.023	0.20	0.006	177	5.8	58	4.4
	Legume	21	5.1	0.42	2.4	0.17	0.21	0.015	5.3	0.41	1.13	0.165	0.48	0.058	0.19	0.011	168	13.7	46	17.7
Black soils	Cotton/maize	60	5.2	0.54	3.8	0.18	0.30	0.013	5.5	0.30	1.41	0.119	0.54	0.031	0.22	0.010	255	9.7	62	7.7
	Sorghum/millet	77	5.3	0.52	3.2	0.16	0.26	0.012	4.5	0.19	1.19	0.094	0.49	0.030	0.21	0.008	243	10.9	68	11.8
	Legume	13	5.2	0.60	4.0	0.40	0.33	0.034	5.4	0.31	1.38	0.204	0.62	0.090	0.29	0.049	288	32.7	40	7.7
F-test probabilities																				
	Soil type		**0.0023**		**0.0000**		**0.0000**		**0.0044**		**0.0003**		**0.0000**		**0.0000**		**0.0000**		**0.0000**	
	Previous crop		0.9660		**0.0306**		**0.018**		**0.0000**		0.521		0.626		**0.0477**		0.1690		0.4570	
	Soil type x previous crop		0.1540		0.1331		**0.0295**		0.5854		0.4552		0.2230		**0.0082**		0.4430		0.6700	

Table 2: Chemical and physical characteristics of three soil profile pits in each farmer-defined soil type in the Koutiala region.

Pit N°	Farmer-defined soil type	Soil classification (FAO)	Horizon	Depth (cm)	Abundance of roots[1]	Sand (%)	Clay (%)	Gravel (%)	Organic Matter[2] (%)	Plant available water (mm)[3]
1	Gravelly soil	Lixisol	A	0-10	many	66	14	52	1.53	5.5
			B1	10-30	common	43	38	50	0.86	15.2
			B2	30-50	common	41	39	64	0.80	12.1
2	Sandy soil	Lixisol	A	0-25	many	57	12	2	0.81	26.1
			B1	25-50	common	46	33	2	0.38	28.4
			B2	50-100	few	36	44	7	0.27	59.5
			B3	100-150	none	36	43	25	0.17	52.5
3	Black soil	Lixisol	A	0-20	many	67	8	3	0.52	16.8
			B1	20-50	common	38	39	6	0.42	35.8
			B2	50-100	few	36	42	1	0.22	61.9
			B3	100-160	few	35	42	0	0.14	75.2

[1] number of roots per square decimetre (FAO, 2006) : None: 0; Very few: 1-20 (<2mm) and 1-2 (>2mm); Few: 20-50 (<2mm) and 2-5 (>2mm); Common: 50-200 (<2mm) and 5-20 (>2mm); Many: >200 (<2mm) and >20 (>2mm).

[2] In the fine earth fraction

[3] Estimated using pedo-transfer functions (Saxton and Rawls, 2006); applies to the bulk soil (fine earth and gravels)

Table 3: Options tested with farmers for sole crops and intercrops. ap= additive pattern, sp= substitutive pattern.

Type of trial	Crop	Number of trials			Treatment	Variety			Fertilizer		Pattern	Inoculation
		First year (2012)	Second year (2013)	Third year (2014)		Local name	Type	Cultivar name	Mineral fertilizer N;P;K (kg ha^{-1})	Manure (t ha^{-1})		
Cereals	Maize	0	45	41	Control	Dembanyuma[1]	Local variety	-	80;7;12[2]	0	-	-
					Variety	Bondofa	Hybrid	EV8444 SR x SR22[a]	80;7;12[2]	0	-	-
					Fertilizer	Dembanyuma[1]	Local variety	-	80;7;12	9	-	-
					Variety + Fertilizer	Bondofa	Hybrid	EV8444 SR x SR22[a]	80;7;12	9	-	-
	Sorghum	0	23	26	Control	Segetana	Local variety	-	0	0	-	-
					Variety	Pablo	Hybrid	FambeA x Lata[b,e]	0	0	-	-
					Fertilizer	Segetana	Local variety	-	14;15;0	9	-	-
					Variety + Fertilizer	Pablo	Hybrid	FambeA x Lata[b,e]	14;15;0	9	-	-
Legumes	Soyabean	0	39	25	Control	Houla1	Landrace	-	0	0	-	No
					Inoculum	Houla1	Landrace	-	0	0	-	Yes
					Fertilizer	Houla1	Landrace	-	0;20;0	4	-	No
					Fertilizer + Inoculum	Houla1	Landrace	-	0;20;0	4	-	Yes
	Cowpea	0	39	39	Grain variety	Wulibali	Pure line	IT 90K 372-1-2[e]	0	0	-	-
					Fodder variety	Dounanfana	Pure line	PBL 112[e]	0	0	-	-
					Grain variety + Fertilizer	Wulibali	Pure line	IT 90K 372-1-2[e]	0;20;0	0	-	-
					Fodder variety + Fertilizer	Dounanfana	Pure line	PBL 112[e]	0;20;0	0	-	-
	Groundnut	0	0	24	Control	Kampiani	Local variety	-	0	0	-	-
					Variety	-	Pure line	ICGV 86124[b]	0	0	-	-
Inter-cropping	Maize/ cowpea[3]	12	31	19	Grain variety, ap	Wulibali	Pure line	IT 90K 372-1-2[d]	80;7;12	0	ap	-
					Fodder variety, ap	Dounanfana	Pure line	PBL 112[e]	80;7;12	0	ap	-
					Grain variety, sp	Wulibali	Pure line	IT 90K 372-1-2[d]	80;7;12	0	sp	-
					Fodder variety, sp	Dounanfana	Pure line	PBL 112[e]	80;7;12	0	sp	-
	Sorghum/ cowpea[3]	0	5	4	Grain variety, ap	Wulibali	Pure line	IT 90K 372-1-2[d]	0	0	ap	-
					Fodder variety, ap	Dounanfana	Pure line	PBL 112[e]	0	0	ap	-
					Grain variety, sp	Wulibali	Pure line	IT 90K 372-1-2[d]	0	0	sp	-
					Fodder variety, sp	Dounanfana	Pure line	PBL 112[e]	0	0	sp	-

[1] Farmers use the same name as the improved variety bred by CIMMYT/CRI

[2] No mineral fertilizer in 2013

[3] Intercropping trials also contain a sole maize, a sole grain cowpea and a sole fodder cowpea plot. In the intercropping trials, the maize and sorghum varieties are "Dembanyuma" and "Segetana" respectively.

Institute that released the variety: [a] INERA; [b] ICRISAT; [c] IRAD; [d] IITA; [e] IER

3.2. Effect of treatments on grain and fodder yields

We observed a huge variability of yield in the control plots: maize yield in the control plot varied from 0.20 to 5.24 t ha^{-1}, sorghum yield from 0 to 3.53 t ha^{-1} and soyabean yield from 0 to 2.48 t ha^{-1} (Figure 2a, b, c). Maize grain pLER ranged from 0.32 to 1.97 (Figure 3a). We also found a large variability in response to the treatments (Figures 2 and 3).

There were no significant differences in grain yield between the hybrid varieties and the local varieties of maize and sorghum (Figure 2a,b and Table 4). Inoculation did not result in an increase in soyabean grain yield (Figure 2c and Table 4). The fodder variety of cowpea yielded no grain (Figure 2d). Improved groundnut yielded significantly more grain compared with the local variety ($P<0.001$) (Table 4). Use of fertilizer significantly increased maize, sorghum, soyabean and cowpea grain yield ($P<0.01$) (Figure 2a,b,c,d and Table 4). The fodder variety of cowpea yielded significantly ($P<0.0001$) more fodder compared with the grain variety (Table 4). There were no significant interactions (i.e. fertilizer x variety or fertilizer x inoculation) for any of the sole crops.

For the maize/cowpea intercropping, the cowpea fodder variety resulted in a significantly smaller ($P<0.001$) pLER of maize grain and a significantly greater ($P<0.001$) pLER of cowpea fodder compared with the cowpea grain variety (Figure 3a,c and Table 4). This was true for both the additive and the substitutive pattern. The substitutive pattern significantly increased ($P<0.01$) the pLER of cowpea fodder while significantly ($P<0.01$) decreasing the pLER of maize grain when compared with the additive pattern (Figure 3a,c and Table 4) for both the grain and the fodder variety of cowpea. No significant effect of the intercropping pattern on pLER of cowpea grain was found (Figure 3b and Table 4). As in the sole crop, the fodder variety yielded no grain in the intercrop. For the sorghum/cowpea intercropping, the pattern had no effect on sorghum and cowpea pLERs. Pattern x variety interaction significantly ($P<0.05$) affected sorghum pLER (Figure 3d): the cowpea fodder variety grown in the substitutive pattern resulted in the smaller sorghum pLER.

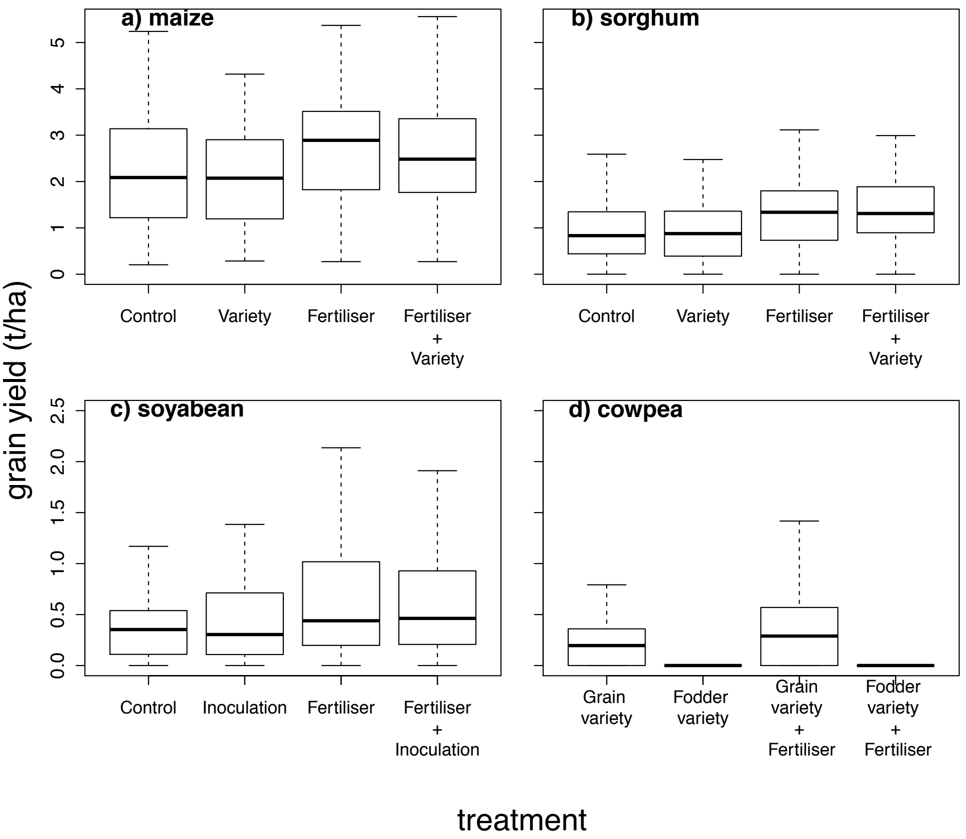


Figure 2: Grain yield for the four treatments of the maize trial (a), the sorghum trial (b), the soyabean trial (c) and the cowpea trial (d) over the two years of the trials (2013-2014). A detailed description of the treatments is given in Table 3. The horizontal line in the box indicates the median. The height of the box represents the interquartile range. The whiskers extend to the most extreme data point which is no more than 1.5 times the interquartile range from the edge of the box

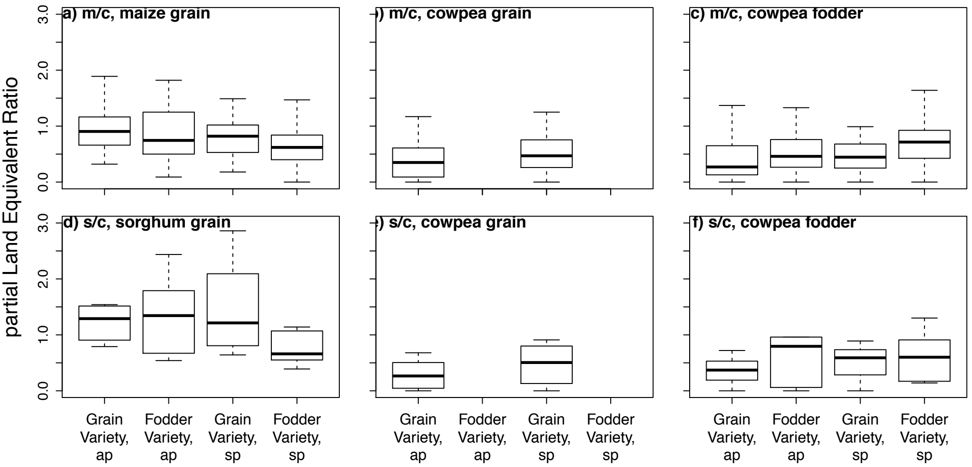


Figure 3: Partial Land Equivalent Ratio (pLER) for maize grain, cowpea grain and cowpea fodder in the maize/cowpea intercropping trial (m/c) and in the sorghum/cowpea intercropping trial (s/c) over the three years of the trials (2012-2014). ap = additive pattern, sp = substitutive pattern. A detailed description of the treatments is given in Table 3. The horizontal line in the box indicates the median. The height of the box represents the interquartile range. The whiskers extend to the most extreme data point which is no more than 1.5 times the interquartile range from the edge of the box.

Table 4: Average yields (t ha^{-1}) for sole crops and pLER for intercrops for the different treatments (square-root transformed values between brackets).
Significant effects ($P < 0.05$) are shown in bold. Maximum Least Significant Differences (Max LSDs, values between brackets) were calculated based on the transformed yield and pLER data.

		Sole crops					
Treatment	Level	Maize grain	Sorghum grain	Soyabean grain	Cowpea grain	Cowpea fodder	Groundnut grain
Fertilizer	No	1.6 (1.26)	0.86 (0.93)	0.33 (0.58)	0.15 (0.37)	1.29 (1.14)	-
	Yes	2.02 (1.42)	1.22 (1.11)	0.55 (0.74)	0.21 (0.46)	1.67 (1.29)	-
	Max LSD	(0.03)	(0.06)	(0.04)	(0.06)	(0.13)	-
	P-value	**0.0000**	**0.0000**	**0.0000**	**0.0039**	**0.0213**	-
Variety/Inoculation[1]	Local/no	1.96 (1.40)	1.02 (1.01)	0.41 (0.64)	-	0.71 (0.84)	0.48 (0.69)
	Improved/yes	1.87 (1.37)	1.05 (1.02)	0.46 (0.68)	-	2.49 (1.59)	0.57 (0.75)
	Max LSD	(0.05)	(0.03)	(0.05)	-	(0.09)	(0.03)
	P-value	0.2010	0.642	0.1762	-	**0.0000**	**0.0001**

		Maize/cowpea			Sorghum/cowpea		
Treatment	Level	pLER maize	pLER cowpea grain	pLER cowpea fodder	pLER sorghum	pLER cowpea grain	pLER cowpea fodder
Pattern	Additive pattern	0.84 (0.92)	0.29 (0.54)	0.42 (0.65)	1.36 (1.16)	0.22 (0.46)	0.42 (0.64)
	Substitutive pattern	0.69 (0.83)	0.49 (0.7)	0.54 (0.74)	1.17 (1.08)	0.44 (0.67)	0.43 (0.66)
	Max LSD	(0.05)	(0.21)	(0.06)	(0.15)	(0.28)	(0.3)
	P-value	**0.0014**	0.1256	**0.0050**	0.1455	0.2909	0.7798
Variety	Cowpea grain variety	0.85 (0.92)	-	0.4 (0.64)	1.41 (1.19)	-	0.31 (0.56)
	Cowpea fodder variety	0.69 (0.83)	-	0.56 (0.75)	1.12 (1.06)	-	0.55 (0.74)
	Max LSD	(0.05)	-	(0.06)	(0.15)	-	(0.3)
	P-value	**0.0002**	-	**0.0002**	**0.0187**	-	0.2455

[1] Variety for maize, sorghum, cowpea and groundnut, Inoculation for soyabean

Table 5: Sole crop control yields and relative increase in yield due to fertilizer or variety/inoculation as affected by soil type or previous crop. Control yields and relative increase in yield due to treatment were averaged per level of covariate when there was a significant interaction between treatment and covariate or averaged across levels of the covariate when there was no significant interaction (see Table 4 and Table A2).

			Average control yield (t ha^{-1})		Average increase in yield due to fertilizer		Average increase in yield due to variety/inoculation[1]	
Crop	Covariate that significantly affected yield	Levels of the covariate	Wetter years	Drier years	Wetter years	Drier years	Wetter years	Drier years
Maize	Previous crop	Cotton/maize	3.15	-	40%	Not tested	No significant effect	
		Sorghum/millet	1.60	-				
		Legume	2.42	-				
Sorghum	Soil type	Gravelly soil	0.52		56%		No significant effect	
		Sandy soil	0.85					
		Black soil	1.39					
Soyabean	None	-	0.41		126%		No significant effect	
Cowpea grain	None	-	0.34	0.13	49%		No yield with fodder variety	
Cowpea fodder	Soil type	Gravelly soil	0.55	0.66	60%	34%	185%	
		Sandy soil	0.80	0.75			243%	
		Black soil	1.08	0.88			413%	
Groundnut	Previous crop	Cotton/maize	0.87	-	Not tested		28%	Not tested
		Sorghum/millet	0.51	-				
		Legume	0.22	-				

[1] Variety for cereals, cowpea and groundnut, Inoculation for soyabean

3.3. Effect of topsoil characteristics, soil type, previous crop and season on yields

Yield of maize, soyabean and cowpea increased significantly (*P*<0.05) with soil P content. Soyabean and groundnut yield increased significantly (*P*<0.05) with soil K concentration, and groundnut yield increased significantly (*P*<0.05) with pH, Ca and Mg. Sorghum grain yield was larger (*P*<0.05) on soils with more gravel.

There was significant (*P*<0.01) variation among farmer-defined soil types in grain yield of sorghum, with greater yields on black soils than on sandy and gravelly soils (Figure 4a). We found no significant relationships between soil type and grain yield of the other crops nor on pLERs in the intercropping trials. The effect of fertilizer on grain yield was not altered by soil type as illustrated by the lack of any interactions between soil type and fertilizer for sorghum (Figure 4a). The variety x soil type interaction was significant (*P*<0.0001) for cowpea fodder yield and the effect of variety on fodder yield was stronger on black soils than on sandy and gravelly soils (Figure 4b).

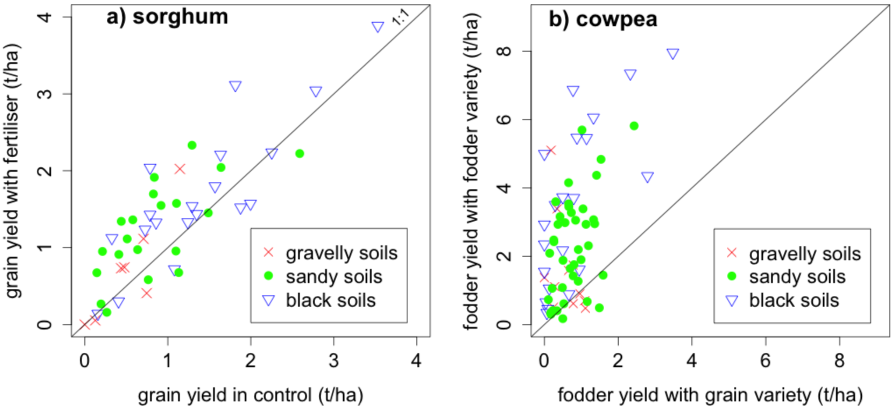


Figure 4: Treatment (fertilizer or variety) effect for different soil types in the sorghum (a) and cowpea (b) trials over the two years of the trials (2013-2014). A detailed description of the treatments is given in Table 3.

The previous crop in the field where the trial was planted had a significant effect ($P<0.05$) on grain yield of maize and groundnut, on pLER of maize grain and cowpea fodder in the maize/cowpea intercropping trial and on pLER of sorghum grain in the sorghum/cowpea intercropping trial. We found no effect of previous crop on cowpea grain and fodder yield. Maize and groundnut grain yields in the control were larger when the previous crop was cotton or maize compared with sorghum and millet as previous crop (Figure 5a,b). There was no significant interaction between fertilizer and previous crop for maize and between variety and previous crop for groundnut (Figure 5a,b). When the previous crop was cotton or maize, maize grain pLER was larger and cowpea fodder pLER was smaller, while it was the opposite when sorghum or millet was the previous crop (Figure 5c).

Maize and cowpea grain yields and also cowpea fodder yields differed significantly ($P<0.01$) between the two years of experimentation. The average grain yield of local maize with mineral fertilizer and manure was smaller in the relatively dry 2013 season (1.86 t ha^{-1}) than in the wetter 2014 season (2.75 t ha^{-1}). By contrast, mean cowpea grain yield in the control plot was larger in 2013 (0.34 t ha^{-1}) than in 2014 (0.13 t ha^{-1}). Sorghum and soyabean grain yields and maize and cowpea pLER did not differ significantly between seasons. The fertilizer x season interaction was significant ($P<0.001$) for cowpea fodder yield, with a stronger effect of fertilizer in 2014 (Figure 6). When averaged per significant covariate, (i) control yields varied by a factor two to four depending on conditions of previous crop, soil type and/or season (Table 5), (ii) the tested options resulted in a yield increase ranging from 34 to 413% depending on the crop and the covariate (Table 5), and (iii) maize/cowpea intercropping LER was always above one and high maize grain pLER was associated with low cowpea fodder pLER (Figure 7).

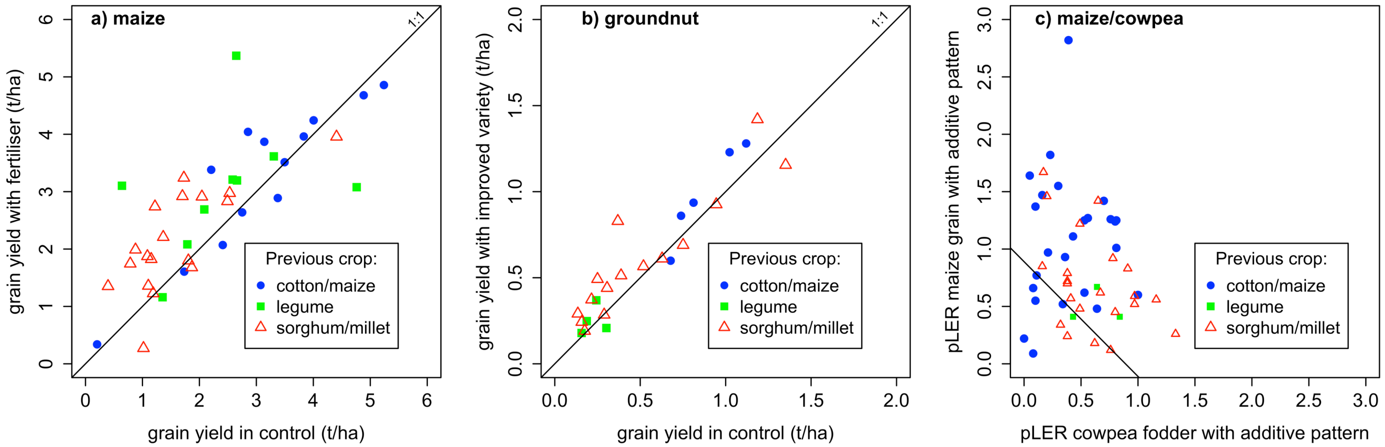


Figure 5: Fertilizer and variety effect for different previous crops in the maize (a) and groundnut (b) trials over 2013-2014; maize and cowpea pLER for different previous crop in the maize/cowpea intercropping (c) trials over the three years of the trials (2012-2014). A detailed description of the treatments is given in Table 3. The black line in c) indicates an overall LER of one.

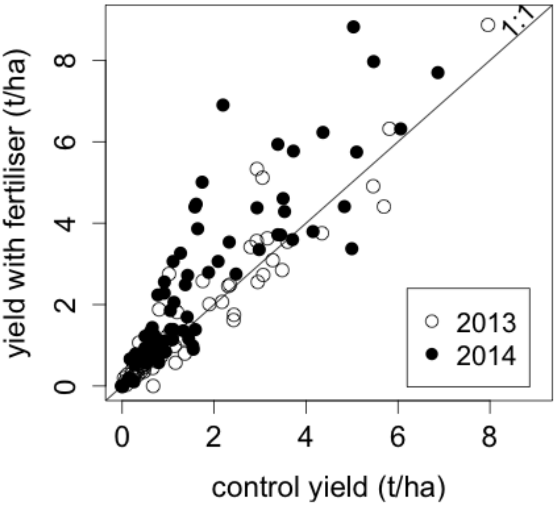


Figure 6: Effect of P fertilizer on cowpea (grain and fodder variety) fodder yield for the two years of the trials (2013, 2014).

In the final statistical model which contained all significant treatments and covariates, soil type and/or previous crop explained between 9 to 44% of yield variability. Taking into account covariate information helps to define niches with greater probability of an increase in yield. For example, the cowpea fodder variety resulted in at least a 3.7 relative increase in fodder yield compared with the cowpea grain variety for half of the farmers on black soils and for only 30% of farmers on other soil types (Figure 8a). After cotton and maize, a maize grain pLER of at least one was achieved by half of the farmers and by only 22% of farmers after other crops (Figure 8b). A soyabean yield of at least 0.6 t ha^{-1} was achieved by half of the farmers on black soils after cotton or maize and by only 13% of farmers with other soil type or previous crop conditions (Figure 8c). 37% of the farmers cultivating soyabean on black soils after cotton or maize produced at least 1 t ha^{-1}, whereas only 2% reached a similar yield in other conditions (Figure 8c).

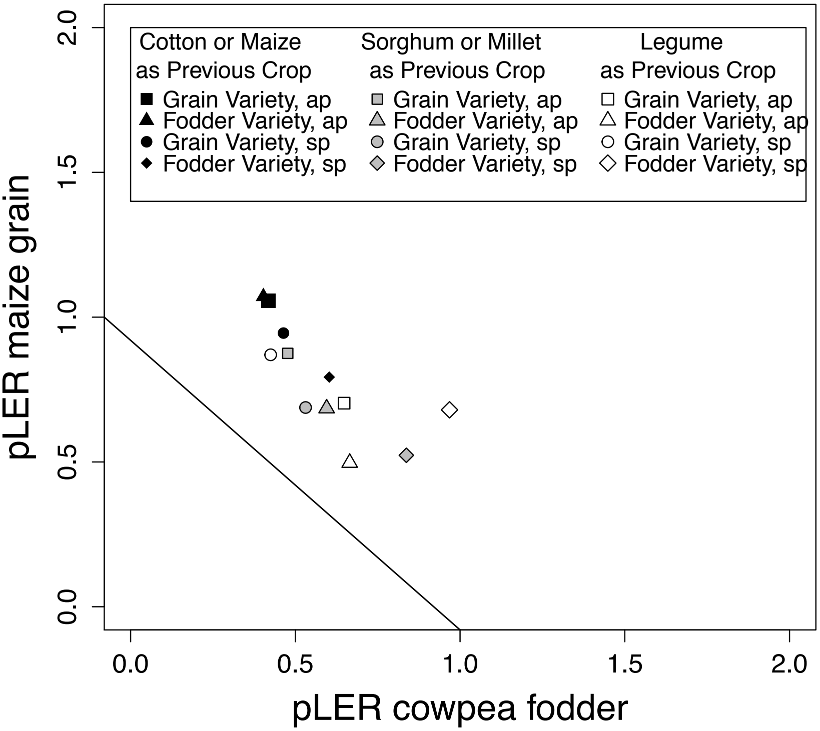


Figure 7: Average Partial Land Equivalent Ratio (pLER) of maize grain and cowpea fodder for different intercropping patterns (ap, sp), cowpea varieties (grain or fodder) and previous crops. ap=additive pattern, sp=substitutive pattern. The black line indicates an overall LER of one.

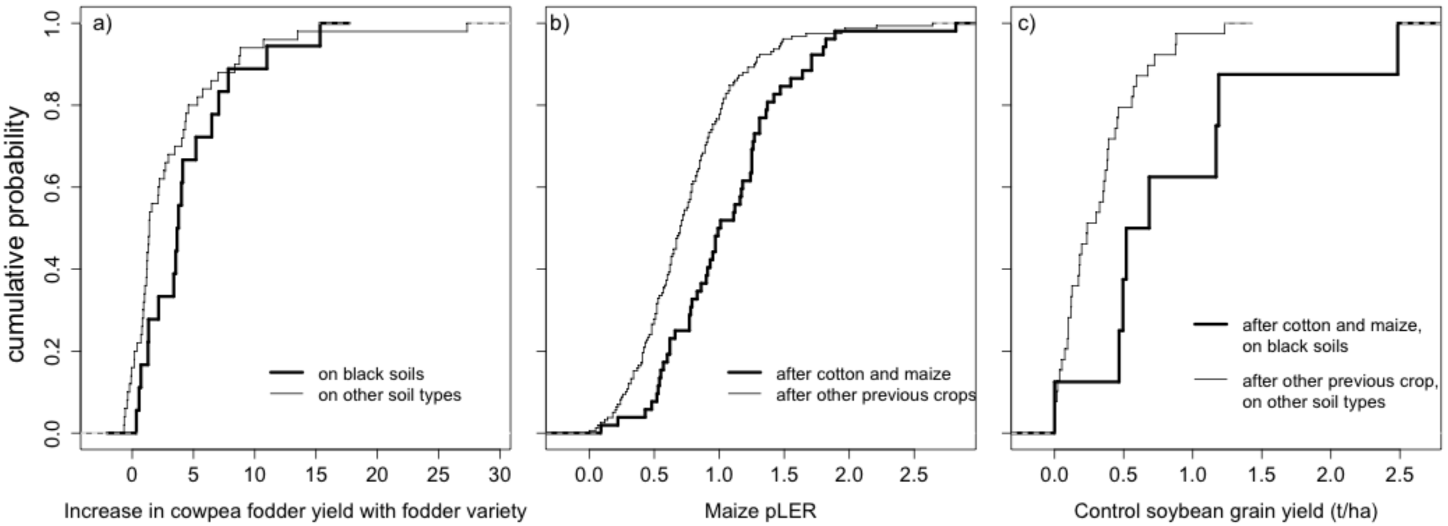


Figure 8: Cumulative probability of observed (a) relative increase in cowpea fodder yield with the fodder variety compared with the grain variety (b) maize pLER and (c) control soyabean grain yield for different conditions of soil type and/or previous crop

4. Discussion

4.1. Variability in control yields and responses to treatments

We found a wide variability in control yields and responses to treatments for all crops, which is a common feature of on-farm trials in the African smallholder context. For example, yields of maize ranged from 0.1 to 3.0 t ha^{-1} in central Zimbabwe (Zingore et al., 2007b) and yields of sorghum from 0.11 to 3.92 t ha^{-1} in northern Zimbabwe (Baudron et al., 2012). With the location of our trials being left to the choice of the farmer, the resulting variability in soil types and management history created a patchwork of soil fertility status prior to trial implementation. Soil nutrients (e.g. P and K) and one other edaphic characteristic, i.e. gravel content, explained variability in yield for some crops. Soil nutrient content, texture and gravel content varied among soil type and previous crop, which were covariates determining the yield and yield response of several crops. By providing quantitative on-farm evidence of the effect of soil type and previous crop on crop yield in southern Mali, our study confirms trends that were observed on research stations (Ripoche et al., 2015) and farmers' estimates (Blanchard, 2010; Djouara et al., 2005; Dufumier and Bainville, 2006). Sorghum yields were decreased threefold on gravelly soils compared with black soils (Table 5). For soyabean, the effect of soil type was weaker and not significant, but grain yield followed a similar trend, with on gravelly soils half of those on black soils. Gravelly soils held two to three fold less water compared with sandy and black soils respectively (Table 2). It is possible that soil moisture depletion was accelerated in gravelly soils, creating stronger water stress during grain filling. Decreasing water availability alongside smaller yield of rainfed crops due to soil type and increasing gravel content was also reported in humid sub-tropical India (Grewal et al., 1984). By contrast, maize and groundnut grain yield were not affected by soil type. With shorter cycles and earlier sowing (as per farmer practice) compared with sorghum and soyabean, it is possible that these two crops escaped the water stress during grain filling on gravelly soils (in the 2014 trials, maize reached maturity on average 25 days before sorghum and groundnut 24 days before soyabean).

We found smaller SOC and nutrient content after legume crops on gravelly and sandy soils (Table 1). This indicates that farmers usually grow legume crops at the end of the cotton/maize rotation and/or in fields without cotton and maize and with little past investment in manure and mineral fertilizer. Similarly, Ebanyat et al. (2010b) found that farmers target legumes (pigeon pea) to low fertility fields. We found a better soil fertility status (N, P, K) at the start of the season in fields previously grown with cotton or maize, compared with fields previously grown with sorghum or millet (Table 1). Cotton and maize are the crops that most often receive fertilizer and show positive N, P, and K partial budgets in southern Mali (Kanté, 2001; Ramisch, 1999). Other studies also reported better availability of mineral N and P for the subsequent crop in rotation with cotton and/or with the use of fertilizer and manure on the previous crop (Bado et al., 2012; Ripoche et al., 2015). The better SOC status we found at the start of the season in fields previously grown with cotton or maize was related to the previous manure inputs by farmers. Depending on soil type, the SOC difference between fields established after cotton or maize and fields established after sorghum or millet ranged from 0.1 to 0.6 g kg^{-1}. It is unlikely that a single manure application led to such a change in SOC. Farmers divide their cropped land into fields where only cotton and maize are grown (application of mineral fertilizer and/or manure every year), fields where cotton and maize are in rotation with sorghum and millet (more sporadic application of mineral fertilizer and manure) and fields where only sorghum/millet are grown (no application of mineral fertilizer and/or manure) (Blanchard, 2010). Therefore, fields previously established with cotton or maize likely had a greater past investment in manure and/or mineral fertilizer, compared to fields previously established with sorghum or millet. Small SOC improvements (as we observed due to previous crops) are unlikely to create a better moisture availability (De Ridder and van Keulen, 1990; Diels et al., 2001), but are related to better availability of additional plant nutrients (De Ridder and van Keulen, 1990). This "previous crop effect", i.e. nutrient carry-over from past fertilizer use and additional nutrient availability related to soil organic matter, explained that control grain yields for maize and groundnut were 1.3 and 1.7 times greater when cotton or maize was the previous crop compared with sorghum or millet as previous crops (Table 5). For sorghum and soyabean, the effect of previous crop was weaker and not significant, but grain yields followed a similar trend, with soyabean grain yield being 1.8 times greater after cotton or maize than after sorghum or millet. The previous crop had no observable effect on cowpea grain yield as pest pressure was overriding.

Cutting across soil type and previous crop, the type of rainy season also explained variability in the yield in the control plots. Yield of the local maize variety with fertilizer was 48% smaller in the drier 2013 season compared with the 2014 wetter season while sorghum yield was not affected by season. Sorghum has a stronger and deeper rooting system than maize (Frere, 1984), which suffered more from water deficit (Muchow, 1989; Traore et al., 2014). Cowpea grain yields followed an opposite trend compared with maize yields and were halved in the wetter season (Table 5) when the high relative humidity favoured infestation of pod borers (Oghiakhe et al., 1991).

Though soil type, previous crop and season explained part of the variability in control yield, these factors seldom explained the variability in response to the various intensification options. As an exception, the fodder yield increase obtained with the cowpea fodder variety (compared with the grain variety) was two times greater on black soils than on gravelly soils (Table 5). The cowpea fodder variety had a longer duration (110 days) compared with the grain variety (70 days), and was more susceptible to water stress on gravelly soils.

4.2. A disappointingly small response to the tested options

The hybrid maize variety "Bondofa" did not out-yield the farmers' local maize, regardless of the fertilizer treatment and the season (Table 4), although the two varieties had similar maturity (95-110 days). The "Bondofa" hybrid is intensively promoted in Mali and Burkina Faso on the basis that it can double farmers' yields yet we found no scientific evidence to support such claims. By contrast, in semi-arid Zimbabwe, maize hybrids yielded 18% more than the best open-pollinated varieties (Pixley and Bänziger, 2001), independent of the use of mineral fertilizer (Chiduza et al., 1994). In the Guinea savannah of Ghana, a newly released maize hybrid yielded better than the local variety in farmers' fields (Buah et al., 2013). The tall-statured sorghum hybrid "Pablo" chosen for testing by farmers, failed to increase yield compared with the farmers' local variety, regardless of the fertilizer treatment and the season (Table 4). Conversely, on-farm comparison of short-statured hybrids with another local variety called "Tieble" (CSM 335), using 40 kg N ha^{-1} and 20 kg P ha^{-1}, in three environments including the Koutiala district, indicated a 30% yield advantage of the hybrid (Rattunde et al., 2013). More intensive on-farm comparison of the wide array of available sorghum (i.e. short-statured and tall-statured) and maize hybrids is thus needed.

We observed no effect of inoculation on grain yield of the soyabean "Houla1" variety used in our trials. It is possible that this landrace from northern Cameroon collected and popularized by the parastatal cotton company (Leroy et al., 2011) nodulated with rhizobia present in the soil. (Pule-Meulenberg et al., 2011) reported that soyabean nodulated well with indigenous rhizobia in the Guinea savannah of Ghana. Competition between introduced rhizobial strain and the native rhizobia population can also explain this lack of response to inoculation (Sanginga and Okogun, 2003).

The breeder's technical manual for the cowpea fodder variety indicates a potential grain yield of 1.5 t ha^{-1} (Dugje et al., 2009). Neem oil was ineffective in control of flower thrips and pod borers. As a result the cowpea fodder variety yielded no grain at all in our trials. The high sowing density (0.4 m within row) is known to favour pests as it eases host colonization and provides a better shelter against natural enemies and adverse weather conditions (Asiwe et al., 2005; Karungi et al., 2000). Less dense planting (>1 m within row) would reduce pest density (Asiwe et al., 2005) but at the same time would decrease fodder production.

4.3. Promising tailored options

A detailed characterization of 37 farms participating in the trials showed that only 14 and 16% of them grew cowpea in 2011 and 2012 and no farmers grew soyabean. Cowpea and soyabean present farmers with an opportunity to diversify their sources of income and diet. Without inputs soyabean yielded best after cotton and maize on black soils with 0.88 t ha^{-1}. Soyabean grain is the most expensive legume grain after groundnut in the Koutiala market. Women use it as a replacement for the seeds of neré (*Parkia biglobosa*) to prepare the local condiment "Sumbala". Similarly, without any fertilizer input (and thus at low cost for farmers), the cowpea grain variety produced at least some grain early in the season (0.34 t ha^{-1} in the drier year and 0.13 t ha^{-1} in the wetter year), together with an average of 777 kg ha^{-1} of fodder. With addition of 20 kg of P ha^{-1} in the wetter year and on black soils, the cowpea fodder variety yielded 6.7 t ha^{-1} fodder, i.e. twice the stover production of maize with fertilizer under the same conditions. As cowpea fodder is a high quality feed (Singh et al., 2003) this option provides an opportunity to alleviate fodder constraints in the dry season. These findings highlight the opportunity for future research on farm scale trade-offs between food and fodder production.

Average total LER in maize/cowpea intercropping was always greater than one, regardless of pattern, cowpea variety and previous crop (Figure 7), indicating no detrimental competition between maize and cowpea. Cowpea creates a "live mulch" that lowers surface soil temperature and evaporation, thus improving water conservation compared with sole cropping (Lima Filho, 2000). Rusinamhodzi et al. (2012) also reported LER values ranging from 1 to 2.4 in additive and substitutive maize/cowpea intercropping in central Mozambique. However, this overall promising picture masked a trade-off for maize grain production (Figure 7). In most treatment by previous crop combinations, the intercropping arrangement produced cowpea fodder but less maize yield compared with the sole crop (maize pLER <1). However, the additive pattern after cotton or maize proved to be a specific niche with great relevance for farmers as there was no penalty for maize grain (maize pLER>1) (Figure 7) and a bonus production of cowpea fodder (0.29 and 1.38 t ha^{-1} on average for cowpea grain variety and cowpea fodder variety respectively). In this niche, nutrient reserves carried-over from the previous fertilization and the cowpea live mulch allowed a maize yield greater than the sole crop yield. Naudin et al. (2010) also reported a bonus of fodder biomass without penalty for the cereal in cereal/legume intercropping while other studies reported a penalty for maize grain (Pitan and Odebiyi, 2001;

Rusinamhodzi et al., 2012). Though for the sole crops, maize grain and cowpea fodder yields were affected by the type of rainy season and the soil type respectively, season and soil type did not affect the performance of the maize/cowpea intercropping options, showing the low inter-annual risk for farmers and the suitability of the option on all soil types.

The R^2 values for relationships between crop yield and soil type and/or previous crop ranged from 9 to 44% depending on the crop. (Bielders and Gérard, 2015) found that management and environmental factors explained 20% of the variation in millet yield under similar conditions. In a widespread testing of soyabean varieties in Northern Nigeria, management and environmental factors explained 16-61% of the variation in soyabean yield (Ronner et al., 2016). In on-farm trial work, a large proportion of the variability tipically remains unexplained which could be due to factors that were not monitored. In our case, these could include incidence of *Striga* on cereals, other pests and diseases especially on cowpea grain and local drought stress. Yet we were able to link local knowledge (i.e. soil type as defined by farmers) and an easy-to-assess indicator of soil fertility (i.e. previous crop in the field) to specific niches with greater probability of an increase in yield (Figure 8). Such contextual variables (soil type, previous crop) ensure that research results are relevant, appropriate and available to farmers and local development organizations who can follow up with a larger number of farmers (Hellin et al., 2008). Similarly, Snapp et al. (2002) showed that linking local knowledge and biological processes through farmer/researcher partnerships helped developing technologies with a wide relevance. The analyses of the trials led to a basket of options (Giller et al., 2011) that are promising in the farmer context and narrower than the initial wide range of options tested. For example the hybrid varieties and inoculation fell from the basket (Table 5), whereas intercropping options with both cowpea varieties and both patterns form part of the basket as all have LER>1 (Figure 7). Farmers may choose from this basket and further tailor the options to their own situations. With these easy to use niche indicators and the basket of options, we provide credible, legitimate and salient “boundary tools” (Clark et al., 2011), which will help communicating with a variety of stakeholders, thus linking research with local decision making.

Conclusion

Testing of options for sustainable intensification within the wide array of conditions found in farmers' fields provided important insights in variability of crop yields and yield responses. We tested different options on cereals (maize, sorghum), legumes (cowpea, groundnut, soyabean) and two intercropping combinations during contrasting seasons and in the wide variety of soil types and previous crops prevailing in the Koutiala district. Our study suggests that little improvement is to be expected from the recommended cereal hybrids we tested, even with combined application of mineral fertilizer and manure in amounts currently available to farmers. Rhizobial inoculation also failed to improve soyabean yields. Soyabean and cowpea, currently not commonly grown, offer opportunities to diversify income and diets and to produce high quality fodder. Our analysis showed that targeting either the best position in the rotation, i.e. after cotton or maize to benefit from nutrient carry over, or the best soil type, i.e. black soils with the greatest water holding capacity, can drastically improve grain and legume fodder yields in farmers' conditions, with and without further inputs. Maize/cowpea intercropping after cotton or maize can provide a bonus of fodder for crop-livestock farmers on all soil types, without penalty on the cereal grain production, regardless of the type of rainy season. Based on a large number of trials on different crops, we developed boundary tools consisting of (i) easy-to-use indicators related to soil type and previous crop for farmers and extension workers to predict the effect of intensification options, and (ii) a basket of options, which are promising in the farmer context. Based on similarities in farming systems, soil types, climate and market context these boundary tools can be scaled out within similar environments in West Africa. Our current work is focused on exploring these promising options at farm scale.

Acknowledgements

We thank the McKnight Foundation for funding through the project "Pathways to Agro-ecological Intensification of Sorghum and Millet Cropping Systems of Southern Mali" and also the CGIAR Research Program on Dryland Systems. We thank Joost van Heerwaarden for advice on statistical analysis and Alice Lame for her valuable contribution to data analysis. We are grateful to farmers of M'Peresso, Nampossela, Nitabougouro, N'Goukan, Finkoloni, Kani, Karangasso, Koumbri and Try for their availability and willingness to participate in the on-farm trials. We thank the Association Malienne d'Eveil au Développement Durable (AMEDD), Ousmane Dembele, Michel Sagara, Bakary Dao, Moumine Toure, Abdoulaye Dembele, Soungalo Bware and several trainees who assisted in data collection.

Chapter 4

Co-learning cycles to support innovation in farming systems in southern Mali

To be submitted to Agricultural Systems as:
Falconnier, G.N., Descheemaeker, K., Van Mourik, T.A., Adam, M., Sogoba, B., Giller, K.E..
Co-learning cycles to support innovation in farming systems in southern Mali.

Abstract:

Farm systems were re-designed together with farmers during four years (2012-2015) in Southern Mali with the aim to improve income without compromising food self-sufficiency. A cyclical learning model with three steps was used: Step 1 was the co-design of a set of crop/livestock options, Step 2 the on-farm testing and appraisal of these options and Step 3 a participatory *ex-ante* analysis of re-designed farm systems incorporating the tested options. We worked together with 132 farmers representing four farm types identified in earlier participatory research: High Resource Endowed with Large Herd (HRE-LH); High Resource Endowed (HRE); Medium Resource Endowed (MRE) and Low Resource Endowed (LRE) farms. In the first cycle of 2012-2014 farmers re-designed their farms with (1) maize/cowpea intercropping combined with stall feeding of lactating cows for HRE-LH and HRE farms, (2) replacement of sorghum by soyabean or cowpea for MRE and LRE farms. These reconfigurations were assessed *ex ante* using the average yields and gross margins obtained in the 2013 on-farm trials. The gross margin of HRE-LH and MRE farms increased by 12 and 18 % respectively (i.e. 236 and 194 US\$ year^{-1}). HRE-LH farmers experienced a disappointing though small 5% decrease in food self-sufficiency with inclusion of maize/cowpea intercropping. MRE farmers were disappointed by the marginal improvement in gross margin. HRE and LRE farms could not reconfigure their farm without compromising food self-sufficiency. In a second cycle in 2014-2015 statistical analysis of trial results and farmer insights gathered during field days allowed niches to be identified within the farms (soil type/previous crop combinations) where options performed better. The farm systems were re-designed using niche-specific information on yield and gross margin, which solved the concerns voiced by farmers during the first cycle. Without compromising food self-sufficiency, maize/cowpea intercropping in the right niche combined with stall feeding increased HRE-LH and HRE farm gross margin by 20 to 26% respectively (i.e. 690 and 545 US\$ year^{-1}) with respect to the current farming system. Replacement of sorghum by soyabean (or cowpea) increased MRE and LRE farm gross margin by 29 and 9% respectively (i.e. 545 and 32 US\$ year^{-1}). Farmers highlighted the saliency of the niches and the re-designed farm system, and indicated that the extra income could be re-invested in the farm. Our study demonstrates the feasibility and the usefulness of a cyclical and adaptive combination of participatory approaches, on-farm trials and *ex-ante* analysis to generate innovative and salient farm systems that improve farm income without compromising food self-sufficiency. The re-designed farm systems based on simple, reproducible guidelines such as farm type, previous crop and soil type can be scaled-out by extension workers and guide priority setting in (agricultural) policies and institutional development.

Key words: food self sufficiency, income, ex-ante analysis, participatory research

1. Introduction

Farmers in southern Mali need to adapt to a number of pressures: land shortage, climate variability and climate change (Traore et al., 2013), uncertainties in markets due to fluctuating support for cotton production (Coulibaly et al., 2015), decreasing fodder availability for livestock (Ba et al., 2011; Breman, 1992; Leloup, 1994), weak access to output markets for livestock products (Sanogo, 2011), and poor price setting power for cereals and livestock (Kaminski et al., 2013). Farming system design can help to generate innovative farming systems to overcome the constraints faced by farmers, increase farm productivity and profitability, and improve households' livelihoods. Farming system design employs qualitative and quantitative approaches to support the analysis of current farming systems and the design and evaluation of alternatives (Le Gal et al., 2011; Martin et al., 2012). Farm systems in sub-Saharan Africa are highly heterogeneous in terms of resource endowment, soil types, cropping and livestock systems, and livelihood strategies (Giller et al., 2011). This implies the need to tailor innovations to the context of the farm (Descheemaeker et al., submitted). Tailoring innovations can be facilitated firstly by farm typologies, which are a useful tool to consider heterogeneity of resource endowment and/or production objectives (Senthilkumar et al., 2012; Tittonell et al., 2010; Zorom et al., 2013). Secondly, strong farmers' participation in the design process may enhance the relevance of the innovations to specific farmer contexts. While participatory research emphasises the generation of qualitative insights (Dorward et al., 2003; Van Asten et al., 2009), Participatory Learning and Action Research (PLAR) was proposed to combine qualitative and quantitative insights (Defoer, 2002). In PLAR, qualitative participatory research provides information that strengthens quantitative assessments, e.g. resource flow maps drawn by farmers used to derive and calculate nutrient balances. Conversely, Paassen et al. (2011) showed that quantitative outputs of multiple goal linear programming models, if presented using concepts and symbols familiar to farmers, enhanced communication between farmers, farm advisors and researchers leading to relevant farm-specific solutions. In other studies outputs from simple models (static simulation of annual farm stocks and flows), representing farmers' reality and concerns were an appropriate discussion support to jointly generate alternative farming systems (Sempore et al., 2015; Andrieu et al., 2015). The approach of combining *ex ante* trade-off analysis and on-farm trials in iterative learning cycles with farmers has been conceptualised in the Describe Explain Explore Design (DEED) cycle (Descheemaeker et al., n.d.; Giller et al., 2011). Where DEED was applied previously, it produced useful insights in the re-designed farm system: e.g. strategies to restore soil fertility led to improved crop and cattle productivity at village scale (Rufino et al., 2011), land allocation to fodder and use of an improved cattle breed resulted in improved farm recycling efficiency (Tittonell et al., 2009). However, most existing studies applied only one DEED cycle, and there is little insight into how methods and solutions can be adapted dynamically in iterative cycles using scientific results and farmers' appraisals (a useful exception is (Dogliotti et al., 2014). Furthermore, in the African smallholder context, modelling outputs have seldom been coupled to real on-farm testing, although farmers were usually willing to test the different re-design elements (urea treatment of straw, compost pits) in their farms (Andrieu et al., 2012). Finally, though the empowerment of stakeholders during the participatory process is widely acknowledged (Defoer, 2002; de Jager et al., 2009; Hellin et al., 2008), there is little empirical evidence that participation can increase scaling-out potential of the research outputs (Sumberg et al., 2003).

The main objective of this study was to design innovative farming systems that improve farm income in the cotton area of southern Mali without compromising food self-sufficiency. Specific objectives were to: i) propose a cyclic series of steps to implement the DEED approach with emphasis on both *ex-ante* impact assessment through modelling and on-farm testing of the re-design elements, ii) illustrate the feasibility and usefulness of such an approach through its ability to generate salient farm systems for farmers and practical scaling-out guidelines for extension workers. The series of steps included the design of farm improvement options based on farmers' constraints and opportunities (Step 1), the on-farm testing and appraisal of options (Step 2), followed by an *ex-ante* analysis of the re-designed farm systems integrating the most promising options (Step 3). Step 2 and Step 3 together formed one cycle, which was carried out twice.

2. Methods

2.1. Study area and farm characteristics

The study area is located in Koutiala district in the cotton zone of Southern Mali where population densities reach 70 people km^{-2} (Soumaré et al., 2008). The uni-modal rainy season starts in May and ends in October, with total annual rainfall ranging from 500 to 1200 mm. Farmers grow maize, sorghum and millet for food consumption and cotton and groundnut to generate income. Livestock provide draught power, milk, meat, manure, and a buffer against risk (Kanté, 2001). Farming is the major livelihood strategy, with achieving food self-sufficiency the farmers' main objective (Bosma et al., 1999) and cash-oriented non-farm activities providing a small (12%) but important share of the income per capita (Losch et al., 2012). A typology based on farm resource endowment (household size, number of workers, total cropped land, number of draft tools and herd size) distinguished four farm types in the Koutiala district: High Resource Endowed Farms with Large Herds (HRE-LH) (1), High Resource Endowed (HRE) farms (2), Medium Resource Endowed (MRE) farms (3) and Low Resource Endowed (LRE) farms (4) (Falconnier et al., 2015b). Farmers participating in this research originated from nine neighbouring villages of the Koutiala district: M'Peresso, Nitabougouro, Nampossela, Finkoloni, Try, Koumbri, Karangasso, N'Goukan and Kani. The share of HRE-LH, HRE, MRE and LRE farms among the participating farmers was close to the average share in the villages of the Koutiala region (Falconnier et al., 2015b), i.e. 22, 44, 24 and 11% respectively. During the design process farmers and researchers interacted most intensively in M'Peresso, Nitabougouro and Nampossela, further referred to as the three "core villages". In 2013, farm characteristics, i.e. size of the household, cropping patterns per soil type, livestock herd size and composition were recorded for 35 participating farms in the three core villages.

2.2. Series of steps and cycles in the design process.

The design process consisted of three steps: Step 1. Design of a set of farm improvement options based on farmers' constraints and opportunities; Step 2. On-farm testing and appraisal of options; and Step 3. *Ex ante* trade-off analysis of re-designed farm systems. Step 2 and Step 3 were repeated in each cycle, each step providing inputs and insights to the other (Figure 1). During the inception year (2012) only a part of Step 1 and Step 2 was carried out with the testing of maize/cowpea intercropping options by 12 farmers. In 2013-2014, Step 1 was followed by a first cycle (T1) of Step 2 and Step 3. In 2014-2015, a second cycle (T2) of Step 2 and Step 3 was carried out (Figure 1).

Step 1 corresponds to the Describe phase of the DEED cycle, Step 2 encompasses Describe and Explain components, while Step 3 encompasses Explore and Design components of the DEED cycle. In figure 1 we refer to tables and figures that illustrate and explain each step and sub-step. Some of these tables and figures are put in Appendix 3 as background and resource for readers who are interested to repeat this exercise. Below we describe the steps and cycles in detail.

2.3. Step 1: Design of a set of options based on farmers' constraints and opportunities

One participatory rural appraisal (PRA) was held in each of the three core villages, each involving 40-50 farmers over three days. Farmers were asked to collectively list (i) the constraints to crop growing for food self-sufficiency and income generation, and to livestock rearing and (ii) the opportunities to solve these constraints. Based on the opportunities identified during the PRA, a range of options for farm performance improvement was discussed. Farmers indicated the improved varieties they wanted to test (e.g. maize and sorghum hybrids). Together, farmers and researchers defined the patterns for intercropping options and chose the rate of fertilser for the intensification options. Seven different crop trials were chosen: maize, sorghum, groundnut, cowpea, soyabean, maize/cowpea intercropping and sorghum/cowpea intercropping. A crop trial was a combination of four treatments, i.e. the current cropping practice as a control, a first option, a second option and the combination of the two options. The trials contained all the different crop options designed by researchers and farmers (Table 1). A more detailed description of the crop trials' setup and treatments can be found in Falconnier et al. (2015a). The livestock trial was executed during the 2014 dry hot season with one to five cows per farm receiving different feeding strategies, namely (i) the farmer practice (grazing of common grassland and residue grazing of cropland), (ii) a supplemented diet (as current farmer practice with extra 1 kg cowpea hay day^{-1} and 1.5 kg cotton seed cake day^{-1}), and iii) animals kept in the stall with 2.5 kg cowpea hay day^{-1}, 2 kg cotton seed cake day^{-1} and 4 kg cereal residues day^{-1}.

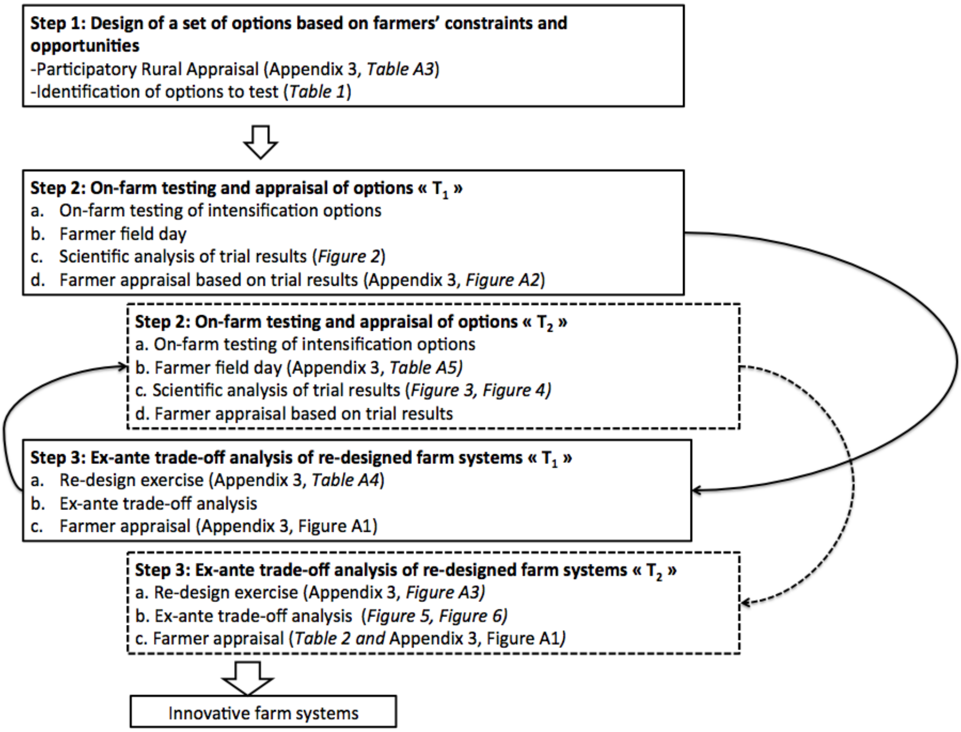


Figure 1: The three steps taken in the design of innovative farm systems. T_1 and T_2 refer to the first and second cycle in which Step 2 and Step 3 were conducted. The tables and figures that illustrate the different steps are mentioned in parenthesis.

Table 1: Current practices, diversification and intensification options identified based on farmers' constraints and opportunities and tested in Koutiala district, Southern Mali in the period 2012-2014.

	Details	Extra cost (US\$ ha^{-1})
Current cropping practices		
Maize	Local variety + mineral fertiliser	-
	Local variety + mineral fertiliser + manure	-
Sorghum	Local variety	-
Groundnut[1]	Local variety	-
Current livestock feeding practices during the dry hot season		
Lactating cows	Open grazing	-
A) Intensification of current crops		
Maize	Hybrid + mineral fertiliser	95
	Hybrid + mineral fertiliser + manure	95
	Intercropped with cowpea grain variety, additive pattern	14
	Intercropped with cowpea grain variety, substitutive pattern	8
	Intercropped with cowpea fodder variety, additive pattern	16
	Intercropped with cowpea fodder variety, substitutive pattern	9
Sorghum	Local variety + mineral fertiliser + manure	60
	Hybrid	14
	Hybrid + mineral fertiliser + manure	74
	Intercropped with cowpea grain variety, additive pattern	14
	Intercropped with cowpea grain variety, substitutive pattern	9
	Intercropped with cowpea fodder variety, additive pattern	16
	Intercropped with cowpea fodder variety, substitutive pattern	11
Groundnut[1]	Improved variety	34
B) Diversification crops without extra inputs		
Cowpea	Improved grain variety	-
	Improved fodder variety	-
Soyabean	Improved variety	-
C) Intensification of diversification crops		
Cowpea	Improved grain variety + P fertiliser	80
	Improved fodder variety + P fertiliser	80
Soyabean	Improved variety + (P fertiliser + manure)	80
	Improved variety + Inoculum	25
		10
	Improved variety + (P fertiliser + manure) + Inoculum	5
D) Improved livestock feeding during dry hot season (March-June)		
Lactating cows	Supplemented	67
	Stall fed	67

[1] Tested only in 2014

Step 2: On-farm testing and appraisal of farm improvement options

2.3.1. General description of Step 2

Step 2 consisted of: i) the testing of options by farmers, ii) a farmer field day before harvest of the crops, iii) the statistical analysis of trial results, and iv) a feedback session with farmers and their appraisal of trial results (Figure 1). Farmers of the nine participating villages tested crop options in 2012, 2013 and 2014 in a total of 372 on-farm trials. Each farmer could choose to implement one or more trials each year.

2.3.2. First cycle of Step 2

In total, 111 farmers of the nine participating villages tested the crop options during the 2013 growing season. During a farmer field day in October 2013, 37 participating farmers from the three core villages visited all trial types in their colleagues' fields to become familiarized with the options they did not test on their own farm. Discussions focused on the description of the treatments and the observed effects. After harvest, gross margin was calculated (assuming all products were sold) as the difference between (i) grain production (and stover production for cowpea) multiplied by the market price and (ii) the variable costs (e.g. seed, fertiliser, inoculant). Output prices and input costs were obtained from a market analysis carried out in 2013. Labour and manure produced on farm were not included as costs. In April 2014, average yield and gross margins of options were presented to the participating farmers during workshops in each village. Posters with drawings symbolized the different options, their yield and gross margins in farmers' units (e.g. harvest in bags of grains). In the three core villages, 30 farmers were invited to distribute 15 stones among the options they appreciated most. Ten farmers tested the livestock options during the dry season of 2014 with a total of 24 lactating cows. In May 2014, all participating farmers from the core villages visited the livestock trials.

2.3.3.Second cycle of Step 2

All participating farmers from the previous cycle and 21 additional farmers (132 farmers in total) tested the crop options in the 2014 growing season. The field day in September 2014 focused on understanding causes of yield variability. One visit to contrasting trials of the same type (a trial with 'poor' crop performance and a trial with 'good' crop performance) was organised in each of six different villages with a total of 108 participating farmers. In each trial, the group of farmers collectively scored the control and the different treatments based on a visual estimate of the yield (1=poor, 2=medium, 3=good, 4=excellent) and gave reasons for this score. During discussions in the field, we recorded farmers' explanations for the observed differences in control yield and treatment effect among contrasting trials. In order to explain yield variability, a statistical analysis was carried out using linear mixed models with treatment, farmer-identified covariates and season as fixed factors and the trial as a blocking random factor. Treatments included fertilisation, intercropping pattern, variety and inoculation and farmer-identified covariates included soil type and previous crop in the rotation (a detailed description of the analysis is given in Falconnier et al. (2016)). For further analysis in Step 3, yields were averaged per level of treatment/covariate in case of a significant effect and otherwise were averaged across the levels and covariates were used to define niches where diversification with legumes yielded best results. Additionally, treatments with extra input compared with farmer practice (e.g. inoculant, P fertiliser) were assessed based on Benefit:Cost ratio and risk. The Benefit:Cost ratio was computed as the difference in grain yield multiplied by the market price of grain, divided by the extra cost incurred. Risk was assessed as the likelihood of generating a profit, i.e. a Benefit:Cost ratio higher than one, considering the spatial variability in all the trials of a given option (Bielders and Gérard, 2015; Ronner et al., 2016).

2.4. Step 3: *Ex ante* trade-off analysis of re-designed farm systems

2.4.1. General approach

Step 3 consisted of: i) a farm re-design exercise, ii) an *ex ante* trade-off analysis of the re-designed farm systems focusing on the objectives of food self-sufficiency and income and iii) appraisal of the re-designed farm systems by farmers (Figure 1). Input data for the *ex ante* trade-off analysis included (i) farm characteristics of 35 participating farms of the three core villages, i.e. the size of the household, cropping patterns per soil type, and the livestock herd size and composition, (ii) the crop/livestock average productivity and gross margins of current practices and tested options, obtained in the on-farm trials (Appendix 3, Table A1). For stall feeding of lactating cows, milk production obtained during the dry hot season was extrapolated to the whole year using results from year–round simulations of stall fed lactating cows of De Ridder et al. (2015).

The trade-off analysis was performed for different degrees of crop replacement. Two indicators were computed for 0, 20, 40, 60, 80 and 100% replacement: household food self-sufficiency (i.e. the ratio of on-farm cereal production over household cereals needs) and farm gross margin (i.e. the sum of the gross margins from cash crops, milk sales and cereal production above household needs). Farm gross margin was chosen as the indicator of income. The equations and intermediary indicators are detailed in Table A2 of Appendix 3. The maximum replacement percentage of a crop by another was calculated as the percentage for which food self-sufficiency was not compromised, i.e. the average minus the standard error of the mean remained above one. For each farm type, the average farm gross margin increase was recorded for this maximum rate of replacement.

2.4.2. First cycle of Step 3

During the 2014 dry season, we selected 11 farmers from the core villages who had participated in the farmer field day, the feedback session on crop trials and the visit of livestock experiments. With each of these farmers, we conducted an individual farm re-design exercise. Each farmer was asked to imagine a reconfiguration of his farm (considering the 2013 season as the baseline) by including some crop/livestock options he had tested and/or seen during the farmer field day and/or feedback session. For the trade-off analysis we used the average yields and gross margins obtained in the first cycle of Step 2. For groundnut and cotton, which were not included in the 2013 trials, we used average farmer-estimated groundnut and average measured (by the CMDT) cotton yields. During the session, food self-sufficiency and farm gross margin for the baseline and for the re-designed farm system were calculated and discussed based on posters and pictures (Appendix 3, Figure A1). Additionally, the reconfigurations mentioned by the eleven farmers were grouped into four types, according to similarities in the chosen re-design elements. Eventually, the trade-off analysis was performed for the farms characterised in detail in 2013 using the first reconfiguration type for HRE-LH (n=5) and HRE farms (n=9 farms with lactating cows), the second reconfiguration type for MRE farms (n=7), the third reconfiguration type for LRE farms (n=6) and the fourth reconfiguration type for all the farms.

2.4.3.Second cycle of Step 3

In 2015, calendars of oxen requirements for crop activities were built to check the feasibility of the reconfiguration types that were based on cropland expansion. Insights in the causes of yield variability and the niches generated during the second cycle of Step 2 were used to refine the four reconfiguration types and the trade-off analysis was repeated for the farms that had access to theses niches. During meetings in each core village, household food self-sufficiency and farm gross margin and other intermediary indicators were discussed with all the participating farmers using posters (Appendix 3, Figure A1). A qualitative assessment of farmers' opinions was based on recorded answers to the open question "What do you think of the differences between the baseline and the re-designed farm system?".

3. Results

3.1. Step 1: Design of a set of options based on farmers' constraints and opportunities

The main constraints to crop production and livestock rearing cited by farmers in all the three villages were lack of oxen, poor soil fertility, animal feeding and animal diseases. Farmers mentioned declining crop yields and gross margins, poor feeding and diseases as the causes for lack of oxen. The final list of options to increase farm gross margin included: (A) intensification of current crops (maize, sorghum and groundnut) with intercropping or the use of improved varieties, mineral fertiliser and manure, (B) diversification with improved variety of cowpea and soyabean without fertiliser, C) diversification with improved variety of cowpea and soyabean with mineral fertiliser, manure and rhizobial inoculation, and (D) improved feeding of lactating cows during the dry hot season with cowpea hay to increase milk production (Table 1). Farmers' current crops with current cropping practices and cows with current feeding strategy were added as a benchmark (Table 1).

3.2. First cycle

3.2.1. First cycle of Step 2

Assessment of crop trial results showed a wide variation in yields and associated gross margins, regardless of the option, with and without intensification (Figure 2). For example, grain yield and gross margin of local maize with mineral fertiliser ranged from 0 to 2600 kg ha^{-1} and from -130 to 340 US$ year^{-1} respectively, while grain yield and gross margin of soyabean ranged from 0 to 1230 kg ha^{-1} and from -40 to 920 US$ year^{-1} respectively. Farmers appreciated a large range of options, with some differences among farm types. All HRE-LH farmers and a quarter of HRE farmers were positive about intercropping maize with the cowpea fodder variety. The soyabean with no extra output was scored highly by a third of the MRE farmers, while the majority of LRE farmers appreciated the cowpea grain variety with P fertiliser. Sorghum/cowpea intercropping options, hybrid maize without manure and soyabean with inoculum were not chosen by any farmer.

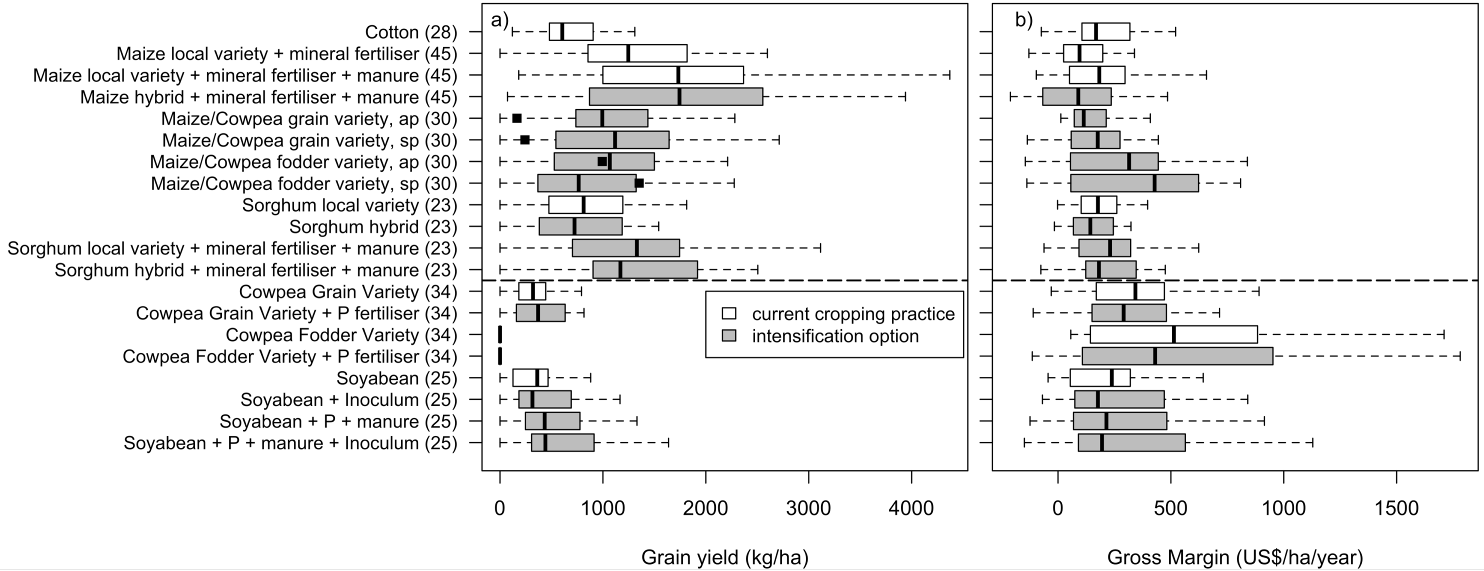


Figure 2: Grain (seed for cotton) yield (a) and gross margin (b) of farmers' current crops (above the dashed line) and diversification crops (below the dashed line) based on data from on-farm testing in 2013 (first cycle of Step 2) for maize, sorghum, cowpea and soyabean and CMDT measurements in farmers' fields for cotton. In 2013, there were no trials on groundnut. Black dots in a) are cowpea fodder yields. ap= additive pattern, sp= substitutive pattern. Number of observations in each case is indicated in parenthesis.

3.2.2. First cycle of Step 3

During the individual farm re-design exercises, farmers who had participated in the field visit and feedback session proposed various reconfigurations to re-design their farm system. All HRE-LH farmers and one HRE farmer were interested in intercropping maize with cowpea (from 30 to 100% of the maize area) combined with stall feeding of 17 to 50% of the lactating cows (Reconfiguration type 1). MRE farmers re-designed their farm system by replacing 20% of sorghum by soyabean (Reconfiguration type 2). One LRE farmer chose to replace 10% of sorghum by the cowpea grain variety (Reconfiguration type 3). Two HRE farmers and one LRE farmer considered expanding their cropland (by 10 to 40%) with the cowpea fodder and/or grain variety (Reconfiguration type 4). The *ex ante* trade-off analysis showed different outcomes for each farm type. Without compromising food self-sufficiency, (i) HRE-LH could intercrop 80% of maize with cowpea, allowing the farmer to feed 74% of lactating cows in the stall and leading to a 12% increase in farm gross margin (i.e. a 236 US\$ year^{-1} absolute increase), (ii) MRE farms could replace 60% of sorghum by soyabean leading to a 18% increase in farm gross margin (i.e. a 184 US\$ year^{-1} absolute increase), (iii) HRE farms could not intercrop maize with cowpea, (iv) LRE farms could not replace sorghum by cowpea grain, (v) Reconfiguration type 4 always increased farm gross margin.

All 11 farmers that participated in the exercise considered the farm gross margin improvement to be a promising outcome. HRE-LH and HRE farmers were concerned by the 5% average decrease in food self-sufficiency due to the penalty to maize grain in intercropping. MRE farms were disappointed about the small absolute gross margin increase from Reconfiguration type 3 (184 US\$ year^{-1}), which could not allow them to buy an ox (435 US\$). Farmers expressed their concern about the limited availability of oxen that would impede the cropland expansion of Reconfiguration type 4.

3.3. Second cycle

3.3.1. Second cycle of Step 2

During the field day in 2014, farmers indicated that the soil type and the previous crop in the rotation could explain yield variability in the control plots. The statistical analysis confirmed farmers' perception and showed that (i) maize, soyabean and groundnut grain yields and maize partial Land Equivalent Ratio (pLER) in intercropping were higher after cotton and maize (the fertilised crops) compared with after sorghum or millet (the un-fertilised crops), (ii) sorghum and soyabean grain yields and cowpea fodder yields were greater on black soils compared with sandy and gravelly soils. Due to pest attacks, cowpea grain yields were not affected by soil type (see Falconnier et al. (2016) for more detailed results). As a result, soil type and previous crop defined niches where diversification with legumes without extra input yielded best results (Figure 3). Without fertiliser, soyabean gross margin was 110% greater than the gross margin of local sorghum without fertiliser (farmer practice) on black soils, provided that the previous crop was cotton or maize, whereas it was only 20% greater and 35% smaller on sandy and gravelly soils respectively (Figure 3a). Conversely, cowpea gross margin was only 41% greater than local sorghum gross margin on black soils (Figure 3b) but 140 and 86% greater on gravelly and sandy soils respectively (regardless of the previous crop, which did not affect cowpea yields). Furthermore, the difference in grain yield between cowpea and sorghum was smaller on gravelly and sandy soils compared with black soils. Maize/cowpea intercropping after cotton and maize with the additive pattern resulted in no maize grain yield penalty compared with sole cropping (average maize pLER=1.07) and extra fodder production (1390 kg ha^{-1} on average, with cowpea pLER = 0.4) (Figure 3c).

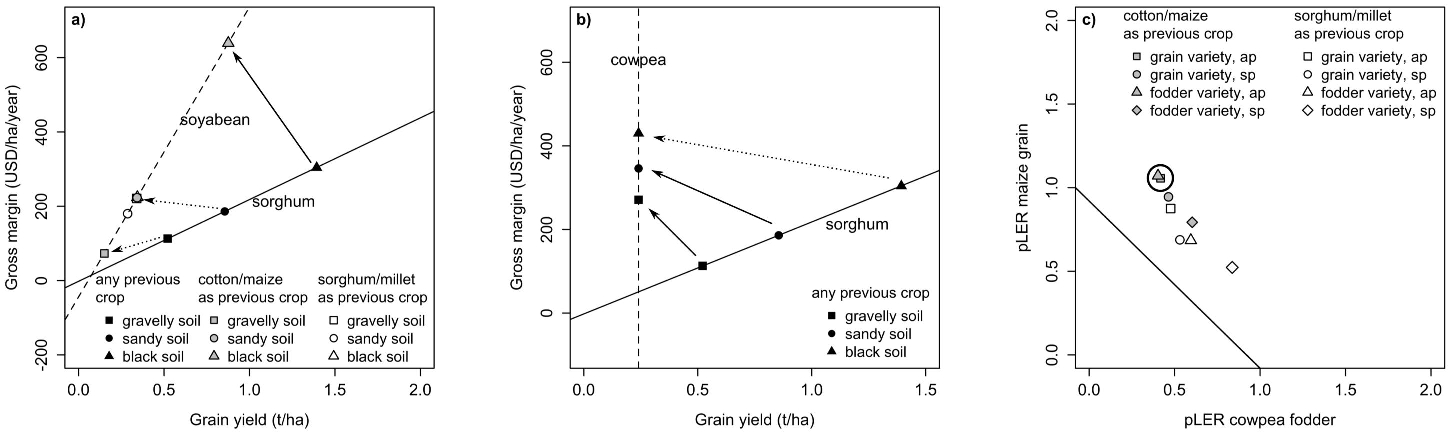


Figure 3: Average gross margin and crop grain yield of the local sorghum variety without fertiliser and soyabean without inputs (a) and the local sorghum variety without fertiliser and cowpea without inputs (b) in different conditions of soil type and previous crop, and maize and cowpea average pLER in maize cowpea intercropping according for different previous crops, intercropping patterns and cowpea varieties (c), based on data from on-farm testing in 2013 and 2014. The slopes of the gross margin lines correspond to the average grain (and fodder for cowpea) yield multiplied by market price, while the intercept represents the sum of variable costs (i.e. seed). ap=additive pattern, sp=substitutive pattern. Plain black arrows represent promising crop substitutions in a given niche (soil type, previous crop) to increase gross margin. Dotted arrows represent unpromising crop substitutions. The black circle in c) represents a promising combination of pattern, variety and previous crop to produce fodder without a penalty to maize production.

Most of the intensification options on current crops and diversification crops had a Benefit:Cost ratio less than two and/or a probability of generating profit of less than 0.5. The soybean option with manure and P fertiliser, the cowpea option with P fertiliser and the groundnut improved variety had however Benefit:Cost ratios higher than two and probabilities of generating profit larger than 0.5 (Figure 4a). The intercropping options with maize and cowpea showed large Benefit:Cost ratios and the probability of generating a profit was always larger than 0.5 (Figure 4b).

3.3.2. Second cycle of Step 3

The oxen-day requirement calendar showed that availability of oxen was a limiting factor during sowing and weeding for all farm types (Appendix 3, Figure A3). Therefore we discarded the fourth reconfiguration type (cropland expansion) that had been proposed by farmers in Step 3 of the first cycle.

Using the information on the niches identified during Step 2 of the second cycle, the refined reconfigurations included: maize intercropped with cowpea only after cotton or maize (refined Reconfiguration type 1), sorghum replaced by soyabean only on black soils after cotton or maize (refined Reconfiguration type 2), and sorghum replaced by cowpea only on sandy and gravelly soils (refined Reconfiguration type 3). *Ex ante* analysis of the re-designed farm systems with the refined reconfigurations suggested that without compromising food self-sufficiency i) HRE-LH farms could intercrop all of their maize with cowpea, allowing on average 93% of lactating cows to be fed in the stall and leading to a 20% increase in average whole farm gross margin (690 US\$ year^{-1}) (Figure 5), ii) HRE farms could intercrop all of their maize with cowpea, allowing on average 92% of lactating cows to be fed in the stall and leading to a 26% increase in average farm gross margin (453 US\$ year^{-1}) (Figure 5), iii) MRE farms could replace 80% of sorghum by soyabean leading to a 29% increase in farm gross margin (545 US\$ year^{-1}) (Figure 6), iv) LRE farms could replace 20% of sorghum by cowpea grain variety, leading to a 9% increase in farm gross margin (32 US\$ year^{-1}) (Figure 6).

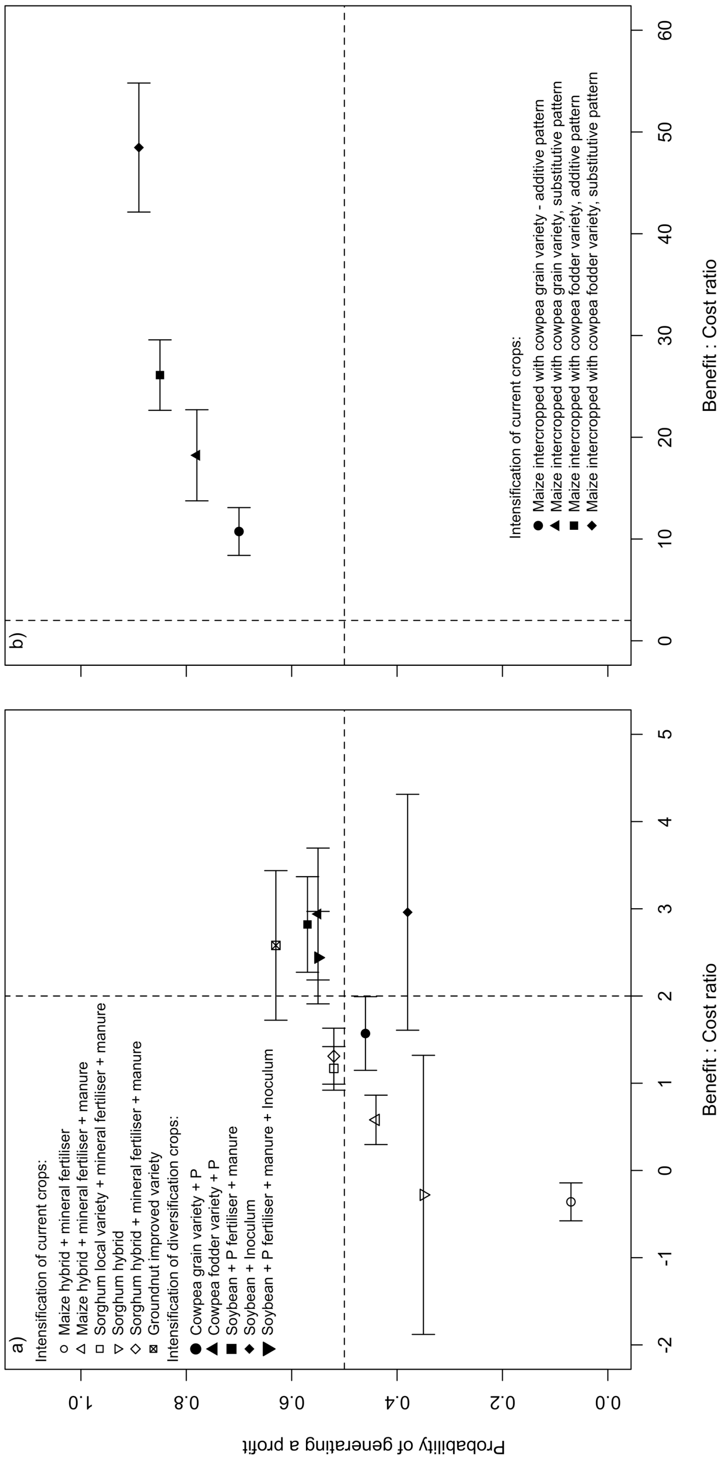


Figure 4: Average Benefit:Cost ratio and probability to generate profit for intensification options for crops (a) and intercrops (b). The horizontal dotted line indicates a probability to generate profit of 0.5, the vertical dotted line indicates a Benefit:Cost ratio of two. Bars indicate the standard error of the mean for Benefit:Cost ratio.

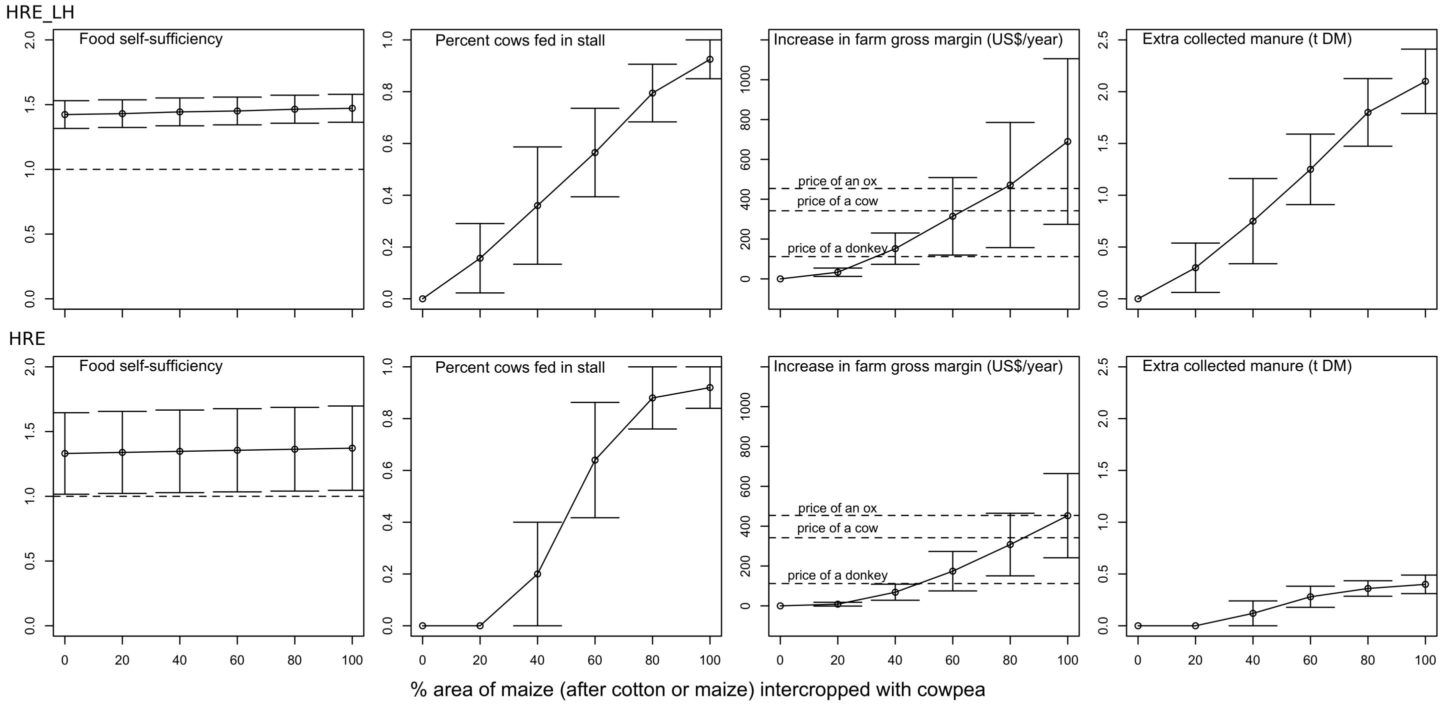


Figure 5: Effects of replacing maize with cowpea after cotton or maize on selected farm performance indicators, resulting from the *ex ante* trade-off analysis for High Resource Endowed with Large Herds (HRE-LH) farms (n=4) and High Resource Endowed (HRE) farms (n=5). Vertical bars represent twice the standard error of the mean. The horizontal dashed line in the "Food self-sufficiency" plots represents the food self-sufficiency threshold of one.

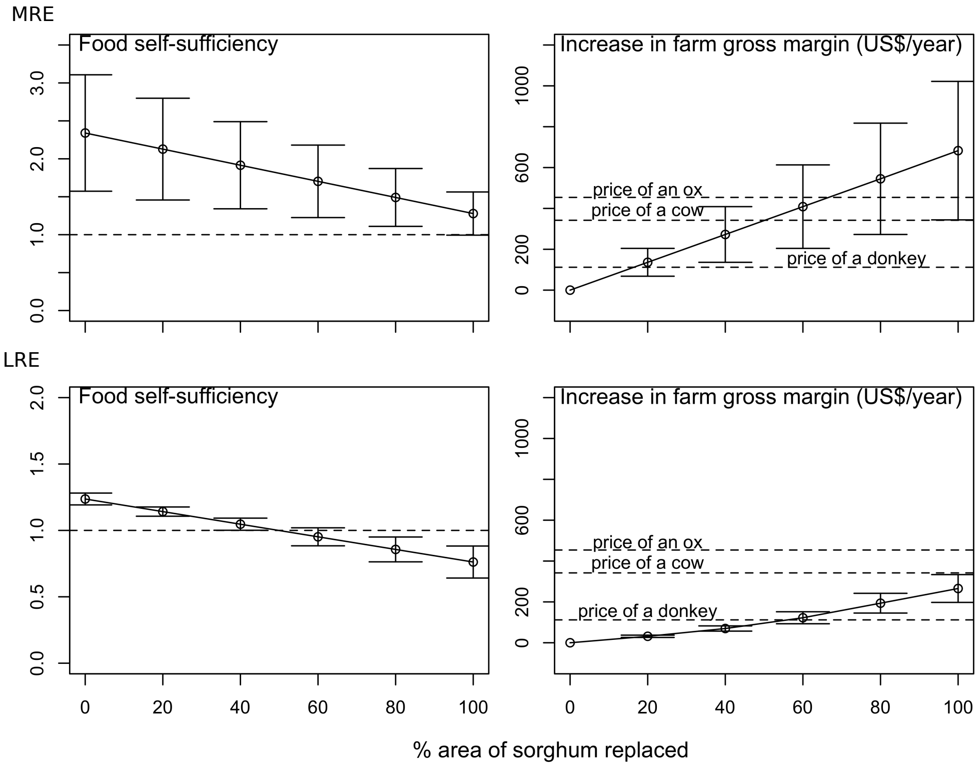


Figure 6: Effects of replacing sorghum on selected farm performance indicators, resulting from the *ex ante* trade-off analysis for Medium Resource Endowed (MRE) farms (n=2) and Low Resource Endowed (LRE) farms (n=4). For MRE farms, sorghum is replaced by soyabean on black soils after cotton and maize, for LRE farms sorghum is replaced by cowpea grain variety on gravelly or sandy soils. Vertical bars represent twice the standard error of the mean. The horizontal dashed line in the "Food self-sufficiency" plots represents the food self-sufficiency threshold.

Table 2: Farmers' evaluation of the re-designed farm systems

Re-designed farm system	Farmers' comments	Lessons learned
Intercropping maize with cowpea after cotton combined with stall feeding (example of a HRE-LH farm)	1) Total cropped land is identical in the baseline and the re-designed farm	Income can be increase without expanding cropped land/ herd size
	2) Fodder production did not compromise food self-sufficiency	
	3) Extra income can be used to buy fertiliser, extra collected manure can increase crop yield in subsequent years	The re-designed farm system can be the basis for a stepping up strategy
Replacing sorghum by soyabean on black soils after cotton/maize, example of a MRE farm	1) As opposed to income from cotton, the income from soyabean is immediately available	The re-designed farm system can be the basis for a stepping up strategy
	2) Extra income can be used to buy (i) fertilisers, thus increasing crop yields and income in subsequent years (ii) a lactating cow, or a new ox	
	3) Trials were an opportunity (i) to grow soyabean, to become aware of its lower labour requirements compared with cotton, (ii) to understand field conditions required to get the best yields and (iii) to start selling of soyabean with the small quantities from the trials	Practical insights gained with on-farm trials complement and strengthen the credibility of the presented scenarios
	4) It is important to plan household needs versus selling of cereal surpluses	Farmers learned how to plan cereal production and sales to fulfil household needs
Replacing sorghum by cowpea grain, example of LRE farm	1) Extra income can be used to (i) buy a donkey and borrow a cart, apply more manure on fields, increase production and thus income in subsequent years, (ii) buy a young calf in year one, a second in year two to have a full span to pull a sowing machine	The re-designed farm system can be the basis for a stepping up strategy
	2) It is important to plan household needs versus selling of cereal surpluses	Farmers learned how to plan cereal production and sales to fulfil household needs

Farmers' evaluations of the re-designed farm system indicated that the gross margin increase appeared significant to them and that it could be re-invested in the farm to buy mineral fertiliser and/or animals (Table 2).

4. Discussion

4.1. Research adaptation is a key feature of the DEED cycle

Performing two iterations of the DEED cycle allowed integrating generated knowledge into the research process, thus enabling the agile reorientation of project actions and increasing the chances of success in the design of alternatives (López-Ridaura et al., 2002; Mierlo et al., 2010). After the first cycle of on-farm trials, researchers did not perceive soyabean as promising, because they relied on summary information such as average yield and gross margin. Conversely, some farmers perceived it as an opportunity and included it in the reconfiguration of their farms, because they relied on their impressions of high performing trials they had seen during the farmer field day (Table 2). This highlighted the difference in "world views" between farmers and researchers, i.e. the different ways of understanding and interpreting field experiments (Sumberg et al., 2003). During the second cycle, farmers' indigenous knowledge and researchers' knowledge complemented each other, resulting in a shared vision of credible explanations for yield variability (Figure 3). The adaptive nature of our approach thus allowed convergent learning (Mierlo et al., 2010). During the first DEED cycle, the farm reconfigurations with the options chosen by farmers performed poorly due to strong trade-offs between food self-sufficiency and gross margin, or the marginal increase in farm gross margin. These disappointing results were mainly due to poor average yield and gross margin of some options (Figure 2). Therefore the first DEED cycle allowed knowledge gaps to be identified and pinpointed the need for a better understanding of yield and gross margin variability. This realisation was crucial for the second cycle, which was initiated with refined methods for the farmer field day and the analysis of trial results. Also the *ex-ante* analysis was adapted, based on the incorporation of farmers' knowledge and a more accurate representation of the performance of options. This allowed achieving more promising re-designed farm systems after the second cycle (Figure 5 and Figure 6).

4.2. Salient, legitimate and credible guidelines

The knowledge generated through this participatory process can be translated into boundary objects, i.e. "methods of common communication across dispersed work groups" (Star and Griesemer, 1989). The outcome of this research can indeed be seen as a set of guidelines to inform the discussions between farmers and extension workers. For a given farmer, this set of guidelines would be: (i) the characterisation of the farm type based on simple resource endowment indicators, e.g. household size, livestock, total cropped land (Falconnier et al., 2015b) (ii) the choice of an option suitable for that farm type, i.e. cowpea for LRE farms, soyabean for MRE farms and maize/cowpea for HRE-LH and HRE farms, (iii) the identification of the niche where this option performs best, based on the local knowledge of soil type and previous crops (Figure 3) (iv) setting the maximum percentage of crop replacement without compromising food self-sufficiency. For effective translation of knowledge into action, boundary objects must meet the saliency, credibility and legitimacy criteria (Cash et al., 2003). Saliency was built up throughout our design process: the generated knowledge was based on farmers' descriptions of constraints and opportunities, exploration of farm reconfigurations imagined by farmers, farmers' understanding of yield variability, and farmers' collective appraisal of the re-designed farm systems (Table 2). Saliency was further ensured by encompassing both crops and livestock activities and thus representing the complexity of farmers' management (Martin, 2015). The qualitative insights obtained through trial visits and farmers' appraisals were supported by measurements and statistical analysis of the results, ensuring the credibility of the generated knowledge. Legitimacy was ensured by the participation of farmers with different resource endowment and production objectives, so that the diversity of farmers' knowledge, interests and perspectives could be taken into account. In Farmer Field Schools, experimentation is often done with an existing farmer group within the community (de Jager et al., 2009), and some types of household may be overlooked. In our approach, we purposively invited some LRE farmers to join the activities, as they were not part of the existing community groups. Our study therefore overcame common pitfalls of participatory research, namely: a focus on better-off farmers at the expense of the less endowed (Degnbol et al., 2001); the generation of simple and standardized technical recommendations (Okali et al., 1994); and a lack of credibility (Van Asten et al., 2009).

4.3. Opportunities for scaling-out of results and approach

The set of guidelines identified holds for an area broader than the nine villages where it has been generated. The "old cotton basin", an area situated in the Sudanian agro-ecological zone (Coulibaly, 2003), groups the districts of Koutiala and Dioila and the northern part of the Sikasso district and comprises more than a million of rural people (Traore et al., 2011). This area is characterized by cotton/cereal rotation with use of manure and mineral fertiliser, draught power by oxen, credit for inputs and guaranteed purchase of cotton by the Compagnie Malienne pour le Développement des Textiles (CMDT) (Soumaré et al., 2008; Tumusiime et al., 2014). With an environment similar to the nine study villages, the guidelines generated could be applied throughout this "old cotton basin". A key partner in this research was a non-governmental organisation involved in extension activities which offers the potential to expand the number of beneficiaries (Hellin et al., 2008; Okali et al., 1994), challenging the common perception that participatory research is not cost-effective (Rusike et al., 2006; Snapp et al., 2002). Furthermore, the approach of adaptive research cycles can be reproduced with a different set of options and/or in another environment. Farmers' understanding of yield variability could be incorporated from the start of the experiments, thus allowing faster progress in the design of successful alternatives. Similarly to PLAR (Defoer, 2002), our approach can be scaled-out to facilitate learning by farmers, extension workers and researchers.

4.4. Farm reconfiguration for sustainable intensification?

The farm reconfigurations inspired farmers to imagine “stepping up” strategies (Dorward et al., 2009; Falconnier et al., 2015b) over a longer term. Farmers suggested that the extra income could be reinvested to buy livestock and/or fertiliser (Table 2), highlighting the opportunities to climb the livestock and agricultural intensification ladder (Aune and Bationo, 2008; Udo et al., 2011). For example, LRE farmers might be able to buy a donkey the first year and a cart in the second year in order to carry compost and fertilise crops, thus increasing yields and income, which would be in turn used to buy a goat or a calf (Figure 6). The other farm types can climb the ladder faster as the income increase related to the farm reconfigurations would allow them to buy a cow or an ox, without endangering food self-sufficiency (Figure 5 and 6). Production of cowpea fodder and stall feeding of lactating cows appears profitable for HRE-LH and HRE farms and can trigger positive feedbacks with the extra manure collected in the stall (Figure 5). Some farms without access to the identified niches (e.g. dark soils) may however not be able to apply these “stepping up” strategies. Furthermore, the wide adoption of farm reconfigurations based on stall feeding is currently impeded by the poorly developed milk sector. Broader institutional change would be needed to improve the availability of cowpea seeds, reduce powder milk imports in favour of local milk (Corniaux et al., 2012), and to develop roads and infrastructure.

Although diversification with legumes offers potential, cotton remains a key feature of the current farming system. Access to subsidised fertiliser for cotton and maize is guaranteed by the Compagnie Malienne pour le Développement des Textiles (CMDT), and the nutrients carried-over benefit the following crops (Falconnier et al., 2016; Ripoche et al., 2015). This carry-over is the backbone of the niches identified for maize/cowpea intercropping and soyabean production (Figure 3) (Falconnier et al., 2016). As the maintenance of a functional cotton sector is uncertain due to world price fluctuations (Coulibaly et al., 2015; Falconnier et al., 2015b), the viability of the farm reconfigurations depends on the development of sustainable alternatives. With a large Cost:Benefit ratio and a low risk for farmers, soyabean with manure and P fertiliser (Figure 4) could partially replace cotton as a cash crop at the start of the rotations. The increase in the demand for livestock products in the cities in Mali and across West Africa and the expected growth in urban poultry production (Amadou et al., 2012) offer opportunities for the development of a soyabean value chain for poultry feed.

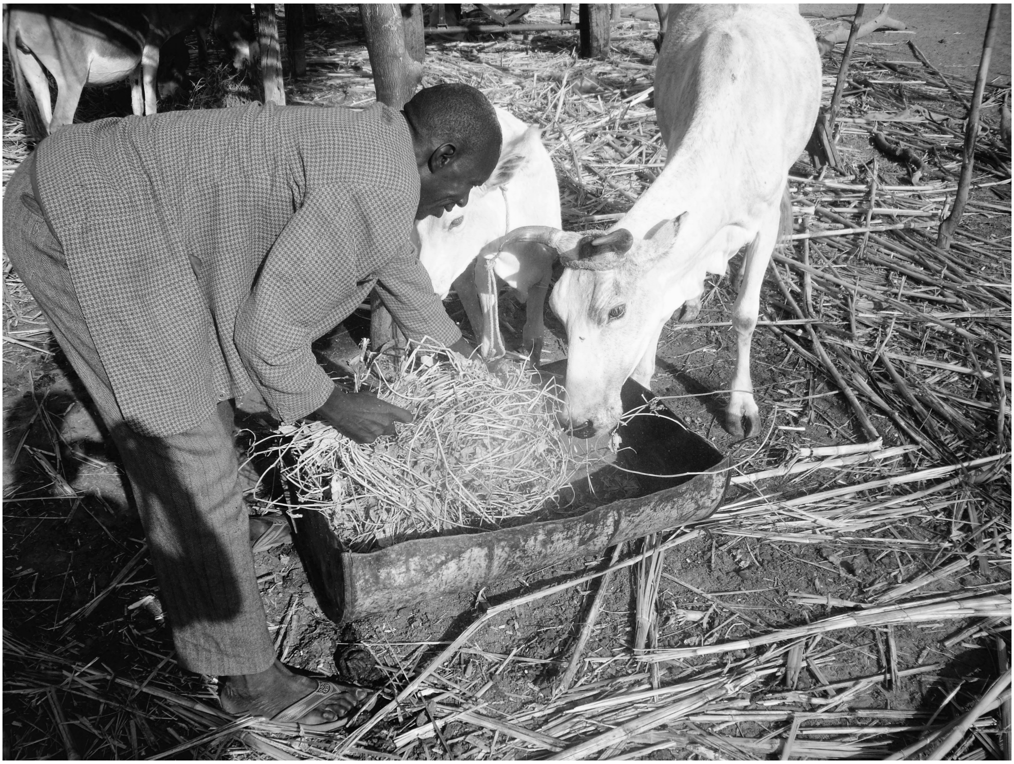
Conclusion

Over a period of four years researchers, development agents and farmers experimented together with a wide array of options related to crops and livestock and explored farm reconfigurations with promising options. Two experimental cycles lead to convergent learning: farmers and researchers were able to share a common understanding of yield variability based on local knowledge and statistical analysis of the trials. The first cycle revealed strong trade-offs between food self-sufficiency and farm income and/or small gross margin increases linked to diversification with legume crops. The knowledge generated during the second cycle allowed defining of niches for diversification with legumes and alleviating some of the trade-offs to achieve more promising farm reconfigurations. These farm reconfigurations increased farm gross margin without compromising food self-sufficiency, based on simple guidelines like farm type, soil type and position in the rotation. Local NGOs and extension agencies can now use these simple guidelines to reach a larger number of beneficiaries in areas with an environment similar to the villages where the guidelines were generated. Further, the research approach is scalable to other environments, where it can trigger learning among stakeholders, and integration of farmers understanding at the very start of the experiments can speed up the re-design process. The farm reconfigurations are promising pathways for both crop and livestock intensification and farms can ‘step up’ to higher levels of productivity. Development of sustainable alternatives to cotton production with stronger support to milk and soyabean production will be needed to trigger adoption of these reconfigurations by a large number of farmers.

Acknowledgements

Funding for this study was provided by the McKnight Foundation through the project 'Pathways to Agro-ecological Intensification of Sorghum and Millet Cropping Systems of Southern Mali' and by the CGIAR Research Program on Dryland Systems. We thank all the farmers of M'Peresso, Nampossela, Nitabougouro, N'Goukan, Finkoloni, Kani, Karangasso, Koumbri and Try for their availability and willingness to participate in the research process.

Agricultural intensification and policy interventions: exploring plausible futures for smallholder farmers in Southern Mali



To be submitted to Regional Environmental Change as:
Falconnier, G.N., Descheemaeker, K., Traore, B., Giller, K.E. Agricultural intensification and policy interventions: exploring plausible futures for smallholder farmers in Southern Mali

Abstract:

Livelihood improvement of rural sub-Saharan smallholders through agricultural intensification, rural-urban migration and reducing birth rates depends on uncertain future socio-economic and biophysical conditions. Based on existing literature, hypothetical changes in farmer practices and policy interventions were described and five contrasting socio-economic scenarios were built towards the year 2027. A simulation framework was developed and used to assess food self-sufficiency and farm income per capita for a representative village of 99 households in southern Mali. Four farm types were distinguished. In the current situation, 45% of the farms of the village were food self-sufficient and above the 1.25 US$ day^{-1} poverty line. Without change in farmer practices or policy interventions and keeping the current population growth rate, i.e. the "Business as usual" scenario, food self-sufficiency and income per capita would fall by 8 to 37% and 10% to 40% respectively, depending on farm type. With this scenario, only 16% of the farms would be both food self-sufficient and above the poverty line in 2027. Diversification with legumes combined with intensification of livestock production and support to the milk sector, i.e. the "Dairy development" scenario, would barely offset the negative effect of population growth on income per capita: depending on farm type, income per capita would still be reduced by seven to 24% and only 27% of farms would be food self-sufficient and above poverty line. Additional policy interventions targeting family planning and job creation outside agriculture would be needed to maintain household food self-sufficiency and increase income per capita in this rural area. In this optimistic scenario, 69% of the farms would be above the poverty line and food self-sufficient in 2027. Additional programs to promote integrated pest management, subsidies for small-scale mechanisation of cotton and mineral fertiliser on sorghum and millet could allow a drastic increase in productivity and would lift 92% of farm population out of poverty. Food self-sufficiency ratio and farm income per capita would increase by 108% to 132% and 88% to 112% respectively depending on farm type. Considering the entire heterogeneous farm population was crucial to accurately assess pathways out of poverty. Our study stresses the need for a strategic and multisectoral combination of interventions to improve livelihoods.

Key words: farm typology, yield gap, rural-urban migration, net fertility

1. Introduction

Africa's population is growing faster than any other continent and will account for more than half of the growth in the world's population between now and 2050 (United Nations, 2015). In many regions across sub-Saharan Africa there is little or no land suitable for further agricultural expansion, therefore farm size is decreasing (Harris and Orr, 2014; Masters et al., 2013; Muyanga and Jayne, 2014). Faced with land shortage, farmers can respond in three ways: intensifying crop and livestock production, migrating out of agriculture and/or reducing human fertility rates (Headey and Jayne, 2014). Policy interventions can favour these strategies, as examples from around Africa illustrate: large scale agricultural input subsidy programmes improved land productivity in Malawi (Dorward and Chirwa, 2011). Educational investment targeting rural areas and creation of non-agricultural wage jobs in the cities favoured rural-urban migration in Uganda (de Brauw et al., 2014; Fox and Sohnesen, 2012). In Rwanda and Kenya, family planning programs (i.e. subsidized contraceptive services and educative campaigns) triggered the transition from high to low birth rates (Bongaarts, 2011). The pace and the direction of such changes in policy interventions are difficult to foresee (Thompson and Scoones, 2009). With more than 95% of the cultivated area of sub-Saharan Africa depending on rain-fed production (FAO, 2005), rainfall variability adds another source of uncertainty in future conditions. Sub-Saharan Africa is currently characterised by widespread poverty and smallholders mainly rely on agriculture for food and income generation (Losch et al., 2012). Assessing how income and food production might change given uncertain and unpredictable socio-economic and biophysical conditions is thus of considerable importance if poverty reduction is to be achieved.

Scenario building is a useful approach to define relevant and plausible futures and cover a large range of uncertainty in socioeconomic and climate conditions (O'Neill et al., 2015). Many studies built scenarios based on hypothetical changes in population, policy interventions and efficiency of institutions and assessed their effect on land use change, intensification and diversification of agriculture (Enfors et al., 2008; García-

Martínez et al., 2011; Herrero et al., 2014; Stephenne and Lambin, 2004). These studies illustrated how scenarios inform decision-making and help to successfully target agricultural development investments. Some of these studies stressed the importance of considering heterogeneity in farm types to increase the assessment accuracy (García-Martínez et al., 2011; Gibreel et al., 2014; Herrero et al., 2014). However they focused on land use change and did not characterise and quantify food production and farm income for the different farm types. Scenario work is widespread for developed countries but remains rare in the specific context of sub-Saharan Africa and little is known on how performance indicators like income and food self-sufficiency will be affected by the changes in the wider context. Furthermore, beyond future changes in representative farms or farm types, changes in entire farm populations are often not considered.

Achieving food self-sufficiency and poverty reduction are the key objectives of the last Malian Agricultural Orientation law (LOA) (http://www.pcda-mali.org/site/index.php/29-mediatheque/31-la-loi-d-orientation-agricole-du-mali-loa, last accessed 19/02/2016). The "old cotton basin" in Southern Mali has experienced fast population growth and increasing land shortage (Soumaré et al., 2008), challenges that are exerting pressure on many land constrained regions across sub-Saharan Africa. The region has shown a promising agricultural intensification pathway linked to cotton production (Benjaminsen et al., 2010; Falconnier et al., 2015b), but future trajectories of change are uncertain. Adding to this uncertainty, the heterogeneous farms of the region (Falconnier et al., 2015b; Giller et al., 2011; Sanogo et al., 2010) are expected to respond differently to various changes in socio-economic conditions.

In the 'old cotton basin', an existing farm typology and longitudinal household survey data (Falconnier et al., 2015b; Sanogo et al., 2010), long-term crop experiments (Ripoche et al., 2015; Traore et al., 2013) and household surveys covering the entire village population provide a rich basis to understand the current situation and explore plausible futures. The objective of this study was to assess the contribution of agricultural intensification, rural to urban migration and net fertility reduction in lifting rural people out of poverty for contrasting plausible mid-term futures (fifteen years ahead) in a case study village of 99 households in the "old cotton basin" of Southern Mali. Specific objectives were to (i) build scenarios that span a wide range of uncertainty in socio-economic futures and rainfall conditions, (ii) develop a simulation framework that accounts for household demographic dynamics, sensitivity of crops to rainfall variability and change in farmer practices for all the 99 farms of the case study village, and (iii) assess trends in food self-sufficiency and farm income per capita for all farms in the village population in the different scenarios.

2. Methods

2.1. Study area

The "old cotton basin" is an area situated in the Sudanian agro-ecological zone of southern Mali (Coulibaly, 2003). The rainy season starts in May and ends in October and total rainfall fluctuates from 500 to 1200 mm. The area groups three districts (Koutiala, Dioila and the northern part of Sikasso) and accomodates more than a million rural people (Traore et al., 2011). Agricultural production is organized in a residential group of descendants related through a common male lineage (Benjaminsen, 2002; Jonckers and Colleyn, 1974): households are extended families comprising the head of the household, his sons and wives and unmarried daughters, and their children. Farmers grow cotton, cereals and groundnut in rotation and use manure, mineral fertiliser and draught power by oxen. The Compagnie Malienne pour le Developpement des Textiles (CMDT) buys the cotton and provides credit for mineral fertiliser for cotton and maize (Falconnier et al., 2015b).

2.2. Datasets

The "Suivi Evaluation Permanent" (SEP) dataset collected by the "Equipe Système de Production et Gestion des Resources Naturelles (ESPGRN)" of the Malian Institut d'Economie Rural (IER) contains information on household resource endowment, input use and CMDT measured cotton yields for 30 farms from three villages of the "old cotton basin” from 1994 to 2010. Farms were classified in four farm types, namely High Resource Endowed with Large Herds (HRE-LH), High Resource Endowed (HRE), Medium Resource Endowed (MRE) and Low Resource Endowed (LRE) farms according to (1) total cropped land (ha), (2) number of workers, (3) herd size and (4) number of draught tools (Falconnier et al., 2015b).

Data on 2013 resource endowment and crop area for the 99 households of the Nampossela village (12°15’ N and 15° 20’ W) situated in the “old cotton basin” was obtained from the CMDT. All households in Nampossela were subsequently classified in one of the four HRE-LH, HRE, MRE and LRE farm types.

2.3. Scenario building

The Nampossela village surveyed in 2013 by CMDT was chosen as the case study and baseline year. We explored the effects of uncertainty in future socio-economic and agricultural conditions within a 15 years time span (2013-2027), corresponding to the ‘near term’ where additional risks (i.e. negative impact on crop yields) due to climate change are assumed to be negligible (Pachauri et al., 2015). The scenarios were built based on plausible changes in agricultural practices and policies, and their combinations. Hypothetical trends in agricultural intensification were conceived based on promising agricultural technologies identified for the region. On the policy side, we took into account expected changes in the cotton and milk context described in the literature and policies that would affect birth and migration rates. Key variables were selected to describe these trends and quantified by extrapolating past trends mentioned in the literature. Eventually, combinations of hypothetical trends were bundled into five coherent and contrasting scenarios. We did not consider technological change - e.g. yield increase due to breeding.

2.4. Simulation framework

A model framework allowing the simulation of three major farm components (household, cropland and cattle herd) and their interactions was built (Figure 1) and run for each of the 99 farms of the Nampossela village. For the baseline (2013) and the final year (2027), food self-sufficiency and farm income per capita were computed for a series of 29 seasons using the 1965-1993 historical records at N'Tarla station (Traore et al., 2013). The two indicators were then averaged per farm type. Three additional indicators were calculated at village level namely (i) percent farms (and people) above the poverty line and food self-sufficient (ii) percent farms (and people) below the poverty line and food self-sufficient and (iii) percent farms (and people) below the poverty line and not food self-sufficient. For these three additional indicators, the average across the 29 seasons and the standard deviation were determined. Below we explain each component and indicator separately.

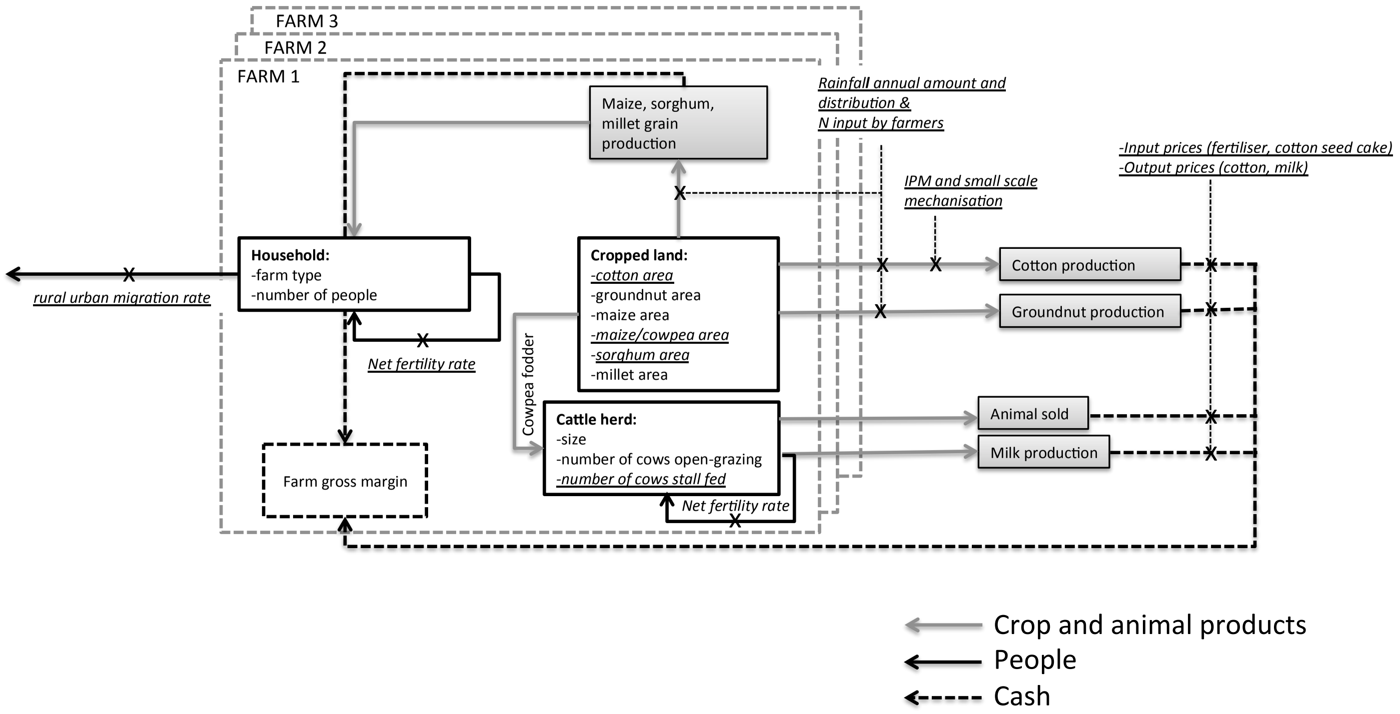


Figure 1: Conceptual framework for simulations of farms with three components: household, cropped land and cattle herd. Arrows symbolize flows of crop products, animal products, people and cash. In underlined italics, the key variables identified and quantified for five scenarios of agricultural intensification and policy intervention (Figure 2 and Table 3 give a detailed description of the scenarios). Only three farms are depicted but in reality 99 farms are simulated.

2.4.1. Household component

For each farm, household size was dynamically simulated over the years (2013-2027) and calculated as follow:

(1) $HH\_size_{i+1} = HH\_size_i \ (fertility\_rate - migration\_rate)$

where HH_size_i is the household size in year *i*, *fertility_rate* is the net (birth-death) fertility rate and *migration_rate* is the rural to urban migration rate. Fertility and migration rates were specific for each scenario and farm type. Traditionally, the eldest son inherits the totality of the land and becomes the new head of the household (comprising the younger brothers), which prevents land subdivision (Jonckers and Colleyn, 1974). In some cases, when a younger brother wants to start his own farm and/or disagrees with the elder on farm management, the household may split and the land holding may be subdivided. The SEP data showed that only one household among the 30 followed was subdivided during the whole 1994-2010 period (Falconnier et al., 2015b). Therefore land subdivision was not considered for the simulations and total cropped land per household was kept constant over the 15 years of the simulation, as there is no arable land available for expansion (Falconnier et al., 2015b).

For each of the four farm types, past average annual growth rate of the household size was calculated using 1994 and 2010 SEP data. Rural-urban migration rate was then estimated as the difference between the observed annual growth rate of household size and the Malian average net fertility (birth-death) rate (3.4%) (World Bank, http://data.worldbank.org/indicator/SP.DYN.CBRT.IN, last accessed 07/10/2015).

2.4.2. Cropped land component

Information on cropland allocation and area was obtained from the survey data. To estimate crop yields as a function of variable rainfall, we used an empirical approach based on experimental results from the region. Correlations between annual rainfall and yield of cotton, maize, sorghum, millet and groundnut were analysed using published studies reporting measured yield with farmer practices in on-station and on-farm trials in the “old cotton basin”. Studies and/or datasets reporting only farmer-estimated or recalled yield were discarded. Additionally, CMDT measured cotton yield in the SEP dataset were analysed. For the crops for which our literature study indicated a significant effect of rainfall on the yield with farmer practice), this yield was simulated using the APSIM model (Keating et al., 2003). APSIM was calibrated for a typical Lixisol (FAO, 2006), the cultivars used by farmers in the “old cotton basin” (Traore, 2014) and N application rates used by farmers (derived from SEP data). In order to span a large range of rainfall conditions, yields were simulated for a series of 29 seasons using the 1965-1993 historical records at N’Tarla station (Traore et al., 2013). For crops without a significant effect of rainfall on yield, the average measured yield in farmer conditions was used and kept constant for all rainfall seasons.

For cotton, water-limited potential yields (van Ittersum et al., 2013) were derived from yield measured from 1965 to 1993 in the N’Tarla experimental station in plots receiving 90 kg N ha^{-1} mineral fertiliser and 12.8 t DM manure ha^{-1} (Ripoche et al., 2015; Traore et al., 2013). For maize, sorghum and millet, water-limited potential yields were simulated using the APSIM crop model (Keating et al., 2003) for the 1965-1993 historical rainfall record of the N’Tarla station. An existing calibration for the Lixisol of the experimental station (a typical soil for the region) and the local cultivars was used (Traore, 2014; Folorunso, personal communication). A nitrogen input of 300 kg N ha^{-1}, spread over two application, was found to release N constraints in all years of the simulation and was therefore used for the determination of the water-limited potential yield. Finally the N input required to reach 90% of the water-limited potential yield was determined.

2.4.3. Cattle herd component

A 10% net fertility rate for cattle was assumed (Ba et al., 2011). Annual animal off-take was assumed to be equal to this net fertility rate to ensure the cattle herd size remained stable throughout the years of the simulations (Ba et al., 2011). Current cattle herd size and number of donkeys for each household was obtained from the survey in

Nampossela in 2013. The proportion of lactating cows in the cattle herd was assumed to be 22 and 34% for cattle herds below and above 23 animals respectively (Ba et al., 2011). Year-round milk production of cows with open-grazing (current farmer practice) and stall feeding (2.5 kg cowpea hay cow^{-1} day^{-1} and 2 kg cotton seed cake cow^{-1} day^{-1} during the dry hot period of 90 days) was obtained from (De Ridder et al., 2015).

2.5. Food self-sufficiency and income per capita

Income per capita was calculated as an aggregate of monetary gross margins from cotton, groundnut, cereals, milk and live-animals sales. For cereal gross margin, both self-consumption and surpluses were valued at the market price. Farm income was expressed in $PPP to allow comparison with the 1.25 $PPP/day/person poverty line (Ravallion et al., 2009). The Average Conversion rate between the Malian currency (FCFA) and $PPP was obtained from the World Bank estimates (http://data.worldbank.org/sites/default/files/wdi08.pdf, last accessed 25/09/2015). Input and output costs at the start of the simulation (2013) were obtained from a market survey carried out in 2013 in Nampossela. For the end of the simulation period (2027), input and output prices for milk, cotton and cereals depended on the scenarios, while other prices were kept constant.

Food self-sufficiency was calculated as the percent fulfilment of household calorific need by on-farm production of calories. An average calorific need of 2406 kcal/person/day was considered (average across all SEP households using age-sex specific daily needs, following Britten et al. (2006) data). The calorie supply was computed based on household cereal production, considering an average supply of 3500 kcal kg^{-1} maize, sorghum and millet grain (FAO: http://www.fao.org/docrep/t0818e/T0818E0b.htm, last accessed 02/10/2015).

3. Results

In what follows, we start by giving the results of the literature and data analysis that helped to conceive the hypothetical trends and scenarios. Then hypothetical trends and scenarios are described and explained and finally the results of the simulations are presented.

3.1. Past observed population growth and migration rate

In the 1994-2010 period, the average observed annual growth of household size ranged from 0.6 to 3.4% depending on farm type. Based on the average net fertility rate of 3.4% for Mali, the estimated rural to urban migration rate ranged from 0 % for the largest farms (type HRE-LH) to 2.8% for the smallest farms (type LRE) (Table 1).

Table 1: Observed annual growth rate of household size and estimated rural-urban migration rate for four farm types during the 1994-2010 period. For a detailed description of the farm types, see Falconnier et al. (2015b). SE=Standard Error. HRE-LH: High Resource Endowed farms with Large Herds, HRE: High Resource Endowed farms, MRE: Medium Resource Endowed farms, LRE: Low Resource Endowed farms.

	Observed household growth rate		Estimated migration rate	
Farm type	Average	SE	Average	SE
HRE-LH	3.4%	0.13%	0.0%	0.13%
HRE	1.7%	0.78%	1.7%	0.78%
MRE	2.2%	0.45%	1.2%	0.45%
LRE	0.6%	1.74%	2.8%	1.74%

3.2. Effect of rainfall variability on crop yields and water-limited potential yields

Sensitivity of maize yield to seasonal rainfall amount was reported in on-station experiments as well as in on-farm trials with farmer practice (Table 2). Therefore, maize with current farmer practice was simulated as impacted by rainfall variability and ranged from 840 to 2290 kg ha^{-1} for HRE-LH, HRE and MRE farms (with a fertilizer application of 60 kg N ha^{-1}) and from 790 to 1680 kg ha^{-1} for LRE farms (with a fertilizer application of 40 kg N ha^{-1}) (Table 2). For maize/cowpea intercropping, cowpea fodder production was assumed to equal 1.38 t DM/ha, independently of rainfall (Falconnier et al., 2016), and the simulated maize yield was multiplied by 1.08, i.e. the maize partial Land Equivalent Ratio for intercropping when cotton is the previous crop (Falconnier et al., 2016).

Table 2: Effect of annual rainfall variability on crop yield and average yield with current farmer practice according to seven studies of on-farm and on-station measured yields of cotton, maize, sorghum, millet and groundnut with farmer practice in the "old cotton basin" of southern Mali. HRE-LH: High Resource Endowed farms with Large Herds, HRE: High Resource Endowed farms, MRE: Medium Resource Endowed farms, LRE: Low Resource Endowed farms.

	Effect of rainfall on on-station yield		Effect of rainfall on on-farm yield		Average yield (kg/ha) with current farmer practice			
Crop	*P*	R^2	*P*	R^2	HRE-LH	HRE	MRE	LRE
Cotton	<0.05[1];<0.001[2]; <0.001[4]	0.56[1]; 0.62[2]	>0.05[1,7]	-	1050[6]	940[6]	910[6]	750[6]
Maize	<0.05[2]	0.37[2]	<0.05[3];<0.01[5]	-	1610 (±320)	1610 (±320)	1610 (±320)	1210 (±220)
Sorghum	>0.05[1, 2, 4]	-	>0.05[5]	-	1030[5]	1030[5]	1030[5]	1030[5]
Millet	>0.05[2]	-	>0.05[3]	-	850[3]	850[3]	850[3]	850[3]
Groundnut	>0.05[1]	-	-	-	530[5]	530[5]	530[5]	530[5]

[1] Traore et al. (2013)
[2] Traore et al. (2014)
[3] Traore et al. (2015)
[4] Ripoche et al. (2015)
[5] Falconnier et al. (2016)
[6] Falconnier et al. (2015b)
[7] This study

On-station experiments showed the sensitivity of cotton yields to seasonal rainfall. However, cotton yields less in farmers' fields than on station and tends not to be impacted by seasonal rainfall because of pests and weeds (Table 2; Traore et al., 2013). Analysis of measured yields in the SEP database consistently showed that farmers' cotton yields were not significantly impacted by total rainfall and rainfall distribution, but by manure input (P=0.02) and oxen per worker (which indicates the ability to weed in a timely fashion) (P<0.001), factors that varied per farm type. Therefore, for the current farmer practice the average cotton yield for each farm type was considered and kept constant for all the rainfall seasons, i.e. 1050, 940, 910 and 750 kg ha^{-1} for HRE-LH, HRE, MRE and LRE respectively (Table 2). For sorghum, millet and groundnut no significant correlations were found between yield and seasonal rainfall in on-farm experiments with farmer practice (Table 2). Therefore, the average yield obtained in on-farm trials with farmer practice was used, i.e. 1050, 850 and 530 kg ha^{-1} for sorghum, millet and groundnut respectively (Falconnier et al., 2016; Traore et al., 2015), and kept constant for all the rainfall seasons.

Water-limited potential yield for cotton in the N'Tarla long-term experiment ranged from 1080 to 3059 kg ha^{1} with an average of 2220 kg ha^{1}. Farmer average yield was 1051 kg ha^{1} for the farm type with the best yield (with on average 43 kg N ha^{1} and 4.9 t ha^{1} DM), i.e. only 47% of the water-limited potential yield, and similar to the yield of the control plot with no mineral fertiliser and no manure input in the N'Tarla experiment. Average water-limited potential yield for maize, sorghum and millet was 2920, 2310 and 1830 kg ha^{1} respectively. 90% of the water-limited potential yield was obtained with 110, 150 and 150 kg N ha^{1} for maize, sorghum and millet respectively. Farmer average yield was 55, 45 and 46% of water-limited potential yield for maize, sorghum and millet respectively.

3.3. Hypothetical trends in policy interventions and agricultural intensification

A continued decline in cotton prices and a long-term structural removal of fertilizer subsidies is not unlikely (Coulibaly et al., 2015). Based on these projections, one pessimistic hypothetical policy trend (P0) included a steady decline in cotton prices and a steady increase in mineral fertiliser prices (Table 3). In more optimistic projections (P1 to P4), cotton prices would stay at the high 2011-2015 level and fertiliser subsidy would be maintained (Table 3). Aparisi et al. (2012) described that in 2008 the high price of milk powder on the world market decreased milk powder importations, obliging dairy industries in Bamako to use more local milk. In combination with the increased popularity of products from local milk (Corniaux et al., 2012), this led to a 10 Fcfa/L/year increase in the price paid to farmers by dairies from 2005 to 2010. This increase rate was used to imagine a progressive policy intervention where the Malian state would use tariffs on milk powder, obliging dairy industries to increase the share of local milk in their processing units and therefore increasing the price paid to farmer (P2 to P4) (Table 3). The market for cotton by-products is poorly understood (Kelly et al., 2010) and we hypothesised that in the favourable policy trends (P2 to P4), the cotton seed cake price would decrease to its lowest level observed in 2003 (Kelly et al., 2010). In the other trends, the current low price for milk and high price for cotton seed cake would continue (P0 and P1) (Table 3).

Family planning can decrease net fertility rates (Bongaarts, 2011) but the possible effect of this has not been quantified for Mali. We hypothesized that family planning would lead to a 35% decrease in fertility rates so that the Malian fertility rate would drop to the Côte d'Ivoire rate of 2.2% (P3 and P4) (Table 3). Creation of jobs outside of agriculture and educational programs to empower rural people can favour rural to urban migration (de Brauw et al., 2014; Fox and Sohnesen, 2012). We hypothesised that such policy intervention would lead to an increase of rural to urban migration rates up to 2.8% for all farm types (i.e. the fastest observed rate in the 1994-2010 period) (P3 and P4, Table 3).

The comparison of water-limited potential yield and actual yield indicated a large yield gap for cotton despite the use of mineral and organic fertiliser by farmers (see section 3.2.), pointing to important pest and weed pressure. To narrow the cotton yield gap, we conceived a hypothetical policy intervention (P4) geared towards relieving pest and weed constraints, through (i) Integrated Pest Management programs that entail close technical supervision and training of farmers to improve spray scheduling and maintenance of application equipment (Hillocks, 2014) and (ii) subsidies for the development of private small-scale mechanization services that would allow farmers to hire cheap two wheel tractors to replace oxen (Baudron et al., 2015), enabling timely land preparation, sowing and weeding of cotton (Table 3). In addition to that, the hypothetical policy intervention includes the extension of the fertiliser subsidy to sorghum and millet (currently only on cotton and maize) as an incentive for farmers to add more nitrogen on cereals, allowing to reach 90% of water-limited potential yield for maize, sorghum and millet (Table 3).

Table 3: Key variables and their quantification under current (2013) and future (2027) management for hypothetical policy interventions (P0 to P4) and hypothetical changes in agricultural practices (A0 to A3).

	Key variables	Trend	Quantification		Reference used to built the trend
			2013	2027	
Hypothetical policy interventions					
No input/output subsidy for cotton production (P0)	Price paid to farmer for cotton (fcfa/kg)	Decrease	250	183	Coulibaly et al., (2015)
	Cost of fertilizer bag for cotton (fcfa/kg)	Increase	12500	17500	Coulibaly et al., (2015)
Input/output subsidy for cotton production (P1 to P4)	Price paid to farmer for cotton (fcfa/kg)	No change	250	250	-
	Cost of fertilizer for cotton (fcfa/kg)	No change	12500	12500	-
No Input/output subsidy for milk production (P0 and P1)	Price paid to farmer for milk (fcfa/kg)	No change	250	250	-
	Cost of cotton seed cake (fcfa/kg)	No change	170	170	-
Input/output subsidy for milk production (P2 to P4)	Price paid to farmer for milk (fcfa/kg)	Increase	250	400	Aparisi et al., (2012)
	Cost of concentrates (fcfa/kg)	Decrease	170	50	Kelly et al., (2010)
No family planning programs (P0 to P2)	Net fertility rate (%)	Current rate	3.4	3.4	-
Family planning programs (P3 and P4)	Net fertility rate (%)	Lower rate	2.2	2.2	Bongaarts, (2011)
Limited job creation outside agriculture (P0 to P2)	Rural urban migration (HRE-LH, HRE, MRE, LRE farms) (%)	No change	0;1.7;1.2;2.8	0;1.7;1.2;2.8	-
Important job creation outside agriculture (P3 and P4)	Rural urban migration (HRE-LH, HRE, MRE, LRE farms) (%)	Increase	0;1.7;1.2;2.8	2.8;2.8;2.8; 2.8	de Brauw et al., (2014)
Integrated Pest Management programs for cotton production (P4)	Existence of the programs	-	No programs	Programs in place	Hillocks, 2014)
Incentive subsidy for the development of private small-scale mechanization services (P4)	Existence of the subsidy	-	No subsidy	Subsidy	Baudron et al., (2015)
Fertilizer subsidy for sorghum and millet (P4)	Cost of fertilizer for sorghum and millet (fcfa/kg)	Decrease	17500	12500	Coulibaly et al., (2015)
Hypothetical change in agricultural practices					
Decreasing cotton cultivation (A0)	Cotton share of cropland (HRE-LH, HRE, MRE, LRE) (%)	Decrease[2]	31;32;21;24	22;11;5;8	Falconnier et al., (2015)
	N input on cotton, maize, sorghum, millet (kg)	Decrease	43;60;0;0[1]	43;40;0;0	Falconnier et al., (2015)
No change in farmer practices (A1)	Cotton share of cropland (HRE-LH, HRE, MRE, LRE) (%)	No change	31;32;21;24	31;32;21;24	-
	N input on cotton, maize, sorghum, millet (kg/ha)	No change	43;60;0;0[1]	43;60;0;0[1]	-
	Percent maize intercropped with cowpea (%)	No change	0	0	-
	Small-scale mechanization for cotton operations	No change	0	0	-
	Percent cows in stall feeding	No change	0	0	-
	Integrated Pest Management on cotton	No change	0	0	-
Diversification with legumes (A2 and A3)	Percent maize intercropped with cowpea (%)	Increase	0	100[2]	Falconnier et al., (2016)
Intensification of livestock production (A2 and A3)	Percent cows in stall feeding (%)	Increase	0	0-100[3]	de Ridder et al., (2015)
Narrowing yield gap (A3)	N input on cotton, maize, sorghum and millet (kg/ha)	Increase	43;60;0;0	90;150;150;150	This Study
	Integrated Pest Management on cotton	Increase	No	Yes	Hillocks, (2014)
	Small-scale mechanization for cotton operations	Increase	No	Yes	Baudron et al., (2015)

[1] for LRE farms: 43;40;0;0

[2] cotton is replaced by sorghum

[3] except LRE farms: 0%

[4] depending on cowpea fodder production

Falconnier et al. (2015b) showed that in the unfavourable cotton context of the past decades (collapse of CMDT), the cotton area of HRE-LH, HRE, MRE and LRE farmers decreased by 30, 66, 75 and 66% and was replaced by sorghum. This decrease in cotton area, alongside a decrease of mineral fertiliser use down to the level of LRE farms was assumed for the less optimistic agricultural change (A0) (Table 3). In the second hypothetical change related to agricultural intensification (A1), no change in farmer practices was assumed (Table 3).. The third hypothetical change (A2) related to agricultural intensification assumes the adoption by farmers of maize/cowpea intercropping (diversification with legume) and stall feeding of lactating cows (intensification of livestock production) using the cowpea fodder produced on-farm (Table 3). This change was conceived based on findings indicating that diversification with legumes can be profitable and at low risk for farmers when maize is intercropped with cowpea (Falconnier et al., 2016). In combination with this, stall feeding of lactating cows with cowpea fodder can increase milk production (De Ridder et al., 2015). For this change, farmers were assumed to intercrop all their maize with cowpea and famers would feed as many cows in the stall as allowed by the available cowpea fodder. Fodder produced beyond the requirements of oxen, donkeys and lactating cows would be sold on the market.

The last hypothetical change related to agricultural intensification (A3) was an increase in the use of mineral fertiliser on maize, sorghum and millet up to the level required to reach 90% of potential yields, and adoption by farmers of small-scale mechanisation for cotton cultivation and Integrated Pest Management (Table 3). Figure 1 gives a comprehensive picture of how the variables (in underlined italics) constituting the trends listed in Table 3 impacted the components of the model framework.

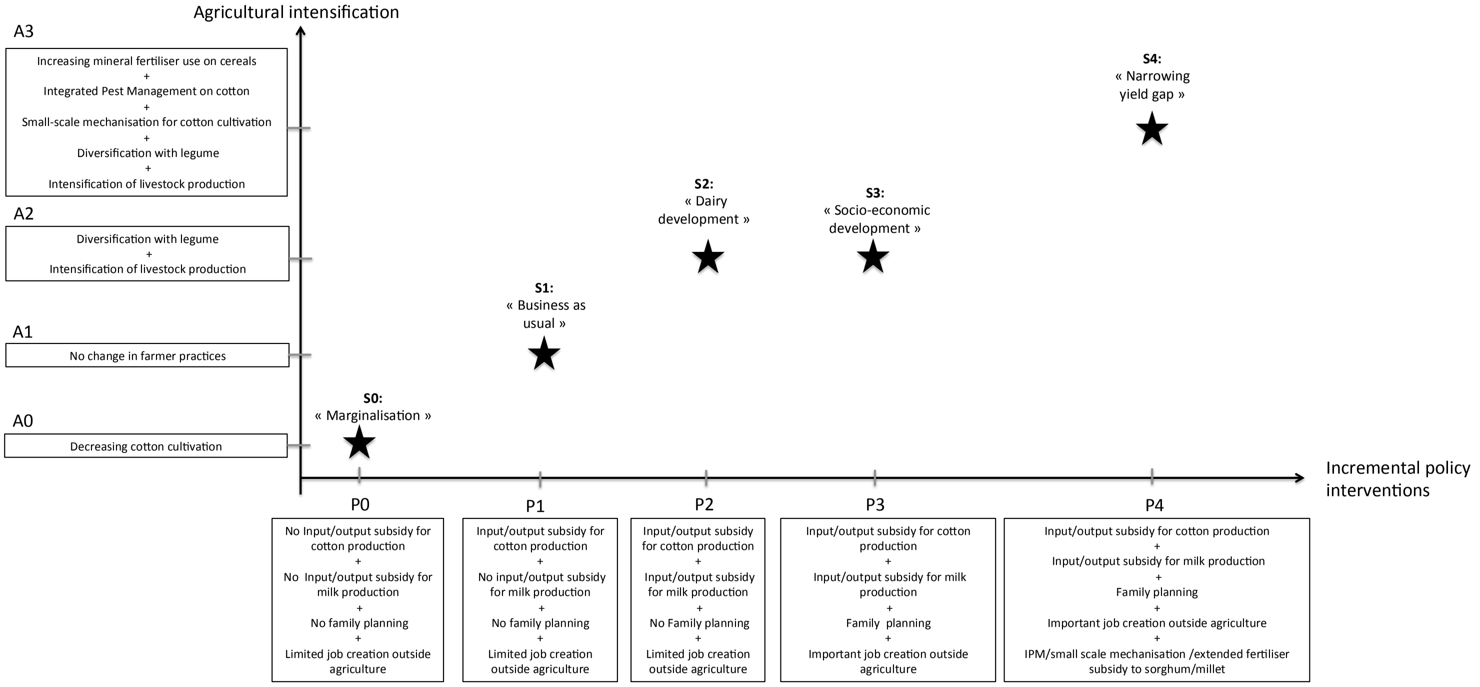


Figure 2: Illustrative mapping of five scenarios according to hypothetical changes in agricultural practice and policy interventions. Key variables quantifying the hypothetical changes are described in Table 3.

3.4. Scenarios

Five scenarios were built by logical combinations of the hypothetical trends in policy and agricultural intensification (Figure 2). In the "Marginalisation" (S0) scenario, enabling policies would disappear and cotton cultivation would decrease. In the "Business as usual" (S1) scenario, only the current policies supporting cotton are included and farmer practices would not change. The other scenarios relied on incremental policy interventions triggering a change in farmer practices toward agricultural intensification. In the "Dairy development" (S2) scenario, policy interventions would be extended to the milk sector, triggering cropping diversification with legumes and intensification of livestock production. The "Socio-economic development" (S3) scenario builds on the "Dairy development" (S2) scenario, with additional family planning to reduce human fertility rates and important job creation outside agriculture to favour rural to urban migration. The "Narrowing yield gap" (S4) scenario is the most optimistic scenario with all the previous policy interventions put in place, and additional interventions to narrow the yield gaps.

3.5. Change in food self-sufficiency and income per capita for different scenarios

All farm types were food self-sufficient on average in 2013, though some variation occurred due to the sensitivity of maize to rainfall (Figure 3). In the "Marginalisation" (S0) scenario, average food self-sufficiency decreased for HRE-LH and MRE farms but increased slightly for HRE and LRE farms. In the "Business as usual" (S1) and "Dairy development" (S2) scenarios, average food self-sufficiency in 2027 decreased compared with the baseline 2013 for all farm types (Figure 3). In some seasons, HRE-LH and HRE farms were close to the food self-sufficiency threshold. For MRE and LRE farms, food self-sufficiency decreased but remained above the sufficiency threshold in all cases of rainfall (Figure 3). In the "Socio-economic development" (S3) scenario, food self-sufficiency was maintained at around its 2013 level (Figure 3) for all farm types. In the "Narrowing yield gap" (S4) scenario, food self-sufficiency increased for all farm types. Concurrently, also the variability of food self-sufficiency was increased in the "Narrowing yield gap" (S4) scenario.

In 2013, only HRE-LH and MRE farms were above the poverty line in all seasons (Figure 4). In the "Marginalisation" (S0) and "Business as usual" (S1) scenario, farm income per capita decreased below the poverty line for all farm types, regardless of rainfall. In the "Dairy development" (S2) scenario, farm income per capita still decreased for all farm types. The "Socio-economic development" (S3) scenario allowed HRE-LH, HRE and MRE farms to increase their income compared with 2013 and move above the poverty line in all seasons. In the "Narrowing yield gap" (S4) scenario, all farm types increased their farm income per capita compared with the baseline (2013) and stayed above the poverty line. The variability in farm income per capita also increased in the "Narrowing yield gap" (S4) scenario. In some years, farm income in S4 was at the level of farm income in S3.

In the baseline year (2013), 45% (±0.6 % depending on the rainfall season considered) of farms of the village were above the poverty line and food self-sufficient (Figure 5a). In the "Marginalisation" (S0) and "Business as usual" (S1) scenarios, this percentage fell to 6 % (±0.4 %) and 16% (±1.6 %) respectively (Figure 5b,c). In the "Dairy development" (S2) scenario, 27% (±1.5 %) of the farms were above the poverty line and food self-sufficient (Figure 5d). With the "Socio-economic development" (S3) scenario, 69% (±1.5) of the farms were non-poor and food self-sufficient (Figure 5e). With the "Narrowing yield gap" (S4) scenario, 92% (±9.2) of the farms were food self-sufficient and above the poverty line (Figure 5f).

In three scenarios (S0 to S2), the proportion of people who were food self-sufficient and not poor was smaller than in the baseline (Figure 6). For the other two scenarios (S3 and S4), the proportion of people who were food self-sufficient and not poor was greater than in the baseline (Figure 6).

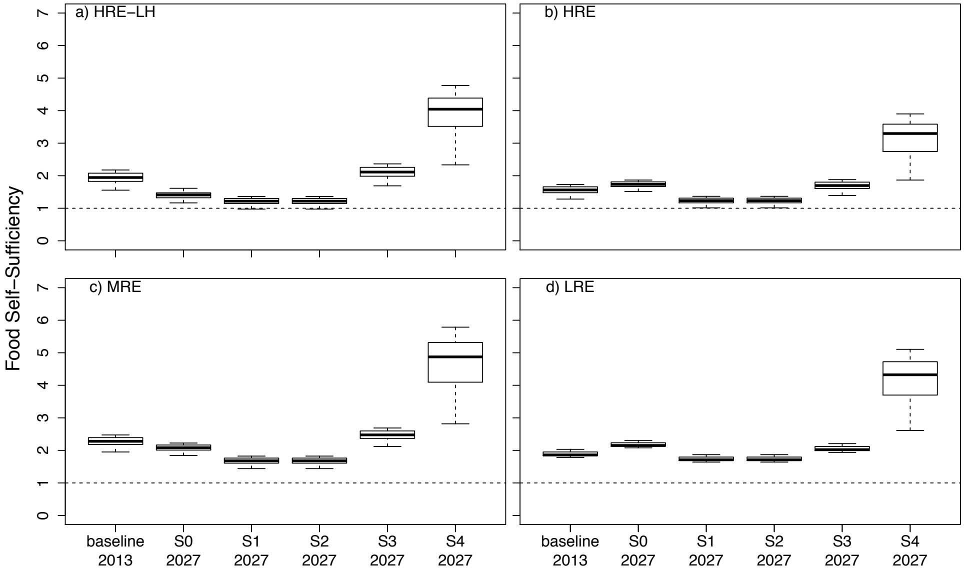


Figure 3: Boxplots showing food self-sufficiency averaged for HRE-LH (a), HRE (b), MRE (c), LRE (d) farms in the baseline (2013) and in 2027 for five scenarios of agricultural intensification and policy intervention. The horizontal line in the box indicates the median for 29 rainfall seasons. The height of the box represents the interquartile range. The whiskers extend to the most extreme data point which is no more than 1.5 times the interquartile range from the edge of the box. A detailed description of the scenarios (S0-S4) can be found in Figure 2 and Table 3. The horizontal dotted line is the food self-sufficiency threshold.

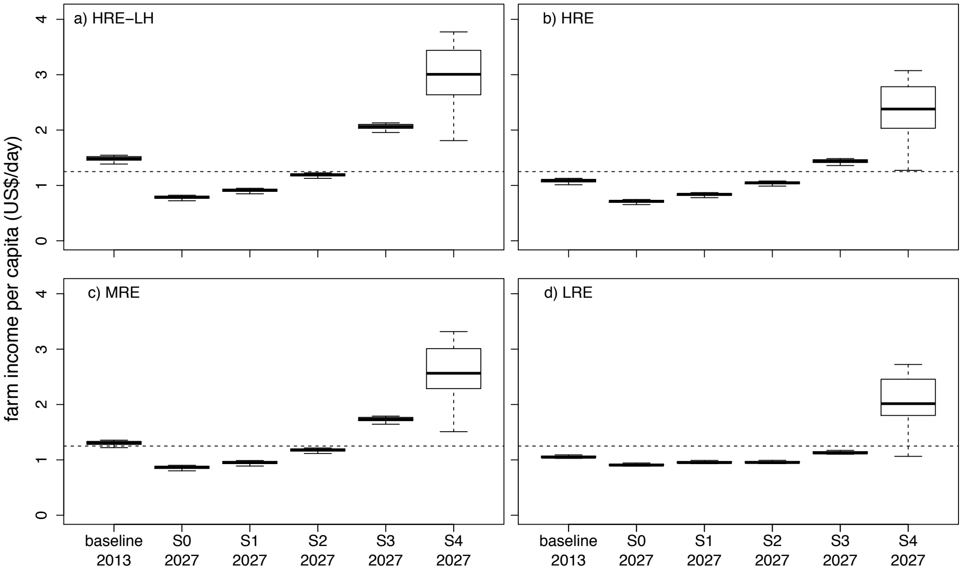


Figure 4: Boxplots showing farm income per capita averaged for HRE-LH (a), HRE (b), MRE (c), LRE (d) farms in the baseline (2013) and in 2027 for five contrasting scenarios of agricultural intensification and policy intervention. The horizontal line in the box indicates the median for 29 possible rainfall seasons. The height of the box represents the interquartile range. The whiskers extend to the most extreme data point which is no more than 1.5 times the interquartile range from the edge of the box. A detailed description of the scenarios (S0-S4) can be found in Figure 2 and Table 3. The horizontal dotted line is the poverty line threshold of 1.25 PPP/day.

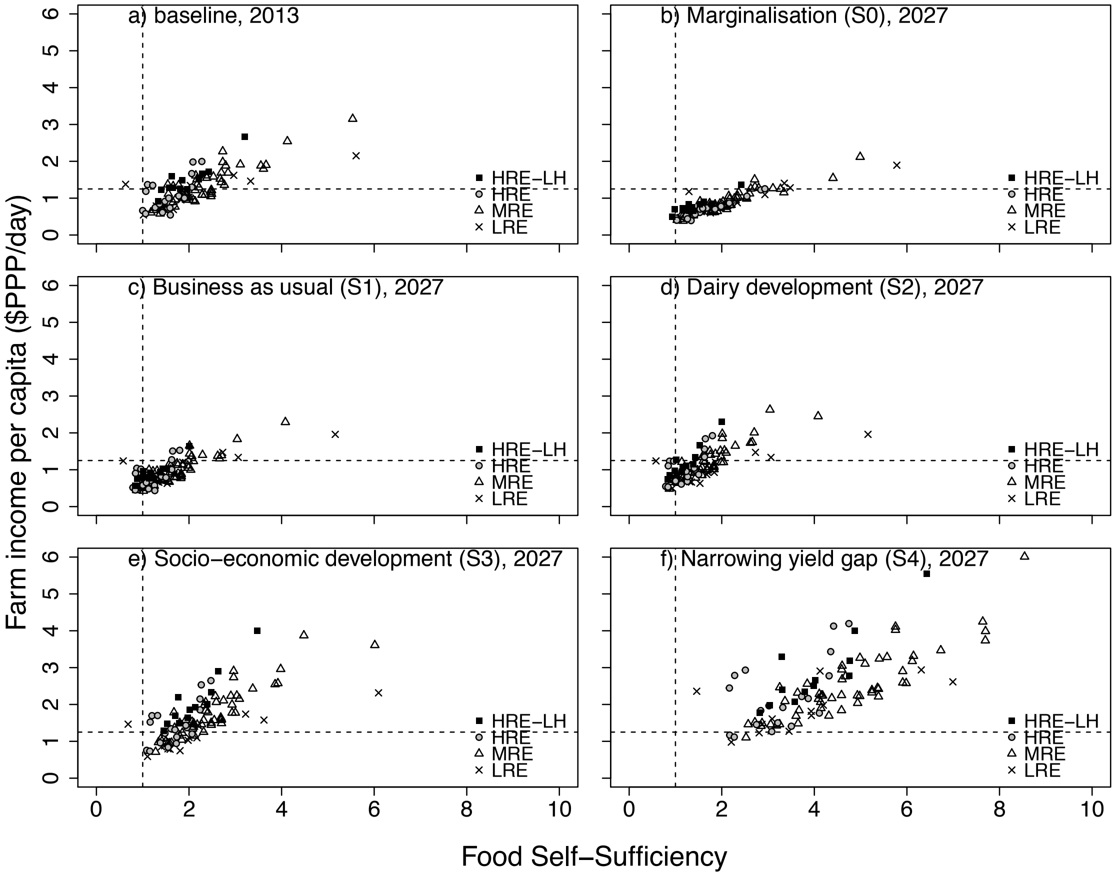


Figure 5: Food self-sufficiency ratio and income per capita of the 99 households of Nampossela village in 2013 (a) and 2027 for different scenarios of agricultural intensification and policy intervention (b, c, d, e, f, h, j, k) for an average rainfall year (734 mm). The horizontal and vertical dotted lines represent the 1.25 PPP day^{-1} poverty line and the food self-sufficiency threshold respectively.

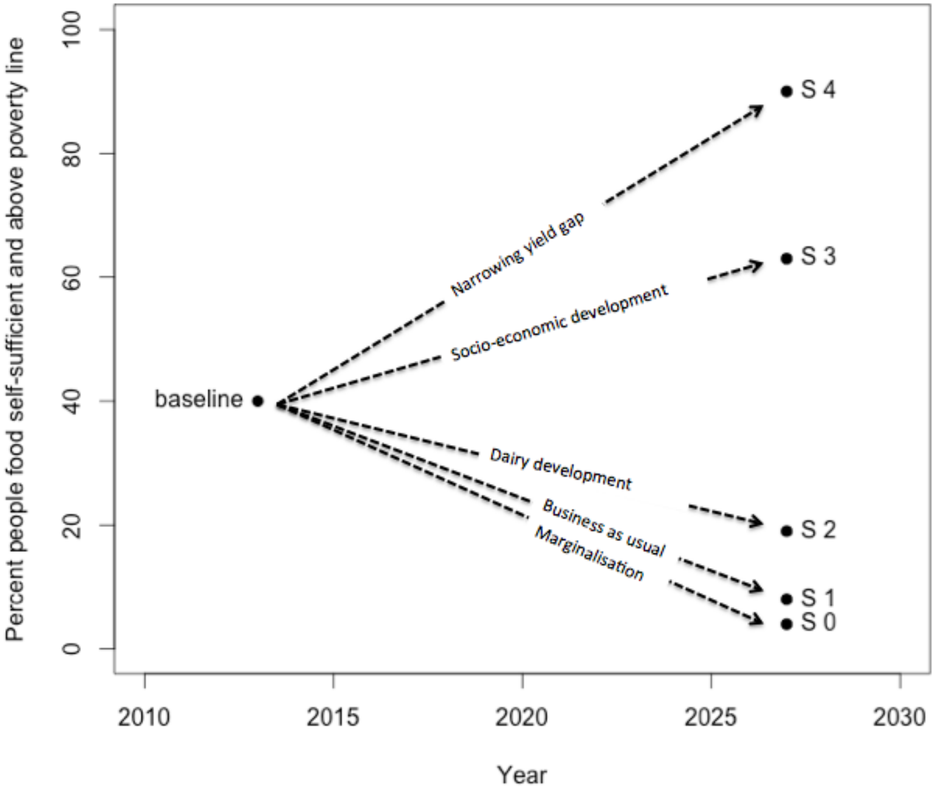


Figure 6: Percent people food self-sufficient and non-poor in the Nampossela village in 2013 and 2027 for five contrasting scenarios (S0-S4). Table 3 and Figure 2 give a detailed description of the scenarios. The straight dotted lines do not necessarily indicate a linear trend.

4. Discussion

4.1. Decrease in farm size?

Farm size in generally expected to decrease with increasing population pressure (van Vliet et al., 2015). We assumed constant farm size and did not consider household subdivision in our simulations, because evidence from the SEP longitudinal data indicated it was a rare phenomenon (Falconnier et al., 2015b). In line with this finding, a comprehensive survey carried out in 2006 with the 146 households of another village of the Koutiala district showed that 71% of the farms originated from a traditional inheritance process without land holding subdivision and only 29% originated from a household subdivision, with 86% of these subdivisions having occurred before 1996 (Poccard-Chapuis et al., 2007). Hence, in the land constrained old cotton basin, population increase results in a decrease in land per capita within farms rather than a decrease in farm size due to landholding subdivision.

4.2. Change in food self-sufficiency and income differed per farm type

Differing migration rates between farm types led to different changes in food self-sufficiency and income per capita (Figure 3 and Figure 4). This factor was overriding differences in farm livestock holdings, practices and yields.

Out-migration in search of remunerative activities is a major element of survival strategies in West Africa (Painter et al., 1994). Our estimate of rural to urban migration during the 1994-2010 period for farms in the old cotton basin (1.4% averaged across farm types, Table 1) is in line with the 2% rate reported by de Brauw et al. (2014) for Mali. In an additional survey carried out in 2012, the heads of SEP farms indicated that household members migrated to Malian, other African cities or European cities (73, 27 and 3% of the farms respectively). 15% of the farm also reported having a worker who migrated to start a new farm in the less densely populated Bougouni region within Mali, indicating that some rural to rural migration is encompassed in our estimates. Migration is usually a result of the difference between the expected return to labour in the home and the potential destination area (Harris and Todaro, 1970; Jayne et al., 2014; Zhu and Luo, 2010). Logically, the farms with the lowest labour productivity, i.e. the HRE and LRE farms (Falconnier et al., 2015b), experienced the highest migration rate in the 1994-2010 period (Table 1). In the “Business as usual” (S1) scenario, higher out-migration relieved some of the pressure on land for HRE and LRE farms who therefore suffered from a smaller decrease in food self-sufficiency and income per capita compared with HRE-LH and MRE farms. Similarly in the “Dairy development” (S2) scenario, HRE farms experienced a smaller decrease in farm income per capita compared with HRE-LH farms, though the latter farms had more cattle and therefore more potential to benefit from improvements in the milk sector. In this scenario for HRE-LH farms with no urban migration, population growth outpaced the benefits associated with diversification with legume and intensification of livestock production. Thus only when out-migration was stimulated by job creation in the cities (S3), the benefits of dairy development could be seen for HRE-LH farms (Figure 4). Interestingly, though they owned less livestock than HRE and HRE-LH farms, MRE farms also benefited from dairy development because they were able to sell surplus cowpea fodder (Figure 4). LRE farms remained 'hanging in" with low income per capita in the scenarios S0 to S3, due to their low cotton area and yield (Figure 3, Figure 4). Population growth had little impact on these small farms given their already rapid rate of out-migration. LRE farms owned few cattle (Falconnier et al., 2015b) and therefore did not benefit from interventions in the milk sector. In the "Narrowing yield gap" (S4) scenario, small farms (LRE type) were the only ones to still run the risk of being below poverty line in some 'bad' seasons.

4.3. Pathways out of poverty?

The marginalisation scenario (S0) resembled strongly what farmers have been experiencing in the previous decades due to instability of the cotton context (Djouara et al., 2005; Nubukpo, 2011). The shift toward "subsistence farming", i.e. the partial replacement of cotton by sorghum, allowed two farm types (HRE and LRE) to increase their food self-sufficiency status (Figure 3), but went hand in hand with a massive increase in poverty rates (Figure 6). Overall, this worrying trend stresses the crucial role of a well-functioning cotton sector for poverty reduction in the region (Djouara et al., 2005).

Dairy development is usually considered unlikely in land-constrained environments, due to the strong competition of forage production with existing cash/or food crops (De Ridder et al., 2015; Herrero et al., 2014; Tittonell et al., 2009). Interestingly, in the "Dairy development" (S2) scenario, the decrease in food self-sufficiency was only due to demographic growth, and not to trade-offs between food and fodder production.

This was achieved by intercropping cowpea with maize after cotton in the rotation, a niche that guarantees no penalty to maize production (Falconnier et al., 2016). When coupled with appropriate socio-economic development measures and price interventions in the milk sector, dairy development through diversification with legumes and intensification of livestock production would lift a significant proportion of the village out of poverty (Figure 6).

Our study adds to the body of literature showing that out-migration can relieve land pressure and improve livelihoods by pulling rural labour out of agriculture (Beegle et al., 2010; de Brauw et al., 2014). Rural to urban migration however encompasses a diversity of realities and can be the expression of either unskilled rural labour being forced to find work outside agriculture or educated people lured into productive non-farm jobs (Jayne et al., 2014). There is evidence across sub-Saharan Africa that rural to urban migration can be a "push" into productive non-farm jobs: in Ethiopia, successful industrial development led to the substitution of shoes imported from China by locally manufactured leather-shoes (Sonobe et al., 2009). With a more favourable industrial environment, Mali could develop its textile industry and become a competitive exporter (Cockburn et al., 1999). More generally, Fine et al. (2012) estimated that 122 million young people will enter the labour market in Africa between 2010 and 2020. They projected for an optimistic scenario that Africa could create 70 million wage-paying jobs, mainly in manufacturing, government and service sectors during the same period. The size of the labour force therefore appears to be growing faster than economies can create job opportunities (Fox and Sohnesen, 2012) and agriculture will still have an important role to play in rural livelihoods.

Family planning exerted the same influence as out-migration and allowed improving farmers' livelihood. In Mali, demographic surveys indicated that 28% of the women expressed an unmet demand for contraception (Population Council and ICF International, 2015), showing the scope for a change in reproductive behaviours and the need for stronger political commitment to family planning. Husband's disapproval may however discourage women from taking control of their fertility (Barnett et al., 1999) and broader change in social and gender norms would therefore be needed.

When added to the previous interventions and change in practices, narrowing the yield gap allowed a massive increase in food self-sufficiency (Figure 3) and lifting almost the totality of the village out of poverty (Figure 6). However, at the same time, it also increased the variability of food self-sufficiency and income, which is explained by the increased crop sensitivity to rainfall in these cases of near-absent nutrient limitation (Affholder, 1995; Ripoche et al., 2015). In some 'bad' seasons, HRE and LRE would come close or below the poverty line (Figure 4). This risk of unfavourable cost:benefit ratios is common in the context of sub-Saharan Africa (Bielders and Gérard, 2015; Ronner et al., 2016) and could impede the adoption of higher fertiliser application rates.

Finally, our analysis indicates that none of these policy interventions and agriculture intensification strategies alone can raise an entire heterogeneous farm population above the poverty line (Figure 6). It is rather the strategic combination of multi-sectoral interventions that may offer a pathway for poverty alleviation. This key finding adds to the increasing recognition that understanding the future of agriculture requires to move from a singular focus on agricultural interventions to a more holistic and multisectoral analysis (Frelat et al., 2016; Thompson and Scoones, 2009).

Conclusion

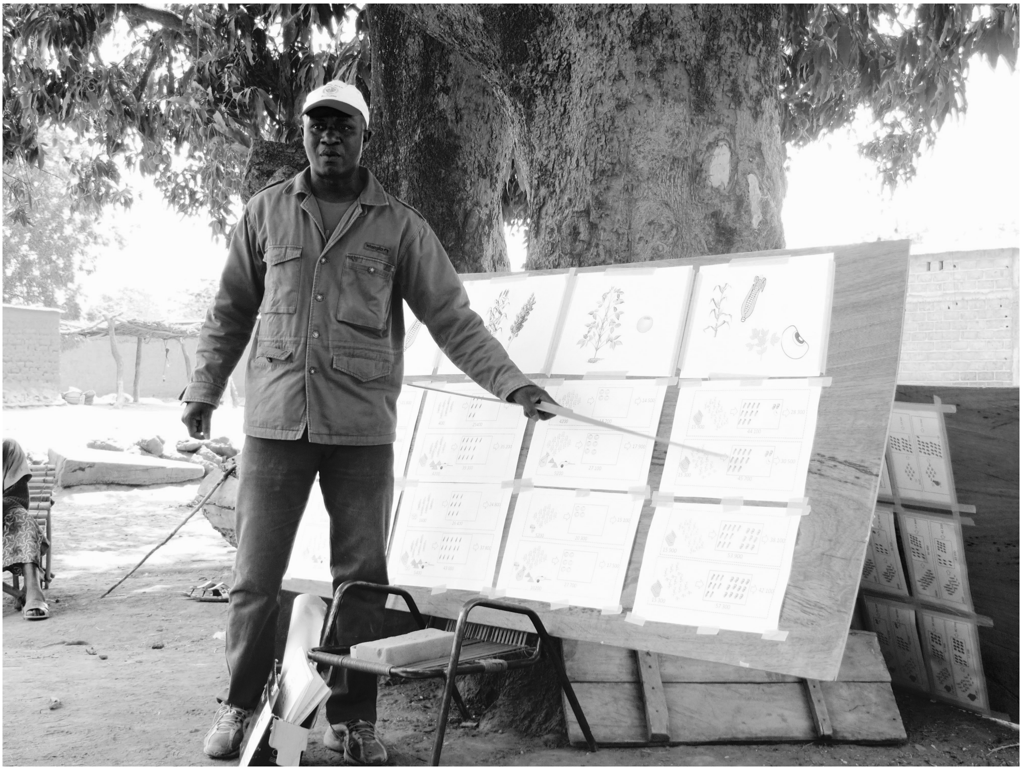
Five scenarios combining incremental policy interventions and agricultural intensification were explored for a village of 99 households in the 'old cotton basin' in southern Mali. For land-constrained areas like the study region, rural-urban migration appeared to be a key factor in understanding the possible responses of diverse farming households. To guarantee food self-sufficiency and poverty reduction in the case of a variable climate, the creation of wage jobs to allow people to move out of agriculture and family planning to reduce human fertility rates should complement interventions focused on agricultural intensification. Our study showed that, along with changes in farmer practices towards intensification, several incremental policy interventions in different sectors are needed to raise the entire farm population above the poverty line.

This calls for a holistic and multisectoral assessment of plausible futures to address rural poverty in land constrained Africa.

Acknowledgement:

Funding for this research was provided by the McKnight Foundation. We thank the Institut d'Economie Rurale (IER) and Cirad for making available the SEP panel dataset and the N'Tarla long-term experiment dataset. We are grateful to the CMDT who made available the Nampossela household survey. We thank Bouba Traore and Akinseye Folorunso for sharing APSIM calibrations for maize, sorghum and millet.

General discussion



Introduction

The overall objective of this study was to understand the local farming systems and based on that understanding, design innovative farming systems to improve and maintain food self-sufficiency and increase farm income in the highly challenging environment of Southern Mali. Chapter 2 demonstrated that resource endowment impacted crop yield and food self-sufficiency and showed possible “stepping up” trajectories to a farm type with higher food self-sufficiency status. Diversification with legume and fodder production targeted to the appropriate soil type and place in the rotation and combined with intensification of livestock production can trigger these stepping-up trajectories (Chapter 3 and Chapter 4). Chapter 5 explored the possible contribution of diversification with legumes and intensification of livestock production in reducing rural people poverty for contrasting plausible mid-term futures. This chapter showed that diversification with legume and intensification of livestock production together play an important but not sufficient role in solving poverty and that broader socio-economic changes like reduction of human net fertility and rural-urban migration would be needed.

In Chapter 5, we assumed widespread diffusion of the outputs from the co-learning cycles described in Chapter 4. In a first section, I critically analyse the requirements and modalities of participatory research. Then I explore the opportunities for a wide diffusion and adoption of the outputs of the co-learning cycles, by analysing different categories of adopters and existing farmers’ groups, and considering appropriate tools to communicate with farmers. The section ends with the proposition of a conceptual framework for diffusion of co-learning cycles outputs.

Similarly, in Chapter 5, we did not assume any soil degradation and impact on crop yield over time. The aspect of soil fertility decline in Southern Mali is therefore analysed in the last section.

1. Modalities of participatory research: the outside and insider perspectives

Farmers participating in this study spoke Bamanan and Mianka and none of them fluent French or English. I am French. The participatory approach used in this study implies intensive exchanges and such cross-cultural research entails the challenge of understanding and interpreting the cultural practices and the language (Skelton, 2009). I began studying Bambara ten months before going to Mali for the first time for my bachelor internship. After three months in Mali, I was able to engage in basic social interactions. During other stays in Mali for my master internship I did several household surveys with an interpreter and stayed during extended periods in the villages of my study. At the end of my master and the start of this PhD work, I was able to discuss fluently with farmers and carry out formal surveys on my own. The insider (Emics) and outsider (Etics) binary is used in cross-cultural research as an indicator of the connection or disconnection of the researcher with the cultural community he/she is working with (Skelton, 2009; Young, 2005). There is no clear-cut distinction between the two statuses but rather degrees of "insiderness" or "outsiderness" (Young, 2005). Both statuses offer advantages and drawbacks: outsiders are kept away from the socio-political relations and tensions among the community groups, whereas insiders become more trusted and reliable than outsiders. Insiders, with good linguistic and cultural understanding, might access more intimate information (Skelton, 2009).

I argue that the involvement in learning the local language and local cultural aspects has led to some improvements in the way this research was carried-out, by cumulating the advantage of both "outsider" and "insider" statuses (Skelton, 2009; Young, 2005). It enabled to establish trust and mutual respect for a collaborative and collegiate participation process (Cornwall and Jewkes, 1995), by promoting open dialogue and reflection (Mikhailovich et al., 2015). A European in Southern Mali is definitely an "outsider" (typically referred to in Bamanan as "*Toubabou*", i.e. the "*white man*"). Local people tend to see project people as ''bearers of resources and funds that could be locally leveraged'' (Mikhailovich et al., 2015). Learning the local language offers the opportunity to move closer to the cultural identity of research participants and therefore slide into the insider status. One farmer said about me: "*Nin kera an dow ye*" which means "*This guy is now one of us*". This illustrates a sense of trust and the strength of the relationship built. The relationship of trust is crucial for the success of the research and can be broken because of un-respectful behaviour: I discovered that in the past, farmers had experienced a disappointing collaboration with one researcher who showed a condescending attitude towards them and therefore the farmers had decided to stop the collaboration.

The insider status also allowed moving closer to the reality of what people have in mind, by avoiding translation/interpretation bias (Birbili, 2000). Very often, the expressions used by farmers gave me clues about how they understood the exercise we were doing together. For example, during the feedback session on trade-off analysis (Chapter 4), a farmer said "*Bolo fila falen do*" ("Both hands are full") which was a metaphor to emphasize the fact that both food self-sufficiency and satisfactory income were achieved in the example presented. "*Yoro fitini, soro ba*", i.e. "small place, high production" was an expression used several times by farmers to stress the advantages of crop intensification. Relying on oral translation by an interpreter can lead to some mis-interpretation and bias in data collection (Shimpuku and Norr, 2012; Squires, 2008). When discussing the possible effect of previous crop (Chapter 4), a farmer mentioned that "*So be do fara kaaba ka nogo kan*" which literally means "cowpea adds some fertiliser to the fertiliser of the maize". This was a rather vague and unclear statement and it needed more discussion to get the exact meaning intended by the farmer. Learning Bamanan, I have been discovering that interpreters, usually local students or technicians, show unintended lack of objectivity and often add their explanation to the oral translations. More practically, focus group discussions with farmers (e.g. on farm typology ; Chapter 2), farmer field days (Chapter 4) or assessments of farm reconfigurations (Chapter 4) were often a work against the clock: we as researchers needed to deliver a complex message as well as getting feedback from farmers in a limited amount of time. Translation can greatly increase the time needed for a focus group discussion and create distraction for participants and facilitator (Scott et al., 2009). Conceptual issues need sometimes do be discussed between the researcher and the interpreter (Birbili, 2000; Temple, 1997) and this further slows down the flow of the discussion. Getting rid of the translation needs therefore allowed having more time to collect farmers' perceptions. Of course I do not claim that every single researcher involved in cross-cultural participatory agricultural research must learn the local languages (which is often impossible for researchers working in numerous zones and countries), but speaking the language of the farmers is a lot of fun and I highlight the advantages of doing so.

2. Opportunities for up-scaling participatory research outputs

Chapter 2, 3 and 4 allowed defining a basket of promising options and building a set of guidelines to support decision-making for farm reconfiguration (Figure 1). This set of guidelines combines a decision tree for farm classification (Chapter 2), decision rules at field scale (Chapter 3, Chapter 4), and results of an *ex-ante* analysis (Chapter 4). At farm level, a decision tree based on resource endowment indicators (e.g. herd size and number of workers) allows classifying farms in a given type. At field level, soil type and previous crop define niches where tested options for sustainable intensification (replace sorghum by soyabean or cowpea; replace sole maize by maize/cowpea intercropping) perform best (Figure 1). The ex-ante analysis allows the increase in income to be calculated for the maximum replacement percentage of maize (by maize/cowpea intercropping) or sorghum (by cowpea or soyabean) without compromising food-self sufficiency. As this set of guidelines is based on easy-to-obtain characteristics (e.g. resource endowment, field type), it offers opportunities for scaling-out. Extension workers can apply the guidelines in the "old cotton basin", i.e. a wider area than the Koutiala district but with similar characteristics (Chapter 4). The decision tree (Figure 1) takes into account the diversity in farm resource endowment but does not account for the diversity of individuals' social status and adopter category as well as their perception and attitude towards risk and uncertainty. A question remains then: what would be the appropriate way to engage with communities that did not participate in on-farm testing and the co-learning cycles described in Chapter 4?

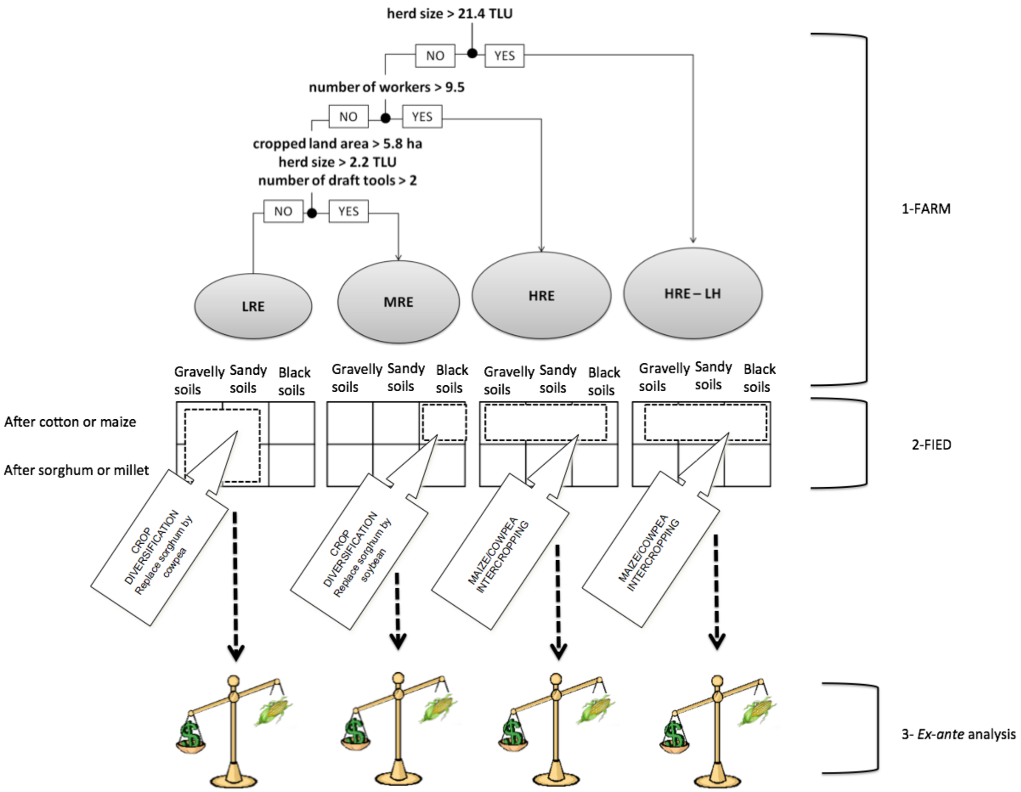


Figure 1: Set of guidelines at farm (1) and field (2) levels and ex-ante analysis (3). HRE-LH: High Resource Endowed with large herds, HRE: High Resource Endowed, MRE: Medium Resource Endowed, LRE: Low Resource Endowed.

In the following sub-sections, I discuss two avenues to further strengthen and facilitate the wider use of this set of guidelines towards diffusion of options for sustainable intensification, namely (i) recognizing farmers' abilities to be a key part of the extension network by taking into account categories of adopters and existing farmers' groups, and (ii) considering appropriate tools to communicate. In a last section I propose a framework for the effective diffusion of participatory research outputs.

2.1. Early adopter and farmers' groups

Farmers respond differently to innovation. Rogers (1983) defined five categories of potential adopters of technologies. "Innovators" and "Early adopters" are likely to innovate or to adopt innovations earlier than the "early majority", the "late majority" and the "laggards". Innovators introduce the innovations into their social network while early adopters help legitimizing their local use thanks to their high degree of opinion leadership (Rogers, 1983). For example, among the farmers that participated in the co-learning cycles (Chapter 4), two farmers were experimenting on their own (i.e. apart from the trials of the project) with different ways of applying manure, and one farmer mimicked the simple experimental design we used in the project. In 2014, we carried out some farmer-designed trials (not reported in this thesis), and the exercise showed that some farmers were creative and experienced trial designers, while others were struggling with the idea of doing a trial and did not think foremost to include a control for example. These categories based on the position of farmers in their social network could be superimposed on the farm typology based on resource endowment (Figure 1). When targeting a community that has not participated in the co-learning cycles described in Chapter 4, extension could then rely on these innovators and early adopters as a gateway to the whole community. The rapid identification of people with theses skills remains challenging and there is conflicting research about the link between resource endowment and adopter category. Some studies found that innovators and early adopters have a high socio-economic status and are usually well educated farmers (Compagnone and Hellec, 2015; Diederen et al., 2003; Rogers, 1983). Conversely, Gebremichael (2014) showed that level of formal education and farm size (livestock and land holding) were not decisive criteria in defining innovators and early adopters. Age has been mentioned as a additional criteria, older farmers being usually more experienced and innovative (Gebremichael, 2014; Long et al., 2016; Tey and Brindal, 2012). Based on this, there are good reasons to think that innovators and early adopters can be found in each of the resource endowment types we defined in this research. Practically, agents of the agricultural services operating in a village often know some local innovators (Compagnone and Hellec, 2015), but they also have a tendency to work with large farms (Degnbol, 2001) and may overlook innovators in smaller farms.

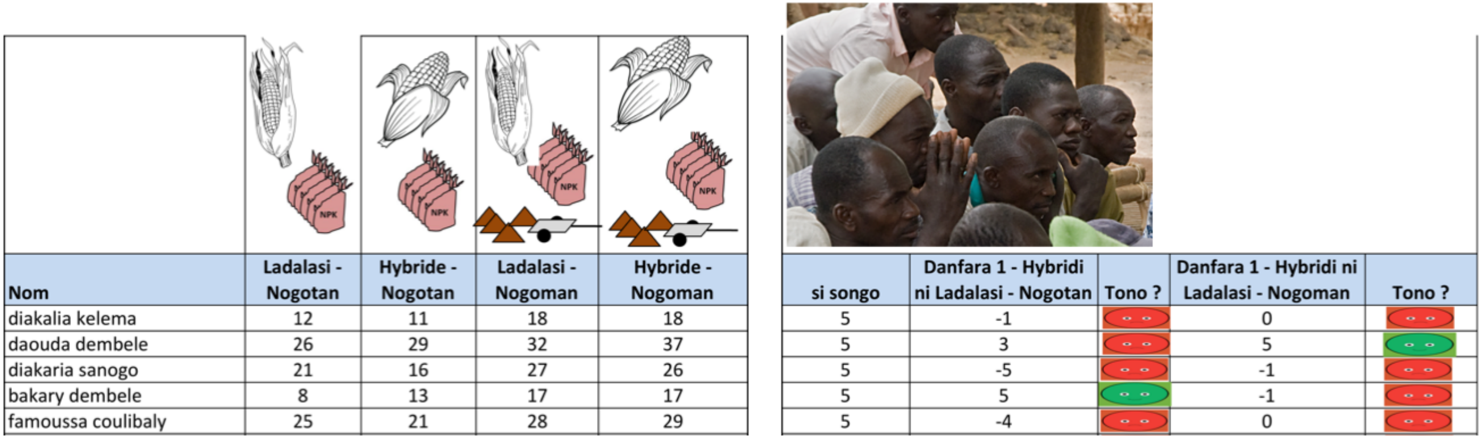
Common interest groups and producers' organisations represent other opportunities for diffusion of participatory research outputs. Farmer groups may form part of the extension network as advisory providers (Heemskerk et al., 2008). Some of the farmers who participated to the co-learning cycles (Chapter 4) were part of a group linked to the "Danaya Nono" dairy cooperative that processes local milk for Koutiala urban consumers. The dairy has been facing financial difficulties over the past years due to competition with cheap imported powder milk (Rietveld, 2009) but was initially providing credit facilities for seeds of fodder cowpea. There are similar farmer groups in other villages of the Koutiala region. This dairy and the farmer groups could be a key channel for wider use of the set of guidelines for diversification with legume and intensification of livestock production. Farmer groups can be cohesive groups, in which innovation can spread quickly, and there is coordination between input supply, financial services (e.g. credit for the seed) and market outlets (Darr and Pretzsch, 2008; Eidt et al., 2012; Heemskerk et al., 2008). Finally, farmer led extension, e.g. voluntary extension by innovator farmers (Ouedraogo, 2000) could also be an avenue to strengthen the diffusion.

2.2. Useful tools to communicate with farmers

During the participatory work described in Chapter 4, we used several tools and approaches, namely i) on-farm trials and farmers' field days ii) games to determine farmer decision-making when reconfiguring their farms and iii) visuals for risk analysis and other feedback sessions. In the section below I discuss the usefulness of these different tools. Trials and field days were key for farmers to build their own perception and opinion on the tested options. When discussing the "niches" concept (Chapter 4), farmers often urged their colleagues to remember specific fields they visited together during the field days to illustrate their arguments. During the feedback session presenting the farm re-configuration (Chapter 4), one farmer supported the presented farm reconfiguration including soyabean mentioning that his own experience with the soyabean trial convinced him that soyabean could be very profitable. Field trials and “try-outs” create practical knowledge and improve farmers perception as farmers often “relied on memory to draw conclusions “ (Misiko et al., 2011).

Probably more important than the form in which the information was presented (e.g. posters) I found that information relevance was a key element in bringing across a message to farmers. When presenting farm income on posters (Chapter 4), we realised that farmers could understand the monetary valuation of on-farm consumed cereals but it made little sense to them, as it does not represent any cash they have ever had in their hands. “I’ve never seen so much money in my household!” exclaimed one farmer. It was therefore decided to value only the cash crops and the cereal produced beyond household needs, and this proved more relevant for farmers (Chapter 4).

Uncertainty and risk perception is an important factor affecting diffusion of innovations and farmers’ decision whether to adopt a technology or not (Long et al., 2016; Luken and Van Rompaey, 2008). For the feedback session on the risk analysis of intensification options (Chapter 4), we used posters to indicate grain yields of the different treatments for all individual farmers involved in the trial in the village (see an example in Figure 2). For each farmer, the facilitator performed a Benefit:Cost analysis with the help of the farmer. Eventually the percentage of farmers in the village who generated profit with a given option was calculated. Interestingly, farmers considered the entire range of Benefit:Cost ratios to make their decision on which treatment they preferred. When discussing the hybrid maize variety, farmers mentioned "There are too many people who failed to generate profit” and "There is no point in paying improved seed if the benefit achieved by the best farmer is so low". Presenting the results in a way that makes sense to farmers allowed building trust: e.g. some farmers recommended the cowpea seed to other farmers and in 2014, 58 farmers (not participating in project activities) bought cowpea seeds from the project.



Nom	Ladalasi - Nogotan	Hybride - Nogotan	Ladalasi - Nogoman	Hybride - Nogoman
diakalia kelema	12	11	18	18
daouda dembele	26	29	32	37
diakaria sanogo	21	16	27	26
bakary dembele	8	13	17	17
famoussa coulibaly	25	21	28	29

si songo	Danfara 1 - Hybridi ni Ladalasi - Nogotan	Tono ?	Danfara 1 - Hybridi ni Ladalasi - Nogoman	Tono ?
5	-1	🟥	0	🟥
5	3	🟥	5	🟩
5	-5	🟥	-1	🟥
5	5	🟩	-1	🟥
5	-4	🟥	0	🟥

Figure 2: Poster for the risk analysis showing on the left the maize grain yields (expressed in 100 kg bags) in the four treatments (maize local variety and maize hybrid with/without manure) for five farmers in the Nampossela village, and on the right the Benefit:Cost analysis where red and green cells mean “no profit” and “profit” respectively.

The use of visuals (drawings and representational diagrams) has been found to make research results more accessible (Tittonell et al., 2008), encourage reflection and help build trust relationships (Mikhailovich et al., 2015; Pain, 2012; Scheer, 1996). This trust between farmers and technology promoters is a crucial prerequisite for potential adoption (Eidt et al., 2012).To make the abstract concept of trade-offs more accessible, we made use of a game-based approach with one board representing the current farmer's cropland (Figure 3), one board representing the different possible options to include (Figure 4) and another board representing the re-configured farm. I calculated the trade-offs on my computer and the farmer's allocation of options and cropland was quickly simulated, enabling the farmer to immediately assess the consequences of his choice. Presenting the "game" to farmers was challenging at the beginning, especially because it was an imaginative reconfiguration and not an real implementation. The visuals were however successful in conveying the re-configuration and trade-off concepts: some farmers liked the game and asked to "play" several times with different re-configurations. Playing this game with different players from a farm type led to generic insights on how farmers would re-configure their farms (Chapter 4). Game-based approaches for farming system design have proven useful to stimulate interactive and reflective analysis of alternative farm configuration (Martin, 2015; Sempore et al., 2015).

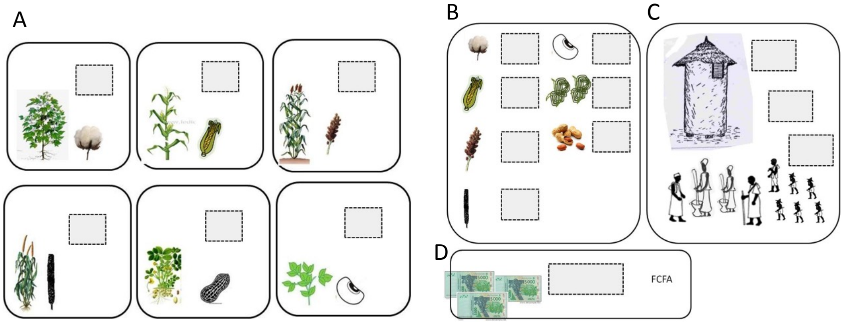


Figure 3: Board used to represent the current area of the different crops (A), the total production for each crop (B), the total cereal production available in the granary compared to the need of the household (C) and the farm income per worker per year (D). A similar board was used to represent the farm reconfiguration.

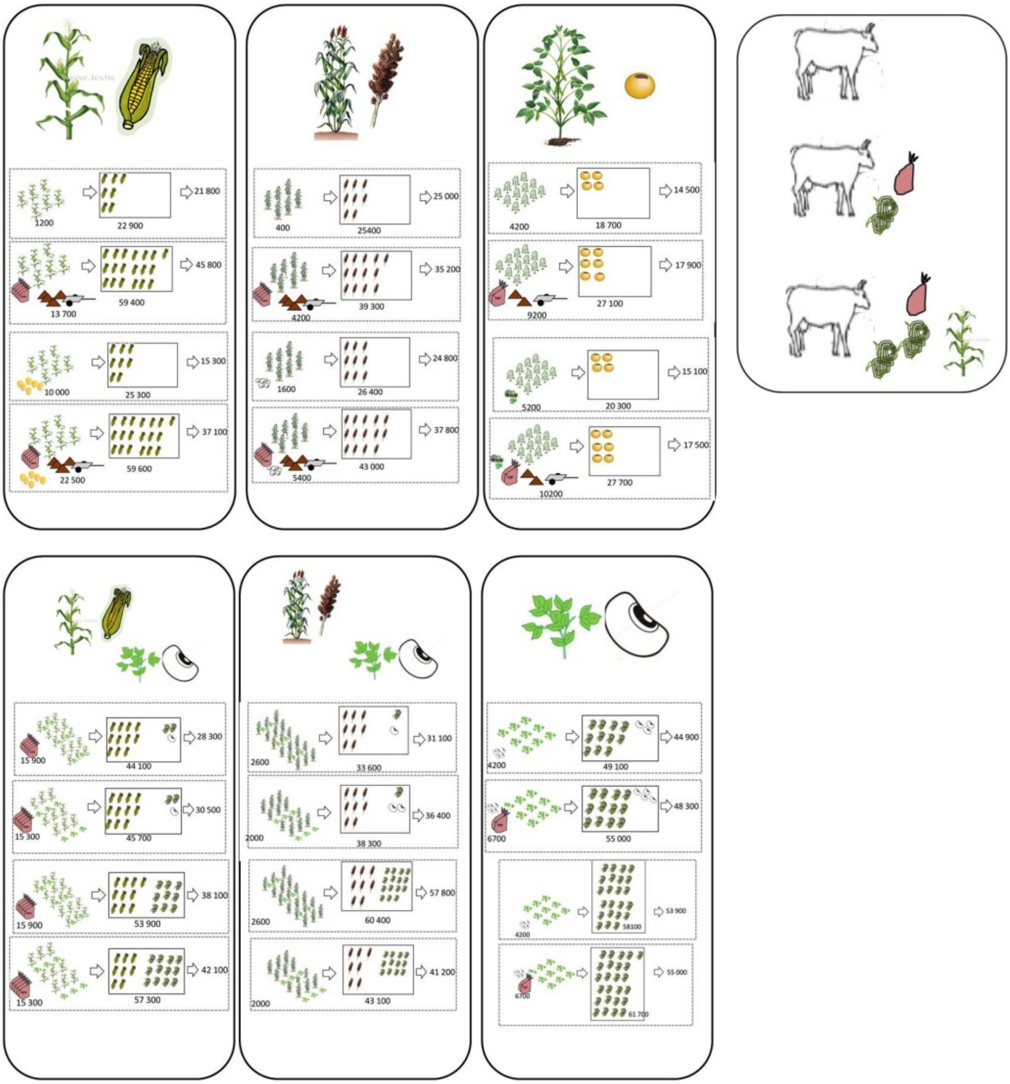


Figure 4: Poster used to present the different options to farmer. For each option, the input cost, the yield and the profitability are displayed. The farmer can indicate what area of a given option he wants to include and where in the cropland (using the board presented in Figure 3).

2.3. A conceptual framework for diffusion of co-learning cycles outputs

One critique of participatory learning cycles, such as described above, is that they are time consuming and cannot be used to reach large numbers of farmers. Building on the insights from the two previous sections, I propose a framework for the "scaling-out" of outputs from co-learning cycle.

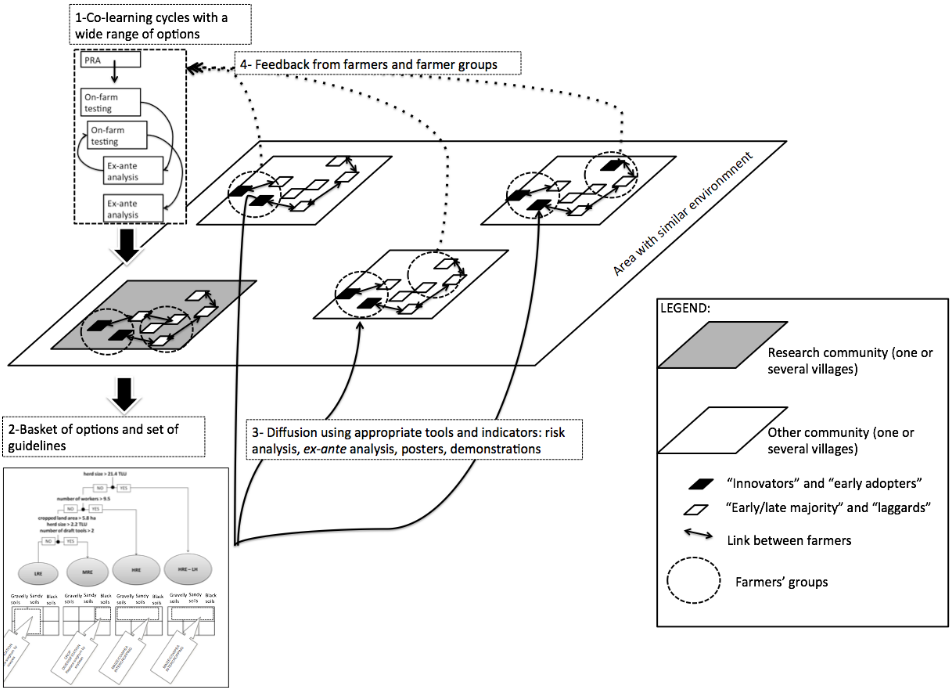


Figure 3: A conceptual cyclical framework with four steps for scaling-out of participatory research outputs generated together with one single community.

In Figure 3, the area with similar environment (i.e. agro-ecological zone, cropping systems, access to market) could be for example the "old cotton basin" (Chapter 4). In a given farmers community, coined the "research community" (Figure 3), the co-learning cycles with a wide range of options can be applied following the approach described in Chapter 3 and Chapter 4 (Step 1). This approach generates a basket of options (narrower than the initial range) and a set of guidelines on how to re-design farms using these options (Step 2). This set of guidelines contains the key characteristics of an appropriate “boundary object”, i.e saliency, legitimacy and credibility (Cash et al., 2003). Saliency is ensured by the involvement of farmers in all the stages and steps of the co-learning cycles. Credibility is obtained through thorough field measurements and statistical analysis, while legitimacy is ensured by the participation of farmers from different types in the co-learning cycles (Chapter 4). In the following phase, these guidelines can be transferred through extension services to other villages within the area with similar environment. Key farmers (i.e. innovators and early adopters) need to be identified and a link with existing farmers’ groups needs to be established to enable spread of the innovations. When communicating to “new” farmers, appropriate tools and indicators can be used to inform them, e.g. posters presenting trade-off analysis and information on risk, games with farmers to perform the trade-off analysis (Step 3). When targeting a new community, a good way of presenting the niche for maize/cowpea (Figure 1) could be for example a poster showing that after cotton and maize, a maize grain pLER of at least one was achieved by half of the farmers and by only 22% of farmers after other crops (Chapter 3). Farmers that participated to the co-learning cycle in the research community could be invited to share their experience. In the “new” community, demonstration could be used and should be smartly implemented to take into account the knowledge generated in the co-learning cycle; e.g by implementing demonstration plots in different previous crops and/or soil types conditions. The last step (Step 4) is the feedback from farmers and farmer groups based on their perception of the basket of options and the set of guidelines. This feedback can be re-integrated into the co-learning cycle, for example through discussion groups including farmers and extension workers from other communities. The learning process would then continue during the implementation (Scheer, 1996) and the set of guidelines could therefore be refined based on the diffusion process and the feedback from other communities. This cyclical approach (Steps 1,2,3,4; Figure 3) thus offers an alternative to the linear and unidirectional (researcher-extension-farmer) approach that is the base of current extension in southern Mali, e.g. the

Transfer of Technology or Training and Visits approaches (Degnbol, 2001; Heemskerk et al., 2008). Our cyclical approach, thanks to the attention to the diversity of farmers and the active involvement of farmers ensures the goodness of fit of the options and guidelines generated (Röling, 2009). The role of the extension worker moves from technology transfer to "capacity building" and "problem solving" (Ramirez, 1997). The main challenge of this approach is therefore the strong reliance on extension workers. I assume here that they understand and master the different tools described and deliver a complex and nuanced message adapted to the different farm categories. In many cases this might require capacity building. Improving the interdisciplinary skills and operation of extension workers is also key (Cundill et al., 2012). Fragmentation of current extension services (e.g. CMDT extension is in charge of cotton-related issues and separated from livestock services (Degnbol, 2001; Heemskerk et al., 2008) adds to this challenge. More broadly, this kind of approach calls for an integrative "innovation system" where farmers have more political control over the agricultural sector and the policies affecting it (Röling, 2009). The scenarios developed in Chapter 5 showed that diversification with legume and intensification of livestock production would benefit from a more favourable milk input/output price ratio, and this implies a lobbying against tariffs for milk imports. Farmers' policy influence in southern Mali is still weak compared with farmers in France, the Netherland or United States for example (Röling, 2009). However the example of the Agricultural Producers' Organisations of West Africa (ROPPA) that regroups 50 millions family farmers across West Africa and defends the right for African states to develop agricultural policies against dumping from Europe (Laroche Dupraz and Postolle, 2013) provides hope that this is not unrealistic.

3. Soil fertility, soil degradation and crop yield

When reading Chapter 5 that explores plausible mid-term futures, one could ask whether some decline in soil fertility should not be taken into account. During the 1990s, soil degradation and nutrient exhaustion was predicted. Van der Pol and Traore

(1993) indicated downward trends in nutrients stocks in southern Mali, i.e. -25 and -20 kg ha^{-1} yr^{-1} for nitrogen and potassium respectively. These authors estimated in 1993 that the potassium reserve of the soil would be totally exhausted within twenty years. Obviously, in 2013, the soil still allowed some crop production (Chapter 3) and longitudinal analysis of crop yield did not show a dramatic decrease (Chapter2). This contradiction between the degradation narrative and the observed sustained crop production can be explained by two main issues that arise when calculating nutrient budgets. Firstly, although nutrient exports (grain and crop residues) and imports (mineral and organic fertilisers) linked to farm management can be easily quantified, the « environmental » nutrient transfers (losses through leaching, denitrification, volatilisation and erosion and imports by atmospheric deposition, biological fixation and weathering of the parent material) are hard to quantify and are estimated using transfer functions. The overall balance is very sensitive to the type of transfer function used (Ramisch, 1999). Secondly, the calculation is "point dependent" (De Ridder et al., 2004), meaning that nutrient transfers can occur from a field to a neighbour one, with erosion at one location and sedimentation down slope. No robust method for scaling-up was developed for the calculation and losses at coarse scale were usually overestimated (De Ridder et al., 2004). For these reasons, nutrient balance calculations are uncertain and are likely to overestimate the problems (Færge and Magid, 2004). Furthermore, this type of "snapshot" analysis does not take into account the adaptive capacity of farmers who respond to decreasing soil fertility by increasing the nutrient transfers from rangeland to cropland through the use of cattle manure (Chapter 2; De Ridder et al., 2004). Benjaminsen et al. (2010) found no clear trend of soil fertility degradation under continuous cotton/cereal cultivation. The capacity of rangeland to support livestock and nutrient collection (to apply on cropland) is therefore crucial (Powell et al., 1996). van Keulen and Breman (1990) estimated that for the Sudan savannah 5 ha of rangeland were needed to sustain the feed requirement of one TLU (Tropical Livestock Unit, an animal of 250 kg live weight). In the Try village in the Koutiala district, Sanogo (2011) indicated that only 2 ha were available per TLU. In line with this, Diarisso et al. (2015) calculated that in a village of the Sudan savannah of

Burkina Faso, biomass from rangelands could provide only 30% of the feed requirements of cattle. This shows that the carrying capacity of the rangelands is already exceeded in many areas of the Sudan savannah, and therefore large herds are herded far away for the cropping areas in a form of transhumance (Diarisso et al., 2015; Sanogo, 2011). Additionally, van Keulen and Breman (1990) calculated that 20 hectares of rangeland per hectare of cropland would be needed to maintain soil fertility through manuring of cropland. In Try, the actual rangeland to cropland ratio was only 1.3 (Sanogo, 2011), indicating that 15 times more rangeland would be needed to maintain soil fertility. The threshold for soil fertility maintenance therefore seems to have been already exceeded in the Koutiala area. However, the estimates by van Keulen and Breman (1990) are already twenty five years old, and an updated estimate would need to take into the increased mineral fertiliser use associated to the favourable cotton context: average N use intensity increased by 60% during the 1994-2004 period in the Koutiala district (Chapter 1). This highlights again the key role of cotton for the sustainability of the farming system.

Concluding remarks

This example in the old cotton basin in southern Mali showed that with close involvement of farmers and a reflexive process, locally grounded agricultural innovations can be developed. These innovations, based on the understanding of the performance of sustainable intensification options in the local context and the interest of local farmers, can in turn contribute to ‘desirable’ pathways to improve rural people’s livelihoods. During my stay in southern Mali I have encountered motivated researchers from the public sector, dynamic innovating farmers, strongly committed extension workers and enthusiast NGO leaders. These inspiring “change-makers” and the fruitful interactions with them are reason for being optimistic for the future. I hope that the methods and outputs of this work can contribute to enhance collaboration between development actors and provide new insights on how to explore concrete pathways to address rural food self-sufficiency and poverty. Farmer empowerment that allows them to gain more power in the political negotiations remains a great challenge, but if successful could further stretch their windows of opportunity.

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Appendix 1: Understanding farm trajectories and development pathways: Two decades of change in southern Mali

Appendix 2: Unravelling the causes of variability in crop yields and treatment response for better tailoring of options for sustainable intensification in southern Mali

Appendix 3: Co-learning cylces to support farming system innovation in southern Mali

Appendix 4: Agricultural intensification and policy interventions: exploring plausible futures for smallholder farmers in Southern Mali

Appendix 1: Understanding farm trajectories and development pathways: Two decades of change in southern Mali

Table A1: Calculation methods of input use, land and labour productivity, grain production per capita and fulfillment of household caloric needs over the monitoring period (1994-2010).

Variable	Unit	Calculation
Input use (nitrogen, phosphorus, potassium, organic fertilizer)	kg ha^{-1}	$\sum_{i=1}^{p} \frac{\mathit{total\ input\ use\ by\ the\ farm\ i\ of\ type\ n}}{\mathit{total\ cropped\ area\ of\ farm\ i\ of\ type\ n}} / p$
Land productivity (cotton, maize, sorghum, millet)	kg ha^{-1}	$\sum_{i=1}^{p} \frac{\mathit{total\ crop\ production\ of\ the\ farm\ i\ of\ type\ n}}{\mathit{total\ cropped\ area\ of\ farm\ i\ of\ type\ n}} / p$
Labour productivity (cotton, maize, sorghum, millet)	kg worker^{-1}	$\sum_{i=1}^{p} \frac{\mathit{total\ crop\ production\ of\ the\ farm\ i\ of\ type\ n}}{\mathit{total\ number\ of\ workers\ in\ farm\ i\ of\ type\ n}} / p$
Grain production per household member	kg person^{-1}	$\sum_{i=1}^{p} \frac{\mathit{total\ grain\ production\ of\ the\ farm\ i\ of\ type\ n}}{\mathit{total\ number\ of\ persons\ in\ farm\ i\ of\ type\ n}} / p$
Percent fulfillment of household calorific need	%	$\sum_{i=1}^{p} \frac{\mathit{total\ calories\ production\ of\ the\ farm\ i\ of\ type\ n}}{\mathit{household\ yearly\ calorie\ need\ in\ farm\ i\ of\ type\ n}} / p$

Table A2: Percent variation of land and labour productivity indicators per farm type when (i) defining the cut-off values between types as the minimum of the variable with the highest median compared to (ii) defining the cut-off values between types as the maximum of the variable with the lowest median (i.e. the method for which results are presented in the paper).

	Low Resource Endowed farms (LRE)	Medium Resource Endowed farms (MRE)	High Resource Endowed farms (HRE)	High Resource Endowed farms with Large Herds (HRE-LH)
land productivity(kg ha^{-1} year^{-1})				
cotton	0	0	-1	-5
maize	1	-2	-2	0
sorghum	-7	2	-4	-3
millet	-4	4	-7	-2
labour productivity (kg worker^{-1} year^{-1})				
cotton per worker	-14	3	1	-2
cereal per worker	-6	4	1	0

Table A3: Proportion of different farm trajectories (%) for two ways of defining the cut-off values between types

Cut-off value definition	**'Hanging in' with high land and labour productivity**[1]	**'Stepping up'**[2]	**'Hanging in' with low land and labour productivity**[3]	**'Falling down'**[4]
Maximum of the variable with lowest median (*)	47	17	23	13
Minimum of the variable with the highest median	37	13	27	23

[1] 'Hanging in' with high productivity = farms that stayed in MRE or HRE-LH.

[2] 'Stepping up' = farms that transitioned from HRE to HRE-LH or farms that transitioned from LRE to MRE.

[3] 'Hanging in' with low productivity = farms that stayed in HRE or LRE.

[4] 'Falling down' = farms that transitioned from MRE to HRE or farms that transitioned from HRE to LRE.

(*) The method for which results are presented in the paper

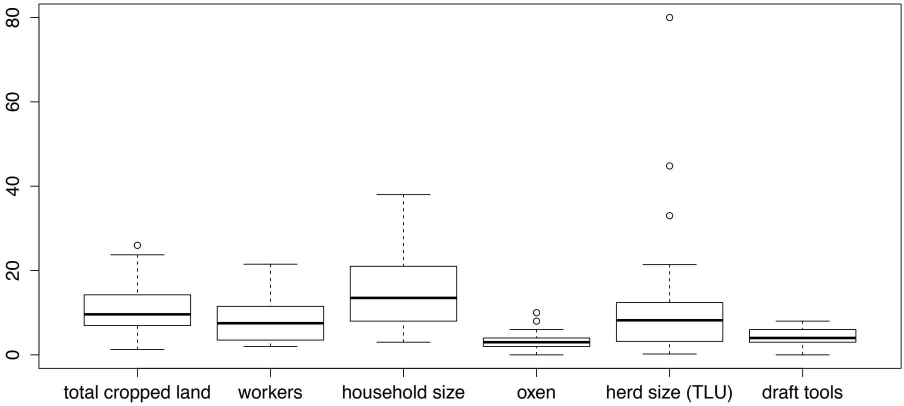

Figure A1: Box plots for six variables describing farm resources for the 30 farms monitored in 1994. Outliers (dots) are data points below Q_1 – 1.5×(Q3-Q1) or above Q_3 + 1.5×(Q3-Q1) where Q1 is the first quartile and Q3 the third quartile.

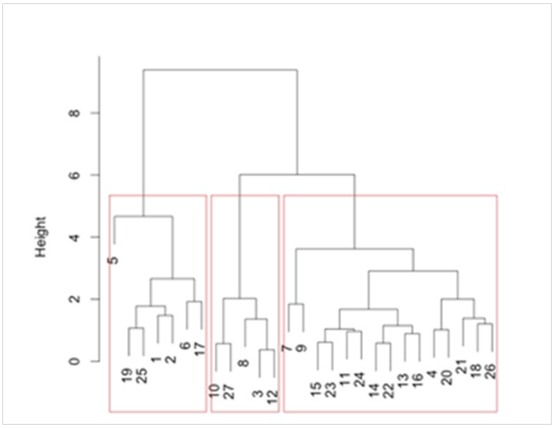

Figure A2: Dendrogram derived using a Ascending Hierarchical Classification (AHC) of 27 farms according to normalized 1994 values of total cropped land, number of workers, household size, number of oxen, herd size and number of draft tools.

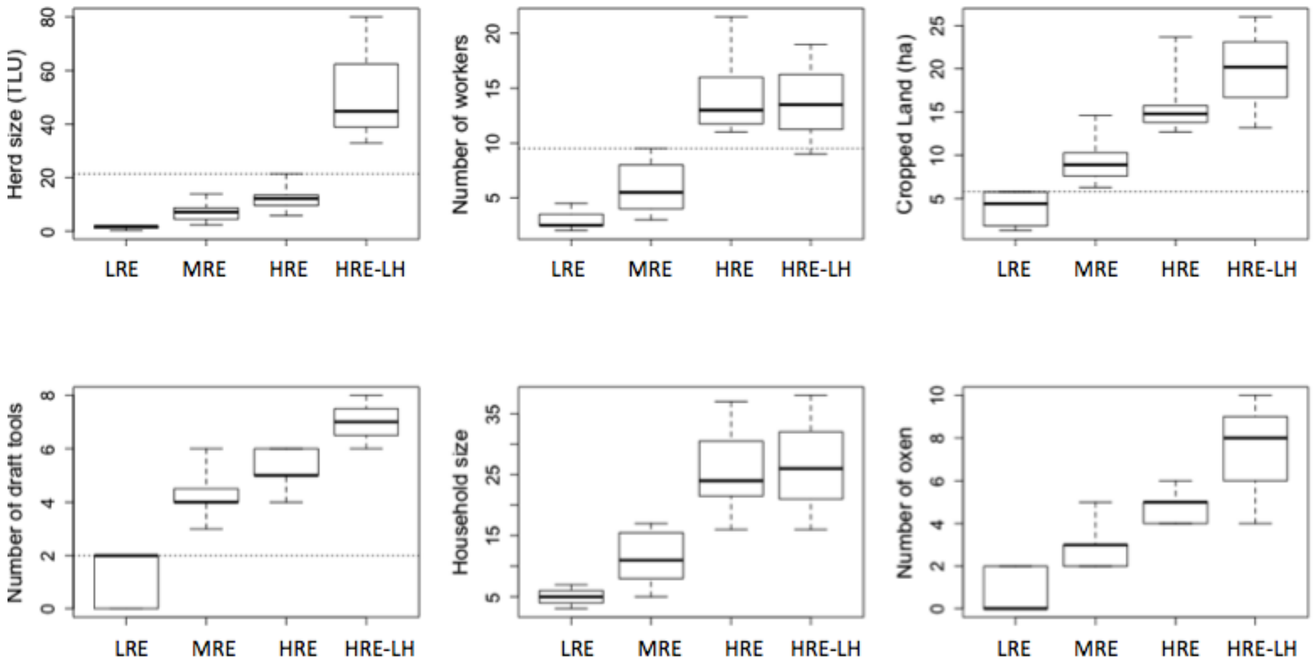

Figure A3: Cut-off values (dotted line) between farm types for the different variables. The whisker bars represent the minimum and maximum of all the data.

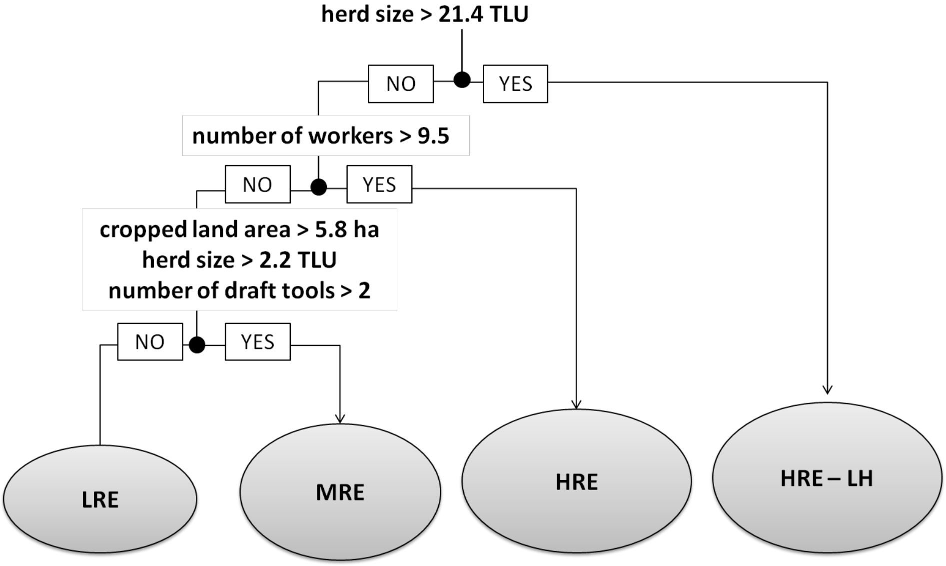

Figure A4: Decision tree to classify farms in a type according to TLU, workers, total cropped land and draft tools. Farms were classified as MRE when they fulfilled at least two of the three criteria distinguishing MRE farms from LRE farms.

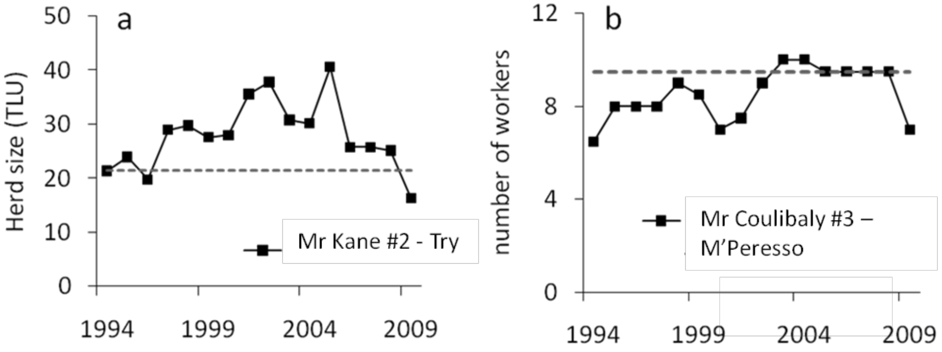

Figure A5: a) Herd size (TLU) of a farm that remained classified in HRE type over the whole monitoring period. b) Number of workers of a farm that remained classified in the MRE type over the whole period. Names of household heads are fictitious. The horizontal dotted line indicates the threshold value that discriminates two farm types

Appendix 2: Unvarelling the causes of variability in crop yields and treatment response for better tailoring of options for sustainable intensification in southern Mali

Table A1: Mineral fertilizer and manure inputs per type of previous crop in the fields where trials were planted (based on farmer's description of previous crops and amount of mineral and organic fertilizer used for the three years prior to the trial).

			N (kg ha^{-1})		P (kg ha^{-1})		K (kg ha^{-1})		Manure (kg DM ha^{-1})	
Soil type	Previous crop	n	mean	SE	mean	SE	mean	SE	mean	SE
Gravelly soils	Cotton	51	42	12	11	0.8	19	1.6	6860	1406
	Maize	19	36	10	11	4	19	7.7	5770	1463
	Millet	30	2	0.9	0	0.3	0	0.3	2010	1208
	Sorghum	55	3	0.9	1	0.3	2	0.6	190	174
	Groundnut	11	0	0	0	0	0	0	0	0
	Cowpea	4	0	0	0	0	0	0	0	0
	Fallow	2	0	0	0	0	0	0	0	0
	Other[1]	5	0	0	0	0	0	0	0	0
Sandy soils	Cotton	137	31	1.6	12	0.5	20	1.1	5770	845
	Maize	97	31	6.5	8	0.6	11	0.6	4160	659
	Millet	146	2	0.6	0	0.1	0	0.1	370	164
	Sorghum	138	2	0.7	1	0.1	1	0.2	190	143
	Groundnut	54	1	0.7	0	0.2	0	0.2	340	230
	Cowpea	13	0	0	0	0	0	0	0	0
	Fallow	13	0	0	0	0	0	0	0	0
	Other[1]	22	4	2.2	1	0.6	2	1.1	120	122
Black soils	Cotton	108	29	1.5	10	0.4	18	0.8	7080	913
	Maize	57	47	20.1	7	0.6	11	1.1	3910	739
	Millet	87	12	6.6	0	0.1	0	0.1	90	61
	Sorghum	132	2	0.5	0	0.1	1	0.2	510	186
	Groundnut	33	1	0.2	0	0	0	0	0	0
	Cowpea	5	0	0	0	0	0	0	0	0
	Fallow	11	0	0	0	0	0	0	0	0
	Other[1]	7	9	4.4	4	1.9	4	2	400	400
F test probabilities										
	Soil type			0.4260		0.0641		0.0500		0.1980
	Previous crop[2]			**0.0000**		**0.0000**		**0.0000**		**0.0000**
	Soil type x previous crop			0.6900		0.3551		0.5490		0.5750

[1] Other crops include for example Bambara nut and hibiscus...

[2] for cotton, maize, sorghum and millet comparison only, as legume and other crops have input use intensity close to 0.

Appendix 2

Table A2: Summary of the results of the linear mixed model analysis for explaining the variability in sole crop yields in the on-farm trials of 2013 and 2014. Significant effects ($P < 0.05$) are shown in bold.

		Cereals		Legumes			
		Maize	Sorghum	Soyabean	Cowpea grain	Cowpea fodder	Groundnut
Treatments	Fertilizer	**0.0000**	**0.0000**	**0.0000**	**0.0039**	**0.0213**	-
	Variety/Inoculation[1]	0.2010	0.6242	0.1762	-	**0.0000**	**0.0001**
Covariates	Soil type	0.8927	**0.0013**	0.1415	0.4654	0.1139	0.5679
	Previous crop	**0.0001**	0.0930	0.2283	0.4511	0.9503	**0.0029**
	Season	**0.0022**	0.4394	0.9165	**0.0018**	**0.0071**	-
Soil characteristics	pH	0.9041	0.0657	0.4127	0.3036	0.2939	**0.0144**
	C	0.5702	0.3121	0.2010	0.4515	0.3812	0.1055
	N	0.4082	0.6324	0.0996	0.6591	0.5779	0.1408
	P	**0.0195**	0.2489	**0.0430**	**0.0446**	0.0534	0.9484
	Ca	0.5816	0.4018	0.1445	0.1638	0.1617	**0.0030**
	Mg	0.1365	0.8898	0.3017	0.0814	0.0885	**0.0032**
	K	0.4522	0.3699	**0.0194**	0.3403	0.4037	**0.0097**
	Clay + Silt	0.5484	0.4360	0.0978	0.0698	0.0544	0.6628
	Gravels	0.8115	**0.0448**	0.2108	0.3485	0.3133	0.6746
Interaction Treatment x Covariate	Variety/Inoculation[1] x Fertilizer	0.6395	0.1896	0.4097	-	0.3603	-
	Variety/Inoculation[1] x Soil type	0.0945	0.6113	**0.0240**	-	**0.0000**	0.6332
	Variety/Inoculation[1] x Previous crop	0.5392	0.4467	0.2663	-	0.0204	0.4805
	Variety/Inoculation[1] x Season	0.6827	0.8397	0.7658	-	**0.0001**	-
	Fertilizer x Soil type	0.8596	0.4320	0.4824	0.2643	0.7235	-
	Fertilizer x Previous crop	0.0513	0.7147	0.6756	0.9030	0.3524	-
	Fertilizer x Season	-	0.0657	0.0566	0.2753	**0.0092**	-

Table A3: Summary of the results of the linear mixed model analysis for explaining the variability in partial Land Equivalent Ratios (pLER) in the on-farm trials of 2012, 2013, 2014. Significant effects ($P < 0.05$) are shown in bold.

		Intercropping					
		Maize/cowpea			Sorghum/cowpea		
		pLER maize	pLER cowpea grain	pLER cowpea fodder	pLER sorghum	pLER cowpea grain	pLER cowpea fodder
Treatments	Pattern	**0.0014**	0.1256	**0.0050**	0.1455	0.2909	0.7798
	Variety	**0.0002**	-	**0.0002**	**0.0187**	-	0.2455
Covariates	Soil type	0.5073	0.9639	0.1486	0.9824	0.1012	0.3720
	Previous crop	**0.0021**	0.1906	**0.0489**	**0.0326**	0.0862	0.4553
	Season	0.8153	**0.0048**	0.2350	0.6043	0.4072	0.9049
Soil characteristics	pH	0.5506	0.4437	0.4661	0.2388	0.6924	0.8137
	C	0.3108	0.4219	0.0791	0.0601	0.0815	0.7293
	N	0.2260	0.4754	0.1706	0.1417	0.0643	0.8362
	P	0.8984	0.6490	0.2563	0.2632	0.9150	**0.0038**
	Ca	0.2528	**0.0120**	0.2381	0.1449	0.2073	0.6872
	Mg	0.9142	0.0852	0.2495	0.0363	0.2434	0.8277
	K	0.1618	0.2476	0.0056	0.5074	0.2293	0.2549
	Clay + Silt	0.6314	0.8690	0.0988	0.7711	0.2417	0.0769
	Gravels	0.6760	0.5006	0.7514	0.6886	0.3080	**0.0419**
Treatment x Covariate interaction	Variety x Pattern	0.3521	-	0.1098	**0.0382**	-	0.6445
	Variety x Soil type	0.3787	-	0.2897	0.3361	-	**0.0039**
	Variety x Previous crop	0.1151	-	**0.0263**	0.7735	-	0.4580
	Variety x Season	0.1994	-	0.9881	0.0727	-	0.1644
	Pattern x Soil type	0.3416	0.5080	0.7580	0.2742	0.0651	0.2701
	Pattern x Previous crop	0.6161	0.4427	0.6780	0.3447	0.2846	0.2873
	Pattern x Season	0.3374	0.5586	**0.0099**	0.7932	0.3816	0.1887

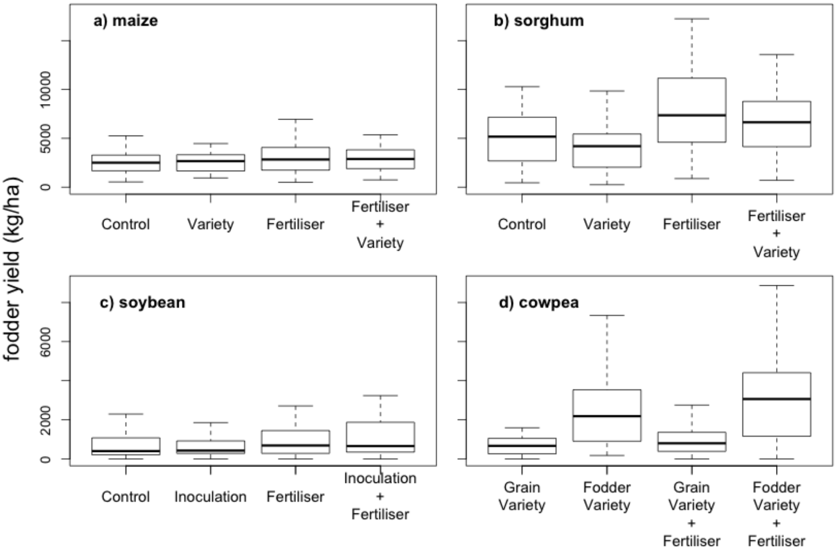

Figure A1: Fodder yield for the four treatments of the maize trial (a), the sorghum trial (b), the soyabean trial (c) and the cowpea trial (d) over the two years of the trials (2013-2014). A detailed description of the treatments is given in Table 3. The horizontal line in the box indicates the median. The height of the box represents the interquartile range. The whiskers extend to the most extreme data point which is no more than 1.5 times the interquartile range from the edge of the box.

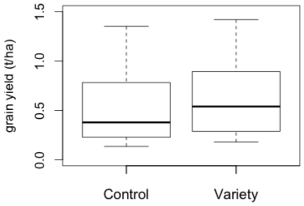

Figure A2: Grain yield for the two treatments of the groundnut trial in 2014. A detailed description of the treatments is given in Table 3. The horizontal line in the box indicates the median. The height of the box represents the interquartile range. The whiskers extend to the most extreme data point which is no more than 1.5 times the interquartile range from the edge of the box.

Appendix 3: Co-learning cylces to support farming system innovation in southern Mali

Table A1: Input variables , parameters and source of the data used for the *ex-ante* trade-off analysis

Input variables and parameters	Unit	Description/ Calculation	Source
Farm characteristics			
$Area_{ijk}$	ha	Area of the crop *i* on soil type *j* after previous crop *k*. *i*=1-8:maize, sorghum, millet, maize/cowpea, cotton, groundnut, soyabean, cowpea, j=1-3: gravelly, sandy, black soils and k=1-3: cotton or maize, sorghum or millet, legume	Detailed farm characterisation
Nb_Animal_l	number	Number of animals in the herd. *l*=1:3: donkey, ox, lactating cow	Detailed farm characterisation.
HH_size	number	Total number of persons in the household.	Detailed farm characterisation
Crop/livestock performances			
Y_{ijk}	t ha^{-1}	Grain yield of crop *i* on soil type *j* after previous crop *k*. In intercropping, the maize grain yield was corrected using the pLER computed from the trial results.	On farm trials
Y_Fodder_{ijk}	t ha^{-1}	Fodder yield of crop i on soil type j after previous crop k. Only fodder yield of cowpea was considered. In intercropping, the fodder yield was corrected using the pLER computed from the trial results.	On farm trials
$Milk\_Prod_m$	t $year^{-1}$	Total milk production per year per lactating cow under feeding management *m*. *m*=1-2:free grazing year round, stall feeding during dry hot period	de Ridder et al. (2015)
Output prices and input costs			
$Price_i$	US$	Farm gate price of grain of crop i	Market analysis 2013
Av_Cereal_Price	US$	Average cereal (maize, sorghum, millet) price	Market analysis 2013
$Fodder\_Price$	US$	Farm gate price of cowpea fodder	Market analysis 2013
$Cost\_Crop_i$	US$ ha^{-1}	Variable cost for crop i (seed, fertiliser, inoculum, pesticide input)	Market analysis 2013
$Cost\_Animal_{lm}$	US$	Variable cost for animal *l* with feeding management *m* (veterinary care and concentrates). *m*=1:2: open-grazing, stall feeding	Market analysis 2013
Food/Feed requirements			
$Fodder\_R_{lm}$	t $year^{-1}$	Cowpea hay requirement for stall fed animal *l* under feeding management *m*	de Ridder et al. (2015); Andrieu et al., (2015)
Cer_R	t $year^{-1}$	Human cereal requirement per year.	Value used by local development actors

Table A2: Performance variables calculation for the *ex-ante* trade-off analysis. Table A1 gives a detailed description of the parameters used in the calculations

Performance variable	Unit	Description	Calculation

Nb_Animal_{lm}	Number	Number of animal of type *l* under feeding management *m*. Donkeys and oxen are complemented with cowpea fodder. The number of lactating cows fed in the stall is computed as the maximum allowed by the available cowpea fodder on-farm produced beyond the needs of donkeys and oxen.	if $\sum_i \sum_j \sum_k Area_{ijk} \times Y\_Fodder_{ijk} - \sum_{l=1}^{2} Nb\_Animal_{l2} \times Fodder\_R_{l2} > 0$:
			$Nb\_Animal_{32} = \min\left(Nb\_Animal_3, \frac{\sum_i \sum_j \sum_k Area_{ijk} \times Y\_Fodder_{ijk} - \sum_{l=1}^{2} Nb\_Animal_{l2} \times Fodder\_R_{l2}}{Fodder\_R_{32}}\right.$
			if $\sum_i \sum_j \sum_k Area_{ijk} \times Y\_Fodder_{ijk} - \sum_{l=1}^{2} Nb\_Animal_{l2} \times Fodder\_R_{l2} < 0$:
			$Nb\_Animal_{32} = 0$

$Cereal\_Surplus$	t year^{-1}	Cereal production beyond household needs	$Cereal\_Surplus = \sum_{i=1}^{i=4} \sum_j \sum_k Area_{ijk} \times Y_{ijk} - HH\_size \times Cer\_R$
$Fodder\_Surplus$	t year^{-1}	Cowpea fodder production beyond donkey, oxen and lactating cow needs	$Fodder\_Surplus = \sum_i \sum_j \sum_k Area_{ijk} \times Y\_Fodder_{ijk} - \sum_l \sum_m Nb\_Animal_{lm} \times Fodder\_R_{lm}$
$Gross\_Margin\_Cash\_Crops$	US\$ year^{-1}	Gross margin from cash crops (cotton, groundnut and soyabean)	$Gross\_Margin\_Cash\_Crops = \sum_{i=5}^{7} Tot\_Prod_i \times Price_i$
$Gross\_Margin\_Cereals$	US\$ year^{-1}	Gross margin from cereal surplus	$Gross\_Margin\_Cereals = Cereal\_Surplus \times Av\_Cereal\_Price$
$Gross\_Margin\_Fodder$	US\$ year^{-1}	Gross margin from cowpea fodder surplus	$Gross\_Margin\_Fodder = Fodder\_Surplus \times Fodder\_Price$
$Gross\_Margin\_Milk$	US\$ year^{-1}	Gross margin from milk	$Gross\_Margin\_Milk = \sum_{m=1}^{2} Nb\_Animal_{3m} \times Milk\_Prod_m \times Milk\_Price$
$Farm\_Gross\_Margin$	US\$ year^{-1}	Farm gross margin	$Farm\_Gross\_Margin$ $= \sum Gross\_Margins - \sum_i Cost\_Crop_i \times \sum_j \sum_k Area_{ijk}$ $- \sum \sum Cost\_Animal_{lm} \times Nb\_Animal_{lm}$
HH_FSS	-	Household Food Self-sufficiency	$HH\_FSS = \frac{\sum_{i=1}^{i=4} \sum_j \sum_k Area_{ijk} \times Y_{ijk}}{HH\_size \times Cer\_R}$

Table A3: Constraints and opportunities to crop production and livestock rearing as mentioned by farmers during participatory rural appraisals in M'Peresso, Nampossela and Nitabougouro villages in the Koutiala district.

	Crop production for food self-sufficiency and gross margin generation		Livestock rearing for traction and manure, milk and meat and buffer against risk	
Importance	Constraints	Opportunities	Constraints	Opportunities
Cited in the three villages	Lack of oxen	Credit; mutual assistance; help of state structure and project	Feeding of animals	Collect residues, grow crops with fodder value, stall feeding of oxen, transhumance
	Poor soil fertility	Production of manure, anti-erosion techniques	Diseases	Vaccinations
Cited in two villages	Lack of rain	Short duration varieties, tree planting	Watering of animals	-
Cited in one village	Striga infestation	Urea, manure, hand pulling	Keep animals alive	Sale of animals to have money to buy medicines
	Soil erosion	Anti-erosion techniques		
	Loss of tree species	Tree planting		
	Access to fertilser	-		
	Pests attacks - seed quality	-		

Table A4: Farm reconfiguration generated during individual exercises with 11 farmers belonging to four farm types and originating from three villages of the Koutiala district. A)= Intensification of current crops, B)= Crop diversification without extra inputs, C)= Intensification of diversification crops and D)= Improved livestock feeding during the dry hot season (March-June)

Farm type	Farmer n°	Reconfiguration type n°	Re-design elements	First redesign element	Second re-design element
HRE-LH	1	1	A) – D)	100 % of maize intercropped with cowpea fodder variety	50% of lactating cows fed in stall
	2	1	A) – D)	30% of maize intercropped with cowpea fodder variety	20% of lactating cows fed in stall
	3	1	A) – D)	33% of maize intercropped with cowpea fodder variety	17% of lactating cows fed in stall
HRE	4	1	A) – D)	100% of maize intercropped with cowpea fodder variety	100% of lactating cows fed in stall
	5	4	B) - D)	Expand cropped land with cowpea grain variety (+7%) and cowpea fodder variety (+7%)	50% of lactating cows fed in stall
	6	4	B)	Expand cropped land with cowpea grain variety (+5%) and cowpea fodder variety (+5%)	-
MRE	7	2	B)	Replace 20% of sorghum by soyabean	-
	8	2	B)	Replace 20% of sorghum by soyabean	-
	9	-	-		-
LRE	10	3	B)	Replace 10% sorghum by cowpea	-
	11	4	B)	Expand cropped land (+40%) with cowpea grain variety and cowpea fodder variety	-

Table A5: Explanatory factors for visual differences between control plots and in the effects of treatments in two contrasting trials for different options in different villages as mentioned by groups of farmers during the field visit in cycle 2 of Step 2.

Crop	Village	Visual differences between control plots	Explanatory factor according to farmers	Visual difference in the effect of fertiliser	Explanatory factor according to farmers	Visual difference in the effect of variety	Explanatory factor according to farmers
Maize	Try	Yes	Soil type/previous crop	No	-	No	-
	Nitabougouro	Yes	Soil type	No	-	Yes	Sowing date[2]
	N'Goukan	Yes	Soil type/previous crop	No	-	Yes	Water logging in a sub-plot
Sorghum	Nitabougouro	Yes	Previous crop	Yes	Previous crop[1]	Can't assess	Crop not mature
	Kani	Yes	Soil type/previous crop	No	-	Yes	Don't know
Soyabean	Kani	Yes	Soil type/previous crop	Yes	Animal damage in a sub-plot	No	-
Maize intercropped with cowpea	Nitabougouro	Yes	Soil type/previous crop	No	-	No	-

[1] residual effect of fertilser from cotton limits visual effect of fertilser

[2] earlier sowing favours the hybrid

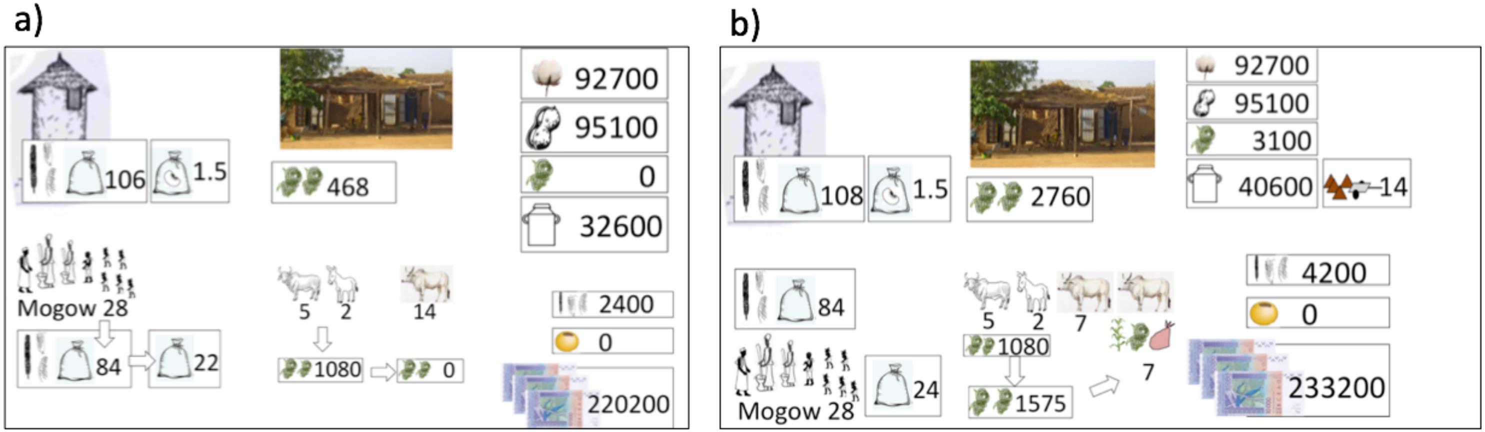

Figure A1: Example of the posters used to show the baseline (a) and the results from the *ex ante* trade-off analysis (b) to farmers. In each poster, total cereal production, household cereal needs, cereal production above household need, animal fodder need, gross margin from crops and milk as well as total farm income are depicted. Cereal production is expressed in bags of grains (100 kg), cowpea fodder in number of bundles, and gross margin in Doromè (FCFA/5).

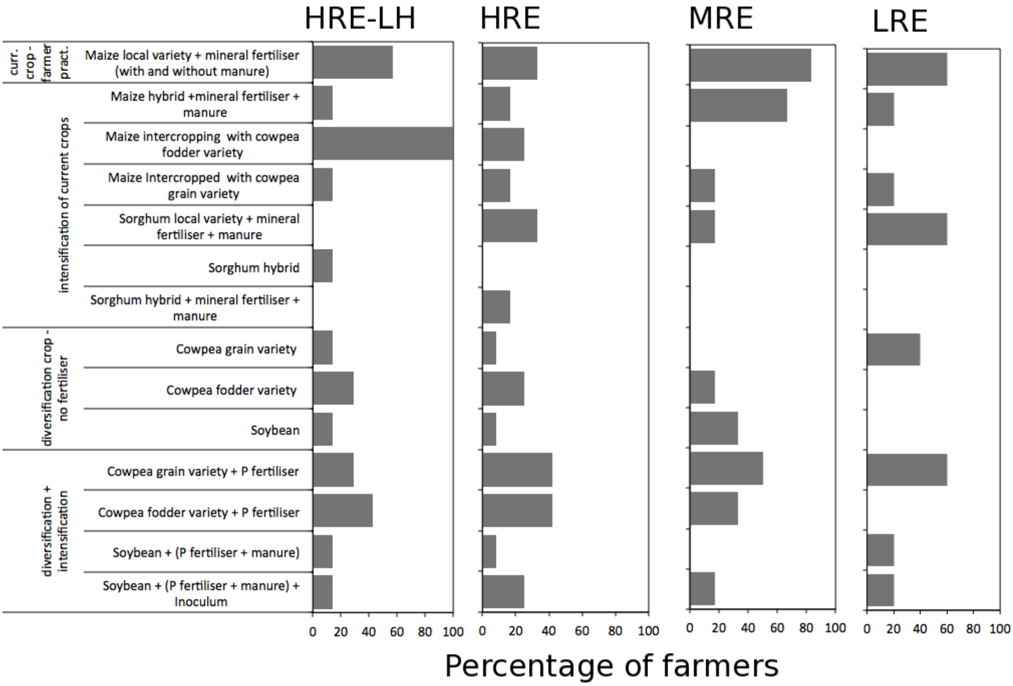

Figure A2: Percentage of farmers who appreciated a treatment after the feedback session in the first cycle of Step 2 (2013). HRE-LH= High Resource Endowed farms with Large Herds, HRE=High Resource Endowed farms, MRE = Medium Resource Endowed farms, LRE = Low Resource Endowed farms. Options that were not chosen by any farmer are not mentioned.

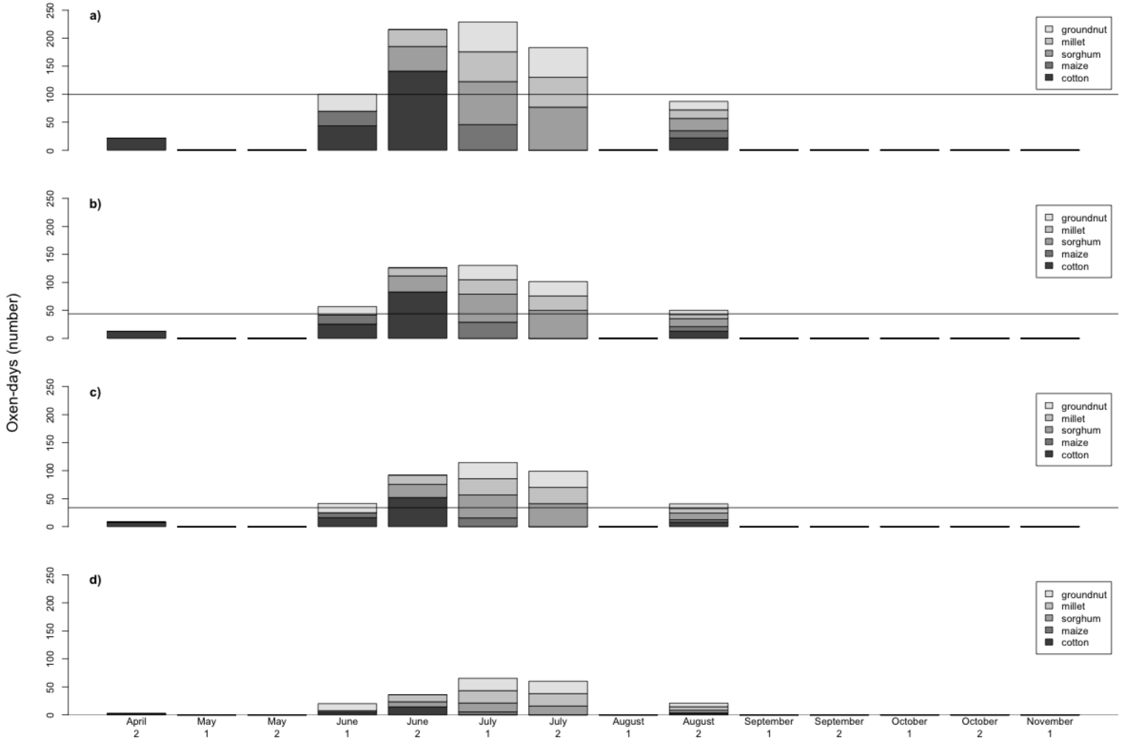

Figure A3: Oxen-day requirements per fortnight for cropping activities for the average 2013 cropping pattern of High Resource Endowed with Large Herds (HRE-LH) farms (a), High Resource Endowed (HRE) farms (b), Medium Resource Endowed (MRE) farms (c) and Low Resource Endowed (LRE) farms (d). The horizontal black line indicates the available oxen-days on the farm. “1” and “2” indicate the first and second fortnight of the month.

Appendix 4: Agricultural intensification and policy interventions: exploring plausible futures for smallholder farmers in Southern Mali

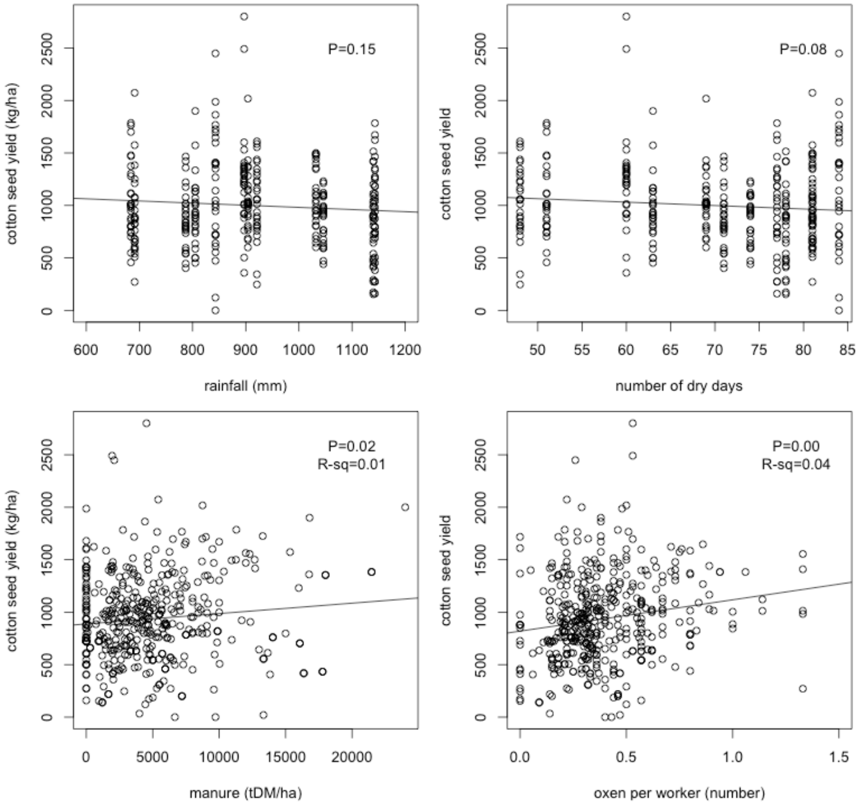

Figure A1: Farmers' cottonseed yields measured by CMDT in 30 farms over 17 years (n=360 observations) according to total rainfall, number of dry days during rainfall season, manure inputs and oxen per worker ratio.

Summary

Farmers in sub-Saharan Africa have to cope with low agricultural productivity, variable rainfall and unstable institutional support. Households are highly diverse in resource endowment and in their responses to this changing environment. Sustainable intensification offers an avenue to improve food production, resilience to climate stresses and maintenance of healthy soils. There are still few studies in the smallholder context analysing how households can improve their livelihoods and how options for sustainable intensification can be tailored to their diverse contexts. Participatory research and farm modelling have proven useful to generate practical recommendations for farmers. This thesis contributes knowledge on how to integrate a diversity of approaches (household typology and understanding of farm trajectories, on-farm trials, participatory *ex-ante* trade-off analysis and scenario building) in order to design innovative farming system to face the challenging environment.

The Koutiala district in the "old cotton basin" in southern Mali has experienced fast population growth, increasing land shortage, and uncertain institutional support for cotton production. This area is therefore currently facing challenges that are exerting pressure on many land constrained regions across sub-Saharan Africa.

We explored farm trajectories in the Koutiala district during two decades (1994 to 2010) and their link with farm resource endowment and government support (Chapter 2). We distinguished a favourable period for cotton production and an unfavourable period during which institutional support collapsed. A panel survey that monitored 30 farms over this period was analysed. Based on indicators of resource endowment and using Ascending Hierarchical Classification (AHC), farms were grouped into four types: High Resource Endowed farms with Large Herds (HRE-LH), High Resource Endowed (HRE) farms, Medium Resource Endowed (MRE) farms and Low Resource Endowed (LRE) farms. Farms remaining in the same type were classified as 'hanging in', while farms moving to a type with larger yields, labour productivity and food self-sufficiency

status were classified as 'stepping up'. Farms following the opposite trajectory of deteriorating farming conditions were classified as 'falling down'. The LRE farms differed from all other farm types due to smaller yields, while both LRE and HRE farms differed from the MRE and HRE-LH farm types due to a combination of less labour productivity and less food self-sufficiency. During those two decades, 17% of the farms 'stepped up', while 70% of the farms remained 'hanging in', and only 13% of the farms 'fell down'. We found no obvious negative impact of the collapse of government support on farm trajectories. Crop yields did not change significantly over time for any farm type and labour productivity decreased.

Together with 132 farmers in the Koutiala district we tested a range of options for sustainable intensification including intensification of cereal (maize and sorghum) and legume (groundnut, soyabean and cowpea) sole crops and cereal-legume intercropping during three years (2012-2014) on on-farm trials (Chapter 3). There was huge variability among fields in crop yields of unamended control plots: maize yielded from 0.20 to 5.24 t ha^{-1}, sorghum from 0 to 3.53 t ha^{-1}, groundnut from 0.10 to 1.16 t ha^{-1}, soyabean from 0 to 2.48 t ha^{-1} and cowpea from 0 to 1.02 t ha^{-1}. Farmers recognized three soil types: gravelly soils, sandy soils and black soils. Yields were very poor on gravelly soils and two to three times greater (depending on the crop) on black soils. Yields were also poor at the end of the typical crop rotation, i.e., after sorghum and millet, and 1.3–1.7 times greater (depending on the crop) after the fertilized crops maize and cotton. Targeting options to a given soil type and/or place in the rotation enhanced their agronomic performance: (i) the biomass production of the cowpea fodder variety was doubled on black soils compared with gravelly soils, (ii) the additive maize/cowpea intercropping option after cotton or maize resulted in an average overall LER of 1.47, no maize grain penalty, and 1.38 t ha^{-1} more cowpea fodder production compared with sole maize.

Farm systems were re-designed together with the farmers involved in the on-farm trials during four years (2012-2015) (Chapter 4). The aim was to improve income without compromising food self-sufficiency. A cyclical learning model with three steps was used: Step 1 was the co-design of a set of crop/livestock options, Step 2 the on-farm testing and appraisal of these options and Step 3 a participatory *ex-ante* analysis of re-designed farm systems incorporating the tested options. In the first cycle of 2012-2014 farmers re-designed their farms with (1) maize/cowpea intercropping combined with stall feeding of lactating cows for HRE-LH and HRE farms, (2) replacement of sorghum by soyabean or cowpea for MRE and LRE farms. These reconfigurations were assessed *ex ante* using the average yields and gross margins obtained in the 2013 on-farm trials. HRE-LH farmers experienced a disappointing though small 5% decrease in food self-sufficiency. MRE farmers were disappointed by the marginal improvement in gross margin. HRE and LRE farms could not reconfigure their farm without compromising food self-sufficiency. In a second cycle in 2014-2015 statistical analysis of trial results (Chapter 3) and farmer insights gathered during field days allowed niches to be identified within the farms (soil type/previous crop combinations) where options performed better. The farm systems were re-designed using niche-specific information on yield and gross margin, which solved the concerns voiced by farmers during the first cycle. Without compromising food self-sufficiency, maize/cowpea intercropping in the right niche combined with stall feeding increased HRE-LH and HRE farm gross margin by 20 to 26% respectively (i.e. 690 and 545 US\$ year^{-1}) with respect to the current farming system. Replacement of sorghum by soyabean (or cowpea) increased MRE and LRE farm gross margin by 29 and 9% respectively (i.e. 545 and 32 US\$ year^{-1}). Farmers highlighted the saliency of the niches and the re-designed farm system, and indicated that the extra income could be re-invested in the farm.

In chapter 5, hypothetical future changes in farmers' practice and policy interventions were described based on findings of Chapter 2, 3 and 4 and existing literature. Five contrasting socio-economic scenarios were built towards year 2027, including hypothetical trends in policy interventions and change towards agricultural intensification. A simulation framework was developed to account for household demographic dynamics and crop/livestock production variability in various rainfall and socio-economic conditions. Food self-sufficiency and farm income per capita was assessed for a representative village of 99 households in the Koutiala district. In the current situation, 45% of the farms of the village were food self-sufficient and above the 1.25 US$ day^{-1}poverty line. Without change in farmers practice, without additional policy intervention and keeping the current population growth rate, i.e. the "Business as usual" scenario, food self-sufficiency and income per capita would fall by 8 to 37% and 10% to 40% respectively, depending on farm type. With this scenario, only 16% of the farms would be both food self-sufficient and above the poverty line in 2027. Diversification with legumes combined with intensification of livestock production and support to the milk sector with tariffs on imported powder, i.e. the "Dairy development" scenario, would barely offset the negative effect of population growth on income per capita: depending on farm type income per capita would still be reduced by 7 to 24% and only 27% of farms would be food self-sufficient and above the poverty line. Additional broader policy interventions like family planning and job creation outside agriculture to favour out-migration would be needed to maintain household food self-sufficiency and increase income per capita in this rural area. In this optimistic scenario, 69% of the farms would be above the poverty line and food self-sufficient in 2027. Narrowing yield gaps through additional Integrated Pest Management programs, subsidies for small-scale mechanisation of cotton and mineral fertiliser on sorghum and millet could allow a drastic increase in productivity and would lift 92% of farm population out of poverty with 108% to 132% increase in food self-sufficiency and 88% to 112% increase in farm income depending on farm type.

The involvement of farmers in the co-learning cycles, the open dialogue and reflections during the participatory process allowed establishing legitimate, credible and salient farm reconfiguration guidelines (Chapter 6). These guidelines can be scaled out to other communities within the "old cotton basin". For such an approach to be effective, extension workers have to be trained to use the participatory and interdisciplinary tools used in the co-learning cycles. Farmer groups would also need to be empowered so that they can have an impact on political decisions, e.g. obtain a stronger support for the milk sector with establishment of tariffs on milk powder imports.

This whole Malian adventure could not have been possible without the help of numerous persons. Patrice Autfray gave me the opportunity to do an internship at Cirad and to have my first fieldwork with Malian farmers. Patrice, thank you for this enriching experience; Eva Weltzien and Fred Rattunde welcomed me at Icrisat and in their house and offered me the luck to push further my immersion in Malian rural areas. Thank you Eva and Fred! At Icrisat, I met Tom "Namaratigui" van Mourik. Tom: from the very start working with you was a great pleasure. I did not hesitate a second when I knew I could be back for a PhD work in Mali with you as a daily supervisor. Thank you for your constant support and your contagious good mood and curiosity!

Though appointing for a position in Mali, my first day as Icrisat staff started in Wageningen at PPS for an "endoctrination". The very first time I entered Ken's office, the professor impressed me and I understood that it was going to be hard, but also a lot of fun! Thank you Ken for being so supportive of this research from the very start, for always pushing me further, for distilling encouragement at the right moment when moral was low (everlasting proposal) and for making this PhD a demanding but very pleasant journey! I am also immensely grateful to Katrien Descheemaeker, most probably the best supervisor on earth. Katrien: thank you for your constant support, thank you for your friendship!

In Wageningen, I am grateful to all the colleagues and friends at PPS. Merel, Esther, João, Renske, Jannike, Lotte K. and Lotte W., Mary, Guillaume, Jiska, Marya, Wim, Greta and many others. Thank you for the great time, and for people in the PhD room, thank you for having endured the drumming on the table! I am grateful to Charlotte, Ria, Linda, Bert Rijk and Alex-Jan who always helped me with practical and administrative issues. Coffee time at FSE (there's only a corridor to cross) was always a great time thanks to Mirja, Stephanie, Jodit, Georges, Carl and many others. I am also profoundly indebted to the Dutch weather that really helped me to stay focus on my research.

At ICRISAT, Farid Waliyar has always assisted me in marrying my assignment duties with my PhD research. Thank you Farid. Sibiry Traore helped me to go through the administrative labyrinth and has always been supportive of my research. Sibiry "I ni ce". I am grateful to Peter Craufurd and Anthony Withbread, who trusted me and facilitated the financial aspects of this research. Anthony: I hope we can meet sometimes on ski slopes. Sharing the same office with Andre was a real pleasure. Andre, thank you for the good times and as you will see I finally managed to make sense out of my farm typology. Coffee time was also grea thanks to numerous joiners. Manda Sissoko, Sidi Touré, Samuel Guindo, Abdoulaye Bah, Gaoussou Coulibaly, Sekouba Keïta and many others, thank you for your company and your friendship. I am hugely indebted to all Icrisat staff that contributed to make my stay there a real pleasure. Sidi Dembele "n'fa" was the best driver ever. Thank you Sidi for all these rides to Koutiala and I hope I can come soon have a tea in the new house!

In Koutiala, all this work would not have been possible without the involvement of a great team. The Ngo AMEDD has been a key partner: Bougouna Sogoba has always managed to make things happen despite all the administrative constraints. Bougouna: thank you for your endless energy and your enthusiasm about research and possible outcomes in the region. Ousmane Dembele was the cornerstone of all the logistic in the field. Thank you Ousmane for your adaptability, your endurance ("sho sira kela, kaba sira fila") and your energy. Arouna Bayoko, thank you for your talented workshop facilitations that inspired me a lot. I am immensely indebted to all the technicians for their endless energy and commitment. Michel Sagara, Bakary Dao, Moumine Traore, Abdoulaye Dembele, Soungalo Bouare, and all the interns who got involved in the trials establishment, thank you! I am gratefull to all the farmers in Kani, Nampossela, Nitabougouro, M'Peresso, Try, N'Goukan, Karangasso, Finkoloni and Koumbri. Having regular contacts with these farmers allowed me keeping on track and not loosing myself into useless details.

IER has also been a key partner: Ousmane Sanogo, Salif Doumbia and N'Golo Coulibaly helped me with the database. Your involvement with farmers in the research villages was of great help. Thank you Ousmane, Salif and N'Golo. I am also grateful to Diakaridia

Diabate for the monitoring of the livestock experiment. Kalifa Traore and Oumar Samake helped me with the soil profile. Thank you Kalifa and Oumar. I am also gratefull to Fagaye Sissoko who supported me when I was visiting in Sikasso. I also wanted to thank Bettina Haussmann, for her constant support and enthusiasm about this research.

In Koutiala, coffee was definitely the best at GERES. Guillaume cheered me up at any time and was afterwards a "colloc en or". Thanks Guillaume for what you did for the family! Stephane and Amandine, thank you for the nice stays in your house. Sofian, Renaud, Rik Schuiling, thank you for the good discussions and beers at "plein air" and "Bakel". Rik: Santjes! I am grateful to Gregoire for the nice stays in his house in Koutiala. And thank you Gregoire for your help during this hard month in Bamako (Ebola-Palu)!

I also wanted to thanks all my wonderful housemates: in Wageningen Marieke, Diego, Renake, Daisy, Andrea, Diana, Elise, Abe. In Bamako, I had a great time with Lise, Kenneth, Kristen, Soungalo, Christophe, Hervé, Benoit, Ombelline, Guillaume. A "coup d'état" can sometimes be funny if you are under house arrest in a house with good friends. In our lovely house in Sprimont (Belgium) Valery was bearing with my changing moods. Valery, thank you for the great time we had in the house, thank you for the delicious beer, delicious bread and our lovely garden. During my short stays in Wageningen, I was staying in Rio and Rik's house, a nice and warm house. Thank you Rik, thank you Rio, for always welcoming me! I also wanted to thank Alice Lame, for the wonderful work she made on the trial data. Simon and Loïc, I had some great time with you, in the tough period of the last stretch.

Via skype, Marc Corbeels empowered me on model use and calibration. Thank you Marc for your availability. I also wanted to thank Myriam for the time she spent helping me with my papers, and for her enthusiasm and commitment about taking over our work in Koutiala. During conference, I met great people: thank you Hélène Marrou, Elodie Dorey, Pierre Chopin and many others. I am also grateful to all the friends in Bamako, Sandrine, Jeanne, Anthony, and my drumming dream team: Djelimoussa, Brama, Modibo, Issa, Papou, Badri and many others. In Montpellier, I am immensely

grateful to Arnaud, Vincent, Sandra, Remi et Franzi who always helped with logistics issues and housing. Thanks a lot! I am also indebted to Clement and Etienne for their friendship.

I am grateful to my parents for their unconditional support every step of the way in my life, it helped me to stay self-confident even in the downs of this PhD research. I also wanted to thank my sister for the Transpalette and my brother for being what he is. Finally, I wanted to thank my love Emeline, for her patience and her constant support, and my son Léo who joined us during the course of this PhD.

PE&RC Training and Education Statement

The C.T. De Wit
Graduate School
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PRODUCTION
ECOLOGY
& RESOURCE
CONSERVATION

With the training and education activities listed below the PhD candidate has complied with the requirements set by the C.T. de Wit Graduate School for Production Ecology and Resource Conservation (PE&RC) which comprises of a minimum total of 32 ECTS (= 22 weeks of activities)

Review of literature (4.5 ECTS)

- Mixed crop- livestock farming: a review of concepts for system analysis

Writing of project proposal (4.5 ECTS)

- Pathways to agro-ecological intensification of sorghum/millet based cropping systems in Southern Mali

Post-graduate courses (4.2 ECTS)

- Farming systems and rural livelihoods: vulnerability and adaptation, Wondo Genet, Ethiopia; PE&RC (2013)
- Experimental design of on-farm trials; Mc Knight Foundation (2014)

Laboratory training and working visits (0.6 ECTS)

- Visit of CRP DS farming system analysis activities in Kurnool and Anantapur, India; ILRI (2013)

Invited review of (unpublished) journal manuscript (2 ECTS)

- Ecolind: empirical evaluation of farm sustainability (2015)
- NJAS: cover crops (2015)

Competence strengthening / skills courses (2 ECTS)

- Communication with the media and the general public; PE&RC (2015)
- Mobilizing your scientific network; PE&RC (2015)

PE&RC Annual meetings, seminars and the PE&RC weekend (0.9 ECTS)

- PE&RC Weekend last years (2015)
- PE&RC Day (2015)

Discussion groups / local seminars / other scientific meetings (6.6 ECTS)

- Africa rising review workshop; Tamale, Ghana (2012)
- Regular scientific interaction; Icrisat-Bamako, Mali (2012-2014)
- Annual meeting of the pathways to AEI project; WUR (2015)

International symposia, workshops and conferences (6.9 ECTS)

- FSD Conference; Lanzhou, China (2013)
- ESA Conference; Debrecen, Hungary (2014)
- FSD5 Conference; Montpellier, France (2015)

About the author

Gatien Falconnier was born in 1986 in a small city at the foot of the French Alps. His first experience with Africa was at the age of six, when the family moved to Côte d'Ivoire where he attended French primary and secondary school. Back in France in 1998 he completed his secondary education in the high school of Villefranche sur Saône. After two years of national preparatory program in Lyon, he went on to study in the "Ecole Nationale Supérieur Agronomique" in Toulouse. He did his bachelor internship with Cirad in Sikasso, Mali where he worked on crop residues management and had his first fieldwork with Malian farmers in different villages across southern Mali. He did his Master on innovation in rural environment in the "Institut des Regions Chaudes" in Montpellier and went back to Mali for his internship with ICRISAT to work on legumes in cropping systems. After his graduation in 2011 he worked with INRA during one year in the rice fields of Camargue to design together with farmers innovative cropping systems for organic farming. At the end of his assignment, he applied for an Associate Professional Officer position in Mali with ICRISAT and was offered the opportunity to carry a PhD research by the same time with the Plant Production Systems group at Wageningen Univestity. Ken Giller, Katrien Descheemaeker and Thomas Van Mourik agreed to be his supervisors.

Funding

The research described in this thesis was financially supported by ICRISAT (International Crops Research Institute for the Semi-Arid tropics) and the Mc Knight foundation.

Financial support for the printing of this thesis was obtained from the Dr. Judith Zwartz Foundation.