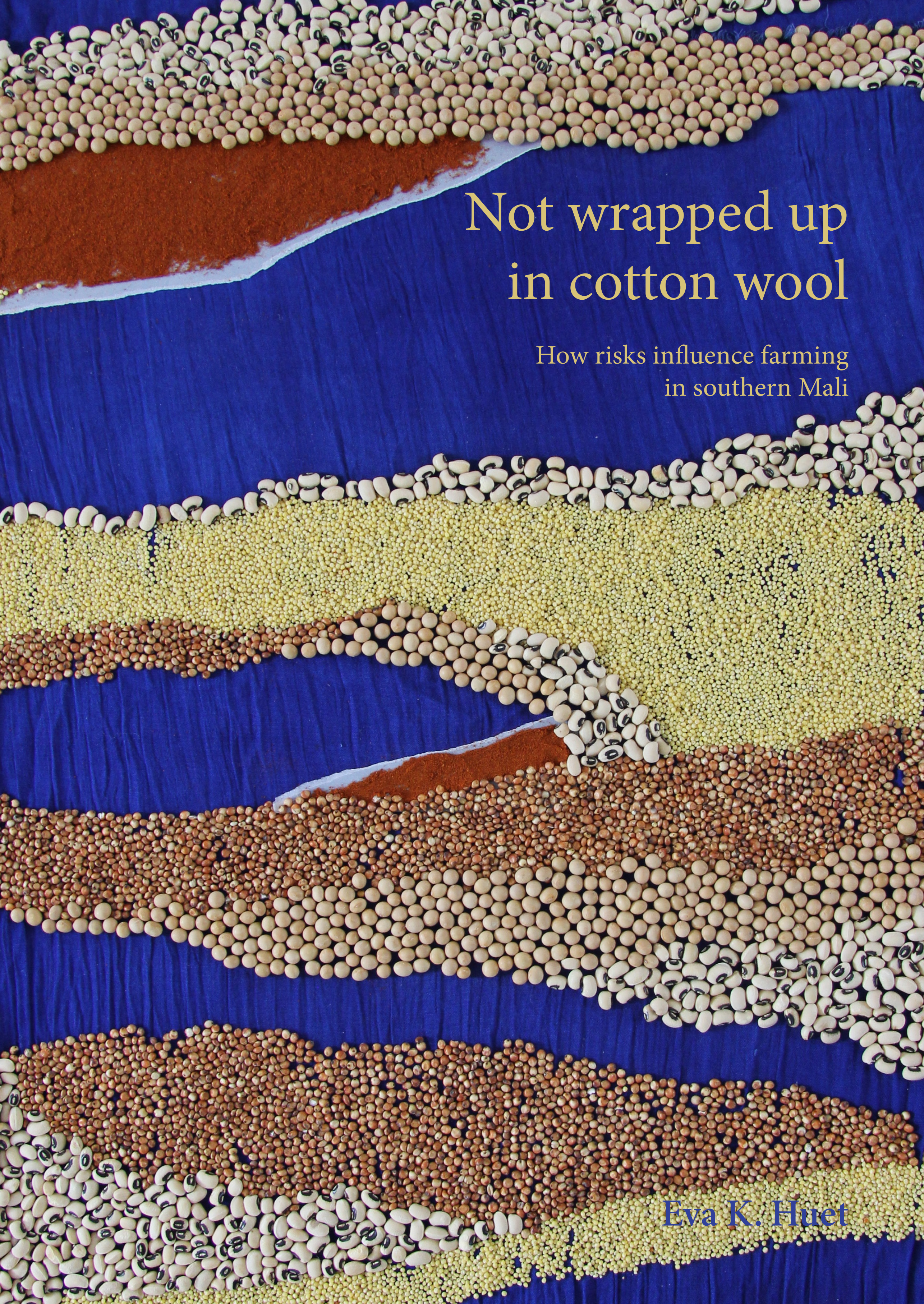
Not wrapped up in cotton wool

How risks influence farming in southern Mali

Eva K. Huet



Propositions

1. Healthcare contributes as much to sustainable production as crops contribute to a healthy diet.
   (this thesis)

2. Improving farm management practices is pointless without investment in public services.
   (this thesis)

3. Research is a clash between allowing for chaos and creativity, and maintaining rigour and order.

4. Searching for innovations is only relevant if we spend equal time on looking back as looking forward.

5. By preparing students to fit within the current economic model, universities are no longer free havens for critical thought.

6. Philanthropy by-passes the democratic process.

7. Efficiency is overrated in our society.

8. Finance schemes and monitoring requirements of development programmes feed donor vanity rather than actual change.

Propositions belonging to the thesis, entitled

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Eva Katrien Huet
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2023

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How risk influences farming in southern Mali

Eva Katrien Huet

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Abstract

West African farmers are exposed to a variety of risks, including climate variability. Moreover, trends of population growth, declining natural resources and climate change increase the probability of hazards and extreme events. In this environments, farmers are often struggling to be food self-sufficient or escape poverty. We focused on the area of Koutiala, southern Mali, as an illustrative region for the challenging farming conditions in West Africa.

The aim of this thesis was to understand farmers' strategies to cope within a variable and hazardous environment. A parallel objective was to analyse which sustainable intensification options could increase productivity and/or reduce risks within the socio-economic and biophysical context. Risk was defined as the combination of the probability of a hazard taking place and the impact this induces. To analyse risk perception and suitability of on-farm options several data sources were combined: responses from individual surveys and focus group discussions, outputs from crop model simulations, long-term weather data and evaluations of trials and try-out fields embedded within a long-term participatory process.

Risks related to health of family members were perceived as the highest, followed by risks related to health of livestock. Farmers managed those risks by maintaining flexibility and diversity in the farm management which allowed them to limit the impact and react quickly when hazards happened. Farmers overcame losses by relying on social interactions and using productive assets, e.g. selling cattle. Hence, they lost capital. Within households, differences in risk perception were related to decision-power, not to gender. Between farms, risk perception was related to resource endowment to a limited extent. The frequency and impact on yield of some hazards were quantified using crop simulation data. Weather hazards occurred at least every five years and reduced cereal yields. The impact of hazards on cereal yields (maize, sorghum, millet) interacted with the cereal management (early sowing, increasing N fertilisation and/or introducing a short duration variety). Increasing maize yields through management did not affect relative yield losses in case of hazards. Adapted millet management caused a trade-off between yield and hazard impact. Adapted sorghum management increased yield and mitigated hazard impacts simultaneously. Further, I demonstrated that on-farm diversification of crop land allocation had the potential to increase stability. The combination of cotton and a cereal had a relatively strong stabilisation benefit, as cotton and the cereals responded differently to weather. While the majority of diversification strategies enabled farmers to meet the food sufficiency requirements, farmers had to target combinations with a high mean return and large variability in order to surpass the poverty line. Within this environment, an iterative and participatory co-learning cycle facilitated a learning environment for researchers and farmers. This process yielded a diversity of options farmers wanted to test in on-farm trials and farmer-designed try-out fields. The findings supported the interest of farmers to diversify their cropping system through, for example, inclusion of grain and fodder varieties and intercropping. Labour needs, costs and limited markets were bottlenecks for applying options.

Overall, farming in Mali is confronted with many risks. Farmers valued diversity and flexibility of farm and field management, as a means to deal with risk. This is expected to contribute to the adaptive capacity and resilience of farms. Farmers maintained food self-sufficiency, but had difficulty to escape

poverty. As productive assets were used to cover for losses, farmers did not have much room to invest. Therefore on-farm options need to be accompanied by institutional measures in the agronomic, market and health domain to strengthen a conducive socio-economic environment.

Contents

1 General Introduction

The presence of risks makes it impossible for farmers to completely protect their farms from dangers. They cannot "wrap themselves up in cotton wool". However, they can be prepared. In this thesis, I investigated how farmers dealt with uncertainty in the old cotton basin of Mali. I analysed the suitability of options to sustain income and food production in this hazardous environment.

1.1 Changing farming environments in West Africa

Farming is an important activity for the 3.4 billion people living in rural areas worldwide in terms of gaining access to food and income (UNDESA, 2019). Around eighty percent of the rural population are smallholder farmers, or are employed on smallholder farms (Byerlee et al., 2008). Collectively these smallholders are strongly contributing to global food production, but individually often struggle to reach food security (Giller et al., 2021a). Agriculture is a contributor in the pathway to reach the Sustainable Development Goal (SDG) 1: No poverty and SDG 2: Zero Hunger, that are set by the United Nations General Assembly. However, in sub-Saharan Africa agricultural productivity is lagging behind compared to the rest of the world. A well-developed farming system can contribute to alleviating poverty and hunger. However, additional off-farm livelihood strategies are likely necessary for farmers to escape poverty (Ollenburger et al., 2019; Woodhill et al., 2022).

Such a farming system should be resilient and able to deal with a variable environment. As was emphasised by Holling (1973):"Change rather than equilibrium is the normal state". Environmental changes can include variations in circumstances that still fit within the current system configuration, gradual changes (trends), or sudden shocks that stretch the boundaries of the suitability of the farming system (Kloos, 2015).

1.1.1 Ongoing trends

Various pressures are driving a need for farming system adaptations. Firstly climate change is expected to have profound effects in West Africa, of which some impacts are already tangible (Trisos et al., 2022). This change in climate is a threat for agricultural productivity and growth (Andrieu et al., 2017). For example, certain regions may require adapted management, change of varieties, or even crop portfolio transformations as the geographical suitability for crops may shift (Rippke et al., 2016; Wichern et al., 2019). The simulation of Rippke et al. (2016) showed a trend of moving crop suitability frontiers along the Sahelian belt. Before 2050, the aptness of crops in this area would already be affected, especially for maize. Climate change may also induce shifts in the prevalence and impact of pathogens for livestock and crops (McDermott et al., 2002; Dinesh et al., 2015).

Secondly, population is growing rapidly. In many areas of West Africa, demographic growth led to the decrease of long-duration fallow periods (Andrieu et al., 2015; Traore et al., 2015), which implies less and degrading rangelands for livestock, declining soil fertility, impairing crop yields. Continuous demographic growth will go hand in hand with increasing demands for food, feed and fuel (Herrero et al., 2010), changing diets, and increasing pressure on natural resources.

These pressures add more challenges to the production of enough and nutritious food in and for West Africa. Moreover, current cereal yields still remain far below the water limited potential (van Ittersum et al., 2016; ten Berge et al., 2019), and yields are stagnating (Tittonell & Giller, 2013; Falconnier et al., 2015). The speed of population growth is likely to exceed the potential productivity increase, so these regions are likely to remain a 'food sink', where import of food is needed (van Ittersum et al., 2016).

1.1.2 Risks and hazards

Apart from gradual changes in the environment (trends), agriculture in West Africa is dealing with multiple types of risks, which entail a certain degree of uncertainty related to the perturbation. In research, the semantics of *risk* have varied, revealing the complexity of the concept (Brooks, 2003). Therefore, Table 1.1 provides an overview of the definitions of risk-related concepts used in this thesis. Risk is seen as the combination of the likelihood of a hazard taking place with the severity of the losses that can be caused by the hazard (World Bank, 2016). Hazard, losses and uncertainty (of the probability or impact) are main characteristics of risk. Uncertainty can refer to a (i) known likelihood, (ii) uncomplete knowledge, or (iii) something that is generally unknowable.

For example climate change comes with uncertainty. Several models have been used to assess the direction of climate change in West Africa. There is consensus that temperatures will further rise due to climate change, while the predictions for precipitation are more debated (Roudier et al., 2011; Nissan et al., 2019). Irregular rainfall patterns were already common but are expected to become more variable and with more extreme events. Hazards induced by biological factors, such as the occurrence of crop pests and livestock diseases may also become more severe due to climate change. A long list of socio-economic risks affect agriculture as well. Examples include hazards associated to health, price volatility, logistics, infrastructure, quality of equipment and input, supply risks, policy changes, corruption or armed conflict (PARM, 2014). Risks can occur simultaneously. In rural areas, market risks are often correlated to production risks: local production shortages can result in local price increases. But global markets also influence commodity prices. Because of the seasonality of production, variability of input and output prices exists both within and between years (Antonaci et al., 2014).

Given the ongoing trends in agriculture, the management of multiple, or compound, risk has become more relevant than ever (Komarek et al., 2020). In addition to assessing options for coping with pressures on the longer term Nissan et al. (2019) stated that research and development interventions should focus on management of short-term variability and hazards as well. For farmers, risk management is an essential factor in the decision-making processes of farm management. How farmers behave towards risk is determined by their risk perception, and their risk attitude, i.e. the level of willingness for risk-taking (van Winsen et al., 2016). Risk management can have different timings (preparation before, or reacting after hazards happen) and can entail a variety of approaches, such as risk avoidance, reduction, transfer, or acceptance (Shaper et al. 2010) (Table 1.1).

1.1.3 The potential of Sustainable Intensification (SI)

To deal with the challenges described and to answer to the increasing demand, food production needs to increase. Godfray and Garnett (2014) emphasised that to eradicate hunger the needs are so high that a combination is required of increased productivity with dietary changes, waste reduction and improved governance of the food system. Sustainable intensification (SI) is a potential pathway to increase food production and income while being resilient to hazards, without increasing pressure on the natural environment (Godfray & Garnett, 2014; Vanlauwe et al., 2014). Similar to the risk concept, the definition of SI has various nuances in research. Some principles, however, are fundamental for SI: producing more on the same amount of land without adverse negative environmental impact (Pretty & Bharucha, 2014; Wezel et al., 2015) (Table 1.1). Additionally, SI as an objective does not describe the technologies or approaches for achieving that goal (Garnett et al., 2013).

Farm management changes could contribute to increased production, provided that the options are tailored to the local context and take into account farmers' decision making processes (Droppelmann et al., 2017; Descheemaeker et al., 2019; Gerard, 2020; Silva et al., 2021). A relevant basket of options contains a range of tailored options from which a diversity of farmers can choose combinations in a flexible manner (Ronner et al., 2021). Understanding farmers' perceptions and management of risks is important in this tailoring process (Schlecht et al., 2006; Kisaka-Lwayo & Obi, 2012; Douxchamps et al., 2016), as it determines how farmers deal with uncertainty. In the context of West Africa, such SI options should not only increase production, but also contribute to farmers' resilience within the hazardous environment.

1.1.4 Paradigm shifts in research

In sub-Saharan Africa promising agricultural options were often not adopted by farmers (Wossen et al., 2015). To better support technological changes, parallel changes in research processes have been implemented and proposed in the last decades (Leeuwis & Van den Ban, 2004; Glover et al., 2019). In order to assess the suitability of options, some methods applied in this thesis aimed to address aspects of proposed paradigm shifts: embracing a farmer-centred approach, considering environmental variation, including diversity (of indicators and risk), and including farm-level evaluation.

First, a focus on farmers' needs, goals and aspirations in agriculture is a necessity to increase the likelihood of future adoption and adaptation of options. Agricultural research has evolved to include more participatory and adaptive processes (Ronner et al., 2021). For example, on-station trials have been supplemented by on-farm trials in more risk-prone circumstances (Franzel & Coe, 2002). Increased agency of farmers in trial implementation, was accompanied by increased farmer input on the design and knowledge-sharing of technologies, for example in Farmer Research Networks (Nelson et al., 2001; Richardson et al., 2021). Adaptation and iteration allow better tailoring of options to the farmers' context (Andrieu et al., 2019; Ronner et al., 2019). Dedicated stakeholder involvement is required from design to implementation of research projects to assure a match between demand and outcome of the process, and to increase efficacy of the interactions (Ollenburger, 2019; Schmidt et al., 2020).

Second, much literature stresses the importance of not only considering maximum average yields but to include variability in the analysis (Urruty et al., 2016; Vanlauwe et al., 2019). Average yield is still the most common indicator used in research to assess the impact of technological options (Baudron et al., 2021a). Nevertheless, existing variability of return plays an important role in farmers decision making, especially in volatile environments. Farmers may prefer stability over maximisation of yields (Descheemaeker et al., 2019; Feyisa et al., 2023).

Third, the assessment of options should include the diversity of drivers in decision-making. In the context of this thesis, such diversity refers to the variety of hazards included, and the performance indicators evaluated. Wauters et al. (2014) noted that the list of risks and relevant management perceived by farmers may be larger and more context-specific than the list typically addressed by research. Regarding the performance indicators, yield remains crucial for farmers. Nevertheless, farmers could have complementary objectives. Other characteristics farmers may appreciate are for example taste, harvest time, fodder production, cost-benefit or labour requirements (Michalscheck et al., 2018; Ronner et al., 2019).

Finally, evaluations at field level may not be sufficient to reflect the impact at farm level. The potential of SI options at field level may be promising, while at farm level other constraints arise or the benefit in income or food supply is too limited for farmers to improve their situation (Giller et al., 2011; Thuijsman et al., 2022). The farm level potential of SI options may differ between poorer and better-off farmers.

I apply these approaches to address knowledge gaps in understanding how risk influences agriculture. Agricultural risk assessments often focus on a single commodity or one source of risk (Komarek et al., 2020). There are few studies that expand on differences in risk perception within households (exeptions by Mishra & Pede, 2017; Rao et al., 2020). The quantification of these risks, i.e. measuring the impact of management decisions on the mean and the variability of outputs, are scarce for West Africa, both at field- and farm-level. Model studies generally focus on yields influenced by climate-related trends rather than by current weather variability or other hazards. Risk influences farmers' decision-making on the implementation of SI options. In an ongoing participatory process, tailoring of options for on-farm trials has been investigated (Falconnier et al., 2016). However, it is not known how farmers would (not) apply these options on their own fields, and what factors, such as risk management, influence these decisions.

Table 1.1 Concepts that have diverging interpretations in literature with the definitions as they were used in this thesis. The purpose of this overview is to improve the thesis' internal consistency and readability, not to ignore the value of other definitions.

	Concept	Definitions and descriptions
Risk components	Risk	"Agricultural risk is a combination of the likelihood of a hazardous event or exposure(s) and the severity of the losses that can be caused by the event or exposure(s). The three main attributes of risks are event hazard, uncertainty and losses." (World Bank, 2016)
	Hazard	"An event with the potential to cause harm." (Jones et al., 2003b)
	Uncertainty	"An expression of the degree to which a value (e.g. the future state of the climate) is unknown. Uncertainty can result from lack of information or from disagreement about what is known or even knowable." (World Bank, 2016)
	Constraint	"Conditions that lead to suboptimal performance." (World Bank, 2016)
	Trend	A gradual change over time
	Production risk	"Risks that are present at farm level and affect yields." (World Bank, 2016)
Risk management capacity	Risk avoidance	"Includes measures that reduce the farm's exposure to hazards." (Schaper et al., 2010)
	Risk reduction	"Includes measures that reduce incidence rates or potential damages or losses." (Schaper et al., 2010)
	Risk transfer	"Includes measures that transfer the consequences of risks to others or institutions." (e.g. insurance) (Schaper et al., 2010)
	Risk acceptance	Accepting the risk and refraining from specific measures
	Resilience	"Resilience is the ability of individuals, communities, cities, institutions, systems and societies to prevent, resist, absorb, adapt, respond and recover positively, efficiently and effectively when faced with a wide range of risks, while maintaining an acceptable level of functioning without compromising long-term prospects for sustainable development, peace and security, human rights and well-being for all". (UN, 2020) And specific in relation to a farming system: "The ability to ensure the provision of the system functions in the face of increasingly complex and accumulating economic, social, environmental and institutional shocks and stresses, through capacities of robustness, adaptability and transformability." (Meuwissen et al., 2019)
	Robustness	"The ability to maintain desired levels of system outputs, especially agricultural, despite the occurrence of disturbances." (Urruty et al., 2016)
	Adaptive capacity	"The ability to design and implement effective changes so as to reduce the impacts of harmful perturbations. Adaptive capacity represents the set of natural, financial, institutional or human resources that agricultural systems can mobilize for coping with constraints and overcoming them. i.e. the ability of the studied system to deal with perturbations and increase the extent of variability that it can cope with." (Urruty et al., 2016)
	Adaptability	"The capacity to change the composition of inputs, production, marketing and risk management in response to shocks and stresses but without changing the structures and feedback mechanisms of the farming system." (Meuwissen et al., 2019)
	Transformability	"The capacity to significantly change the internal structure and feedback mechanisms of the farming system in response to either severe shocks or enduring stress that make business as usual impossible." (Meuwissen et al., 2019)
Farming concepts	Farming system	"A population of individual farm systems that may have widely differing resource bases, enterprise patterns, household livelihoods and constraints." (Giller, 2013)
	Farm (system)	"A decision making unit comprising the farm household, cropping and livestock system that transform land, capital and labour into useful products that can be consumed or sold." (Fresco & Westphal, 1988)
	Farm components	The different components that comprise a farm, usually: household, cropping system and the livestock system. (Fresco & Westphal, 1988)
	Household	"A group of people, often a family, who live together." (Cambridge University Press, n.d.)
	Smallholder	"Smallholder agriculture is practised by families (including one or more households) using only or mostly family labour and deriving from that work a large but variable share of their income, in kind or cash. Agriculture includes crop raising, animal husbandry, forestry and artisanal fisheries. […] The definition of smallholder agriculture cannot be rigid […], there are many different variations in each specific context. […] A smallholding is 'small' because resources are scarce." (HLPE, 2013)
	Sustainable Intensification	"Sustainable intensification (SI) is defined as a process or system where agricultural yields are increased without adverse environmental impact and without the conversion of additional non-agricultural land. The concept does not articulate or privilege any particular vision or method of agricultural production. Rather, it emphasizes ends rather than means, and does not pre-determine technologies, species mix or particular design components." (Pretty & Bharucha, 2014).

1.2 Agricultural development in Koutiala, southern Mali

The research was targeted to the Koutiala cercle[1] in southern Mali within the 750 and 1000 mm isohyet (Figure 1.1). As a case study, this area is representative for challenging farming environments throughout sub-Saharan Africa: farmers are dealing with climate variability, declining natural resources and population growth. Of course, farming in Koutiala has its own specific context as well. For instance, the scale of farms and households, as well as the institutional support for the cotton value chain, stood out in comparison to other farming systems (Giller et al., 2021b).

The study area lies within the 'old cotton basin' of Mali. The CMDT (Compagnie Malienne pour le Développement des Textiles), a parastatal cotton company founded in 1974, has supported cotton production through several mechanisms, as for example by promoting animal traction and access to inputs. Cotton has been a crucial crop since the 1950's in Mali, but prices and yields have been declining since 2000, and fluctuating world prices have incited crises in the Malian cotton production (Droy et al., 2012a; Coulibaly et al., 2015). Still, in Koutiala cotton remains one of the main sources of income for farmers. Currently CMDT has a buyer's monopoly, it organises the secured offtake of cotton at a price that is fixed by the state at the beginning of the growing season. Farmers are organised in local cooperatives (CPCV, Coopérative des Producteurs du Coton et des Cultures Vivrières) associated with CMDT for organising input procurement and payments (Dissa et al., 2022). Additionally, CMDT provides access to cotton seeds and subsidised mineral fertiliser for cotton and maize on credit (Droy et al., 2012a). Farmers can pay for the fertilisers in kind through part of their cotton production. Nevertheless, there is a tendency by farmers to use these cotton-financed inputs for cereal production (Coulibaly et al., 2015; Sidibé et al., 2018; Dissa et al., 2022).

Cereals are grown first and foremost to foresee farmers in their food self-sufficiency, as well as to provide a cash income (Bosma et al., 1999). Around two third of cropland is allocated to cereals (Kanté, 2001; Van Dijk et al., 2004; Dissa, 2023). Until the early 90's, sorghum and millet were still the dominant cereal crops in West Africa partly because of their suitability regarding the climatic hazards, with maize gaining more and more importance because of its production potential, provided mineral fertiliser is applied (Fusillier, 1994). The maize area increased together with cotton, as maize follows cotton in the rotation, maize benefits from the carry-over effects of the cotton fertilisation (Falconnier et al., 2015) and the cereal and cotton value chains are closely intertwined (Dissa et al., 2022).

Other relevant crops that farmers cultivate are legumes, mainly groundnut and cowpea. Cowpea is commonly intercropped with cereals, by mixing and planting both crops on the same hill (Sogoba et al., 2020). Traditionally, farmers also intercropped different cereals, with the objective of having more stable yields, reduce risks, and to make effective use of soil and labour capacities, but a tendency towards intensifying sole cereal crops was observed in the 90's (Kanté, 2001).

[1] In Mali, a *cercle* is the administrative unit that is the subdivision of a region. Koutiala is part of the Sikasso region. Since *cercle* is not a commonly used term in English, I will no longer refer to the study area as such. In this thesis, I will use the word (study) *region* not to make reference to an administrative unit of Mali, but to a geographical area with common characteristics.

Crop-livestock interaction is an important component in the system that includes different kinds of animals but with a focus on cattle, followed by small ruminants. Livestock fulfils multiple functions as it provides manure, draught power and potentially income through milk or sales. The animals are an asset for risk management; they can be sold in times of needs for cash (Rufino, 2008; de Ridder et al., 2015). Throughout the last fifty years, the number of cattle of sedentary farmers has increased, partly reinforced by CMDT promotion (Bainville & Dufumier, 2007; Kergna et al., 2020). Together with expanding croplands, and removal of fallow, this evolution has put more pressure on the (grazing) lands. Communal grazing lands became scarcer (Benjaminsen, 2002; Soumaré, 2008). After harvest, livestock are allowed to graze free on crop residues (from November to June). Farms with large herds may send their cattle on transhumance during the rainy season to safeguard crops. Koutiala is a transit zone for transhumant herdsmen traveling south from the northern Sahelian region (Coulibaly et al., 2017). Due to diminishing grazing resources, the stay of the transiting herds has shortened over time (Umutoni et al., 2016). Although livestock provides manure to maintain soil fertility, nutrient balances in the region were generally negative (Kanté, 2001; Ramisch, 2014).

In conclusion, agriculture, and mainly crop production, is the major source for food and income. Although most families have access to at least some off-farm income the contribution of off-farm sources to the overall income remains limited (Dissa et al., forthcoming). Nevertheless, crop yields are stagnating and labour productivity has decreased since the nineties (Aune & Bationo, 2008; Falconnier et al., 2015). During this time only a minority of farms (17%) simultaneously improved crop yield, labour productivity and food self-sufficiency status (Falconnier et al., 2015), and a quarter simultaneously achieves food self-sufficiency and an income above the poverty line (Falconnier et al., 2018).

Contrary to decreasing soil fertility, lowering cotton prices and stagnating yields; the population is increasing. In Mali, population has grown around 35% in the past 10 years (INSTAT, 2023). This tendency is linked with urbanisation and although globally the rural population is declining, in Mali population growth will still take place in rural areas as well, with an projected increase of 47% by 2050 (relevant to the 2018 level) (UNDESA, 2019). Additionally, the Koutiala region is part of the breadbasket for Mali supplying food to the rest of the country (Segnon et al., 2020), which makes the need for improved food production within a sustainable farming system even more urgent.

Farms are diverse. In this thesis we applied the farm typology based on resource endowment as defined by Falconnier et al. (2015) with the number of livestock, the area cultivated, the size of the household and the number of draught materials as defining farm components. The average resource endowment of the four farm types: High Resource Endowed farms with a Large Herd (HRE-LH), High Resource Endowed (HRE), Medium Resource Endowed (MRE), and Low Resource Endowed farms (LRE), are visualised in Figure 1.2.

Not only farms, but also farmers are diverse. Households in this region are large with several brothers and their spouse or spouses as it is a polygamous culture (horizontal expansion), and several generations (vertical expansion) forming a household unit (Figure 1.3). In such large entities, decision making is a complex process where the end responsibility generally lies with the eldest men, the head of household. The household head can delegate certain tasks, about organising labour to another male of the household, the 'head of labour' (Kanté, 2001; Guirkinger et al., 2015). These large farm households that cultivate large areas of land (around 12ha on average) distinguish southern Mali from other areas in sub-Saharan Africa, where farms are often smaller than one hectare (Giller et al., 2021b).

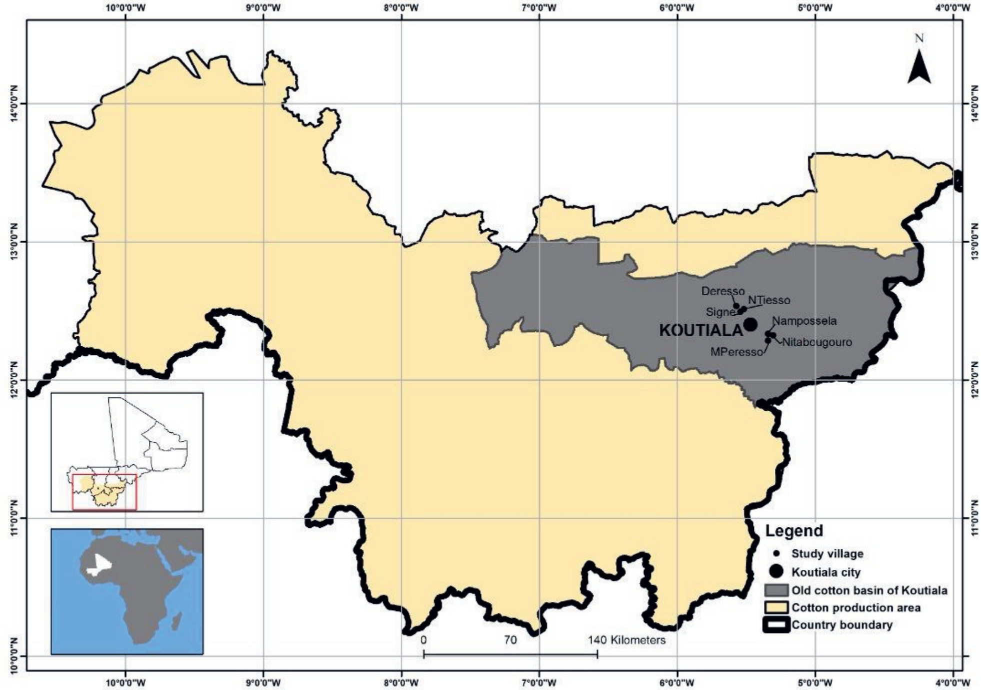

Figure 1.1 Location of the study villages within the cotton production area of Mali. Image from Dissa (2023).

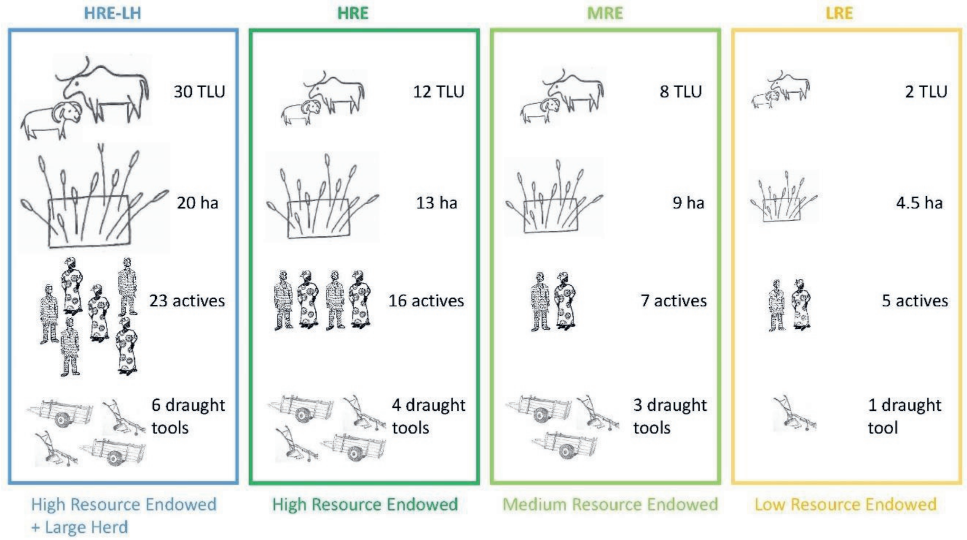

Figure 1.2 Average resources available for the four farm types (High Resource Endowed farms with a Large Herd (HRE-LH), High Resource Endowed (HRE), Medium Resource Endowed (MRE), and Low Resource Endowed farms (LRE)) as classified following Falconnier et al. (2015). The land reflected the cultivated land. TLU stands for Tropical Livestock Unit and is the conversion of the number of farm animals expressed in unit of 250kg. The people active in agriculture were calculated as the sum of all household members between 15 and 60 years old, added with the number of members between 7-15 years and over 60 for whom a conversion factor of 0.5 was applied. Draught tools include ploughs, weeders and sowing machines.

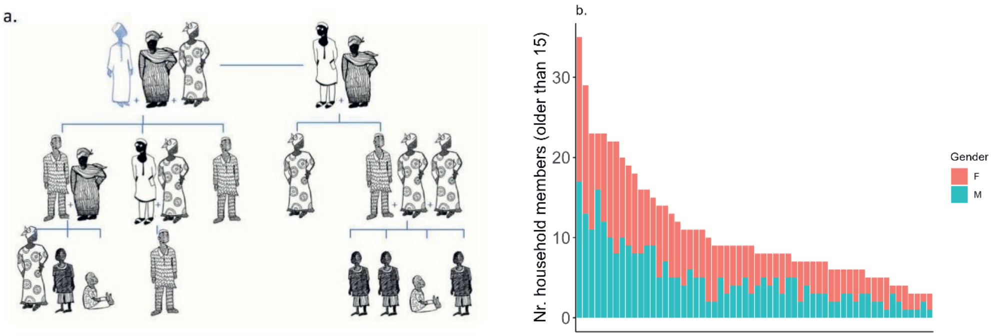

Figure 1.3 a) Illustration of the different members belonging to a same household in Koutiala. The person in blue represents the household head, usually the elder male of the household. Households include horizontal expansion (brothers of the household head, with their spouse(s)) and vertical expansion (sons with their spouse(s)). **b)** The number of male (M) and female (F) household members older than 15 years belonging to the farms that participated in the survey described in Chapter 2.

1.3 Study objectives

The aim of this thesis is to understand farmers' strategies to cope with a variable, and hazardous environment, and in parallel to analyse what options would work within the socio-economic and biophysical context to increase productivity and/or reduce risks. The overall aim is to contribute to a better livelihood for farmers through increased knowledge and understanding of the suitability of SI options.

The thesis is constructed out of the following specific objectives:

1. To analyse which risks farmers perceive to be important and how this perception differs between and within households, and how farmers manage their farm in a risky environment (Chapter 2)
2. To quantify cereal crop yield losses at field level due to the interactions of different production hazards under varied management strategies (Chapter 3)
3. To quantify the potential to mitigate variability in agricultural production by diversifying crop and management allocation at farm level (Chapter 4)
4. To draw lessons on farmer-designed try-outs: how they are evaluated by farmers and how they can be incorporated in agricultural participatory research projects (Chapter 5)

Cross-cutting research questions were:

- What are the most common risks farmers are dealing with? (Chapter 2)
- How are risks affecting agriculture? (Chapter 2, 3 and 4)
- What are the SI options that are suitable in the variable environment of Koutiala? (Chapter 3, 4, 5)

1.4 Thesis outline and research methods

This thesis includes three chapters that contribute to understanding the risks that farmers have to deal with and how farm management can reduce impacts of hazards, and one chapter that analyses the choices farmers made on SI options within this hazardous context (Figure 1.4).

The research was embedded in a long-term project: "Pathways to agroecological intensification in the crop-livestock farming systems in southern Mali" funded by the McKnight foundation, that was present in six villages in the Koutiala region since 2012, and which is currently proceeding in a third phase. Overall, around 400 individual farmers participated in one or more activities of the project within ten years. Some of the activities were organised to answer the objectives of this thesis. These activities followed several avenues of agronomic research for sustainable intensification (Doré et al., 2011). Sources of knowledge comprised existing agronomic knowledge, natural ecosystems functioning and farmers' knowledge, which was used to generate data through modelling (DSSAT crop model), on-farm experiments and participatory research (individual surveys, focus group discussions and village meetings). Additionally, a RHoMIS household survey (van Wijk et al., 2020) was conducted in 2018 on 80 farms, representing the four farm types, to provide additional background information on household characteristics. Farmers' perceptions on risks and options were scanned in a participatory manner, opting to differentiate for inter- and intra-farm variability.

This information allowed me to conduct a risk assessment from different perspectives. Chapter 2 describes farmers' perception of risks and the management options they apply. Subsequently Chapter 3 quantifies the frequency of the most relevant hazards (as defined in chapter 2) and quantifies their impact on cereal production. I used data from the DSSAT crop model to do this. Chapter 4 builds on the same data to look at the potential of diversification at farm level. Diversification was one of the mentioned strategies by farmers in dealing with risks. In Chapter 5, I returned to the farmers' level by analysing the choices that are made about SI options within this hazardous environment. A long-term trajectory of on-farm trials and try-out fields gave insight in the criteria of farmers' interest.

In a general discussion (Chapter 6) I reflected upon the potential of SI options within the hazardous environment of southern Mali, the decision-making processes of a diversity farmers within this context and how participatory research can contribute to tailoring the options to the context.

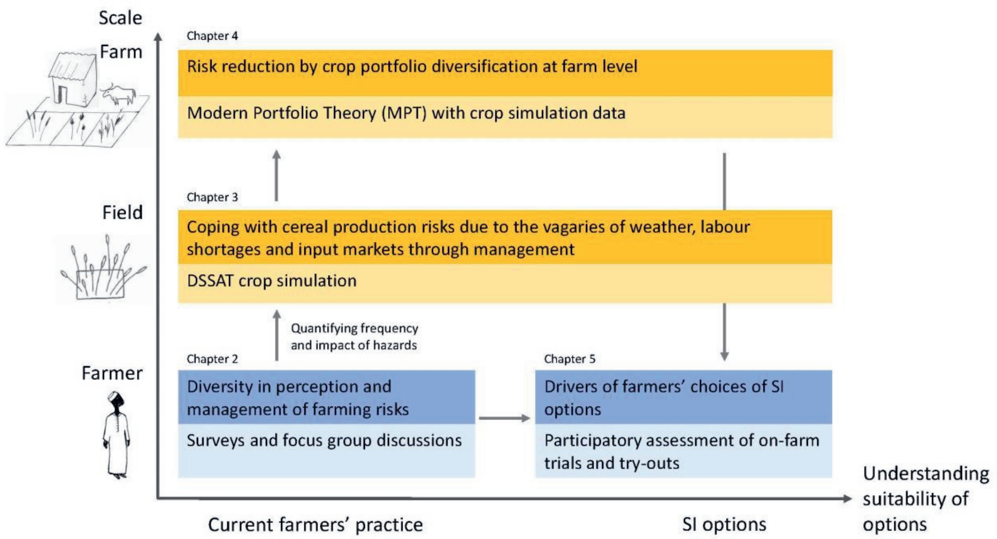

Figure 1.4 Thesis outline of the different chapters related to the scale (farmer, field and farm) and management (current farmers' practice and SI options) taken into account (yellow blocks represent a quantitative analysis, while the blue blocks represent a qualitative approach). For each chapter the topic and the methodology are given.

2 Diversity in perception and management of farming risks

This chapter has been published as:

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Abstract

A deeper understanding of how smallholder farmers perceive and manage risks is crucial to identify options that increase farmers' adaptive capacity. We investigated a broad range of risks that play a role in farmers' decision-making processes. In the cotton zone of Mali opportunities and constraints vary with the resource endowment of farms. Furthermore, as households are large in this region, often comprising 20-50 family members, intra-household diversity may influence perceptions and risk management. For this reason, we analysed diversity both among and within farms. Information was gathered through focus group discussions and a survey with 250 people from 58 households. Risk was assessed as the combination of the perceived frequency of occurrence of hazards and the impact on food availability and income. Farmers faced a diversity of risks, with hazards related to animal and personal health, and climate variability of highest concern. Resource endowment of farms was related to risk perception to a limited extent. Differences within the household were related to the generational factor and decision power, and not to gender. Farmers with decision power worried most about risks. Almost a quarter of described hazards occurred with a high frequency and led to a high impact on food availability and income. Low resource-endowed farms were more often exposed to high risks than other farm types. Farmers applied a variety of actions to cope with hazards, yet in many cases farmers lacked a response. Medical actions were targeted to human and animal health hazards. Changes in field and animal management practices, adapted consumption rates and calls on social interactions, were combined for a diversity of hazards. By assessing the diversity of risks encountered by farmers and the diversity of risk management actions taken by farmers, this study goes beyond common risk research that focuses on a single hazard. Our results suggest that development interventions should not focus on either agronomic or economic options separately, but combine both to strengthen social well-being and agricultural production.

Keywords

Farm type, Intra-household, West Africa, Mali, uncertainty, hazard

2.1 Introduction

Smallholder farmers in West Africa face many risks. Climate variability is a well-known source of risk that is expected to increase due to climate change (e.g. Akumaga & Tarhule, 2018; Schmitt Olabisi et al., 2018; Tiepolo et al., 2018). However, the agricultural risks that farmers face are not only related to the weather. Risks represent the negative impact of a hazard and the frequency with which a hazard occurs. Both elements are associated with uncertainty, resulting in difficulties for farmers to manage risk. Hazards are diverse and can be related to biophysical as well as to marketing, financial, legal and human resources (Baquet et al., 1997). For example, drought, pest attacks and variable prices impair West African farmers' production and income (e.g. Schlecht et al., 2006; Aune & Bationo, 2008).

Agriculture in West Africa is additionally under pressure due to population growth, urbanisation and declining natural resources. To break the current trend of stagnating yields (Tittonell & Giller, 2013; Falconnier et al., 2015), agricultural technologies and farm management changes are needed to increase production and income in a sustainable way. To increase the probability of adoption, these options should be tailored to the local context, and take into account farmers' decision making processes (Giller et al., 2011; Descheemaeker et al., 2019). Understanding farmers' perceptions of and attitude toward risks and coping strategies is important in this tailoring process (Schlecht et al., 2006; Kisaka-Lwayo & Obi, 2012; Douxchamps et al., 2016), as they determine how farmers deal with uncertainty. Both perception and attitude are dynamic and can be influenced by a plethora of personal and social factors such as culture, beliefs, habits, personality, past experiences and motivation (van Winsen et al., 2011). Building on farmers' current practices in dealing with uncertainty is crucial to identify options that increase farmers' adaptive capacity (Cooper et al., 2008; Milgroom & Giller, 2013).

Risk management can be divided into reactive management (ex-post, after the event has taken place) and preventive management (ex-ante, before the event takes place). Besides this division, Schaper et al. (2010) distinguish possible strategies as risk avoidance, risk reduction, risk transfer or risk acceptance. Risk avoidance relates to the exclusion of practices that are prone to a risk, thereby limiting the exposure. Risk reduction covers diminution of the farm's sensitivity to hazards, or occurrence probability of the hazard. The consequences of a farming risk can also be transferred to others, for example through insurances or long-term contracts with price guarantees. Risk acceptance (i.e. to do nothing) is the last option for farmers. Some examples of risk management practices that farmers in sub-Saharan Africa implement are (i) generating income from off-farm sources (Douxchamps et al., 2016; Wichern, 2019), (ii) adapting or spreading planting dates (Milgroom & Giller, 2013; Traore et al., 2014), (iii) maintaining crop diversity (Frison et al., 2011), (iv) keeping livestock (Valbuena et al., 2015), (v) having fields for shared and individual production within a household (Guirkinger & Platteau, 2014) or (vi) reducing food consumption (Wichern, 2019).

Within a single smallholder farming system, farms vary enormously in available resources, the capacity to invest, the constraints that are faced and the objectives farmers set. A farm typology based on resource endowment is often used to understand this farm diversity (e.g. Falconnier et al., 2015; Alvarez et al., 2018). The resource endowment of the farm may not only define the production strategy, but also the perception of which hazards are relevant, their impact and the risk management strategies that are feasible. Hence, poor farmers are likely to be more risk averse (Kisaka-Lwayo & Obi, 2012). The relation between risk perception and management on the one hand and socio-economic farm characteristics on the other hand is described in the literature (e.g. Mubaya & Mafongoya, 2016; Asravor, 2018; Tarfa et al., 2019). However, this diversity among households has not been explored through the use of farm types for West African farming systems. Additionally, apart from inter-household variability, also intra-household variability may influence risk perceptions and attitudes. Malian households are often large entities extending both vertically and horizontally (Guirkinger & Platteau, 2014). Vertical extension refers to sons continuing to live with their parents after marriage, while horizontal extension means that the brothers of the household head together with their wives and children also form part of the household. Most decision power lays with the household head, who is usually the eldest man in the household, accompanied by a head of labour (Kanté, 2001). Within such large households, access to resources, interests, constraints and opportunities differ between household members (Droy et al., 2012b; Guirkinger & Platteau, 2015; Paresys et al., 2018). Michalscheck et al. (2018) advocate to analyse diversity at the level of individual farmers to understand the perception and impact of agricultural technologies and suggest people should be differentiated in terms of decision-power (the household head versus other household members), gender and generation. Intra-household variability is usually not accounted for in agricultural risk assessments, with the exception of a few studies differentiating gender groups (Mishra & Pede, 2017; Rao et al., 2020).

We focus our research on the cotton region of southern Mali, an important agricultural zone in Mali both for cash generation and food production. Farmers are generally food self-sufficient but remain poor and lack a nutritious diet (Falconnier et al., 2018). In this area farmers and researchers have jointly participated in co-learning cycles since 2012 to tailor options to the farming context (Falconnier et al., 2017). Existing agricultural hazards are variable rainfall, volatile commodity prices, moments of insufficient labour, agricultural pests and diseases, and human diseases affecting family members (Van Dijk et al., 2004). It is not known how farmers perceive the risks associated with these hazards and what management strategies they apply or have access to.

In the West African context agricultural risk studies often focus on a single commodity or one source of risk, such as climate change and variability (Komarek et al., 2020), with exceptions like Asravor (2018) who examined the major sources of risk in Northern Ghana through farmers' perception and management strategies. In our research we broaden the scope to the system level and include all possible risks perceived to be influencing overall farm production and livelihood of diverse farms and household members. Our participatory risk assessment expands the approach of the World Bank (2016) and Kisaka-Lwayo and Obi (2012) with the inclusion of intra-household diversity and in-depth interviews. The first objective of this study is to analyse which risks farmers perceive to be important and how this perception differs between and within households. Secondly, we assess how farmers manage their farm in a risky environment. Through this research, we aim to answer the following questions. (i) What hazards do farmers perceive within the agricultural system? (ii) What are their perceptions of the frequency and severity of those hazards? (iii) How does risk perception differ among farms with different resource endowment and between different household members? (iv)

How do farmers prepare for and react to hazards? We hypothesise that both the risk perception and the related coping strategies depend on farm resource endowment and hence differ among farm types. A second hypothesis is that different household members have a different risk perception, related to the responsibilities they hold within the household.

2.2 Materials and methods

2.2.1 Conceptual framework

Agricultural risk has been described in many ways in the scientific literature. Brooks (2003) highlights a main difference in the interpretation of risk as "the probability of a certain hazard taking place", referring to the event itself, versus "the probability of reaching a certain outcome", referring to the combination of event and possible impact. The latter is followed by the IPCC Working Group II (2001), Jones et al. (2003b) and the World Bank (2016). Here we follow the World Bank definition of agricultural risk: "Agricultural risk is a combination of the likelihood of a hazardous event or exposure(s) (to the hazard) and the severity of the losses that can be caused by the event or exposure(s)". First, we used farmers' perception of the frequency of a hazard as a proxy for the likelihood of the hazard happening. Secondly, we described the severity of losses by the perceived impact on farm food availability and income (Figure 2.1). These two indicators for loss were chosen because food self-sufficiency and income are important objectives of farmers, and because they are relevant in the policy debate on poverty reduction (Ollenburger et al., 2019).

A certain level of uncertainty --either in probability of the hazard or in the possible outcome-- is an essential aspect of risk (PARM, 2014) and it limits effective planning. The concept of uncertainty can be further disentangled into a probability (a known likelihood) and a real uncertainty (not-knowing). Not-knowing can refer to something an individual is unaware of but knowable, or to something that is generally unknowable. In our case, we consider all three forms of uncertainty in our assessment of perceived hazards.

The term hazard refers to the triggering event that may cause a loss. Hazard is often used to describe biophysical events such as droughts, floods or storms (Brooks, 2003), but can also refer to shocks in the social or economic domain. The uncertainty aspect distinguishes a hazard from a constraint. Constraints are existing "conditions that lead to suboptimal performance" (World Bank, 2016). Trends are different from hazards since they display a longer-term structural pattern of change (World Bank, 2016) and are therefore more predictable. Constraints and trends were not subject of this research.

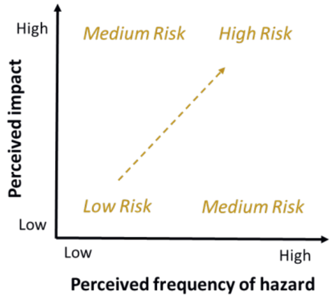

Figure 2.1 Graphical representation of the different factors determining risk. After Vose (2008) and Ratliff and Hanks (1992).

This theoretical framework was operationalised by first evaluating farmers' concerns, without pre-defining the type of hazards. We asked farmers to identify all the possible shocks they could be susceptible to. This implies that both catastrophic risks and risks with lower impact but higher frequency were included. Next, the most important risks were quantified by assessing farmers' perceived frequency and perceived impact of the hazards on food availability and income. Finally, farmers described both their reactive and preventive management options for these hazards.

2.2.2 Study area

The study was carried out in four villages in Koutiala district, situated in the Sudano-Sahelian agro-ecological zone in southern Mali. The nearby N'Tarla research station recorded an average rainfall of 850 mm/year with a high variability ranging between 500 and 1200 mm/year in the period 1965-2005 (Traore et al., 2013). This rainfall pattern is unimodal and extends from May until October. Temperatures range between a mean annual minimum of 19.2°C and maximum of 35.7°C. Soils are mainly Lixisols (FAO, 2006). Two of the villages, Deresso and N'Tiesso (12°31'31"N, 5°20'20"W, elevation 340m), were located at a distance of 15 - 20 km north of the city of Koutiala, near the main tarred road. Two other villages, Nampossela and M'Peresso (12°19'00"N, 5°32'30"W, elevation 350 m) were at a similar distance south of the city with poor access roads.

The region is known as the "old-cotton basin of Mali" that benefitted from the cotton boom in the 1980s and 1990s (Van Dijk et al., 2004). The cotton production is supported by the partly state-controlled CMDT (Compagnie Malienne pour le Développement des Textiles) which sets a fixed price at the beginning of the season, secures and organises collection of the harvest, and provides access to subsidised fertiliser (Droy et al., 2012b). Farmers' first objective is to produce enough food for the household with the cultivation of maize, millet and sorghum (Bosma et al., 1999; Kanté, 2001; Falconnier et al., 2015). Agricultural activities are the main source of income for households (Losch et al., 2012), which is generated mostly with the cultivation of cotton and maize. Both mineral and organic fertiliser are principally targeted to these two crops. Livestock plays an important role in the system providing draught power, manure and cash because animals are often sold in times of need (Kanté, 2001; Van Dijk et al., 2004). Only a quarter of farms achieve both food self-sufficiency and an income above the poverty line (1.9 $ PPP/day/person) (Falconnier et al., 2018).

The population is mainly Minianka, with presence of other ethnic groups as the Fulbe, Dogon or Bambara (Jonckers, 1981; Van Dijk et al., 2004). Population density reaches 70 people km^{-2}, which is high compared to the rest of the country (Soumaré et al., 2008). Almost all land suitable for agriculture in this area is cultivated, indicating pressure on (communal grazing) land (Benjaminsen, 2002; Van Dijk et al., 2004; Soumaré et al., 2008). Because of this pressure, some livestock that is not needed for animal traction or milk production is moved to grazing areas outside the village territory during the rainy season to avoid crop damage on fields (Sanogo, 2010; Turner et al., 2014). Nevertheless, most cattle are grazed year-round on communal rangelands during the day and kept in corrals overnight. During the dry season, livestock grazes on the crop residues in the field (de Ridder et al., 2015).

Diversity between households is captured by a farm type classification developed by Falconnier et al. (2015) based on resource endowment. The number of livestock, the area cultivated, the size of the household and the number of draught tools (ploughs, weeders and sowing machines) are the farm components that define the type (Table A.1). The four farm types are High Resource Endowed farms with a Large Herd (HRE-LH), High Resource Endowed (HRE), Medium Resource Endowed (MRE), and Low Resource Endowed (LRE) farms.

2.2.3 Focus Group Discussions

A first round of focus group discussions (FGD) was organised during the rainy season of 2017 in four villages (Nitabougoro, Nampossela, Deresso and N'Tiesso). One session per village was organised at which men, women and youth from the four farm types were invited. Each session lasted around two hours and attracted between seven to 24 participants. The main goal was to list the spectrum of agricultural risks farmers feel they are facing, by asking them about events that are a source of risk. The question to farmers was framed as follows: "What are the events related to agricultural activities (crop and livestock) that might happen before, during and after the growing season, and that you worry about because it might result in a loss?". The concept of risk was translated to the Bambara word "farati", which means "danger". In communication with farmers, the aspects of uncertainty of events and possible negative outcome were emphasised. This exercise led to a list of 24 hazards that was the basis for the individual survey on risk perception. Farmers categorised the hazards according to the timing (start, during, or end of the rainy season) when the hazard is likely to cause the biggest impact on farm production and income. The category "Other" was given to hazards without a clear time component.

After the individual surveys, experts on specific topics were consulted and a second cycle of FGDs was held in Nampossela, N'Tiesso and Deresso in 2018, attracting four to five participants each. This round of information gathering was organised to complement the first analysis of perceived risks. For example, after it became clear that health issues of people and animals were of high importance, the local health centres and a veterinarian were contacted to give more insight on the incidence of common diseases. For the second cycle of FGDs, the aim was to gain insight in how risks and coping strategies are expressed at village level. For instance, farmers' health influences labour availability. To understand the possibilities of mechanisation as a solution, it was asked how many tractors are present in the village. For understanding access and quality of inputs, the different access points in the village were discussed. In N'Tiesso, one extra FGD was held inviting only women (n=4), discussing the topics that appeared of more interest to them, e.g. market activities. Since the objective was to collect specific and additional information, small groups with key informants sufficed.

2.2.4 Individual surveys on risk perception

A total of 250 members from 58 households participated in an individual survey assessing risk perception in 2018. The households were selected based on availability, willingness and farm typology. The distribution of the farm types included in the survey is similar as the overall distribution for the Koutiala district described in Falconnier et al. (2015), i.e. 16% HRE-LH, 34% HRE, 40% MRE and 10% LRE (Table A.1). For every household, minimum three and maximum seven different family members were interviewed. These individuals were selected randomly from the members that were present at the time of surveying, but at least included a decision maker (the household head or the head of labour), another male or female household member and a young person between 15 and 25 years old (United Nations, 1995). Another condition was that the household member should live on the farm and participate in farm activities for at least three months a year. The surveys were conducted in isolation from other family members to reduce influence on the answers.

The age of respondents varied between 15 and 97 years of age. The average age of youth (n=49) was 17 years, that of other farmers (n=117) 33 years, while decision makers (n=67) were 49 years old on average.

Respondents ranked the five most important hazards from the list defined in the FGD's. During this survey they also gave a score (Likert-type item) expressing their concern for the related risk (0 = "no", 1 = "little", 2 = "medium", 3 = "high" concern). They were free to include additional hazards if they felt the list was not complete.

2.2.5 Semi-structured interviews on hazard impact and frequency, and risk management strategies

Risk impact and frequency as well as the related risk management practices were assessed through a semi-structured interview with one single person of the household that holds decision power, be it the household head or the head of labour (n=58). Invariably, this was a man. The average age of the subgroup of decision makers was 46 years of age and ranged from 24 to 70 years of age. The youngest household head was not classified as youth because of the role of decision maker he took in the household.

While perception of risk is individual, the management of risks is largely executed at farm level. Most fields are family fields, and also livestock management is generally organised centrally. Decision making processes in such large households are complex, and all household members have some influence (Michalscheck, 2019). However, the majority of decisions is taken, or at least supported, by the decision maker (household head or head of labour) (Kanté, 2001). Therefore, farm risk management strategies were assessed by interviewing a single decision maker.

For the three hazards the decision maker ranked as most important, he was asked to assess the risk for the last time the hazard took place. This was done by scoring the perceived impact at farm level and the frequency of this hazard taking place. Out of the 24 hazards, 20 were ranked in the top three risks of a decision maker during this exercise. First, farmers indicated the frequency of the hazard as follows: improbable (every 40 years), isolated (every 20 years), occasional (every ten years), probable (every five years), very probable (more or less every three years), every year, and several times a year (World Bank, 2016). Secondly, farmers scored the impact at farm level by answering the questions: "what were the losses at farm level related to food?" and "what were the losses at farm level related to income?" Impact scores are ranked going from none or negligible (losses <5%), moderate (losses 5-15%), considerable (losses 15-50%), to catastrophic (losses >50%) (World Bank, 2016). Specifying losses for every impact level ensures that every level has a similar meaning for every farmer. As the estimation of an exact proportion of loss is challenging for farmers, this method allowed to categorise impact, rather than to quantify it.

To assess farmer risk management, respondents were encouraged to tell the story of what happened on their farm the last time the hazard took place. By so doing we avoided hypothetical questions such as "how would your farm be affected if?" and "how would you react if?" (Azevedo et al., 2000). First, farmers described how the hazard impacted the different components of the farm (crops, livestock, farming activities) in the past. Afterwards, the respondents expanded on how they minimized losses when or after the event took place (ex-post, or reactive action). Finally, they added detail on what they are now doing to prevent losses, knowing that there is a likelihood that the hazard will strike again (ex-ante, preventive action). These preventive actions describe farmers' current management in anticipation of hazards and give insight on how farmers deal with uncertainty. In three cases the farmer did not finalise the questions, so in total 171 hazardous events were recorded.

2.2.6 Data analysis

2.2.6.1 Overall perception of hazards: analysis of ranks and scores

Out of the list of 24 hazards, all respondents ranked their five most important. The most important one was given five points, and the fifth hazard one point. For each hazard, the points given by every respondent were summed and a percentage out of the maximum score (i.e. five points times 250 respondents) was calculated.

The Likert-type scores for the concern of farmers were analysed as ordinal data (Jamieson, 2004) to assess the perception of the risk related to each hazard. Plots are constructed using the "likert" package in R. The perception was compared between both inter-household groups (farm types) and intra-household groups (gender, position in the household). First, the overall comparison of perception between groups was made for the hazards collectively. When comparing two groups, we used the Wilcoxon test, whereas for more groups the Kruskal-Wallis test was applied. The statistical test was performed simultaneously for the 24 hazards, so an adjustment of the alpha value was made using a Bonferroni correction to reduce the family wise error rate (i.e. the desired alpha value is divided by the number of hypotheses; $\alpha=0{,}05/24=0{,}002$). Secondly, if a difference in perception was established, the pairwise Wilcoxon test was used to determine which groups differed. This step included a Benjamini and Hochberg (1995) correction for multiple group testing to control for the false discovery rate. As no women held the position of household head or head of labour, the comparison between women and men excluded the men with decision power. Finally, the exercise was repeated for all hazards individually.

2.2.6.2 Impact and frequency of hazards define risk

The assessed impact on food availability and farm income was plotted against the frequency of the event happening, in line with the conceptual framework (Figure 2.1).

When hazards happened every ten years or less (occasional, isolated or improbable) and had relatively little impact (negligible or moderate), the risk was considered low. If hazards occurred every five years or more often (probable, very probable, every year or several times a year) and at the same time implied a high impact (considerable or catastrophic), the risk was high. Other combinations of frequency and impact were categorized as medium risk.

2.2.6.3 Strategies applied

Actions in response or anticipation of risks were categorised according to the farm component where changes occur (Table 2.1). Farmers were asked to describe the actions they were already applying, yet in some cases farmers described their intentions for preventive management. This minority of cases was also included in the analysis. The links between the actions applied and the hazards they are related to were visualised in a heatmap (ggplot package, R). The categorisation of management actions according to timing (reactive and preventive action) and resources used (farm component) is an intermediate step to link farmers actions to the different risk management strategies according to Schaper et al. (2010) (risk acceptance, risk reduction, risk transfer and risk avoidance). Risk reduction as a reaction to a hazard (ex-post) attempts to reduce the impact of the hazard. When applied as a preventive strategy, it can attempt to reduce of the impact but also the frequency of the hazard.

Table 2.1 Farm component categories used for the different risk management actions mentioned by farmers (NA = Non-Applicable)

Farm Component	Explanation	Farming domain	Level
Nothing	No action	NA	NA
Field	A change in the field management	Agronomic	Field
Input	A change in type, quantity and allocation of inputs	Agronomic	Farm
Crop	A change in area allocated to different crops	Agronomic	Farm
Animal	A change in animal and herd management	Animal husbandry	Animal+Farm
Consumption	A change in planned consumption and sales rates of food products	Socio-economic	Farm
Social	Farmers calling on formal and informal social networks and institutions	Socio-economic	Community
Labour	A change in family and external labour division and agreements	Socio-economic	Farm
Medical	Modern or traditional medical treatment of people or animals	Socio-economic + animal husbandry	Individual/Animal + Farm
Other	Actions that do not fit in one of the categories above	NA	NA

2.3 Results

2.3.1 Important hazards

The focus group discussions yielded a list of 24 diverse hazards farmers deemed important (Figure 2.2a and Table A.2). These hazards were associated with rainfall patterns or other environmental conditions, access and quality of inputs and equipment, the market, and social and human resources.

The most important risks were related to labour availability and weather hazards occurring at the beginning of the growing season. Family members falling ill was the major concern. Local health care services explained that malaria was the primary cause of illness. Farmers' ranking scores for this hazard added up to 65% of the maximum score, while the remaining hazards scored far less (Figure 2.2a). Cattle suffering from illness was the second ranked hazard, at 37% of the maximum score. Animal morbidity is related to the lack of feed during the dry season, which weakens the animals, and the incidence of diseases, such as foot and mouth disease in 2018 (personal communication local veterinarian, Mr. Toure). As cattle are highly valued for draught power, sick animals mainly affected land preparation and weeding, while reduced labour of household members affected weeding and harvesting (Figure A.2). The top five of most important hazards was completed with different climate-related hazards that tended to affect all crops. Rains starting late, poor rainfall distribution, or insufficient annual rainfall amount all scored around 30% of the maximum. Almost all farmers (95-100%) were medium to highly concerned about the top-five hazards related to sickness and rainfall (Figure 2.2b).

Farmers also worried about the incidence of crop pests and diseases (20% of the maximum score), and the exhaustion of the granaries during the lean season (16%). Next, farmers ranked a group of hazards related to poor quality of inputs (fertiliser (13%), seeds (11%) and pesticides (8%)). Bad quality of pesticides affected cotton production, whereas bad quality of fertilisers affected mostly maize and cotton (Figure A.2). According to some of the household heads they received fertiliser of poor quality in 2013 and 2014.

Market risks (bad market prices, and no timely access of inputs) were perceived as relatively less important (all less than 10% of the maximum score). The hazard "bad market price" can refer to both selling and buying prices. The social hazards (theft, migration and misunderstandings between household members) scored low. The specific health hazard from using pesticides was perceived least important. Overall, the hazards occurring at the end of the rainy season were perceived less important compared to those happening at the beginning or during the season. For the bottom ten ranked hazards, more than 50% of farmers are not worried (no or little concern) about the possible impact on their farm.

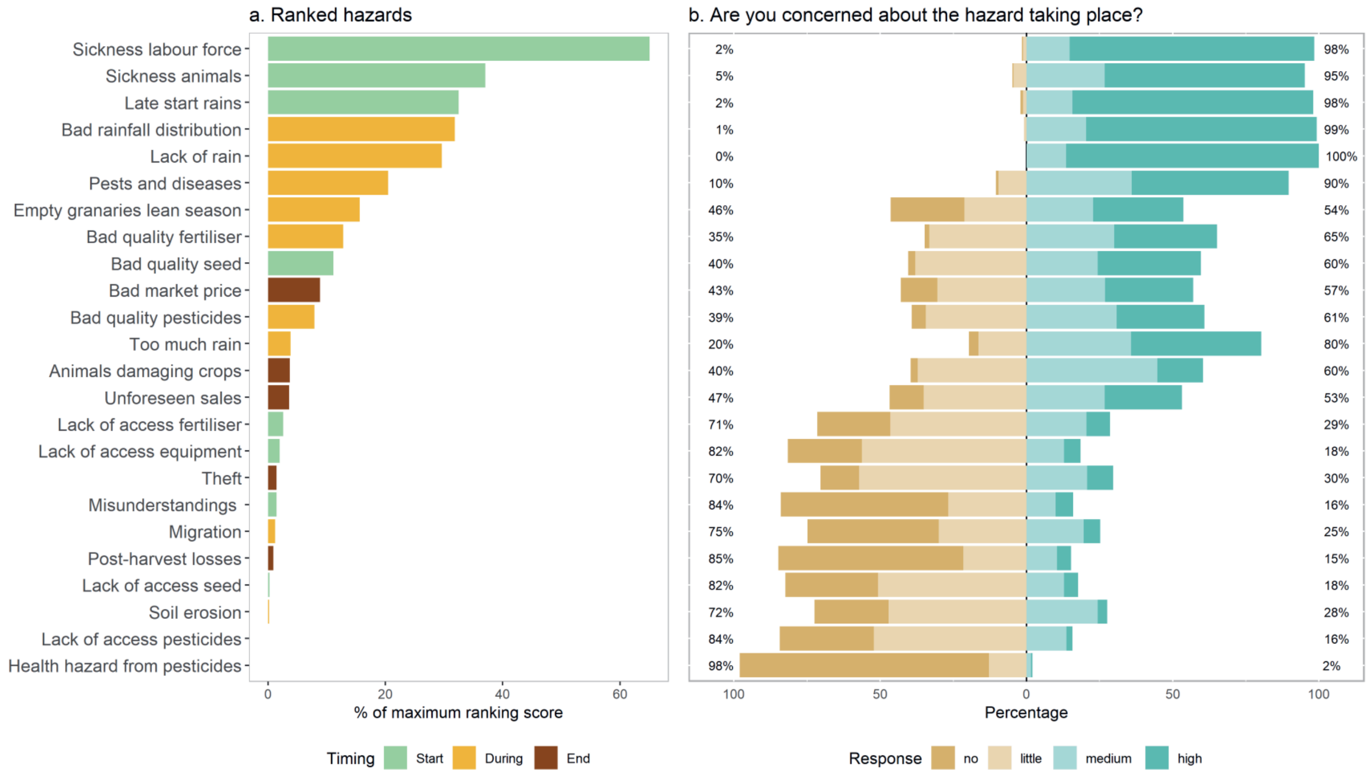

Figure 2.2 a) The 24 hazards that farmers worried most about during the focus group discussions, ranked according to importance given by farmers in surveys (expressed as the percentage of the actual score out of the maximum score of a hazard if all farmers would score it as most important). The colouring represents the timing in the growing season when the hazard is most likely to occur. **b)** The proportion of respondents answering "high", "medium", "little" or "no" to the question "Are you concerned about the hazard taking place?". The percentage on the left side is the combined % for "no" and "little", and the one of the right side for "medium" and "high".

2.3.2 Perception of risks by different groups of farmers

The overall risk perception differed between farm types (*P* = $8e^{-6}$) (Figure 2.3a). LRE and HRE households had a stronger concern than MRE and HRE-LH, although the differences are small. For six out of 24 hazards there was a significant difference in risk perception (Figure 2.3b). The farms with a large herd (HRE-LH) had a significantly lower concern than the high resource endowed without a large herd (HRE) for agricultural pests and diseases, bad quality fertiliser, and post-harvest losses. The HRE-LH also showed least concern of exhausting their granaries during the lean season compared to other farm types; the LRE worried most about this happening. The higher resource endowed farmers (HRE-LH and HRE) showed greater concern than the lower resource endowed farmers for social hazards, such as misunderstandings among household members, as well as migration of household members. Nevertheless, the general concern was low for these social hazards.

In general, men and women had a similar risk concern (*P* = 0.5) (Figure 2.4a). However, for two hazards, the concern differed significantly (Figure 2.4b). More women than men were strongly concerned about unfavourable market prices (*P* = $3e^{-5}$) and the occurrence of unforeseen sales of farm products during the year (*P* = 0.009). Farmers turn to sell farm products which were foreseen for consumption, when they are in a sudden need for cash without having the financial reserves, for example for contributing in weddings or funerals.

The risk perception differed between farmers with different positions in the household (*P* = $2e^{-16}$) for all hazards together (Figure 2.5). In general, the person with most decision power (household head or head of labour) was most concerned about all hazards taking place. Youth showed less concern. For every hazard individually, similar differences in concerns were detected. Only the hazards "health issues due to a high use of pesticides", "pest and diseases" and "theft" were perceived equally by the different groups.

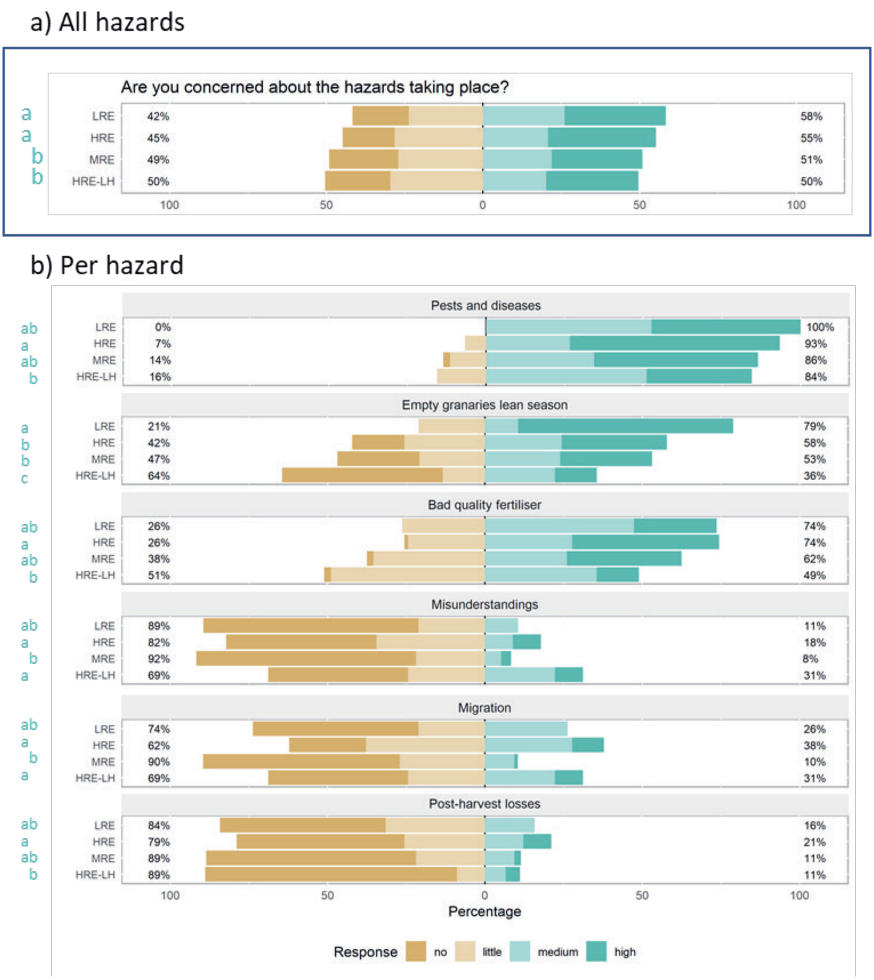

Figure 2.3 Proportion of answers on the Likert-type scale given by farmers when asked for their concern, grouped by farm types: High Resource Endowed farms with Large Herds or HRE-LH (n=45), High Resource Endowed farms or HRE (n=90), Medium Resource Endowed farms or MRE (n=96) and Low Resource Endowed farms or LRE (n=19) (farm types with the same letter do not differ significantly (P<0.05)). **a)** All hazards grouped together, **b)** Individual hazards with significantly different perception between farm types.

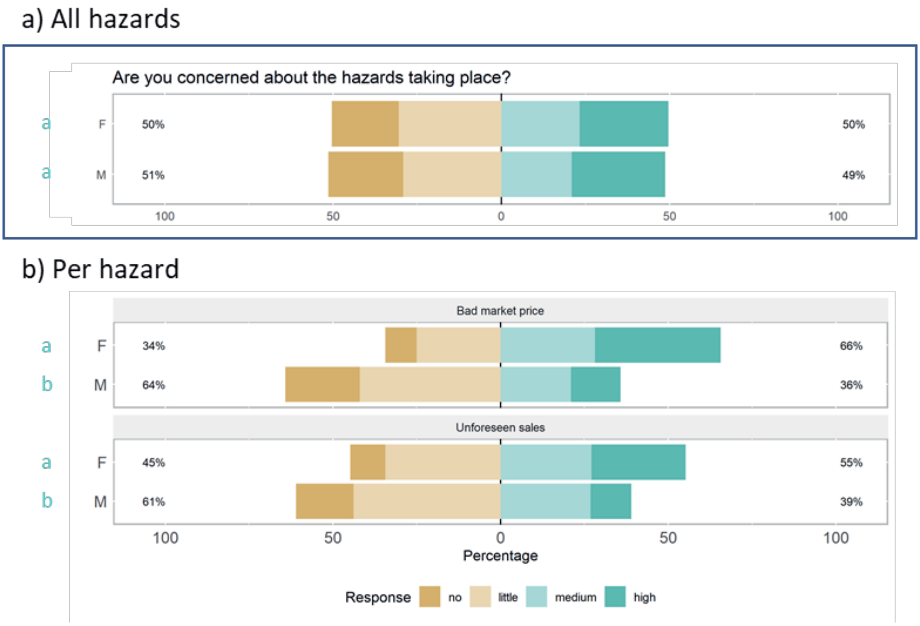

Figure 2.4 Proportion of answers on the Likert-type scale given by farmers when asked for their concern grouped by gender (M: male (n=82) and F: female (n=96) (gender groups with the same letter do not differ significantly (P<0.05)). **a)** All hazards grouped together. **b)** The individual hazards where perception was significantly different between genders.

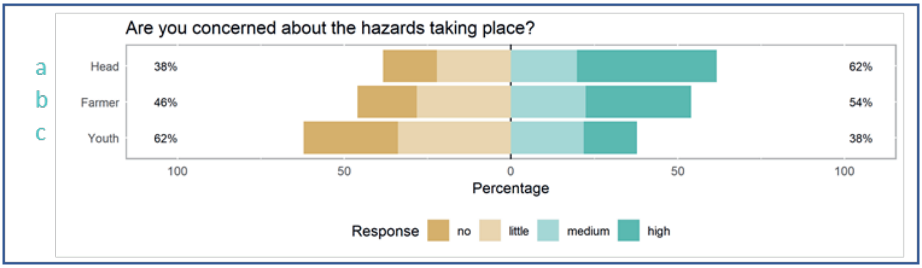

Figure 2.5 Proportion of answers on the Likert-type scale given by farmers when asked for their concern, for all hazards together, grouped by position in the household (positions with the same letter do not differ significantly (P<0.05)). "Head" includes the head of the household and the responsible for labour (n=72), "Farmer" includes male and female farmers (n=125), and "youth" includes members between 15-25 years old (n=53).

2.3.3 Impact and frequency of hazard defined risk

The perceived impacts and frequencies were plotted in Figure 2.6 to assess the perceived risk following the conceptual framework (Figure 2.1). The hazard frequencies ranged from occurring in isolation to happening annually. Farmers of all types described this diversity in frequency, except the LRE farmers, who did not report annual or isolated frequencies. Farmers remembered cases from up to 18 years ago (Figure A.1).

The impact of the hazards ranged from negligible to catastrophic, but many times remained negligible or moderate. LRE, and to a lesser extent MRE farmers, described more cases with a catastrophic impact than the other farm types. In general, the losses on income were perceived larger than the losses on food availability. The impacted crops were mainly cotton, followed by maize and sorghum (Figure A.2). In terms of farm activities, the hazards mainly impaired weeding, sowing and harvesting. Cattle was only affected in the case of the specific animal-related hazards as "livestock falling sick", and "lack of access to animal feed" (Figure A.2).

Almost a quarter of the hazards carried a high risk for income (40 cases out of 171), while 11 % of the hazards resulted in a high risk for food availability (Table A.3). Most hazards bore a medium risk (68 % and 78 % of the described cases for food and income risk respectively). Low risks were observed in 8 % of described cases for both income and food. All farm types were susceptible to risk, but the group of LRE farms was exposed to a high income risk in 44 % of the described cases compared to 20-26 % for the other farm types. The risk of lack of food was high in 33 % of cases for LRE farms, compared with 5-10 % for the other farm types.

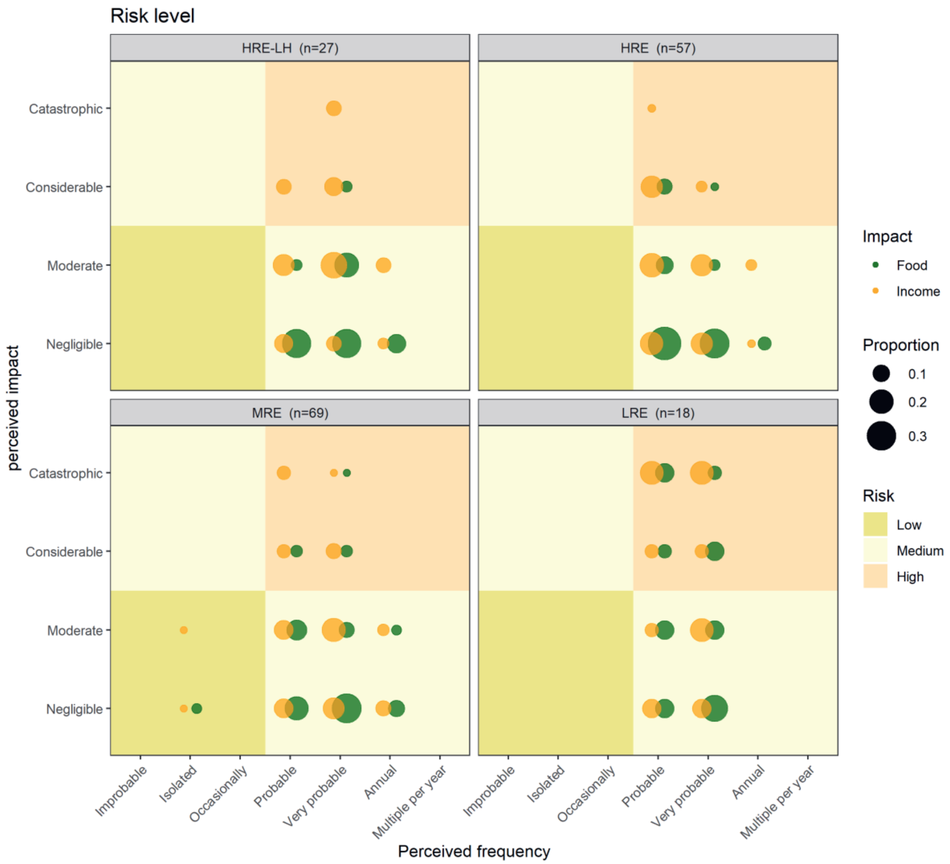

Figure 2.6. Perceived impact on food availability and income and frequency of the hazards per farm type: High Resource Endowed farms with a Large Herd or HRE-LH (n=27), High Resource Endowed Farms or HRE (n=57), Medium Resource Endowed farms or MRE (n=69) and Low Resource Endowed farms or LRE (n=18). The size of the dots indicates the proportion of farmers of that farm type who mentioned this combination of frequency and impact. The background colour of the quadrants represents the risk level. Impact scores are: none or negligible (losses <5%), moderate (losses 5-15%), considerable (losses 15-50%), catastrophic (losses >50%). Frequency is indicated as follows: improbable (every 40 years), isolated (every 20 years), occasionally (every 10 years), probable (every 5 years), very probable (more or less every 3 years), annually, and multiple times a year.

2.3.4 Risk management strategies

Farmers applied a broad range of both reactive and preventive risk management actions (Table 2.2, Figure 2.7). Nevertheless, many farmers accepted the risk without applying a reactive response (23% of the cases), and this for a diversity of hazards. In addition, in 30 % of cases farmers mentioned not to apply preventive actions.

With respect to the agronomic domain, farmers adapted their field management in 19% of the cases by re-sowing, possibly with another variety, or changing the harvesting date. Specific changes in input management (13% of reactive cases) included increasing the dose of fertiliser, buying a new product when the quality seemed inadequate, or applying the fertiliser to other crops. Whereas field and input management were less common as preventive strategy (9% and 8% of cases respectively), changing the choice of crops (e.g. growing more fodder crops) at farm level was used more often as a preventive (15%) compared to a reactive action (10%).

Changing animal management is mentioned as a reactive (15%) and preventive (11%) action to increase draught power (buying or borrowing oxen), or to obtain cash (selling animal). Farmers tried to adapt the storage of feed and feeding regimes to keep the animals healthy during the dry season.

Other management occurred in the socio-economic domain. Adapting the amount of sold cereals was mostly a reactive action (11%). Some farmers consumed less diverse food than they preferred when hazards affected their food availability. In 16% of the cases, farmers relied on their social network to ask for remittances, loans or credit in the village. Farmers did not rely on official credit schemes for cash. As a preventive action, farmers saw benefits in joining cooperatives, or less formalized group sales (16%). To a lesser extent, farmers adapted the labour division of household members (10% reactive, 5% preventive) or hired people. Sending household members to conduct off-farm labour was both an ex-post and ex-ante action. Medical treatment was applied for mitigating health risks of people and animals (18% reactive, 15% preventive), by applying both traditional and modern care.

Most actions were part of a risk reduction strategy (Table 2.2). Farmers that did nothing accepted the risk. Risk transfer occurred through social interactions. Agricultural risk avoidance could only be seen in seeking off-farm labour or migration when this would replace agricultural production. However, in our results, off-farm work was an addition to farming rather than a replacement.

For most hazards, no action appeared as the standard solution used by all farmers. Figure 2.7 and Figure A.4 illustrate that a diversity of actions was applied per hazard, and that a single action could be used for different hazards. For example, changing field management (for 13 different hazards), changing labour assignments (ten hazards), changing consumption patterns (nine hazards), and calling on social interactions (eight hazards) were applied as reactions to a large range of hazards (Figure 2.7). Medical action was very much targeted to the hazards of human and animal health, yet it was not the exclusive action. For example, to obtain cash for treatment some farmers mentioned selling cereals (reducing consumption of own cereal produce; farm component "consumption") or animals (component "animal"). Weak animals prompted some farmers to switch from animal labour for land preparation to mechanical labour by renting a tractor (component "field") or to using draught power by cows instead of oxen (component "animal"). The ex-post actions were more diversified for the higher ranked hazards compared to the hazards perceived as less important.

With respect to preventive management, farmers relied on social and institutional interactions for several hazards (ten) (Figure A.4), such as trying to influence CMDT for guaranteeing quality and uniformity of inputs. Likewise, adapting crop choice was commonly applied for nine hazards. Namely for the climate-related hazards, farmers included early maturing cereal varieties on their farm, or increased the area of millet, which is more drought-resistant.

All farm types applied a similar range of management actions (Figure 2.8). However, the higher resource endowed farms (HRE, HRE-LH), who also have larger herds, referred to animal related actions more often. LRE did not mention changes in input use and field management but adapted cereal consumption rates more frequently as a response to hazards affecting the farm. All farm types called upon social interaction, yet the HRE-LH to a lesser extent.

Table 2.2 Examples of reactive and preventive risk management actions (reactive or preventive), categorised according to the farm component where change occurs, and the percentage of the cases in which that action was applied of the total number of risk cases described (n=171). The set of actions is linked to the corresponding risk management strategies following (Schaper et al., 2010).

Farm Component	Reactive risk management actions (ex-post)		Preventive risk management actions (ex-ante)		Risk management strategies applied
	%	Examples	%	Examples	
Nothing	23	-	30	-	Acceptance
Field	19	Change variety; re-sow; harvest early	9	Early maturing varieties; spread sowing dates; germination test	Reduction
Medical	18	Traditional or modern medical treatment	15	Traditional or modern preventive treatment	Reduction
Social	16	Remittances; borrow oxen, seeds or food in the village; get credit	16	Sell in group; associate with cooperatives; keep family reunions	Transfer, Reduction
Animal	15	Sell animal; stall feeding; buy or loan ox	11	Buy animals; store more fodder	Reduction
Inputs	13	Increase dose of fertiliser; buy other product; change targeted crops	8	Increase production of organic fertiliser	Reduction
Consumption	11	Buy or sell more cereals; consume lower diversity of food	3	Calculate how much cereal the family needs and store this amount; sell less	Reduction
Crops	10	Reduce cropped area; change crops	15	Cultivate fodder; reduce cropped area	Reduction
Labour	10	Work harder; hire labour; off-farm labour	5	Off-farm labour	Reduction, Avoidance
Other	0	-	8	Build a granary; buy material	Reduction

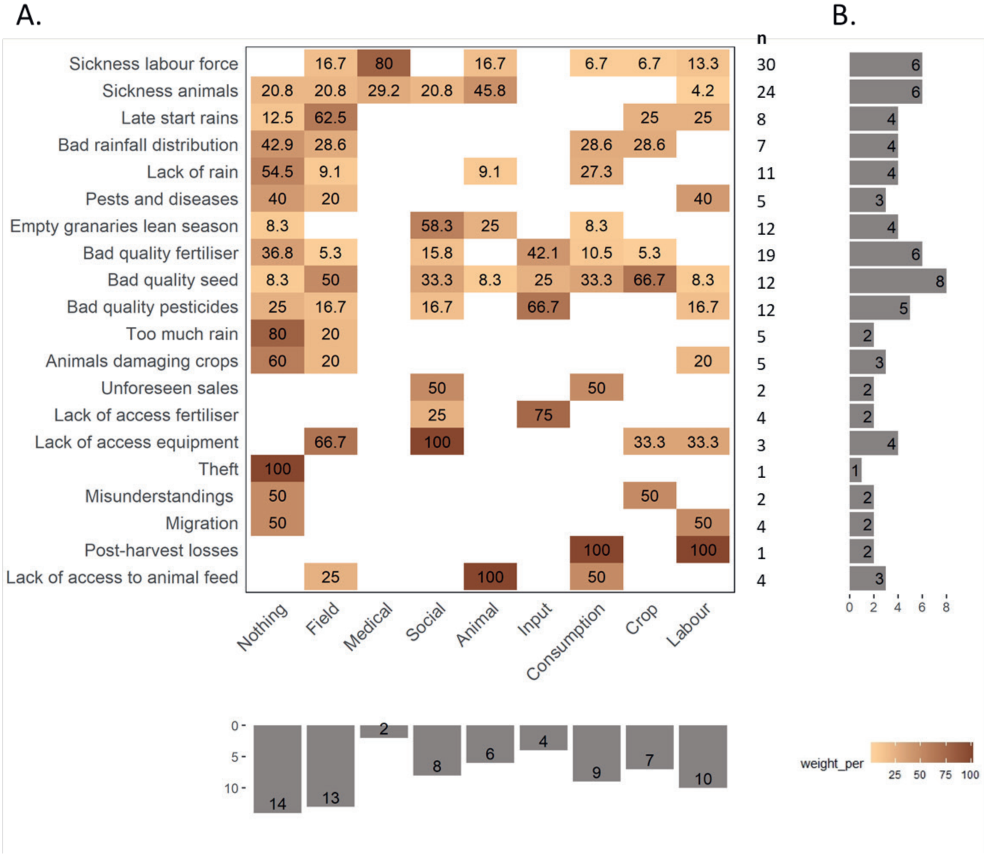

Figure 2.7 A) Heatmap of the actions per farm component applied as reactive management to the different hazards, with the intensity of the colour representing the abundance of an action to deal with a hazard. The number in the boxes represents the percentage of cases that a specific action was applied out of the number of hazard cases described by farmers (n). Several actions could be applied simultaneously by the same farmer, so that the sum of the rows is 100% or more. The hazards are ordered according to farmers' ranking, and the actions are ordered according to the number of times they were applied (total count). **B)** The bar chart on the right represents the number of actions that have been applied for every hazard. **C)** The bar chart on the bottom shows the number of hazards for which that action has been applied.

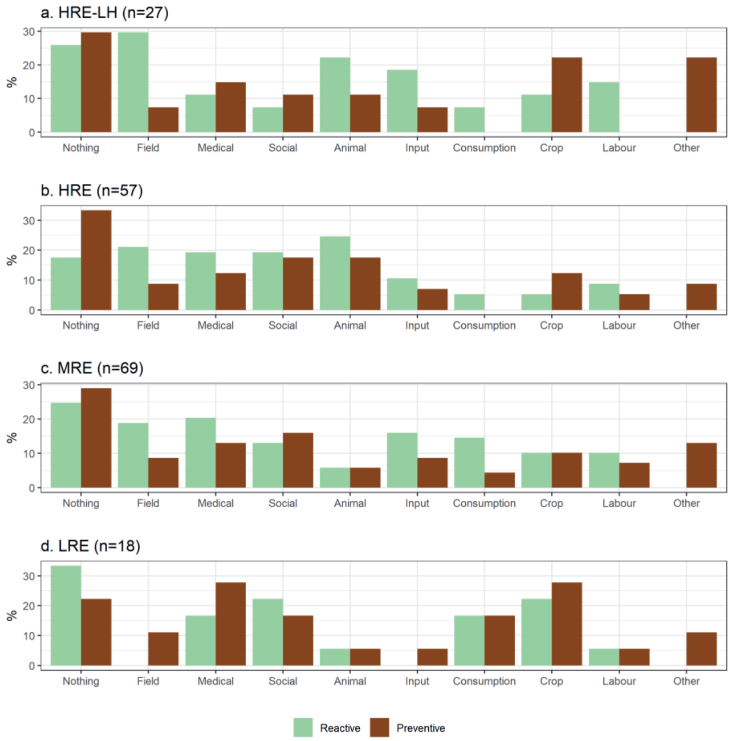

Figure 2.8 Bar charts for the four farm types representing the percentage of the times a reactive or preventive management action was applied out of the total number of hazards described. The four farm types are High Resource Endowed farms with a Large Herd (HRE-LH), High Resource Endowed farms (HRE), Medium Resource Endowed farms (MRE) and Low Resource Endowed farms (LRE).

2.4 Discussion

2.4.1 An agricultural system with abundant risks

Climate-related hazards were important for farmers, in line with literature that describes the frequent risks of weather variability, which are likely to increase with climate change (e.g. Akumaga & Tarhule, 2018; Schmitt Olabisi et al., 2018; Tiepolo et al., 2018). Yet farmers had concerns for a much broader range of hazards (Figure 2.2), which are often not given enough attention (Komarek et al., 2020). Indeed, we identified health hazards as the most worrying for farmers. Also in other regions in Mali, farmers prioritized health above the need to improve land use practices (Ollenburger, 2019). Paradoxically, the health hazard from using pesticides was perceived to be least important. Nevertheless, in Mali pesticides are applied mainly on cotton and given the rare use of protective gear, this can be hazardous to health (Jepson et al., 2014). The large perceived importance of hazards related to the health of livestock affirmed livestock's importance for traction, manure and as a capital source (Van Dijk et al., 2004; Traoré et al., 2017). Decreasing forage and water resources during the last 30 years (Umutoni & Ayantunde, 2018) contributed to the difficulties of keeping animals healthy during the dry season. Finally, farmers doubted the quality of fertiliser acquired from the CMDT, which has been criticised openly in the past for providing low-quality inputs to contracted farmers (RFI, 2015; Theriault et al., 2018). This emphasises the need for institutions to guarantee input quality and (re-)build trust with the farmer community (Theriault et al., 2018).

The highest-ranked hazards occurred at the start of the growing season, which is a critical period for farmers' decision making (Traore et al., 2014). When the rainy season starts, farmers prepare their fields in a narrow time window (Soumaré, 2008), so if this start is disrupted, because of labour shortages or untimely access to inputs, the yield of maize, sorghum and cotton is often reduced (Traore et al., 2014). A further difficulty occurs when rains start late, forcing farmers to adapt their planning or to include short-cycle varieties, which usually have a lower yield potential (Traore et al., 2014; Traore et al., 2017). Also other periods of the year were risk-prone due to weather hazards and crop pests and diseases. Indeed, intra-seasonal climate risks are well described for this agro-ecological zone (Boansi et al., 2019) with dry spells negatively affecting crop growth especially during July and August. Hazards happening after the cessation of rain mostly affected the availability of food in the granaries (unforeseen sales, post-harvest losses, theft).

Surprisingly, market risks were of relatively little concern. This contrasts with risk assessments carried out elsewhere in Africa, where the volatility of crop prices was an important source of risk (Kisaka-Lwayo & Obi, 2012; Gebreegziabher & Tadesse, 2014). Farmers in northern Ghana for example ranked variability of input (fertiliser) and product (crop) prices as the second and third most important risks (Asravor, 2018). In Mali however, both the access to subsidised fertiliser on credit and the guaranteed off-take of the main cash crop cotton is coordinated by the CMDT (Theriault & Tschirley, 2014; Laris et al., 2015). Although fluctuating world prices of cotton affected farmers in the past (Van Dijk et al., 2004; Falconnier et al., 2015), normally cotton and fertiliser prices are fixed well before the start of the season so that farmers can incorporate this knowledge in their seasonal planning. Hence, the presence of CDMT possibly buffers some of the market risks to which farmers would otherwise be exposed. Another possible explanation for low perceived market risks, is that most farms are food self-sufficient (Falconnier et al., 2018) and therefore relatively independent of the market for their basic food needs.

2.4.2 Uniformity, as well as diversity, in risk perception

Our analysis showed that perception differed among and within households, but that differences were small and often occurred for specific hazards that were not ranked in the top five (Figure 2.3, Figure 2.4, Figure 2.5). In other words, the most important risks were of concern for everyone.

Much literature suggests that women in sub-Saharan Africa are more vulnerable to climate related hazards than men (Perez et al., 2015), linked, among others, to a gender-based division of labour in agriculture, and unequal access to land and equipment (Droy et al., 2012b; Guirkinger & Platteau, 2015; Paresys et al., 2018). However, no gender-defined pattern was observed in our data on risk perception, except for market risks (Figure 2.4). Women mentioned they often sell vegetables or household products on a small scale in order to buy condiments or small goods for the family. Hence, they have more regular market contact, compared with men who are involved in seasonal transactions of cotton and cereal. In the Sahelian region of Senegal differences in preoccupations between women and men mostly related to constraints rather than risks (Tschakert, 2007). Similar as in our study, Senegalese farmers' mainly worried about health, which was ranked equally by men and women.

We found the clearest difference in risk perception between generations, with the household heads and the heads of labour most concerned (Figure 2.5). As in similar farming systems in West Africa, decision power is related to gender and generation (Michalscheck, 2019). As risk concern tends to decline with age (Asravor, 2018), decision power probably is a better explanatory factor for risk perception than age itself, or gender. Rural youth often have other aspirations than a life in farming (Van Dijk et al., 2004) and seek education and employment through (seasonal) migration (Kanté, 2001). Possibly the tempered interest in farming, next to limited decision power in the household, lowered the risk perception of young people.

The positive relationship between resource endowment and land productivity in southern Mali (Falconnier et al., 2015) did not translate into large differences in risk perception between farm types (Figure 2.3). However, the two farm types (LRE and HRE) with the lowest income per capita (Falconnier et al., 2018) had a slightly, yet significantly higher concern for risks. HRE have more resources at farm level than MRE, but they also have more mouths to feed (Falconnier et al., 2015). Likewise, with more people in the household it is not surprising that both the HRE-LH and HRE had a greater concern for hazards related to social interactions than the two other farm types.

LRE farmers were not only more concerned with hazards, but also described the impact, especially on food availability as more severe compared to other types of farmers (Figure 2.6). The relatively high food availability risk implies that LRE farms lack food surplus or income to compensate for some of the food production losses. In contrast, when a hazard affected the better-off farms, the impacts more often remained negligible or moderate. Indeed, Struif Bontkes and van Keulen (2003) found that farmers who cultivated larger land areas were more prepared and capable to take risks than farmers owning less land. Even then, also the better endowed farmers were very concerned for risks. Although farmers are generally food self-sufficient, only 25% of farms, mostly the HRE-LH, are both above the poverty line and food self-sufficient (Falconnier et al., 2018). Hence, the majority of farmers are vulnerable to losses, which may induce a poverty trap when resources are used to recover from shocks and can no longer be used to invest (Hansen et al., 2019). Furthermore, several hazards occurring in the same year (Figure A.1) can aggravate losses, which may influence the perception on impact of each individual hazard.

Our results (Figure 2.6) did not confirm the expected prevalence of hazards occurring with low frequency-high impact on the one hand and high frequency-low impact on the other hand (World Bank, 2016). Whereas the risks in Figure 2.6 reflect farmers' interpretation of the hazards they find most relevant in their farming system, additional hazards with other frequency-impact combinations may exist. Farmers' concern for high probability hazards could possibly be explained by farmers' vulnerability, since the majority lives below the poverty line. As such, any small shock could already be perceived substantial, because even relatively moderate losses may surpass farmers' reserves. When hazards happen very often, the degree of uncertainty disappears and they could be defined as constraints instead. Nevertheless, we interpret the listed hazards not as constraints because they all relate to an event and not to a fixed state and in interactions with farmers the uncertainty of hazards was emphasised. Moreover, a minority of farmers said that the hazards happened every year.

2.4.3 Diversity of risk management strategies

Farmers dealt with a diversity of hazards through applying diverse strategies; there was no single solution for every specific problem (Table 2.2, Figure 2.7 and Figure A.4). Diversification is common for communities in semi-arid areas to deal with uncertainty and variability (Mertz et al., 2008; Mubaya & Mafongoya, 2016), which can effectively mitigate the everyday risks farmers face (Brouwer et al., 2007). The available resources used to deal with risks differed slightly between farm types (Figure 2.8). For example, higher resource endowed farms (HRE-LH and HRE), with larger herds (Table A.1), relied more often on livestock, whereas LRE farms called more on social interactions. To structure the diversity of risk management actions, we discuss them according to the following four strategies: risk acceptance, reduction, transfer and avoidance in the following paragraphs (Schaper et al., 2010).

Risk acceptance was common. Many farmers in our study did not deal with hazards, especially not through preventive actions and when applied, these were mostly short term. First, this could be explained by a lack of knowledge on feasible risk management strategies, or investment needs beyond the farmer’s capacity (Schaper et al., 2010). Secondly, farmers possibly do not apply actions for specific hazards, but have risk spreading inherently built into the farm structure by diversifying crops, varieties and livestock on their farms (Mertz et al., 2008). Some farmers said that they did not apply any action, except for praying or making traditional sacrifices. When related to rainfall events, the latter is often a communal activity and demands some investment and solidarity from farmers (Jonckers, 1976). We categorized these actions as “risk acceptance”, since farmers themselves classified them as “doing nothing”. Overall, farmers focused more on ex-post risk management, and not as much on specific risk management planning that deals with uncertainty.

Actions categorised under risk-reduction were applied with the intent to decrease the farms’ sensitivity to the impact (e.g. selling animals to generate income), or to decrease the probability of the hazard (e.g. preventive health treatments). The reactive actions only intended to reduce the impact, and indicated the flexibility of farmers’ management when a hazard strikes. For example, farmers commonly change the planned variety of a crop when rains start late. Farmers applied reactive and preventive risk reduction through diversifying agronomic technologies or by using productive assets to overcome losses.

Diversification was a common risk reduction strategy at field and farm level. For example, sowing dates were targeted strategically or spread. The former could increase production (Traore et al., 2014), while the latter decreases chances of crop failure (Milgroom and Giller 2013). Next, farmers mentioned to increase fodder crops in their rotation. Improving feeding regimes of cattle through stall feeding in the dry season can improve the health of animals and increase the potential of milk production (de Ridder et al. 2015). Furthermore, farmers sent family members to do off-farm work to have another source of income. This can provide a safety net and help in maintaining food security (Douxchamps et al. 2016).

Using productive assets as a risk reduction strategy can lead farmers into a poverty trap (Hansen et al., 2019). Farmers mentioned to work harder or consume less diverse foodstuffs. Wichern (2019) describes this same strategy by poorer farmers in Uganda who have limited options for coping with climate variability. Especially the larger farms (HRE-LH and HRE) sold livestock to cope with losses. This is a common coping practice in time of food shortage for farms with a cattle herd (Traoré et al., 2017; Wichern, 2019), whereas farmers owning few livestock typically turn to borrowing cash (Traoré et al., 2017).

With respect to risk transfer, social interactions were very important for farmers who relied on family and community members in time of need, or when preparing for risks in the future. As farmers did not mention formal insurance schemes, risk transfer only happened informally by farmers borrowing from each other or relying on remittances. Although some farmers sold cereals in group, transferring the risk to buyers through long term contracts with guaranteed prices was not mentioned for products other than cotton. This means there is scope to strengthen the role of cooperatives to increase farmers' negotiating power, as well as to investigate opportunities for insurance schemes. However, such formal structures may damage the existing social cohesion (Sidibé et al., 2018). Perez et al. (2015) suggest that interventions in the social domain should be gender sensitive, since men and women rely on different kinds of networks. Men tend to join formal, regional networks more easily, while women usually connect to informal groups within the community.

Besides risk acceptance, reduction and transfer, the fourth strategy is risk avoidance (Schaper et al., 2010). However, our results do not include such actions, since we asked for hazards that they worried about. This implies that they were still exposed to the hazard. Nonetheless farmers, especially LRE, reported on hazards with high impact and probability (Figure 2.6), which suggests that farmers have no other choice than to keep farming and do not have the means for risk avoidance. In addition, although farmers are poor and potentially caught in a poverty trap, they seem to be able to overcome regular and substantial losses, suggesting robustness of the farming system as a consequence of the diversity of risk management practices. Yet, this robustness may suggest the households are simply "hanging in" (Dorward, 2009), and the R4 Rural Resilience Initiative (WFP & Oxfam, 2019) suggested that livelihoods could be improved if farmers would have the means to take prudent risks. This could also enhance the adaptability and transformability of the system, which together with robustness, are key components of resilience (Meuwissen et al., 2019).

2.4.4 Methodological considerations for future research

We focused on farmers' interpretations of the hazard, as well as their perceptions on and experiences with those hazardous events. The consequences of this approach need to be considered when interpreting the results. Firstly, the hazards are not independent of each other (Brooks, 2003). For example, when farmers are confronted with empty granaries, this is a result of one or more other hazards such as production shocks (pests, bad rainfall) or post-harvest losses. Simultaneous incidence of hazards makes it hard to measure the exact contribution of each event to the impact (World Bank, 2016). Secondly, some hazards could also be interpreted as representing a longer lasting trend, such as the incidence of soil erosion, or the lack of animal forage (Umutoni & Ayantunde, 2018). Finally, interpretation of risk and risk management may differ between farmers and researchers. We tried to minimise this by setting clear definitions, conducting several rounds of discussions, and involving local, trained enumerators in the survey work.

Our analysis gives a snapshot in time. Risk perception can be dynamic in a changing environment (van Winsen et al., 2011) or be stable over time (Wustro & Conradie, 2019). In our research there are arguments for both possibilities. For example, in 2018 the region was struck by foot and mouth disease, which was relatively unknown to farmers and could have influenced the focus on animal health hazards. All data is based on farmers' perception and recollection, so the recall period may have influenced their answers (Nikoloski et al., 2018). The period in which the survey was conducted spanned the course of the rainy season (May-October 2018). This may have directed farmers' attention towards common hazards for that specific time. Furthermore, younger respondents might be less influenced by hazards that are infrequent and did not occur yet during these farmers' lives. Many farmers indeed described recent events, but some farmers recalled events that happened almost 20 years ago (Figure A.1).

The approach enabled us to assess the diversity of risks encountered by farmers, filling a gap in risk research which often focuses on a single hazard (Komarek et al., 2020). This research describes applied and intended strategies but does not intend to assess their effectiveness. Quantifying the effects of hazards on farm production, as well as the mitigating effects of farm management and policy strategies could shape a following step of research.

2.5 Conclusion

Farmers deal with a broad range of risks, with production and human risks more important than financial, legal or market risks. Human and animal health, and climate-related hazards were of great concern for everyone, regardless of the farmers' resource endowment. Risk perception differed among farms and household members with the largest difference between generations and degrees of decision power. Farmers reacted to these risks with a variety of practices, although many farmers had no solution, especially for preventing risks. Both the hazard and the risk management strategies are influenced by off- and on-farm factors. Whereas research on poverty alleviation has often focused on on-farm components (Brooks, 2003), our findings suggest a need for research and policy to develop both off- and on-farm innovative options to enable farmers to adequately react to and prepare for risks. For example, farmers who want to diversify their varieties need access to good quality seeds; farmers who want to form a cooperative need information and formal means to do so; access to a local weather forecast could help farmers in preparing their field management. The hazards (partly) born outside of farmers' influence emphasise the need for improvements in health care, opportunities for off-farm work and farmers' capacity building. Providing access to micro-credits, could allow households to invest in their farms and take prudent risks that also carry the opportunity to improve their livelihood (as is promoted by the R4 Rural Resilience Initiative (WFP & Oxfam, 2019)).

With respect to on-farm management options, our risk analysis identified some key traits of suitable options for the risky environment of southern Mali. Options should (i) be complementary to each other in their suitability for different weather situations, (ii) not increase labour requirements especially in the beginning of the season, (iii) focus on quality fodder production to improve feeding regimes of cattle, or (iv) strengthen cooperation or increase negotiating power of farmers.

The differences in risk perception and management between farm types were subtle, but taking into account the available resources of farm types they suggest how to tailor options. The impact of hazards on food availability was relatively strong for the poorer households. Therefore, food security should be a main priority for LRE farms. These farms also rely on their social network and could be supported in joining community associations. Options for better animal management could be targeted to the higher resource endowed farmers. The complexity of farmers' risk realities indicates that development interventions should address both socio-economic wellbeing and agronomic options to improve the livelihood and resilience of farmers in southern Mali.

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Related databases

Huet, E. K. (2021a). *Risk Perception of Farmers in the Koutiala Region of Mali.* Africa RISING, IFPRI. Harvard Dataverse. Retrieved from: https://doi.org/10.7910/DVN/IW8V0R

Huet, E. K. (2021b). *Perception of Frequency and Impact of Risks in the Koutiala Region of Mali.* Africa RISING, IFPRI. Harvard Dataverse. Retrieved from: https://doi.org/10.7910/DVN/UYBO97

3 Coping with cereal production risks due to the vagaries of weather, labour shortages and input markets through management

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Abstract

Production of cereals (maize, sorghum, millet) in southern Mali is challenged by several hazards that affect yield and yield variability. The research aims to inform decision making towards effective risk management by quantifying cereal yield losses at field level due to production hazards under different management strategies. Five hazards relevant for farmers were analysed: late onset of rains, insufficient total rainfall, dry spells, low fertiliser quality and sudden lack of labour. The frequency and impact on yield of these hazards were assessed by combining a long term weather database (1965-2019) with outputs of the DSSAT crop model (baseline and optimised variety, fertiliser rates and sowing dates), and visualised in a risk matrix. The prevalence of the weather hazards was common, with all of them occurring at least once every five years. Frequency of non-weather hazards were perceived to occur once every five years (labour hazards) and once every ten years (fertiliser hazards). Under baseline conditions maize (3.39 t / ha) outperformed sorghum (1.74 t / ha) and millet (1.33 t / ha), except in cases of fertiliser hazard when sorghum yielded more than maize. Maize responded relatively well to N application, and sorghum performed relatively well without N application. The benefit of millet resided in low yield variability, and lower sensitivity to the weather hazards. Changing management to optimise yields generally involved early sowing (22 days, 2 days and 27 days after onset for maize, sorghum and millet), increased N applications (66 kg N / ha, 27 kg N / ha and 111 kg N / ha for maize, sorghum and millet), and using short duration varieties. For millet the long duration variety was more beneficial. For maize there was opportunity to increase the yield without affecting the risk of yield loss, while for sorghum there was a synergy and for millet a trade-off between yield increasing management and risk. The different interactions between hazards and management for the three cereals stress the importance of maintaining farm diversity, as well as operational farm flexibility to respond to production risks.

Key words

hazard, maize, millet, sorghum, West Africa, crop model

3.1 Introduction

Smallholder farmers in West Africa are challenged by a diversity of agricultural risks for both food production and income (Huet et al., 2020; Komarek et al., 2020), with climate change likely to increase the hazards (Campbell et al., 2016; IPCC, 2012). The risk for farmers depends on both the impact of a hazard and the frequency with which it occurs (World Bank, 2016). In such volatile circumstances, much research focuses on how farmers can build resilience because they are vulnerable to hazards and the resulting production variability leads to food insecurity and low income (Kloos et al., 2015; Bullock et al., 2017; Meuwissen et al., 2019). Further, climate hazards are linked to migration and conflicts, although this relationship is complex and remains debated (Benjaminsen et al., 2012; Mach et al., 2019). By understanding the extent of risks and identifying possible mitigation measures, research can generate knowledge needed to build farmers' resilience. Such risk information helps farmers to fine-tune farm management and helps policy makers to define policies to mitigate risk (Descheemaeker et al., 2016).

In Sudano-Sahelian farming systems, cereals play a central role as staple crops, contributing to food self-sufficiency, as well as generating income (Falconnier et al., 2015). Current cereal yields remain far below the water limited potential (ten Berge et al., 2019; Adam et al., 2020). In addition, yields vary strongly between fields, farmers, and years (Falconnier et al., 2016). For example, in the cotton zone of Mali farmers obtain average maize (*Zea mays* L.) yields of 2 t / ha, while 5 t / ha is obtained by some in good years (Traore et al., 2014; Falconnier et al., 2016). Sorghum (*Sorghum bicolor* (L.) Moench) and millet (*Pennisetum glaucum* (L.) R.Br.) yield less: on average 0.9 and 0.8 t / ha with maxima of around 3 and 2 t / ha respectively (Traore et al., 2014; Falconnier et al., 2016; Adam et al., 2020). Crop yield variability is partly induced by incidences of hazards, including climate hazards (Aune & Bationo, 2008; Schmitt Olabisi et al., 2017; Akumaga & Tarhule, 2018), pest attacks (Schlecht et al. 2006) and farmer or animal illness (Huet et al., 2020; Segnon et al., 2020).

Farmers' perceptions and attitudes towards such hazards guide crop management decisions to prioritise either maximising or stabilising yield (Descheemaeker et al., 2016; Khumairoh et al., 2018). Furthermore, smallholder farmers apply several measures to deal with risks in semi-arid regions. For example, farmers might target or spread sowing dates strategically (Milgroom & Giller, 2013; Traore et al., 2015), plan fertiliser use carefully (Piha, 1993; Freduah et al., 2019; Adam et al., 2020), or use diverse varieties that have a different response to stress (Frison et al., 2011; Adam et al., 2018). Many risk management decisions are operational or tactical, which means they are planned and implemented on a short- to medium-term horizon going from a couple of days (e.g. adapting fertiliser application, harvest timing, pest management) to a couple of months (e.g. land allocation, selection of crop cultivars, planning of fertiliser application) (Nissan et al., 2019). The long-term strategic decisions that farmers implement are diversification (Mubaya & Mafongoya, 2016) and maintaining flexibility so that they are prepared for, and can adapt to occurrences of hazards that influence crop production (van Noordwijk et al., 1994; Brouwer et al., 2007). However, the effect of these management decisions in the face of hazards, both in terms of average yields as yield variability, is often not well quantified for West African cropping systems.

Crop growth models, combined with long-term weather data, are powerful tools to assess crop production risks (van Noordwijk et al., 1994; Ewert et al., 2015). In West Africa, crop models have been extensively used to understand the response to climate change (Traore et al., 2017; Amouzou et al., 2019; Sultan et al., 2019; Defrance et al., 2020). Less literature describes the effects of current seasonal variability (e.g.Fosu-Mensah et al., 2012) or non-climate related hazards. Yet, understanding how farmers can deal with current variability helps to design risk management strategies for a future affected by climate change (Cooper et al., 2008). When crop models are used to assess risks they are also often focused on a single crop, and on a limited set of management practices without including their interaction (Ewert et al., 2015), or on the impact without taking into account the frequency of the hazard (Challinor et al., 2018). Of the three cereals commonly grown in the drylands of West Africa (maize, sorghum, millet), millet is less investigated through crop models (e.g. Akponikpè et al., 2010).

In this paper we address the above knowledge gaps by using a crop model to explore impacts on three major cereal crops in southern Mali, a region prone to risks as is much of semi-arid West Africa. The research aims to inform decision making towards effective risk management by quantifying cereal crop yield losses at field level due to the interactions of different production hazards under varied management strategies. Firstly, we assess the frequency of the most important hazards in the region. These hazards were identified and defined by farmers; a starting point deemed crucial by Challinor et al. (2018) for a meaningful risk assessment. Secondly, we quantify the impact of the hazards on crop yields and explore how current and optimised management practices influence yield and yield stability. Additionally, frequency and impact of the hazards are combined in a risk matrix for both current and optimal management. Finally, we explore the interaction effects of management factors (variety, sowing dates, fertiliser rates and soil type) on yield to understand where the baseline and optimal management are situated within the decision space available to farmers.

3.2 Methods

3.2.1 Site description

Our study area comprises the rural area around Koutiala (12°23′ N, 5°27′ W) in the cotton zone of southern Mali, located in the semi-arid, Sudano-Sahelian region. With Lixisols as the dominant soil type (FAO, 2006), farmers recognise three subgroups (Falconnier et al., 2016): sandy soils were most common on farmers' fields, occupying 65% of the cultivated area, followed by black (25%) and gravelly soils (10%). Agriculture is rainfed during a unimodal rainy season between May and October.

Farmers aim to cultivate sufficient maize, millet and sorghum to feed their households (Kante, 2001). Income is generated by cultivating cotton and by selling their surplus of cereals, especially maize (Bosma et al., 1999; Losch et al., 2012; Falconnier et al., 2015). On average farmers cultivated 12.6 ha and targetted 8.6 ha to cereal production, of which 27% was maize, 30% sorghum and 43% millet. Crop-livestock interaction is important in this farming system with crops providing feed and livestock providing manure, as well as draught power and cash (Kanté, 2001; Van Dijk et al., 2004).

3.2.2 Hazard identification and general approach

Huet et al. (2020) described the hazards that farmers perceived important. Here we consider a subset of these hazards that affect cereal production (Table 3.1). The risk of these hazards is quantified by the simulated impact on cereal yield and the frequency with which they occur.

The frequency of weather hazards was analysed based on long-term weather data (see section 3.2.3). For the additional hazards, such as sickness of animals or labour force, and bad quality of fertiliser, the frequency was estimated by farmers as described in Huet et al. (2020). The crop response to hazards was evaluated by comparing simulated yields under hazardous and non-hazardous conditions. The non-weather hazards were reflected by changes in crop management practices (Table 3.1) which can be captured by a crop model.

Table 3.1 The hazards farmers ranked as having strongest impact on cereal production according to Huet et al. (2020).

Hazard	Rank	Risk assessment	Hazard type
Sickness labour force	1	Evaluate impact of late sowing because of labour shortage	Non-weather
Sickness animals	2	Evaluate impact of late sowing because of labour shortage	Non-weather
Late onset	3	Evaluate frequency and impact of late start rains	Weather
Bad rainfall distribution	4	Evaluate frequency and impact of dry spells during the growing season	Weather
Lack of rain	5	Evaluate frequency and impact of low total yearly rainfall	Weather
Bad quality fertiliser	8	Evaluate impact of smaller N application rate (set to 0 kg N / ha)	Non-weather

Table 3.2 Farmers' definition of weather hazards, complemented with information from literature and definition of thresholds.

Hazard	Farmers' definition of hazard	Threshold	Level of hazard	Rainfall-based parameters from literature used to calculate threshold	Reference
Late onset rain	After 1 June (some farmers mentioned 15th June)	1st June	Moderate	First day in sowing window when >20mm of rainfall is received cumulatively within 7 consecutive days	Wolf et al. (2015); GYGA (2020)
		15th June	Strong		
Uneven distribution of rain	Dry spells are problematic from 1-2 weeks without rain. In the middle of the rainy season, dry spells can last up to 3 weeks without doing much harm.	1-3 moderate dry spells (7-14 days) in first 60 days after onset	Moderate	The length of a dry spell is the number of consecutive dry days between two rainy days. A day with a rainfall amount less than 1 mm is considered a dry day.	Sivakumar (1992); Salack et al. (2011); Boansi et al. (2019)
		> 3 moderate dry spells in first 60 days after onset	Strong		
		Long dry spell (>14 days) in first 90 days after onset	Strong		
Low total rain	<750-800 mm	750 mm	Moderate	Annual rainfall	
		650 mm	Strong	Annual rainfall below limit of Sudano-Sahelian agro-ecological zone	

3.2.3 Frequency of weather hazards

During four focus group discussions, farmers defined at what point they judged a certain weather situation to be problematic (Table 3.2). For example, an onset of the rainy season after the 1st of June was deemed late in one focus group (i.e. moderate hazard level), while the other groups benchmarked the 15th of June (i.e. strong hazard level). Dry spells longer than one week in the early stages of the rainy season and total rainfall of less than 750 mm / year were also seen as problematic. Definitions for onset and dry spells obtained from literature (Table 3.2) were used to complement farmers' definitions when setting thresholds for different hazard levels.

Long term daily observed weather data (1965-2019) from the nearby N'Tarla research station (12°35' N, 5°42' W) (Traore et al., 2013) were used to calculate the frequency of weather hazards using the above definitions. Recent (2012-2019) solar radiation data was extracted from the Prediction of Worldwide Energy Resource (POWER) dataset (NASA, power.larc.nasa.gov, accessed 24/09/2020), often used in crop growth simulations (Van Wart et al., 2015; Joseph et al., 2020).

3.2.4 DSSAT crop model for estimating yields

3.2.4.1 General settings

Crop growth and development was simulated with the Cropping System Model (CSM) (Jones et al., 2003a) of the Decision Support System for Agrotechnology Transfer (DSSAT) Version 4.7.5 (Hoogenboom et al., 2019) using the CERES model components (Jones & Kiniry, 1986; Ritchie et al., 1998). Crop growth is simulated on a daily time step based on cultivar genetic coefficients, crop management, weather conditions, and soil water and nutrient dynamics, with a re-initiation of the model each year. N and P are the most limiting nutrients in the region (Fosu-Mensah & Mensah, 2016), but as the effects of P on crop growth are only included in DSSAT for CERES-maize (Dzotsi et al., 2010) and CERES-sorghum (Adam et al., 2018), we focused only on N. The CENTURY method (Parton et al. 1988, 1994) was used to simulate soil organic matter dynamics (Gijsman et al., 2002; Jones et al., 2003a). For other soil-plant-atmosphere calculation methods, we used the default DSSAT methods. We indicated sowing dates manually (at five-day intervals within a sowing window of 10th of May to the 1st of August), but harvesting was simulated automatically at crop maturity. The sowing window was set with a minimum starting date to exclude false starts of the rainy season and to reflect general farmers' practices.

The DSSAT soil and cultivar parameters were obtained from peer-reviewed publications that parameterised and evaluated the soils and cultivars in semi-arid regions of West Africa, as specified below. Three soil subgroups were considered for the area: sandy (baseline), gravelly and black soils. The DSSAT soil profiles (*.SOL) were constructed with information from soil analysis described in Falconnier et al. (2016) (Table B.1). The SLPF parameter (soil-limited photosynthesis factor) was set to 0.7, similar to on-station soils in Mali (Singh et al., 2014), and confirmed by comparing simulated and observed yields from a three-year cereal trial in the nearby N'Tarla research station (Traore et al., 2014). With a high content of sand, all soils were considered well drained with a respective drainage rate (SLDR) of 0.6 fraction / day (Gijsman et al., 2007). Crop residues were not taken into account, as farmers' practice is to remove a large proportion of them for animal feed or composting. The simulations were initiated on the first of April of each year, when the water content was considered to be at wilting point for all soil profile layers. For the sandy and black soils, mineral N at the start of simulation was estimated at 20.8 kg N / ha (Falconnier et al., 2020). The initial mineral N content of the more shallow, gravelly soils was set at half this content, being 10 kg N / ha.

For each of the cereals, we compared a baseline variety considered as an intermediate crop cycle that is regularly used by farmers in Koutiala, with a short and long duration variety. If no parameters were available for varieties grown by farmers, we used parameters for similar varieties (Table B.5). An overview of general cultivar characteristics is provided in Table B.6. For maize, parameters of the baseline Obatampa variety and the short duration TZEEY-SRBC5 variety were obtained from Freduah et al. (2019) while parameters of the long duration SUWAN 1-SR were used from Falconnier et al. (2020). The sorghum variety CSM335 was used as baseline (Adam et al., 2018; Faye et al., 2018b). CSM 63E is a Malian variety that has a shorter maturity cycle (100 days), while IS15-401 generally has a longer cycle (110-160 days). For all sorghum varieties, we used the DSSAT parameters of Adam et al. (2018). Parameters for millet varieties grown in West Africa are scarce. CIVT is a variety that is best described and parameterised, often for studies in Niger, and therefore used as baseline variety in our study. Singh et al. (2017) defined parameters for CIVT, as well as a hypothetical short duration CIVT variant (10% shorter) and a hypothetical longer duration CIVT variant (10% longer). Planting density was set at 50,000 plants per ha for sorghum and millet, and at 62,500 plants for maize (Traore et al., 2014).

3.2.4.2 Cereal management

DSSAT was run for a wide range of factor level combinations for varieties (short, intermediate and long duration), sowing dates (18 fixed sowing dates between 10th May and 1st August), soil types (sandy, black and gravelly), and fertiliser (N) rates between zero and 200 kg N / ha given in split-application (Table B.6) to understand how these management factors interacted in affecting yield, yield variability and yield loss due to hazards. Within this range of management settings in DSSAT we defined specific management combinations that reflect (1) farmers' practice as baseline management, (2) management leading to optimal yields and (3) management reflecting non-weather hazards.

Baseline cereal management practices were derived from detailed farm management surveys conducted with 25 farmers in 2018 and 2019 (Dissa A., personal communication). The baseline N application was rounded to 50 kg N / ha for maize, 10 kg N / ha for sorghum and 15 kg N / ha for millet. In 2018 and 2019, on average farmers planted millet first on the 9th of June, followed by maize on the 24th or June, and sorghum on the 1st of July. These sowing dates occurred 23, 36 and 39 days after the onset of the rainy season respectively, confirming that farmers first target sowing of cotton (Soumaré, 2008). For the baseline simulations, each year's sowing date was based on the above average number of days after the onset of the rainy season.

Optimal management was defined for a single factor under otherwise baseline conditions and for all factor combinations, whereby the method for calculating the optimal level differed per management factor (fertiliser, sowing date, variety), as explained below. The optimal sowing date of each year was defined as the sowing date relative to the onset of the rainy season (i.e. number of days after onset) that resulted in the largest yield. The average of these number of days was regarded as the period between onset and yearly optimal sowing date. Conversely, the least optimal sowing date was the average sowing date resulting in the smallest grain yield. The optimal variety was the variety that most often resulted in the largest yield over the 55 years. The optimal N rate was the average of the rates that resulted in the maximum yield per year with a positive return on fertiliser investment (Getnet, 2016). Applying one extra unit of N obtained from subsidised fertiliser cost 4.87 USD PPP / kg N, while the grain price was 0.50, 0.52 and 0.66 USD PPP / kg for selling maize, sorghum and millet respectively. Grain prices were averaged from monthly prices in 2016 (OMA, 2016) and fertiliser prices from a market analysis (Dissa A., personal communication; World Bank (2020)). The optimal management for the combined factors was defined by first identifying the variety that most often gave the largest yield, and then determining the combination of sowing date and N rate that gave the largest yield with a positive return on investment.

Hazards not related to weather events (Table 3.1) were reflected in a change in crop management within DSSAT. Household members or draught animals falling sick at the beginning of the rainy season affects land preparation and sowing of crops. We assumed that this labour shortage delays the sowing date by two weeks. Bad quality of fertiliser was reflected by setting the mineral N application rate to zero.

3.2.5 Impact of hazards and crop response to management

We compared crop yields in years with and without weather hazards under baseline and optimal management. For the non-weather hazards, baseline yields for all years were compared with yields under adjusted management. The impact of a hazard was indicated by the percentage yield loss. For each of the cereals, this percentage yield loss (*YL*) is calculated as follows:

$$YL = \frac{\left(\sum_1^n Y_{man,NH_i} / n - \sum_1^m Y_{man,H_i} / m\right)}{\sum_1^n Y_{man,NH_i} / n} \times 100 \qquad (3.1)$$

Where,

man:	Type of crop management (baseline, optimal)
Y:	Cereal yield (kg / ha)
NH:	Years with no hazard, and management not affected by hazard *i*
H:	Years with hazard, or management affected by hazard *i*
i:	Type of hazard (late onset, low total rainfall, fertiliser, labour hazard)
n:	Number of years without hazard *i* (in case of the fertiliser or sowing hazard, *n*=55 because they are independent of the weather conditions)
m:	Number of years with hazard *i* (in case of the fertiliser or labour hazard, *m*=55 because they are independent of the weather conditions)

We also assessed the effects of management practices and their interactions on yields and on the stability of yields over the 55 years. The stability of yields was determined by the coefficient of variation. Analysing how management factors interact helps to understand how baseline and optimal management relate to each other within the decision space that farmers have. When focussing on certain management interactions, the other management factors were held at baseline level.

3.2.6 Risk assessment

Risk is a combination of the frequency and impact of hazards, which was visualised in a two-dimensional risk matrix, with frequency following the scale of the World Bank (2016) on the x-axis and impact as the percentage yield loss on the y-axis. A high frequency in combination with a high impact, indicated a high risk. The frequency of two hazards occurring simultaneously was calculated by multiplying the probability related to each individual hazard. For example, if the first hazard occurs one out of two years, and the second hazard one out of three years, we assume the combination occurs once every six years. In the case of two simultaneous weather hazards, the frequency was deduced from the weather data. The risk matrix was constructed for baseline and for optimal management.

3.3 Results

3.3.1 Frequency of weather hazards

Long-term weather data over 55 years gave insight into the likelihood of occurrence of climatic hazards that were important to farmers: a small total rainfall amount, late onset of the rains, and dry spells. The mean total annual rainfall was 863 mm, ranging from 482 mm to 1249 mm. Total rainfall was less than 750 mm in 35 % of the years (Figure 3.1a). Nevertheless, in five out of these 19 years the rainfall dropped less than 10 mm below the 750 mm threshold. In 7 % of the years a strong hazard with less than 650 mm occurred.

The onset of the rainy season was on average on the 23rd of May and ranged from the 10th of May (in nine years), to the 1st of July (Figure 3.1b). On average, the rainy season lasted 168 days and ended on the 7th of November, with a range between the 20th of September and the 29th of November. A moderately late onset of the rainy season, after the 1st of June, occurred in 18 % of years, whereas the rains started after the 15th of June in 7 % of the years (strong hazard). Moderately late onset of the rainy season combined with a moderately low total rainfall happened in 13 % of the years.

On average a rainy season counted 116 dry days and 52 rainy days (Figure 3.2). Dry spells of at least a week within the first month after onset occurred in 71 % of years, and in 7 % of years these lasted longer than 14 days. After this first 30-day period after onset, dry spells tended to be shorter. Overall, a quarter of the years did not exhibit any hazardous dry spells.

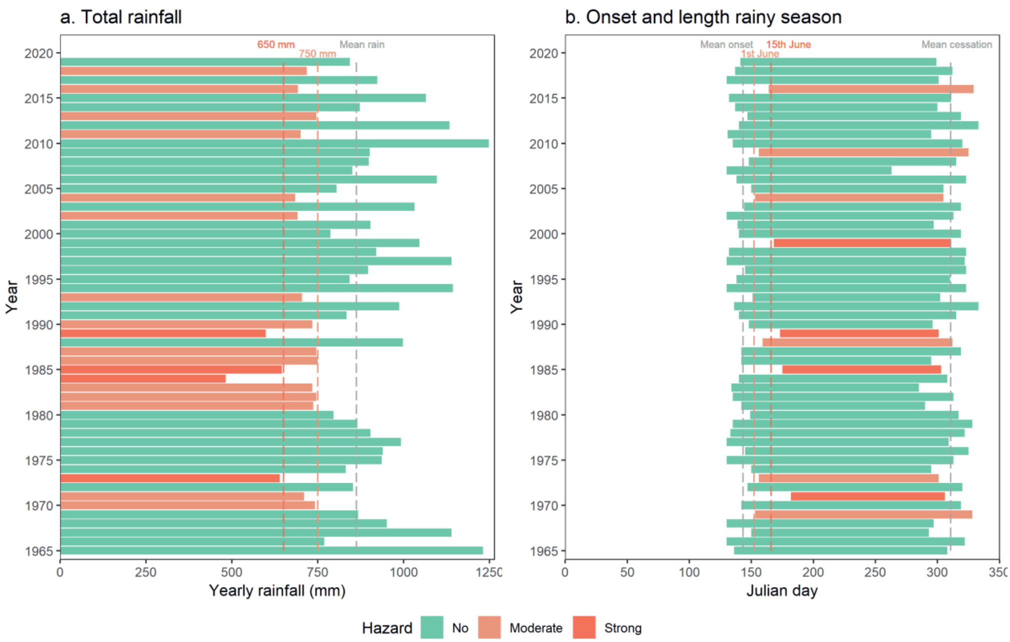

Figure 3.1 Overview of years (1965-2019) from the N'Tarla weather data that carry a climatic hazard according to farmers' definitions. The grey dotted lines represent the average situation, the red dotted lines the hazard benchmark of total rain and day of onset. Years with hazards for total yearly rainfall (**a**) and onset of the rainy season (**b**) are coloured red for strong hazards and orange for moderate hazards.

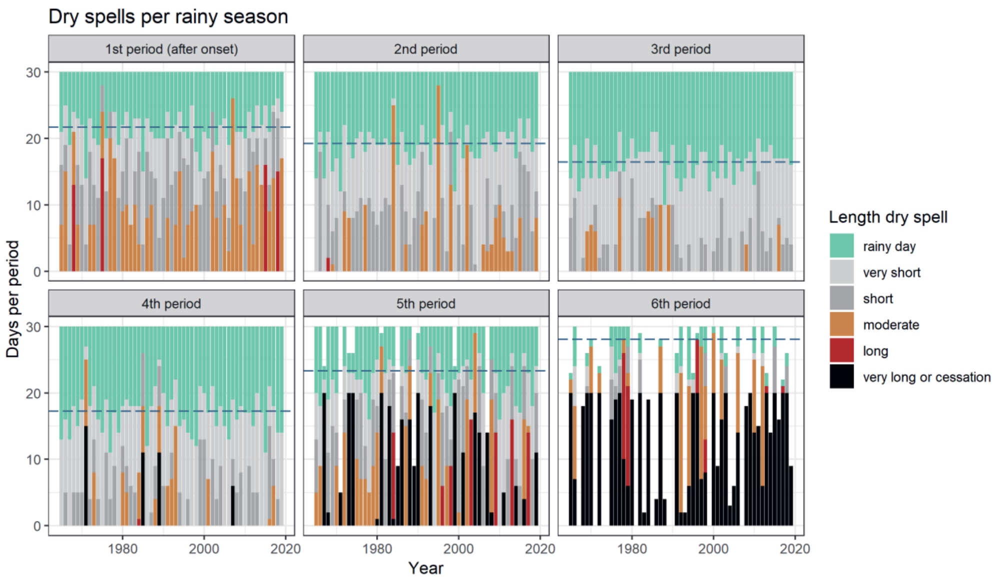

Figure 3.2 Number of dry days within six subsequent 30-day periods counting from the onset (numbered in the facet label). The colours represent the length of the dry spell the day belongs to, being a very short dry spell (1-3 days), a short dry spell (4-6 days), a moderately long dry spell (7-13 days), or a long dry spell (14-20 days). The dotted blue lines represent the average number of dry days within that period. The black bars represent the dry days leading up to the cessation of the rainy season. A dry day is defined as receiving less than 1 mm of rainfall.

3.3.2 Crop response to hazards under farmers' practice

Maize, which received more N under baseline management, yielded more than sorghum and millet overall, with an average yield of 3.39 t / ha, 1.74 t / ha, and 1.33 t / ha, respectively. When comparing yields under baseline management in years with and without a weather hazard (Figure 3.3), sorghum and maize performed worse in years with low total rainfall, while millet yields were more robust and did not exhibit such variation (Figure 3.3a). In years with a late onset of the growing season, all three cereals yielded less, although for millet only in years with a strong hazard (Figure 3.3b). The presence of dry spells had a limited effect on cereal yields (Figure 3.3c). The small positive tendency in yields with dry spells could be related to a confounding effect with the other two weather characteristics analysed. Years with a hazardous dry spell had an earlier average onset of the rainy season (18^{th} May) and a higher mean total rainfall (874 mm) compared to years without a hazardous dry spell (30^{th} May and 830 mm). Additionally, cereals are sown relatively late under farmers' practices compared with the onset, which allows these crops to escape the early dry spells that are seen as most hazardous by farmers.

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Of the non-weather hazards, a lack of good quality fertiliser influenced the mean yield negatively, especially for maize (Figure 3.3d). Labour hazards, expressed by delayed sowing, also reduced cereal yields, although to a lesser extent (Figure 3.3e).

3.3.3 Cropping risk with farmers' practices

The risk matrix combines the above findings on frequency and impact under baseline management (Figure 3.4). Since the impact of dry spells (Figure 3.3c) did not indicate a risk for cereal yields under baseline conditions, we excluded this hazard from further analysis on yield loss. The hazards that induced a larger yield loss occurred less often, suggesting that impact and frequency are inversely related. Sorghum responded differently than maize and millet to different types of hazards. For sorghum, yield losses were larger than for the two other cereals, except for the fertiliser hazard.

Under baseline conditions, the yield was largest and most stable for maize compared to the other two cereals (Table 3.3). The coefficient of variation was largest for sorghum (0.49) while it remained below 0.2 for millet and maize. Among the hazards, a low total rainfall occurred most often but had relatively little impact on maize and millet (8% and 5% yield loss respectively), but affected sorghum with 24% yield loss. Also the impact of a late onset and the labour hazard was larger for sorghum (65% and 32% yield loss respectively), compared with maize (17% and 5%) and millet (12% and 3%). A late onset and labour hazard both happened around once every five years. Fertiliser hazards occurred rarely, once every ten years, but had a large effect on maize yields (54% yield loss), followed by millet (19%) and sorghum (9%).

The risk of simultaneous hazards was not larger than that of the individual hazards, since the frequency decreased and the impact only increased to a limited extent (not more than 10%) compared with the impact of the most influential hazard. However, for millet and sorghum, a labour hazard combined with a late onset or a low total rainfall increased the yield loss substantially (more than a 10 % point increase).

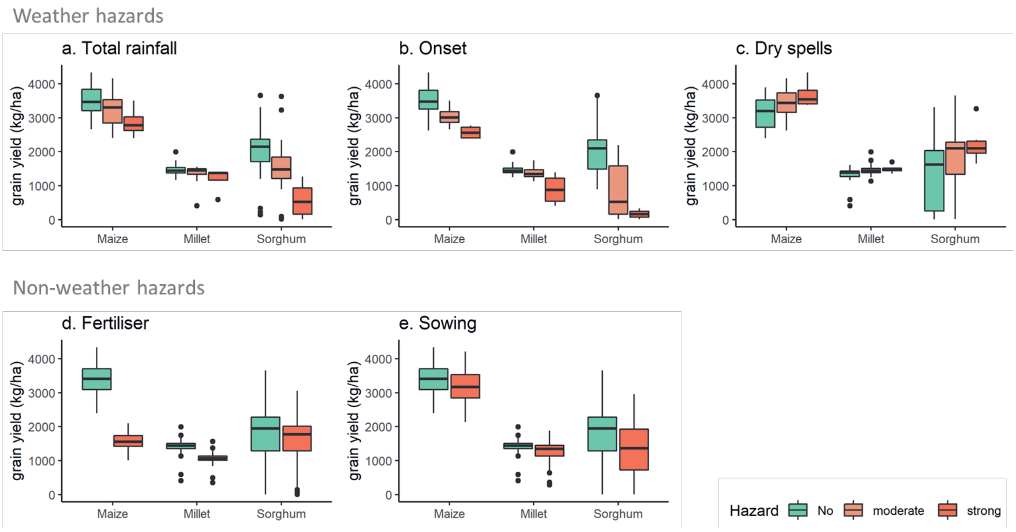

Figure 3.3 Cereal yields under baseline crop management for years with and without weather hazards, and for management reflecting non-weather hazards. The definitions of the hazards are given in Table 3.2. **a)** Years with a moderate hazard of low total rainfall (n=15) and a strong hazard (n=4) are compared with higher rainfall years (n=36). **b)** Years with a moderate hazard of a late onset (n=6) and with a strong hazard of a very late onset (n=4) are compared with years with a normal onset (n=45). **c)** Years with a moderate hazard (n=35) and a strong hazard of dry spells (n=6) are compared with years with shorter dry spells (n=14). **d)** Baseline management is compared to management reflecting the fertiliser hazard (no N applied) for all 55 years. **e)** Baseline management is compared to management reflecting the labour hazard (sowing two weeks delayed) for all 55 years.

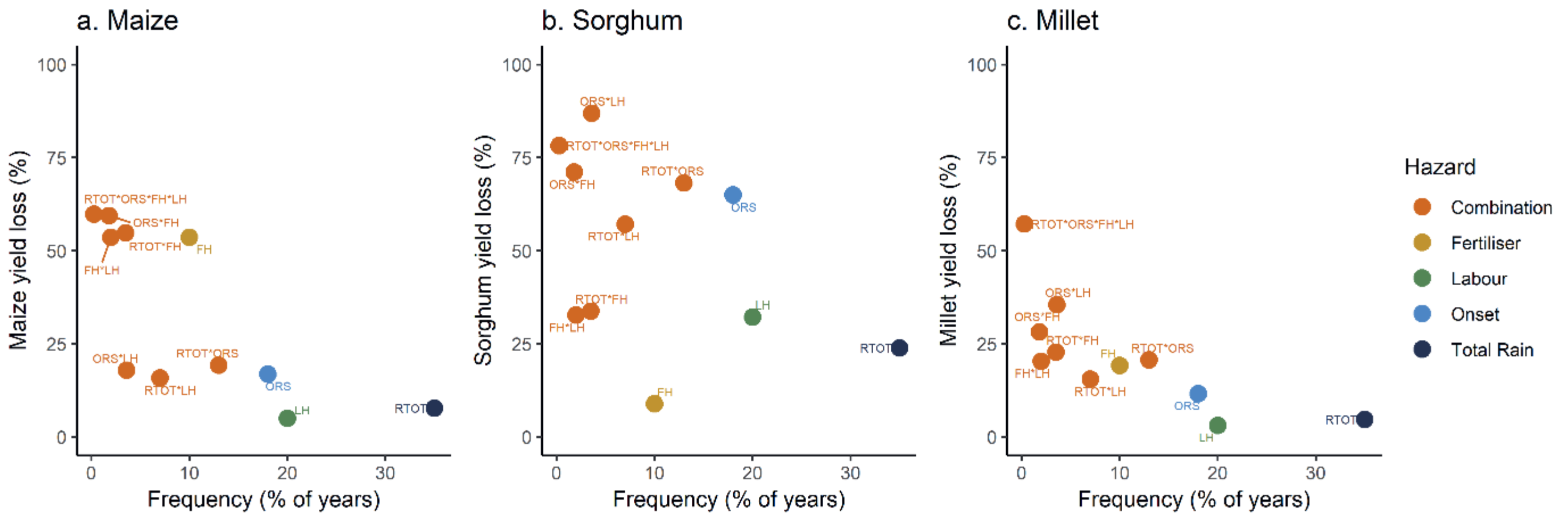

Figure 3.4 Risk matrix with cereal yield loss plotted against frequency of hazards for **a)** maize, **b)** sorghum and **c)** millet, under baseline management for two weather hazards (late onset (ORS) and low total rain (RTOT)), two non-weather hazards (no fertiliser (FH) and labour (LH)) and their combinations.

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3.3.4 Optimal management

First, we defined the optimal level per factor with the other management factors held constant under baseline conditions. The optimal N rates were 66 kg N / ha, 27 kg N / ha, and 111 kg N / ha for maize, sorghum and millet respectively (Table 3.3b). The optimal sowing date was 22 days, 2 days, and 27 days after onset for maize, sorghum and millet, whereas the optimal variety was the short duration variety for maize and sorghum, and the long duration variety for millet.

Secondly, when allowing for interaction between management factors, the optimal levels shifted (Table 3.3b, NO*SO*VO). Generally, when sowing date or variety were optimised, the optimal N rates were larger. With optimal N rates and variety, the optimal sowing date for maize remained similar, while for sorghum and millet it was brought forward. The average optimal sowing date of sorghum (baseline variety) even appeared before the onset, suggesting that the drought tolerance at early vegetative stages of the sorghum baseline variety is strong enough to benefit from the minor rainfall events that led up to the onset of rains. The optimal combined management included the baseline variety for sorghum, while for maize the short and for millet the long duration variety.

The optimised management was based on maximum yields, with for N application a limit when the profit from additional yield became equal to the cost of additional input. However, not only the absolute yield matters but also the stability of the yield over the years (Table 3.3). Optimising N management more than doubled yield for millet and lowered the coefficient of variation (CV). Sorghum yields increased by 50%, while halving the CV. Optimising N resulted in a limited benefit for maize yield (less than 20% increase) while it increased variability. The optimal N rates for millet were much higher than those for maize and sorghum, which is related to a different fertiliser response and a better price for millet grain. Although also beneficial for maize and millet, sowing earlier or cultivating a short duration variety, especially benefitted sorghum both in terms of absolute yields (50% yield increase) and yield variability (CV dropping below 0.2). For sorghum the lag between optimal and farmers' sowing dates spanned more than five weeks, while for maize and millet this gap was less than two and one week respectively. Optimising the variety increased maize and sorghum yields with about a third, while it reduced the coefficient of variation of sorghum to below 0.2 and did not affect the CV of maize much. Benefits for millet were less striking.

Yield of all three cereals benefitted from optimising all management practices simultaneously compared with optimising one factor at a time. The gain was mainly in a raise in absolute yields, while for sorghum the CV was also reduced.

3.3.5 Cropping risk with optimal management

Adapting crop management alters the risks associated with various hazards (Figure 3.5), and the changes in risk were more pronounced for sorghum and millet than for maize. The relative yield loss of maize under optimal management remained fairly similar (less than 10 % point difference in yield loss) compared with baseline management for all hazards. The late onset of the rainy season was the exception, where the yield loss reduced from 17 % to 3 % when optimising all management factors combined, and to 5 % when only optimising sowing dates. Thus overall, optimal management improved maize yields and did not increase the risk.

For sorghum, most optimal management options reduced, or did not influence, the relative yield loss (compared to yield loss under baseline management). This means that optimal management that increased absolute yields, did not increase risks in general. Sorghum yield losses were only slightly exacerbated when applying optimal N rates in the case of weather hazards, yet with less than 10 % point increase in yield loss. The other management practices decreased the yield loss in case of weather hazards. This was most pronounced for applying the optimal variety when rains started late (65 % to 17 %) and for adapting sowing date when total rainfall was low (24 % to 9 %). Cultivating the optimal short duration variety also induced a reduction in the yield loss for the labour hazard (32 % to 4 %). The risk related to fertiliser hazards was less influenced by management.

Optimal management often increased relative millet yield losses under hazardous circumstances, contrary to what was the case for maize and sorghum. Nevertheless, the differences were negligible for the fertiliser and labour hazards. The yield loss was greatest when combining management (N rate, sowing date and variety) when a late onset (increasing from 12 % to 36 %) or low rainfall (5% to 25%) occurred. While optimised N rates contributed most to the absolute yield increase for this combined management of both weather hazards, they contributed relatively little to worsening relative yield loss.

Table 3.3 Factor combinations, of variety, N rate and sowing date (DOS), that represent the baseline, a certain hazard, recommended management, or the optimal treatment (average of treatments that that maximised yield, with the standard deviation between brackets) for the three cereals on sandy soils. For each treatment the average yield (t / ha) and coefficient of variation is presented. Variety 1 represents the baseline, Variety 2 the short duration and Variety 3 the long duration variety.

Type of treatment	**Code**	**Treatment description**	**Crop**	**Variety**	**N rate [kg N / ha] (sd)**	**DOS [days after onset] (sd)**	**DOS [date]**	**Yield [t / ha]**	**Coefficient of variation**	**Explanation**
a) Baseline	BL	Baseline situation	Maize	Baseline	50	36	28th June	3.39	0.13	Farmers' practices
			Sorghum	Baseline	10	39	1st July	1.74	0.49	
			Millet	Baseline	15	23	15th June	1.33	0.17	
b) Optimal	NO	BL + optimal N	Maize	Baseline	66 (15)	36	28th June	3.60	0.18	Average N rate that gives the largest yield with an economic margin >0
			Sorghum	Baseline	27 (23)	39	1st July	2.65	0.27	
			Millet	Baseline	111 (16)	23	15th June	2.93	0.12	
	SO	BL + optimal sowing date	Maize	Baseline	50	24 (26)	16th June	3.63	0.10	Average sowing date that gives the largest grain yield per year
			Sorghum	Baseline	10	2 (20)	25th May	2.67	0.16	
			Millet	Baseline	15	27 (22)	19th June	1.47	0.12	
	VO	BL + optimal variety	Maize	Short	50	36	28th June	4.62	0.16	Variety that most often gives the largest grain yield
			Sorghum	Short	10	39	1st July	2.27	0.14	
			Millet	Long	15	23	15th June	1.54	0.13	
	NO*SO *VO	BL + optimal N + sowing + optimal variety	Maize	Short	68 (10)	24 (27)	16th June	5.63	0.11	Average N rate, sowing date and variety that gives the largest yield (with economic margin >0)
			Sorghum	Baseline	85 (24)	-10 (13)	13th May	4.19	0.26	
			Millet	Long	160 (25)	4 (19)	27th May	4.04	0.12	

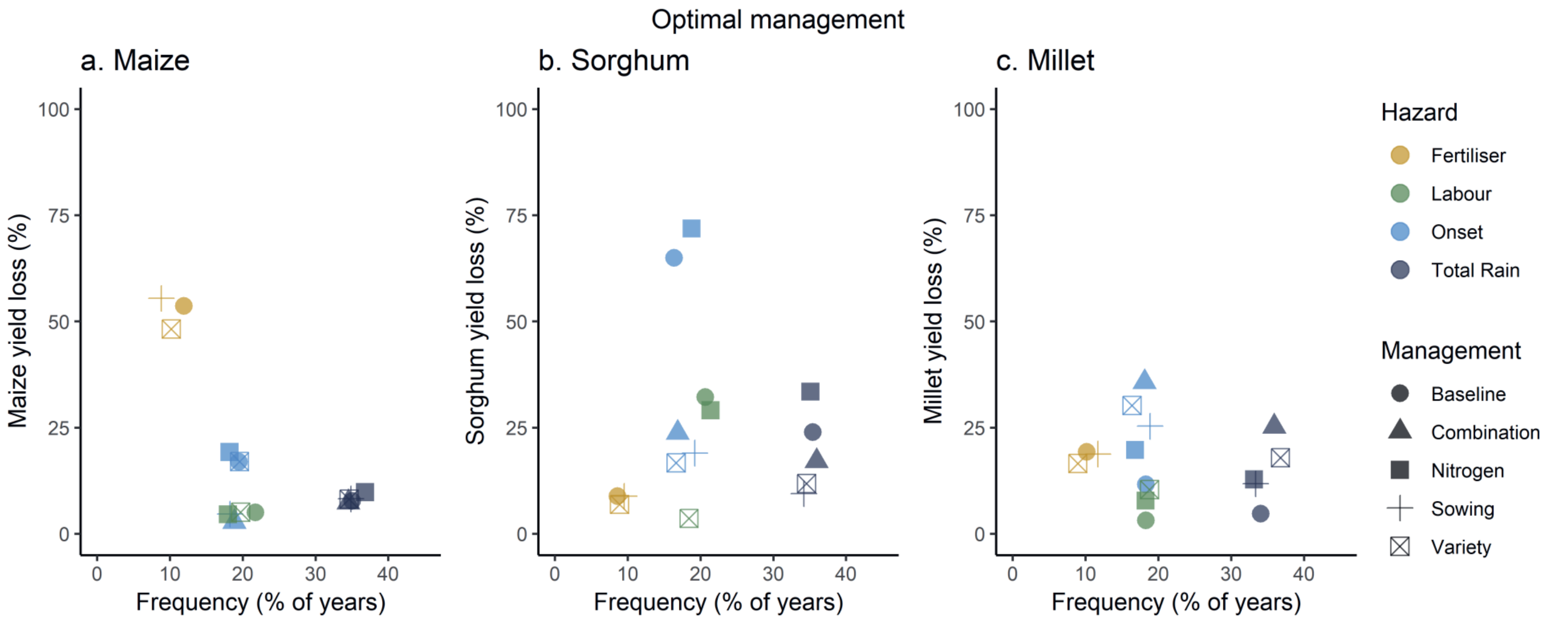

Figure 3.5 Risk matrix with cereal yield loss plotted against frequency of hazards for **a)** maize, **b)** sorghum, and **c)** millet, under baseline and optimal management for two weather hazards (late onset and low total rain), two non-weather hazards (no fertiliser and labour). Optimal management reflected optimal N rates, sowing date and variety, or a combination of these three factors (Combination), as described in Table 3.3.

3.3.6 Crop response to baseline and optimal management within a window of management options

Baseline and optimal management are only a selection of management options farmers have. To better understand the crop response to adapted management, we examined in detail the yield response to the interaction of a range of levels of management factors (soil, variety, N rates and sowing date) over the 55 years.

Firstly, we explored the interaction of N rates with soil types. The cereals yielded similarly on sandy (baseline) and black soils, but yields were less and more variable on the shallow gravelly soils (Figure 3.6). With small N rates, sorghum outperformed maize and millet on sandy and black soils, but not on gravelly soils. Nevertheless, sorghum responded little to N addition, and millet and maize yields were better than sorghum yields at larger N application rates on all soil types. Although maize yielded best at almost all N application rates, millet yields showed less variability and plateaued at larger rates (around 140 kg N / ha). Maize yields plateaued at around 100 kg N / ha, and sorghum around 40 kg N / ha.

Secondly, we scrutinised the interaction between variety, sowing date and N rate. The yields and N response curves changed when adapting sowing dates. Focusing on sorghum, which benefited most from optimising the sowing date, we compared the average yields of optimal sowing dates with that of the least optimal sowing date for the three varieties (Figure 3.7a). Without adding fertiliser, sorghum yields ranged from an average of 0 to 2 t / ha between least optimal and optimal sowing dates. The baseline sorghum variety yielded best (at optimal sowing date), except at small N rates when the short duration variety (CSM63E) yielded equally well, yet with a weaker N response. At larger N rates the longer duration and short duration varieties gave similar yields. In most years, it appeared optimal to sow the baseline and long duration variety early in the sowing window (Figure 3.7b). For the short duration variety, it was often beneficial to wait until mid-June to sow; in about half of the years the optimal sowing date was after the 10th of June, regardless of the N rate. When small rates of N were applied, the optimal sowing dates were generally more spread out and later than with high N rates, for all varieties. Yield losses could reach 25%, when sowing only five days earlier or later than the optimal sowing date, and crops could entirely fail when sowing was postponed by two months. With small N rates the relative yield loss was similar when sowing too early or too late, while with larger N rates the yield penalty was larger when sowing too late, explaining the optimal management combination of high N rates with early sowing.

Maize and millet had a similar, yet less pronounced, behaviour (Figure B.1 and Figure B.2). Yields also improved considerably when sowing dates were optimised to relatively early in the season (early to mid-June). When applying less N, it appeared beneficial to sow millet and maize later (Figure B.1). The long duration variety of millet yielded slightly better than the two other varieties, but when sowing late, the difference in yield between the varieties disappeared, which explains that the optimised management contains the interaction of the long duration variety at large N rates and early sowing. The difference in yield between optimal and least optimal sowing date was least pronounced for maize (Figure B.2). The short duration maize variety yielded best across all N rates.

The baseline and long duration variety had similar yields, but the long duration variety benefitted more from large N rates.

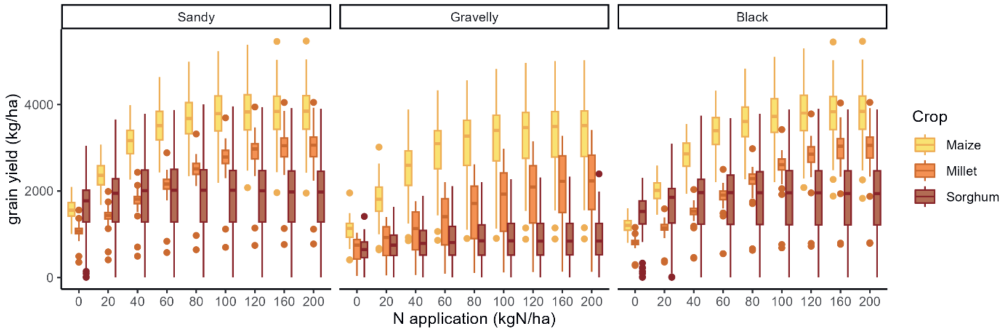

Figure 3.6 Response curve of maize, sorghum and millet grain yield to different rates of N application on three soil types (sandy, gravelly and black soils) with baseline sowing date and variety

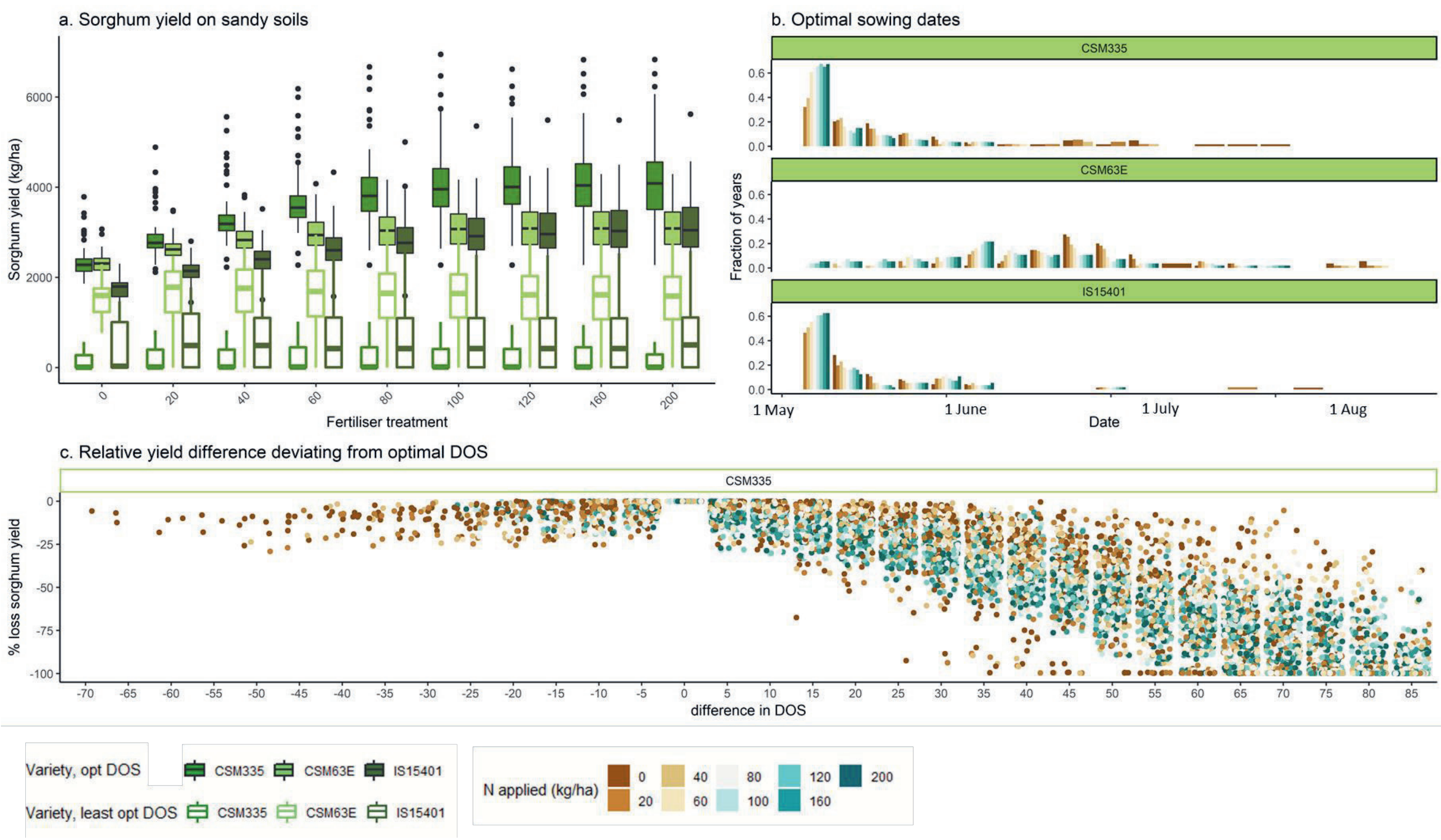

Figure 3.7 a) Sorghum yield for different fertiliser rates and varieties on sandy soils, for the defined optimal sowing date (DOS) of each year (filled boxplots) and the least optimal DOS of each year (open boxplots). **b)** Histogram of the optimal sowing dates for the different years and **c)** Relative yield loss when deviating from the optimal sowing date for the baseline variety. Nine N rates (0 kg N / ha - 200 kg N / ha) and three varieties are represented.

3.4 Discussion

3.4.1 Frequency of production hazards

The prevalence of dry spells, insufficient total rainfall and late onset of the rains confirmed the hazardous nature of agriculture in southern Mali. In an earlier study in the same region, farmers perceived these three weather hazards to become more frequent and severe over time, which they attributed partially to climate change (Traore et al., 2015). Nevertheless, no significant changes in rainfall variability (onset and total rain) were found over time (1965-2005), except for an increase in total number of dry days and an increase in minimum daily temperature (Traore et al., 2013). This is in line with the findings of the latest IPCC report on West Africa, that stated an increase in temperature accompanied by higher variability of precipitation (e.g. fewer but more intense rainfall events) (Trisos et al., 2022).

Dry spells were more complex to define and interpret than the two other weather hazards. The severity does not only depend on the number, but also on the sequence and timing of dry days as farmers deemed the hazard stronger if more and longer dry spells occurred early after the onset of the growing season. Hence, the impact depends a lot on the sowing date, which was relatively late for sorghum, and only somewhat earlier for maize and millet, which explains why we did not discern yield losses related to this hazard under baseline conditions (Figure 3.3). In Koutiala, farmers first sow the cotton fields, thus delaying sowing of the cereals (Soumaré, 2008). Another possible reason for not observing a negative impact on cereal yields could be that hazardous dry spells occurred more often in years with a relatively early onset of rains and high total rainfall, both positively related to yields.

By considering only the hazards that farmers perceived as most important, some weather characteristics were not taken into account. For example, rising temperatures (Traore et al., 2013) are known to result in shorter crop cycles, or induce grain sterility (Bassu et al., 2014). There is agreement that temperatures will further rise due to climate change, while for precipitation the climate models are more uncertain on the direction of change, although the frequency of more intense rainfall events is expected to increase (Roudier et al., 2011; Niang et al., 2014; Sultan et al., 2019; Trisos et al., 2022).

Our risk assessment comes with some uncertainty as the frequency of weather hazards depended on farmers' definition of the hazards, while the frequency of the non-weather hazards was entirely based on their perception. Farmers tend to have several biases that lead to either under-estimating or over-estimating the probability of a hazard, with the latter particularly common for hazards that have recently taken place (Hardaker et al., 2015). In our assessment, we reduced the amount of N application to zero in case of poor fertiliser quality. This is only valid in the most extreme case, but could also be a result of other circumstances (e.g. lack of access to fertiliser). The most important hazards for farmers were related to labour issues. As the start of the season is a critical period for farmers' decision making (Traore et al., 2014), we mimicked labour hazards by inducing late sowing in our analysis, while we did not take into account effects on weeding and harvest time. Although late sowing avoids water stress due to early season dry spells (Figure 3.3), there are also negative effects of delayed farming practices (Wolf et al., 2015), for example from plants missing the possible benefit from the N flush with the first rains (Milgroom & Giller, 2013; Masvaya et al., 2018).

3.4.2 Management influences yields and impact of hazards

Under baseline conditions maize outperformed millet and sorghum in all studied circumstances, except in cases of fertiliser hazard when sorghum yielded more than maize (Figure 3.2, Figure 3.4). Farmers generally applied more N to maize than to sorghum and millet, which is justified since maize responds strongly to N application, and sorghum performed relatively well without N (Figure 3.4, Figure 3.3d). These crop characteristics drive farmers' choice to grow sorghum in semi-arid areas as well as maize in case fertiliser is available (Kante et al., 2019). Millet yielded less than sorghum and maize at low N rates, but surpassed yields of sorghum when more N is applied. The benefit of millet resided in its low yield variability (low CV in Table 3.3), and less sensitivity to the weather hazards (Figure 3.3). Indeed, millet is often promoted as the more drought tolerant cereal (Ewansiha & Singh, 2006), and it increases in importance north of Koutiala where the climate becomes increasingly drier and hotter.

Adapting management aspects does not only influence average yields but the potential impact of different hazards as well. The hazards of late onset of the rainy season and the lack of labour are closely related. In Malian cropping systems, late sowing often results in yield losses in maize, sorghum and cotton (Traore et al., 2014) while a late starting date of the rainy season forces farmers to adapt their planning and affects the feasibility of crop varieties, with short duration varieties usually having smaller potential yields (Traore et al., 2017). Our analysis nuanced this commonly spread information: early sowing is a good strategy, but in some circumstances it could also be beneficial to wait, for example when applying low N rates (Figure 3.7). Short duration varieties of maize and sorghum yielded most and reduced the yield losses when there was a late onset of the rainy season (Table 3.3 and Figure 3.5). The use of photoperiodic sensitive varieties of millet and sorghum, which flower and mature at the same time of the year regardless of their sowing date, could allow for more flexibility in targeting the optimal sowing date (Traore et al., 2014; Faye et al., 2018b). Since labour is a bottleneck for farmers, with a lot of activities in the beginning of the season, and farmers' first focus is cotton, we hypothesise that farmers will be interested to sown cereals later when this can be done without much yield penalty. Also for the hazard of total rainfall, adapting the variety or sowing date reduced risk most while increasing yield, compared to adapting N rates. Increasing N rates even increased the risk of sorghum yield losses under weather hazards.

The optimised management treatments differed from what is currently advocated in the region. For example, CMDT (Compagnie Malienne pour le Développement du Textile) recommends maize fertiliser rates of 80 kg N / ha (Falconnier et al., 2016; Traore et al., 2017), whereas the recommended rates for both millet and sorghum in the Sudano-Sahelian region are around 40 kg N / ha (Kanté, 2001; Akponikpè et al., 2010; Traore et al., 2017; Amouzou et al., 2019). For maize (66 kg N / ha) and sorghum (27 kg N / ha) our simulation results indicated lower optimal N rates, while for millet the optimal rates were much higher (111 kg N / ha). Nevertheless, since the risk increased for several hazards by applying such high fertiliser rates for millet, lower N rates may be more appropriate for farmers (Akponikpè et al., 2010). Recommended management further included using a short duration variety (Niang et al., 2014) and the strategy of farmers to sow as early as possible (Huet et al., 2020). In our simulations for millet the long duration variety led to the highest yield, which is in line with other model findings for Niger and Mali (Singh et al., 2017).

3.4.3 Risk mitigation

Much literature stresses the importance of not only considering maximum average yields in volatile environments, but to include variability in the analysis (Urruty et al., 2016; Vanlauwe et al., 2019). Our analysis revealed differences in trade-offs between maximising yields and mitigating risk between the three cereals. Sorghum had the highest crop production risk of the three cereals, yet benefitted most from applying optimal management since it increased yields and simultaneously reduced yield losses under hazards. Millet had a comparable risk to maize, but for millet the risk often increased when adapting management to optimise yields. Applying optimal management for maize did not increase the risk. These different responses of cereals show the multiple options within the decision space of farmers when planning field and farm management.

Farmers prepare for, and deal with, several hazards by adapting field management practices related to, for example, fertiliser application, choice of varieties and sowing dates (Huet et al., 2020). Some hazards allow for a reactive flexible response, which means crop management can be adapted as the season progresses (Piha, 1993; Andrieu et al., 2015). For example, when the onset of the rainy season is late, farmers have time to adapt the sowing date, variety and allocation of fertilisers, without losing much investments. This could be especially useful for millet since the relative impact of the hazard increases under optimal management compared with baseline millet management, or in other words, investing in yield increasing management is less beneficial for millet in case of late onset the rainy season. Andrieu et al. (2015) described that farmers in Burkina Faso plan and implement operational flexibility options of adapting crop choice, land allocation, and input use, confirming that the options analysed in our study are within the decision portfolio of farmers. The potential of reactive flexibility was demonstrated since it limited farm gross margin variability (Andrieu et al., 2015). Piha (1993) suggested to split fertiliser applications so that the amount of N applied as top-dressing could be adjusted to the likely crop demand as the season develops. From our results, such an approach could be useful for millet and sorghum fields, where higher fertiliser use increased the risk when rainfall is limiting. Overall, maintaining a short-term operational flexibility requires an enabling environment that foresees access to inputs and labour throughout the growing season, as well as storage facilities. Currently, access to subsidised fertilisers on credit for cotton and maize production is readily available through the parastatal CMDT at the planification phase in August-September, more than half a year before the actual start of the rainy season. Apart from input supply through CMDT, access to mineral fertiliser through other sources or later in the year is difficult for farmers (Koné et al., 2020b). Additionally, access to improved cereal varieties is limited in the region (Koné et al., 2020a). Other hazards occurring at later stages or after crop growth, cannot readily be addressed by reactive flexible management. Longer term strategies like maintaining farm diversity of crops and management or keeping a strategic buffer of resources to maintain flexibility are more suitable for dealing with such hazards.

Diversifying to spread the risk by growing more crops, more varieties of crops and with differing management might be beneficial since crops responded differently to hazards and management (van Noordwijk et al., 1994). Farmers often cultivate several sorghum varieties on their farm (Siart et al., 2008), but not so much for maize and millet, although they intercrop many cereal fields with legumes as a within-field diversification of crops (Ganeme et al., 2021). Targeting or spreading sowing dates requires access to labour. Good access to animal and human health care may reduce the frequency of the labour hazard, while mechanisation tools potentially make field practices more efficient and reduce the delay of sowing in case there is a lack of manual or animal labour. Policies that support farmers to maintain these strategies of diversification and flexibility by for example enabling continuous access to inputs, storage facilities, weather forecasts or mechanisation, would contribute to increased resilience to risks.

3.4.4 Limitations of tools and further research

The DSSAT-CERES crop model is able to predict maize and sorghum crop yields in the Sudano-Sahelian region reasonably well (Adam et al., 2018; Worou et al., 2018; Falconnier et al., 2020). Nevertheless, the simulated yields in our study are higher than average observed yields under smallholder conditions (Traore et al., 2014; Falconnier et al., 2016), which could be due to hazards and management factors not taken into account, model characteristics, or parameter uncertainty. Firstly, yield reducing factors that are not taken into account in the model are for example the incidence of pests and diseases, bad weeding management, or lack of good quality inputs other than fertiliser, which are all potential stressors present in the area (Huet et al., 2020; Segnon et al., 2020). Secondly, DSSAT-CERES does not take into account soil nutrient dynamics other than N, and overall soil fertility was reflected through a single parameter (SLPF). In a comparative study, Falconnier et al. (2020) found that DSSAT-CERES was one of the more consistent crop models for maize yield simulation and that overall model uncertainty was relatively high for low-input systems where adequate calibration of soil processes is extremely important. Nevertheless, this comparative study did not find any increase in uncertainty of model response to rainfall with low N rates for the Mali case, which reflects our baseline situation. Lastly, parameter uncertainty may play a role, with cultivar settings for millet varieties particularly difficult to obtain. CIVT, which we used in the baseline, is a hybrid millet variety that has a higher yield potential than what is expected of the varieties used by farmers, which could partly explain the relatively good yields simulated by DSSAT (Faye et al., 2018a). Although all parameters were evaluated in literature, it is known that there is GxE interaction when cultivar parameters are calibrated (Fleisher et al. 2019, Jones et al. 2012), which could also have influenced our results when using these cultivars in slightly different circumstances. Nevertheless, in our study we focus on relative yield changes under changing circumstances rather than the absolute yields, keeping confidence in the model dynamics.

Farmers' criteria served as a starting point for our hazard selection and analysis, which makes the risk assessment relevant for stakeholders (Challinor et al., 2018). Nevertheless, the production hazards that farmers ranked highest among the perceived important hazards (Table 3.1) (Huet et al., 2020), were not necessarily the ones that bore the highest risk (frequency x impact) (Figure 3.4). This discrepancy implied that farmers' risk perception sprouted from a farm perspective, also taking into account other crops and farm components. The analysis focused on cereal risks at field level, and gave insights in crop management that could increase production without increasing the variability and the risk. Other management practices that could be taken into account have a strong interaction with the livestock component of the farm, such as applying organic fertiliser or mulching (leaving the crop residues unavailable as animal feed). A next step to inform measures to build farmers' resilience would be to analyse how risk management and cereal production play out at farm level.

3.5 Conclusion

Our analysis revealed differences in trade-offs between maximising yields and mitigating risk between the three cereals. Sorghum had the highest crop production risk out of the three cereals, for all analysed hazards (late onset of the rainy season, low rainfall and sudden lack of labour) except for the fertiliser hazard. An additional hazard of labour shortage on top of weather hazards increased yield losses of millet and sorghum substantially. Nevertheless, sorghum benefitted most from applying optimal management since it increased yields and simultaneously reduced yield losses under hazards. Millet and maize had similar relative yield losses under hazards, but for millet the risk often increased when adapting management to optimise yields. Applying optimal management for maize did not increase the risk.

The management options we explored (adapting fertiliser rates, choice of varieties and sowing dates) are within the decision space of farmers and provided opportunity to increase yields. The analysed hazards all occurred more than once every ten years, making it relevant for farmers to take these hazards into account in their farm management decision making. Since the consequences on risks are different per crop, the interaction between management practices and hazards stress the importance of famers to maintain farm diversity and operational flexibility. This requires an enabling environment that foresees storage capacities as well as year-round access to labour and inputs as fertiliser and varieties for farmers to build resilience.

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4 Risk reduction by crop portfolio diversification at farm level

This chapter will be submitted as:

Huet, E.K., Ejiri, K., Adam, M., Giller, K.E., & Descheemaeker, K. Risk reduction by crop portfolio diversification at farm level in southern Mali.

Abstract

Modern Portfolio Theory (MPT) was used to evaluate the farm-level effects of diversified crop land allocation in dealing with weather variability. MPT is a tool frequently used in economic research to determine the variability and the mean expected return when two assets are combined, in order to assess the stabilisation benefit of diversification. We expressed the return in weighted farm-level yield, food (energy) and in economic terms. The assets that were combined on the farm land included different crops, varieties, and fertiliser rates of four main crops (maize, millet, sorghum, cotton). Cereal yields (maize, sorghum, millet) and variability were obtained from model simulation output from the DSSAT-CERES crop model for the years 1965-2019. Cotton yields were observed in a long-term trial from 1965-1993. The MPT outputs were compared with average farmer practice and farm requirements. For each farm type the minimum food requirement to obtain food self-sufficiency at household level was calculated, as well as the minimum economic return to exceed the extreme poverty line. Allocating crop land to combinations of two assets had the potential to increase the farm-level stability and the combinations that diversified the crop component allowed for most stabilisation benefit (more than only diversifying varieties and fertiliser rates). Millet and sorghum contributed most to stability. Maize and cotton were important contributors to increased yields, energy and/or economic return. The combination of cotton and a cereal had a relatively strong stabilisation benefit, as there was a weak correlation between cotton and the different cereals in their response to the weather. Diversification strategies were more constrained by the income than by the food self-sufficiency thresholds for all farm types. For bridging the poverty line farmers had to take risks and had to target combinations with a high mean return and large variability. We conclude that diversification had the potential to increase stability. Nevertheless, crop production alone was not sufficient to provide a balanced livelihood, and diversification with other crops, livestock and/or complementation with off-farm income would be essential.

Key words

Modern Portfolio Theory, cereal, cotton, food self-sufficiency, poverty line, Mali

4.1 Introduction

Farmers in West Africa often have limited farm resources to manage their farm in a variable environment under pressure (Giller et al., 2006; Falconnier et al., 2015; Huet et al., 2020). Gradual pressures in the bio-physical and socio-economic environment are manifold: soil fertility is declining, climate is changing, and population is growing. On top of that, there are risks throughout all levels of farming. One of the main hazards farmers are concerned with is irregular rainfall patterns (Boansi et al., 2019; Huet et al., 2020). As farmers depend largely on farming activities for their livelihood and income, the combination of limited resources and a harsh environment contributes to food insecurity and poverty (Tittonell & Giller, 2013; Connolly-Boutin & Smit, 2016).

Notwithstanding their limited resources, farmers apply strategies at different levels to deal with environmental constraints and hazards. At field level, practices that have shown potential are, for example, concentrating fertiliser or manure through micro-dosing (Aune et al., 2017), adapting sowing dates and varieties according to the weather conditions (Huet et al., 2020), or intercropping cereals with legumes which can provide additional fodder and grain from the legume at the cost of a limited penalty in cereal yield (Falconnier et al., 2016; Abdul Rahman et al., 2021). At household or farm level, farmers tend to not put all their eggs in one basket and instead diversify, including activities on- and off-farm (van Noordwijk et al., 1994). For example, combining hybrid and local varieties is described to have an insurance effect (Yachi & Loreau, 1999; Altieri et al., 2015) since the different responses of hybrid and local varieties contribute to an overall decreased yield variability. While hybrid varieties often have a higher productivity than local varieties, the latter are often better adapted to the local environment (e.g. El-Namaky et al., 2017). Traore et al. (2015) found that about four out of five farmers perceived the cultivation of a short duration variety as a good measure to deal with deficit rainfall (moderately or highly satisfied). In the same study, even more of the farmers appreciated crop diversification. Cultivating different crops is recognised by farmers and researchers as a means to spread risks (e.g.Mertz et al., 2008; Frison et al., 2011; Yegbemey et al., 2017; Ado Abdou et al., 2020). Diversifying fertiliser rates among fields is another option, and farmers could target inputs to the best suitable lands (Aune et al., 2017). While applying fertiliser usually increases yields, there is a risk that crops do not respond to fertiliser (Traore et al., 2015). The combination of a low water-holding capacity of the soil and high fertiliser rate may increase the chance of crop failure (van Noordwijk et al., 1994). In southern Mali, an example region for the variable environment in West Africa, diversification is a popular strategy with potential to mitigate the variability in agricultural production (Traore et al., 2015; Huet et al., 2020), yet few studies have quantified this effect.

In most research, the impacts of management options were measured at field level, and the average yield increase is the most common indicator of the potential of an agronomic option (e.g.Baudron et al., 2021a). Many studies highlighted the limitations of such an approach and suggested a paradigm shift (Giller et al., 2006; Giller et al., 2011; Urruty et al., 2016; Descheemaeker et al., 2019). First, promising options at field level may not provide the increase in income or food supply at farm level that is needed for farmers to improve their situation (Thuijsman et al., 2022). Second, the average yield does not take into account the variability existing in time and space, which plays an important role in farmers' decisions (Vanlauwe et al., 2019). Farmers may prefer a stable but lower yield instead of a higher yield with the risk of losses (Feyisa et al., 2023). Third, grain yield is a crucial indicator for farmers, yet it does not take into account other factors that farmers might appreciate such as taste, harvest time, fodder production, cost-benefit, or labour requirements (Michalscheck et al., 2018; Ronner et al., 2019). In this research we addressed the first two knowledge gaps by assessing the farm-level output in terms of income and energy generation, next to yield, throughout time. We focused on the variability and mean effect of diversification strategies in dealing with weather variability.

Modern Portfolio Theory (MPT) is a tool developed in the 1950s (Markowitz, 1952) which has often been used in economic studies to quantify the benefits of diversification (Elton & Gruber, 1997). It quantifies the total value of the expected return and the variability when two financial assets are combined instead of just targeting one asset. In agricultural studies MPT has been applied by assessing the weighted farm-level yield and variability that can be expected when combining different management practices on the cultivated farm land. Paut et al. (2019) used MPT in horticulture systems in France and van Noordwijk et al. (1994) studied fertiliser rates in Burkina Faso. Paut et al. (2019) defined the benefit of diversification as the reduction in variability. Yield variability is related to hazards which are probabilistic events. In this study, we investigated the variability in yield as affected by weather conditions. Agricultural risk is defined by the frequency and impact of a hazard (World Bank, 2016). As a proxy of risk, we assessed the probability of the annual returns to drop below the farm-level income or food self-sufficiency threshold.

We assessed the farm-level effects of diversifying different crops and management options using MPT, and compared the output with average farmers' practice. We focused on the variability in yield (and the related energetic and economic return) as a result of weather variability. As not all farms have the same resources and needs, we applied diversification strategies that were relevant and feasible per farm type. These diversification strategies entailed different combinations of crop management allocation for four main crops in the farming system of southern Mali (maize, sorghum, millet and cotton). Overall, by applying MPT, we addressed the following questions: (i) How does the diversification strategy in terms of crop land allocation affect the mean return (weighted yield) and its stability at farm level? (ii) Which management component (crop, variety, fertilisation and their combinations) has the potential to increase stability most through diversification? (iii) What are adequate diversification strategies in terms of contribution to poverty alleviation and food security, and (iv) how do these strategies differ among farm types?

4.2 Methodology

4.2.1 Conceptual framework: Modern Portfolio Theory

For MPT in agricultural applications an asset was defined as a set of agricultural field management practices (van Noordwijk et al., 1994; Paut et al., 2019) and the combination of assets was translated as the proportion of cultivated land allocated to each asset. The weighted farm-level yield was the indicator used for return, and the variability was represented by the standard deviation (SD) of the yield (Table 4.1).

In our research, we looked at the variability as a result of the different weather conditions over the years. By applying MPT, we assessed the effect of allocating two different assets on the cultivated land. When different assets react differently to environmental conditions (low correlation between the yields of the two assets), a combination of these assets leads to a more stable return at farm level compared to the situation where all land is cropped with either one of the assets. This theory is explained visually in Figure 4.1, where asset A has a relatively low yield with a low variability, while asset B has a larger yield, and also a higher variability. Each point along the curve represents a proportion of assets on the cultivated land, going from 100% allocated to asset A and gradually interchanging towards 100% asset B. For each proportion of the assets the return (farm-level yield) and variability (standard deviation) were plotted. Several combinations of assets had a lower variability than all land allocated to asset A or to asset B.

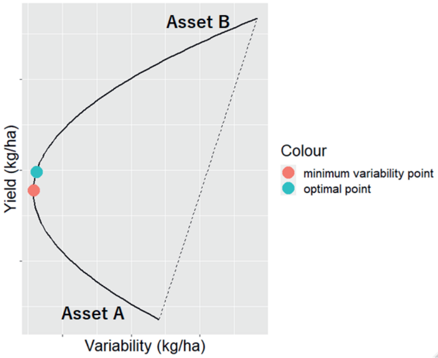

Figure 4.1 The relationship curve between variability and mean return (weighted farm-level yield) created by modern portfolio theory for different proportions of land allocated to asset A and asset B. The dashed line represents the hypothetical case where A and B are completely correlated. The blue point and red point represent the optimal and minimum variability point respectively. The optimal point is where the variability reduction (compared to the dashed line) is maximised.

Mathematically MPT can be represented using the following formulas. The land allocation is calculated as:

$$c_A + c_B = 1 \tag{4.1}$$

Where:

c_A: proportion of cultivated crop land allocated to asset A

c_B: proportion of cultivated crop land allocated to asset B

MPT returns were expressed as the weighted farm-level yield for different proportions of land. The farm-level yield was calculated as the weighted sum of the average yield of each asset. In other words, the return of the diversification is the sum of the average yield of each asset taking into account the proportion of land allocated to it:

$$Y_f = Y_A c_A + Y_B c_B \tag{4.2}$$

Where:

- Y_f: average weighted farm-level yield (kg/ha) over the assessed years (from here onwards we will refer to Y_f as farm-level yield
- Y_A: average yield of asset A
- Y_B: average yield of asset B

The variability of the diversified situation was represented by the combined standard deviation of the assets:

$$\sigma_f = \sqrt{{c_A}^2{\sigma_A}^2 + {c_B}^2{\sigma_B}^2 + 2c_A c_B \sigma_A \sigma_B \rho_{AB}} \tag{4.3}$$

Where:

- σ: standard deviation, with σ_f the combined farm-level standard deviation, σ_A and σ_B the individual standard deviation of both assets
- ρ_{AB}: correlation coefficient between asset A and B

A smaller σ_f indicates a more stable weighted farm-level yield. Therefore, smaller individual standard deviations of the assets and a low correlation between A and B lead to more stable yields. Consequently, diversification leads to a larger stabilisation benefit when the assets react differently to a hazard. If the two assets are completely correlated with each other, there is no stabilisation benefit which is represented with the dashed line in Figure 4.1. Comparing the point on the dashed line with the point on the curve for a specific proportion of assets reveals the reduction in variability due to diversification.

Using the MPT curve in Figure 4.1 meaningful points for farm management can be deducted, such as the optimal point, representing the largest reduction of variability, the degree of variability reduction was defined as follows (Paut et al., 2019):

$$\Delta\sigma = \frac{\sigma_{AB} - \sigma_f}{\sigma_{AB}} * 100 \tag{4.4}$$

Where:

- $\Delta\sigma$: variability reduction due to the diversification (%)
- σ_{AB}: variability of the asset A and B combined at a certain proportion, excluding the diversification effect. This is the combined variability assuming there is complete correlation which is a point on the dashed line.
- σ_f: the farm-level variability at a certain proportion of asset A and B

Diversifying the assets also affects the farm-level yield. Compared to allocating all the land to the asset with the largest yield, there will be a decrease in farm-level yield when diversifying the assets. The extent of the yield decrease was calculated as follows:

$$\Delta Y = \frac{Y_{max} - Y_f}{Y_{max}} * 100 \qquad (4.5)$$

Where:

ΔY: extent of the yield decrease (%)

Y_f: the farm-level yield at a certain proportion of the assets

Y_{max}: the maximum yield on the modern portfolio curve

For each combination of assets an optimal point was determined. The process to determine the optimal point depended on the shape of the MPT curve (Figure 4.2). The optimal point aimed at maximising Δσ. Unless there was a point with a lower absolute variability and a higher yield, then the optimal point referred to the point with lowest absolute variability (Figure 4.2, Table 4.1). The land allocation that was related to this optimal point, was defined as a strategy of diversification (Table 4.1).

In order to apply the MPT to the farming system in southern Mali (section 4.2.2), the first step was to define the assets to include in the diversification (section 4.2.3). Subsequently we searched for the diversification strategies that were meaningful compared to farmers' practice by translating the return to income and food indicators (section 4.2.4).

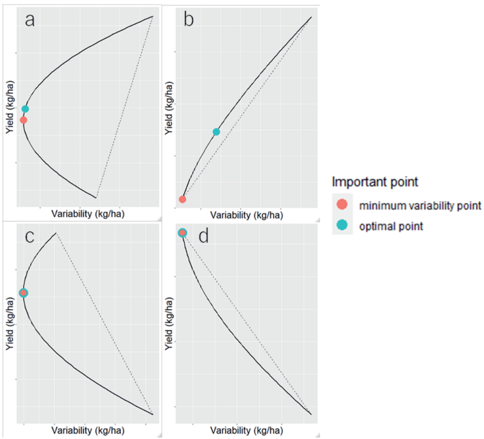

Figure 4.2 Different shapes of the MPT curve. In curves of type shape A and B a high-yield/high-variability asset is combined with a low-yield/low-variability asset, with in shape A a large variability reduction (Δσ), meaning that the variability of the optimal point is lower than that of both assets, and shape B shows a small variability reduction. For shape C and D a high-yield/low-variability asset is combined with low-yield/high-variability asset where in shape C there is a large variability reduction in the optimal point, and in shape D there is such a low variability reduction after combining the assets that the optimal point lays in allocating all land to the asset with high-yield/low-variability

Table 4.1 The terminology of MPT applied to agricultural research. More detailed explanation of the used datasets and indicator calculations in sections 4.2.3-4.2.4

Terminology MPT	Definition in agriculture	Unit (or more info)	Reference
Asset	Set of field management practices (based on crop, variety and fertiliser rate)		Table 4.3
Combination of assets	Farm land allocated to two assets	rate 0-1	Equation 4.1
Return	Weighted farm-level grain yield (translated into economic value, or energy)	kg / ha USD PPP/ha; kcal/ha	Table C.1, Equation 4.2
Variability (σ)	Standard deviation of the farm-level grain yield	kg / ha	Equation 4.3
Variability reduction (Δσ)	The reduction in variability of the farm-level grain yield compared to the hypothetical situation where both assets are completely correlated.	kg / ha	Equation 4.4
Optimal point	Land allocation to both assets in a combination when: - Variability reduction is maximised (for combinations of assets with a synergy between yield and variability) Or - Variability is minimised (for combinations of assets that have a trade-off between yield and variability)	rate 0-1	Figure 4.2
Strategy	A specific combination of two assets where the allocation has reached optimal variability reduction. Average farmers' practice is the baseline strategy to which other strategies were compared.		

4.2.2 Farmers' practice in the study area

The MPT analysis was done with data that represented farms in southern Mali, around Koutiala (12.3774° N, 5.4725° W). The diversity of farms was clustered by Falconnier et al. (2015) into four farm types according to their resource endowment in terms of number of livestock, area cultivated, number of household members and draught tools: High Resource Endowed farms with a Large Herd (HRE-LH), High Resource Endowed (HRE), Medium Resource Endowed (MRE) and Low Resource Endowed (LRE) farms.

For all farm types, cotton is an important cash crop. In this area the cultivation of cotton is supported by the CMDT (Compagnie Malienne pour le Développement des Textiles) for access to inputs, management advice and off-take of cotton (Benjaminsen et al., 2010). Cereal crops such as maize, millet and sorghum, are the main staple crops for consumption, but part is also marketed.

Data from two surveys gave detailed insights on farmers' practice and land allocation (Table 4.2). RHoMIS is a standardised household survey tool that has been applied several times across African countries (van Wijk et al., 2020), one of which in Koutiala on 80 farms in 2018. Additional management information was obtained from surveys with 25 farmers in 2018 and 2019 for the development of a planning tool (Dissa, 2023). The farmers included in the planning survey were a subgroup of the farmers involved in the RHoMIS survey. On average, farmers cultivated 12.7 ha of land, of which they targeted 8.2 ha to cereal production, 3.5 ha to cotton, and 0.6 ha to legumes. Legumes were not included in this research because of (i) their limited relative area on farms, and

(ii) lack of long-term yield data. Farm types had similar field management for cereals in terms of fertiliser and variety use, but the cultivated areas differed (Figure C.1).

On average it rains 863 mm per year, although totals ranged between 500-1250 mm/year in the period 1965-2019 (Traore et al., 2013; Huet et al., 2022). Farmers were concerned about hazardous rainfall events such as low rainfall, a late onset of rainfall or dry spells (Huet et al., 2020).

Table 4.2 Household characteristics and farmers' practice of cereal management; in general and for different farm types (HRE-LH, HRE, MRE, LRE). AME stands for 'Adult Male Equivalent'.

Farm characteristics	Overall Baseline	HRE-LH	HRE	MRE	LRE	Source
n RHoMIS	80	12	31	28	9	RHoMIS
n Planning Tool	25	5	9	10	1	Planning Tool
Nr household members	25	48	28	16	12	RHoMIS
Nr AME	19	35	21	12	10	RHoMIS
Area cultivated *(ha)*	12.7	20.3	12.5	8.4	5.0	Planning tool
Area allocated to cereals *(ha)*	8.2	14.5	8.8	5.0	3.6	Planning tool
Area allocated to cotton *(ha)*	3.5	4.1	4.4	2.4	1.0	Planning tool
Area allocated legumes *(ha)*	0.6	1.3	0.2	0.6	0.3	Planning tool
Area allocated other crops *(ha)*	0.4	0.2	0.7	0.1	0.0	Planning tool
% of cereal area						
Maize	27	26	32	25	41	Planning tool
Sorghum	30	31	34	24	34	Planning tool
Millet	43	43	34	51	26	Planning tool
% of cereal consumed						
Maize	78	82	79	75	80	RHoMIS
Sorghum	80	82	79	80	73	RHoMIS
Millet	68	62	73	65	66	RHoMIS
N application (kg N/ha)						
Maize	53	53	56	48	52	Planning tool
Sorghum	11	7	12	13	6	Planning tool
Millet	16	15	15	18	13	Planning tool

4.2.3 Defining assets and strategies based on crop production datasets

The management characteristics comprised in the assets were crop, variety and fertiliser rate. The four main crops of the farming system were included in the research: maize, sorghum, millet and cotton. For each crop we compared a variety regularly used by farmers (or with similar characteristics) with an early-maturing variety. Cereal varieties with a short cycle were of interest to farmers (Traore et al., 2015; Huet et al., under review). Only one cotton variety was included in the assets, as cotton seeds were provided by the CMDT and only a limited set of varieties is present in Mali (ICA Bremen, 2018; Avadí et al., 2020). The average fertiliser rate currently used by farmers was compared with an increased rate. For cereals, the increased rate was the one with the highest grain yield while maintaining a positive return on investment as defined by Huet et al. (2022). Each combination of management characteristics comprised an asset in the MPT (Table 4.3). For each crop the combination of farmers' practices was seen as the baseline asset for that crop.

The cereal yields (maize, sorghum, millet) and variability were obtained from model simulation output from the DSSAT-CERES crop model for the years 1965-2019. Details of the simulation set-up, including farming practice, and outputs were described in Huet et al. (2022). The cotton yields were observed data from a long-term trial from 1965 to 1993 in N'Tarla described in detail in (Traore et al., 2013). When cereal and cotton were combined, the cereal dataset was equally limited to the period 1965-1993. Both datasets refer to the same location and respective weather data (N'Tarla weather station). Cotton was grown under on-station conditions where pests, weeds and diseases were controlled As such we allowed for comparison with cereal simulation data where pests, weeds and diseases were ignored.

Table 4.3 Overview of the management characteristics that build the different assets. Each asset was given a code constructed of the following abbreviations for crop: MZ (maize), ML (millet), SG (sorghum); for variety: LV (Locally used Variety), SV (introduced Short duration Variety); and for fertiliser rate: LF (Low Fertiliser), HF (High Fertiliser). The assets in bold font represent the baseline management (farmers' practice). The returns were analysed in terms of the yield (Y) and food (F) return for the cereal assets only, the analysis on economic return (E) included all assets.

Crop	Variety	Fertiliser rate *(kg N / ha)*	Asset code	Return Indicators applied
Maize (MZ)	**Obatampa**	**50**	**MZ-LV-LF**	Weighted yield (Y), Food (energy) return (F), Economic return (E)
		70	MZ-LV-HF	
	TZEE-SRBC5	50	MZ-SV-LF	
		70	MZ-SV-HF	
Millet (ML)	**CIVT**	**15**	**ML-LV-LF**	Weighted yield (Y), Food (energy) return (F), Economic return (E)
		100	ML-LV-HF	
	CIVT-10	15	ML-SV-LF	
		100	ML-SV-HF	
Sorghum (SG)	**CSM335**	**10**	**SG-LV-LF**	Weighted yield (Y), Food (energy) return (F), Economic return (E)
		80	SG-LV-HF	
	CSM63E	10	SG-SV-LF	
		80	SG-SV-HF	
Cotton (CT)	**CMDT cultivar**	**17**	**CT-LV-LF**	Economic return (E)
		40	CT-LV-HF	

4.2.4 Thresholds for return on food and income

The farm-level yield, entails the weighted yield of two assets, yet the value of one kg of one crop is not equivalent to that of one kg of another crop. To facilitate comparison, we complemented the analysis by expressing the return in food (energy) and economic values. Overall, we applied three indicators for return: weighted farm-level yield (kg / ha), the related energy (kcal / ha) and the related economic value (USD PPP / ha). The diversification strategies that included cotton were only assessed for the economic value, since cotton cannot be consumed (Table 4.3).

Accordingly, these energetic and economic returns of different strategies were compared to farm-level thresholds for food security and income, specified for each farm type. Firstly, we calculated the required energy production per ha for each farm type to obtain food self-sufficiency (based on energy levels of the crop) and/or the required economic value (USD PPP / ha) to exceed the poverty line. Secondly, we compared these thresholds with the return of different strategies in order to deduct promising diversification strategies per farm type. The formulas for conversion and threshold calculation are described in detail below.

4.2.4.1 Food self-sufficiency indicator and threshold

The yields were multiplied with the energy level per kg of grain for the cereals, which were 3650, 3780 and 3290 kcal / kg for maize, millet and sorghum respectively (USDA, 2019) (Table C.1).

For each farm type the minimum food requirement to obtain food self-sufficiency was calculated at household level. Assuming the daily caloric need per capita is 2500 kcal/capita/day (for an adult man) (FAO/WHO/UNU, 2001) and that the production of calories was targeted to the cereals, the total yearly requirement for the household was calculated as follows (the values for each farm type were obtained from Table 4.2):

$$\mathrm{F\_hh_i} = \frac{\mathrm{F\_cap} * \mathrm{AME_i} * 365}{\mathrm{c\_cereal_i}} \qquad (4.6)$$

Where:

F_hh:	Yearly required calories to feed the household (kcal/ha/year)
i:	Farm type (HRE-LH, HRE, MRE, LRE)
F_cap:	Daily calorific need per capita (2500 kcal/capita/day)
365:	Number of days per year (day)
AME:	Adult Male Equivalent
c_cereal:	Land area allocated to cereal crops (ha)

An additional assumption was made to reflect that farmers always sell a certain amount of their cereal production to provide for other needs than food:

$$\mathrm{TF_i} = \mathrm{F\_hh}_{\mathrm{i}} * \frac{100}{100 - \mathrm{S_i}} \tag{4.7}$$

Where:

TF: The food self-sufficiency threshold (kcal / ha / year)

S: Average percentage sold of the total cereal production (maize, millet, sorghum) (%)

4.2.4.2 Economic indicator and threshold

For the economic indicator calculation, the gross margin per unit area (USD PPP / ha) was calculated by assuming all produce is sold, and deducting the input costs of seed and fertiliser only (Table C.1). We used the Purchasing Power Parity (PPP) exchange rate for Mali of 211,41 West African CFA (XOF) for 1 PPP USD (World Bank, 2020). The total value of produce was obtained by multiplying the grain yield by the monthly average grain price of 0.50, 0.52 and 0.66 USD PPP / kg for maize, sorghum and millet respectively (OMA, 2016). The average local price for selling cotton (between 2015-2021) was set at 1.23 USD PPP / kg (personal communication Dissa, 2021).

Farmers in the region tend to use a combination of fertiliser types, which we assumed was on average 1/3 NPK (17% N) and 2/3 urea (46% N) (Traore et al., 2015). Farmers obtain most fertiliser through CMDT at a subsidised price (Ripoche et al., 2015) of 11,650 FCFA per bag of 50 kg regardless of the type of fertiliser (information based on communication with farmers and expert knowledge between 2017-2019). This meant the fertiliser price per kg was set at 1.10 USD PPP/kg, and taking into account the proportion of types of fertiliser used, the average price of adding 1 kg of mineral N was 3.03 USD PPP / kg N.

For the seeds, we only considered a cost for cotton and the introduced cereal varieties (i.e. the early maturing variety), as farmers tend to recycle their seeds of the local varieties of cereals (Huet et al., under review). For the cereals, information on seed rates and prices were deducted from the inputs used in crop trials of the project "Pathways to Agroecological Intensification of Crop-Livestock Farming Systems in Southern Mali" (more details in Huet et al., under review), while for cotton this information was acquired from (Coulibaly et al., 2015). The seed price per unit area used was 71.0, 39.0 and 16.4 USD PPP / ha for the introduced maize, millet and sorghum varieties respectively, and 4.90 USD PPP / ha for cotton.

For each farm type the minimum income requirement was calculated to exceed the extreme poverty line, that is set at 2.15 USD PPP / day / capita by The World Bank (2022). Under the presumption that farmers derive this income from selling all their production of cereals and cotton, the required returns per hectare were calculated as follows:

$$\mathrm{TE}_{\,\mathrm{i}} = \frac{\mathrm{p} * \mathrm{HH_i} * 365}{\mathrm{Land}_{\,\mathrm{i}}} \tag{4.8}$$

With:

TE:	Economic Threshold (USD PPP / ha)
p:	Extreme poverty line defined by the World Bank (2.15 USD PPP / day / capita)
HH:	Number of household members (total number, not expressed in AME)
365:	Number of days in a year (days)
Land:	Area of land cultivated by cereal and cotton (ha)

4

4.2.5 Steps in the MPT analysis

For each step of the MPT analysis, two assets were combined and the land allocation of the optimal point defined. An overview of the assets included in each step is given in Table C.2. We started with a baseline analysis, where we diversified one asset component (crop, variety, fertiliser) while keeping the others on baseline management. This means 13 possible asset combinations were included. Second, we combined all components of the cereals including 66 possible asset combinations, before combining all management components of all four crops which includes 91 possible asset combinations. The return and variability of each combination in its optimal point was then assessed to see whether the diversification strategy carried a benefit compared to farmers' current allocation of land.

The most common land division of the crops under farmers' practice, the baseline strategy, was considered the reference point (Table 4.2). Strategies that were superior to the baseline strategy had a higher yield and a lower variability, while inferior strategies had a lower yield and a lower variability. Trade-offs exists when the assessed strategy showed a lower variability but a loss in yield, or the other way around. The probability of the return falling below the threshold indicated the risk of the diversification strategy. Diversification strategies that were superior, were included in the final step of the study where we compared the return and variability to the poverty and food self-sufficiency thresholds per farm type. Additionally (i) five strategies with the highest mean return, (ii) five strategies with the largest variability reduction, (iii) the reference point, and (iv) the situation of allocating all land to baseline management of the different crops, were evaluated in relation to the thresholds as well.

4.3 Results

4.3.1 Return and variability when diversifying crop baseline management

As a first step we applied the Modern Portfolio Theory to a combination of a first asset, which was a crop cultivated under baseline management, with a second asset, which differed from the first in one component only (crop, fertilisation level, or variety) (Figure 4.3 a, b). Because the correlations between assets expressed in yield and energy were the same, and thus the shapes of the MPT curves were similar, we included the MPT curves for the energy return in the supplementary material (Figure C.2).

First, we looked only at the cereals. Overall, the shapes of MPT analysis were relatively little curved (Figure 4.3a), and the maximum variability reduction (Δσ) was 14%. The combinations that diversified the crop component allowed for most stabilisation benefit with a yield correlation coefficient for millet-sorghum of 0.49, for millet-maize of 0.54, and for maize-sorghum 0.74 (all under baseline management, i.e. low fertilisation and local variety). For the combinations with different fertiliser rates or varieties of the same crop the yield correlation was stronger, except for the two sorghum varieties (correlation coefficient of 0.73) (Table C.3). The strongest diversification benefit at the optimal point occurred under crop diversification, more specifically millet-maize (Δσ of 12%) and millet-sorghum (Δσ of 14%). At the optimal points 68% and 80% of land were allocated to millet in the millet-maize and millet-sorghum combinations respectively. As mentioned earlier, the interpretations were similar for the results expressed in yield or energetic return, yet in the strategy millet-sorghum, the loss was less pronounced in energetic return (ΔF was 9%) than in yield (ΔY was 19%). Because although sorghum yields more than millet, the amount of kcal per kg was lower, so in terms of energy both crops had a similar mean return under baseline management. For the combination of maize and sorghum under baseline management, there was no diversification benefit and allocating all the land to maize seemed the best option.

When increasing fertiliser rates, both the mean and variability of the yield increased for all three cereals compared to the baseline situation. Thus, when combining assets with different fertiliser rates, there was a trade-off that led to optimal points where a bit more than half of the land was allocated to the low fertiliser rate management (most stable management).

When diversifying the varieties, the MPT curves had a different shape for each cereal. For maize and millet there was a trade-off between yield and variability of the two varieties; for millet it was the short duration variety that had the lowest yield and variability compared to the baseline, while for maize this was the baseline variety. So for both crops the pairwise combinations of varieties, resulted in around 60% of the land being allocated to the more stable variety, which was the short variety for millet and the baseline for maize. For sorghum there was no diversification benefit and it appeared most beneficial to target all land to the short duration variety (higher yielding with lower variability). Nevertheless, for both fertiliser and cultivar diversification, the diversification benefit (Δσ) of the optimal points remained very limited, ranging between 0-6% depending on the strategy (Table C.3), while the loss in mean weighted farm-level yield was generally larger (4-34%).

In a second step, we expressed results with the economic indicator and added cotton to the combinations. This led to more pronounced curves in the MPT plots (Figure 4.3b), with larger Δσ's for cotton-cereal combinations compared with the cereal-cereal combinations. Indeed, the correlation between cotton and cereals was lower than for other combinations, being -0.02, 0.16 and 0.04 between baseline cotton and baseline maize, millet and sorghum respectively (Table C.4). This led to optimal points where cotton was allocated to 27%, 20% and 40% of the land in the combinations with baseline maize, millet and sorghum respectively. The variability reduction was pronounced as the related Δσ was 30%, 24% and 28%. Nevertheless, the accompanying mean economic loss compared to sole cotton was also relatively high (73%, 80% and 47% respectively).

In the economic analysis, we also diversified the cotton baseline with an asset with increased fertiliser rates to cotton, which had a larger economic return accompanied by a relatively limited increase in variability. At the optimal point around half of the land was allocated to both assets with a Δσ of 9%. The interpretation of the fertiliser and cultivar diversification of the cereals remained the same when expressed in economic terms, except for the combination with fertiliser diversification of sorghum. Applying fertiliser diversification of the baseline sorghum increased the mean yield, but lowered the economic return. So from an economic perspective, it would be more beneficial to allocate all land to baseline sorghum management, rather than allocating land to sorghum with higher fertiliser rates. Expressing the sorghum yield in economic return also changed the perspective on the relation with millet, as the baseline millet yield was lower than that of sorghum, yet the economic return was higher because of the higher price for millet on the market.

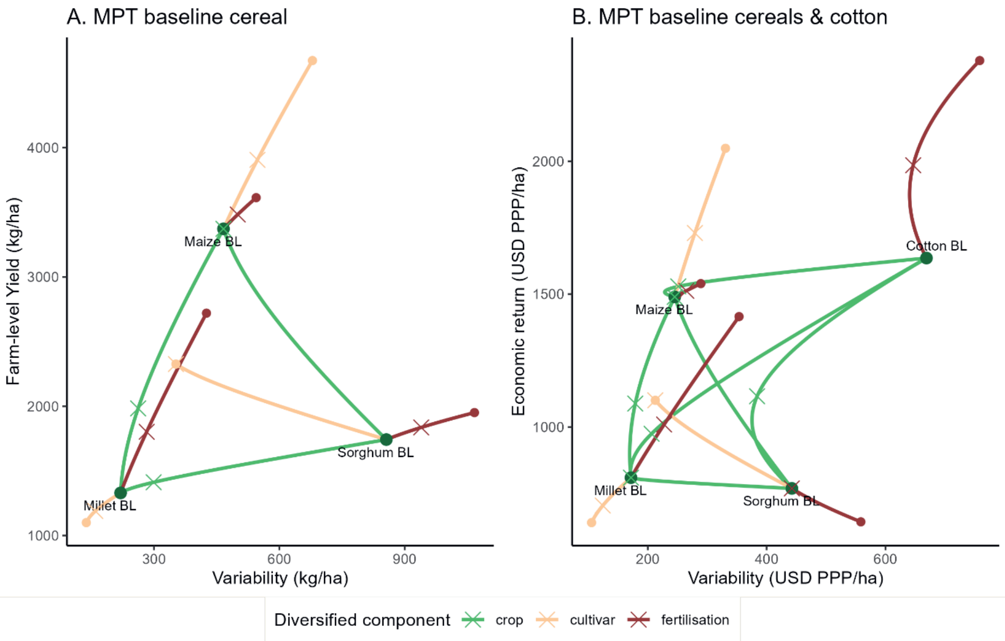

Figure 4.3 A) The cereal baseline MPT curves expressed in weighted farm-level yield (kg / ha) and variability (kg / ha). **B)** The cereal and cotton baseline MPT curves expressed in weighted farm-level economic return (USD PPP / ha) and variability (USD PPP / ha). Baseline (BL) points show the return and variability when all land was allocated to the baseline management of a crop. For each of these points the MPT curve was drawn with one asset component diversified (crop, fertiliser rate, cultivar). The crosses determine the optimal points on each diversification curve.

4.3.2 Optimal points when allowing for different levels of diversification

When allowing combinations without restricting to diversifying only one component in relation to a baseline asset, more than half of the MPT curves had a shape B (Figure 4.2), regardless of the indicator (Table 4.4). A shape B indicated a high return-high variability asset combined with a low return-low variability asset and limited variability reduction (Δσ) in the optimal point. A limited number of strategies followed shape A or C: 5 and 8 out of 66 strategies when considering yield and energetic return, and 20 out of 91 when assessed for economic return. In shape A and C the variability of the optimal point was lower than the variability of that of both assets individually. For 22-24% (depending on the indicator assessed) of all the combinations, there was no stabilisation benefit and all the land was allocated to the higher yielding asset (type D). The maximum economic variability reduction (Δσ) that could be obtained was 33%, while for yield and energy this was 19%. A large diversification benefit did not necessarily result in a large yield loss as there was no overall trend between Δσ and ΔY for different crop combinations (data not given). Diversifying more components simultaneously resulted in higher Δσ (Figure C.3).

When all optimal points were plotted against farmers’ practice of land allocation (reference point) and against the 100% allocation for each crop baseline management, most optimal points had a trade-off compared to the reference point. Sixteen strategies were superior (higher return, lower variability), which included the maize baseline management when assessed economically. For the yield and energetic return, two points (including all land allocated to sorghum baseline management) were inferior to the reference point, while for the economic assessment four inferior points were diagnosed.

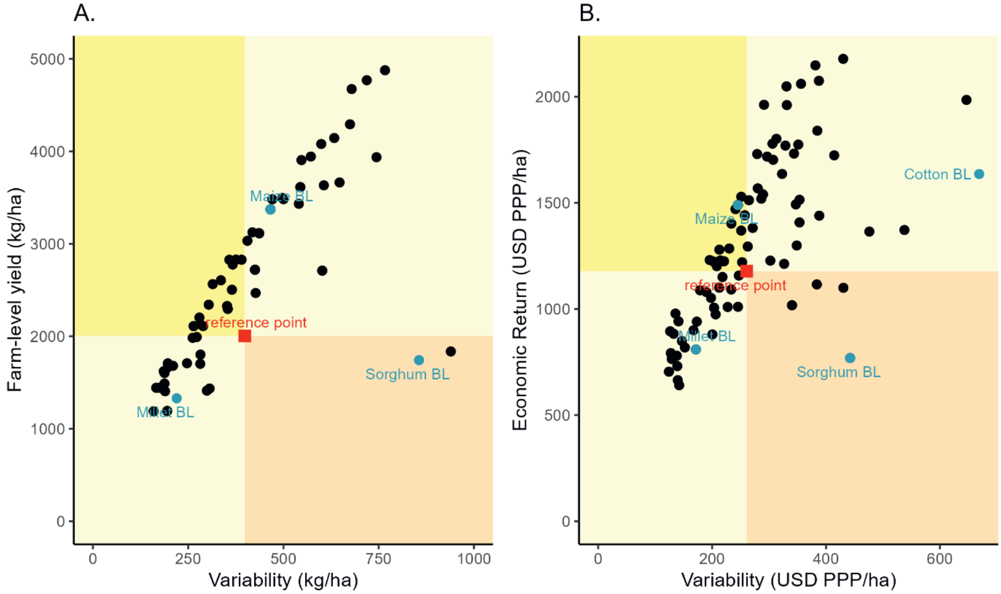

Figure 4.4 The farm-level return and variability of the optimal points of the different pairwise strategies. The red point represents the reference point, being the average land allocation of different crops under baseline (BL) management. The blue dots represent the situation where 100% of land was allocated to that crop under baseline management. A strategy was seen as superior to the reference point if it had both a higher return and a lower variability (green background), as inferior if there was a higher variability and lower mean return (orange background), and in other cases as a trade-off (yellow background). **A)** The optimal points of 66 different asset combinations (crop, fertiliser rate and/or variety diversification) on land allocation of three cereals, expressed in yield. **B)** The optimal points of 91 different asset combinations (crop, fertilisation rate and/or variety diversification) on land allocation of three cereals and cotton, expressed in economic return.

Table 4.4 The number of diversification strategies according to the type of MPT shape (Figure 4.2), with the maximum achieved variability reduction (Δσ) in and optimal point of the strategies included.

	Indicator yield		**Indicator energy**		**Indicator economic return**	
Shape	**Nr strategies**	**Max Δσ** *(%)*	**Nr strategies**	**Max Δσ** *(%)*	**Nr strategies**	**Max Δσ** *(%)*
A	2	12	3	12	12	33
B	45	19	44	19	51	33
C	3	6	5	7	8	28
D	16	0	14	0	20	0
	66		**66**		**91**	

4.3.3 Threshold analysis: potential land allocations per farm type

In order to understand the meaningfulness of the diversification strategies, we compared a subset of strategies to farm requirements. The required farm-level return per hectare to fulfil the household's needs in terms of energy levels and income differed per farm type (Table 4.5). The LRE farms had the least resources but needed to achieve the highest energy and economic returns per ha in order to obtain food self-sufficiency or to cross the poverty line. The LRE farms were closely followed by the HRE-LH farms. The MRE farms required the smallest economic return, while the HRE farms required the smallest energy return.

The difference in the order of farm types with the most demanding thresholds for energy and economic return can be explained through the differences in household characteristics, such as the household composition. For the energy requirement the AME (Adult Male Equivalent) was used as a measure for household size. For the income thresholds we did not discriminate for age and gender when assigning the required income per person, and the actual number of people in the household was used as the household size.

When it comes to obtaining food self-sufficiency, all subsets of strategies (including the reference point, baseline management, smallest Δσ, superior points and largest returns) gave a mean farm-level return larger than the required minimum for all farm types (Figure 4.5 a). These required thresholds were below the range of one standard deviation from the mean as well, indicating that these strategies were suitable in most years. The lower limit of one standard deviation from the mean dropped below the LRE energy requirement when all land was allocated to baseline sorghum management. Put in another way, sorghum under baseline management only would regularly not produce enough food to feed the LRE farms, making it an unsuitable strategy.

The strategies with the largest variability reduction (Δσ), all allocated a large portion (>0.75) of the land to millet (often the short variety with low fertiliser rates), which were also the assets with lowest overall variability (Figure 4.5b). The strategies superior to the reference point were diverse in the assets that were combined, yet millet was an important contributor: in 12 out of the 17 superior strategies, more than half of the land was allocated to millet (generally the short variety with high fertiliser rates). The local variety of sorghum was only present in the strategies with largest Δσ, while the short variety of sorghum appeared in the superior strategies. Maize, for both varieties and fertiliser rates, pushed out the other crops in the strategies with the highest mean energy return.

The choice of suitable strategies was more restricted when it came to exceeding the poverty line (Figure 4.6a). The means (including the error bars) of the reference point, millet and sorghum baseline were below the trheshold for all farm types. The strategies with lower variabilities (largest Δσ and superior points), including the maize and cotton baseline, were only sufficient for MRE farms under beneficial weather conditions. In other words, for these strategies the mean return was under or slightly over the threshold, but for some strategies the error bars (one standard deviation of the mean) still crossed the threshold. The two most suitable strategies from this set included land allocation to cotton (low fertiliser rate) with the local variety of maize (low and high fertiliser rate) who were able to cross the HRE poverty threshold within the error bar (Figure 4.6a, b). The thresholds for the other farm types were stricter, and thus none of these strategies were suitable for them. Only the strategies with the largest overall economic return had a mean sufficient for all farm types, yet these strategies also comprised a larger variability. All farm types, except for MRE farms, had a risk of not exceeding the poverty line even with these high yielding strategies (thresholds larger than mean minus one standard deviation). So farmers have to take risks in order to have a chance of exceeding the poverty line.

When looking at the land allocation of the strategies with the largest return, these all included the short variety of maize, pushing out the other crops, except cotton (with high fertiliser rates) in two strategies (Figure 4.6 b). Thus for the economic indicator, allocating land to cotton and (short variety) maize contributed to increased return, although variability was large. On the other hand, allocating around a quarter of land to cotton (low fertilisation), in combination with a cereal also obtained the strategies with the largest variability reduction. The superior strategies that included millet incorporated the high fertilisation component (in seven out of eight strategies) and those that included sorghum entailed the short variety (five out of five strategies).

Table 4.5 The required farm-level energy and economic return per ha for each farm type (HRE-LH, HRE, MRE, LRE).

Farm type	**Threshold energy** *(10^6 kcal / ha / year)*	**Threshold economic return** *(USD PPP/ ha / year)*
HRE-LH	2.9	1856
HRE	2.8	1758
MRE	2.9	1495
LRE	3.4	1883

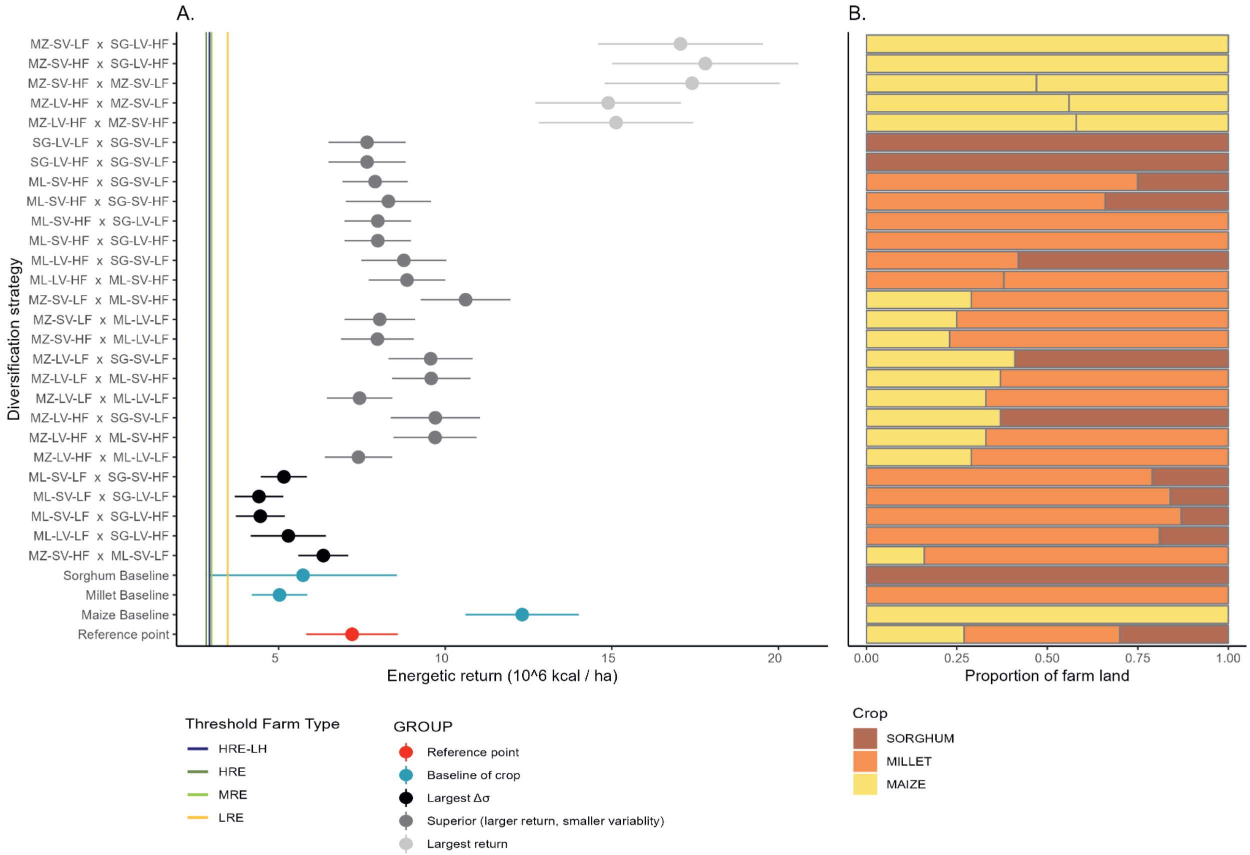

Figure 4.5 A) The mean energy return and variability (indicated by the error bar representing the standard deviation) of the optimal points for different strategies. The strategies represented are the reference point (farmers' practice), the baseline management per crop, the five strategies with the largest Δσ, the (additional) strategies superior to the reference point (when the optimal point had a larger return and a smaller variability), and the five strategies with the largest return at the optimal point. The food self-sufficiency thresholds for the different farm types are plotted as vertical lines. **B)** The crop allocation ratio for the assets at the optimal points of the respective strategies.

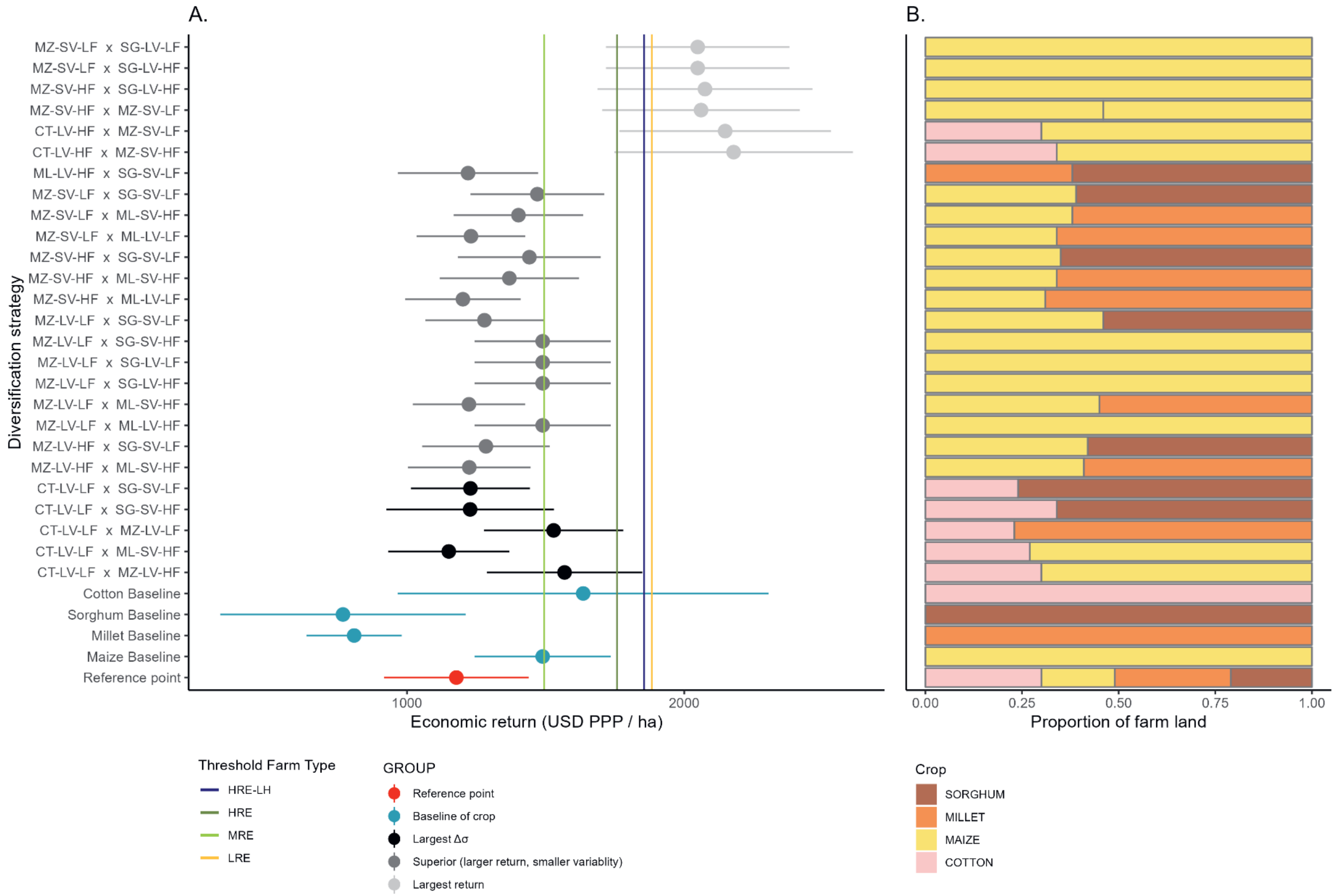

Figure 4.6 A) The mean economic return and variability (indicated by the error bar representing the standard deviation) of the optimal points for different strategies. The strategies represented are the reference point (farmers' practice), the baseline management per crop, the five strategies with the largest Δσ, the (additional) strategies superior to the reference point (when the optimal point had a larger return and a smaller variability), and the five strategies with the largest return at the optimal point. The poverty thresholds for the different farm types are plotted as vertical lines. **B)** The crop allocation ratio for the assets at the optimal points of the respective strategies.

4.4 Discussion

4.4.1 Return and stability affected by strategies

Allocating crop land to pairwise combinations of assets had the potential to increase the farm-level stability, yet the maximum variability reduction reachable was 33%, which was less than the maximum of 77% described in the French horticultural system by Paut et al. (2019). Most combinations in our research entailed a low variability-low yield asset combined with a high variability-high yield asset, for which the combination resulted in a trade-off of gaining in stability and losing in yield, and included very few strategies where the variability was reduced to a below that of either one of the assets (Type A or C MPT shapes). This was because the different assets were fairly well correlated and thus expressed a similar response to the weather. So the reduction in variability was generally obtained by introducing a crop in the combination with less variability, rather than through the combination of two assets with a completely different or opposite response to weather (Figge, 2004). This was not completely surprising as three of the four crops included were cereals, and the lowest correlations were found between cotton and cereals (around 0, or slightly negative).

In our results, millet was the crop that contributed most to stability, and it is often promoted as a more drought tolerant cereal (Ewansiha & Singh, 2006). Maize and cotton were important contributors to increased yields, energy and/or economic return. These latter crops also received more inputs than sorghum and millet in farmers' practice, which constituted the baseline. Regardless of the relatively low return and high variability of sorghum, the relatively low correlation with the other crops sometimes still lead to a stabilisation benefit by allocating some land to sorghum, for example in the combinations of millet-sorghum that had the largest yield variability reduction. Nevertheless, in other combinations sorghum was pushed out at the optimal points. This was in line with the findings of Falconnier et al. (2016); (2017) who observed relatively low yields of sorghum and through co-learning cycles suggested to replace 25% of sorghum with cowpea for HRE-LH farms. The sorghum variety CSM63E, which was our 'short' variety, was grown in on-farm trials near our study area in 2019, a year with waterlogging, and proved to be relatively high-yielding an spatially stable under these weather conditions (Müller et al., 2020). Millet and sorghum are considered more drought resistant crops than maize, which indicates a benefit of cultivating these crops in hazardous years. Nonetheless, seasons with a rainfall of 700 mm / year were perceived as relatively bad years by farmers in this area (Falconnier et al., 2016; Huet et al., 2020), which is still an appropriate amount of rainfall for maize production as well (Hadebe et al., 2017).

The introduced varieties as alternatives for the baseline variety were selected for their short cycle since it is a commonly promoted and requested crop characteristic in risky environments (Traore et al., 2015; Sultan et al., 2019). Nevertheless, for the three cereals the alternative varieties responded differently to the weather variability compared to the baseline variety, so the duration of the cycle was not the only characteristic determining relevant land allocation combinations in this environment. The same dataset was used in a risk analysis at field level (Huet et al., 2022), where these short-duration varieties of maize and sorghum appeared as appropriate options in years with a late onset.

In this study, increased millet fertiliser rates were also proven to increase the yield without resulting in greater relative yield losses under hazards such as a late onset and low rainfall. When it comes to increasing fertiliser rates, these increased yields, but not necessarily the economic return at the optimal points, so the advantage of increasing fertiliser rates depended on the objectives and resources of the farmer.

Comparing the optimal points with farmers' practice of land allocation to the three cereals (reference point), several superior diversification strategies were revealed. A suggestion that came forward was to include millet with high fertilisation and sorghum with a short-duration variety in the combination. Fertiliser application strongly increased millet yield compared to the millet baseline and the short-duration variety of sorghum strongly decreased the variability compared to the sorghum baseline. Traore et al. (2017) also mentioned increased fertilisation as an effective climate adaptation strategy, whereas Sultan et al. (2014) recommended using the short duration variety of sorghum to adapt to climate uncertainty. Whereas the short duration variety resulted in lower yield compared to the other variety (Traore et al., 2014), our results indicated that the short duration variety still has an advantage in terms of diversification benefit. Then, combining those assets with maize, which was characterised by high yield and high variability, led to a higher yield than a single asset of sorghum or millet. It is recommended for farmers who want to keep yield variability low to allocate land to sorghum or millet. Of all the combinations assessed, most had a trade-off compared to the reference point, indicating that farmers' current diversification strategy was already well targeted.

Depending on the fertiliser rates maize, gave a similar economic return to cotton. Nevertheless, both crops have different advantages in the farming system. Maize directly contributes to food self-sufficiency, one of the main objectives of farmers. Cotton was an important contributor for variability reduction when combined with a cereal. Also, farmers receive inputs via CMDT when growing cotton, and it seems many farmers use some of these inputs also for cereal production (Coulibaly et al., 2015; Sidibé et al., 2018). Farmers allocated 32% of their farmland to non-cereal crops, including cotton (RHoMIS survey as described in the methodology). Through personal communication with experts, we learned that CMDT unofficially promotes a maximum of 30% of land allocation to cotton, with the objective of diversification.

For options adding different varieties on farm land and increasing fertiliser rates, the inputs need to accessible and affordable for farmers. Hence, depending on the objectives and resources of farmers, different strategies might be more adequate. For example, in Kenya, it was found that when farmers applied more fertiliser, they diversfied less in terms of crops, meaning that they spread the fertiliser among different crops and applied less fertiliser per unit of area (Ochieng et al., 2020).

4.4.2 Adequate strategies for farm types in the contribution to poverty alleviation and food security

Land-use diversification is commonly promoted as a risk coping strategy (Mertz et al., 2008; OECD, 2009). In this study we addressed risk as the probability of dropping below the food self-sufficiency or income threshold. We assessed which diversification strategies had most potential to deal with weather variability in terms of reaching a high enough mean, yet stable, return, in order to exceed the thresholds in most years . As the cereal yields were simulated, influenced by weather variability only, and thus higher than observed yields, Our outputs in relation to the thresholds, were optimistic. The farm types with the least resources needed to achieve the highest yields in order to fulfil the energetic and income needs for the household; the MRE were best positioned. Unfortunately, the low-resource endowed farms were obtaining lower average yields than other farm types (Falconnier et al., 2015; Dissa et al., forthcoming).

Diversification strategies were more constrained by the income than by the food self-sufficiency thresholds for all farm types. Our results further supported the statement by Falconnier et al. (2015) and Giller et al. (2021) most households in southern Mali are food secure, except for LRE farms, yet that it was difficult for all types of farms to exceed the poverty line. Nevertheless, it should be taken into account that the diet in Mali is cereal-centred (Smale et al. 2020), and such a monotonous diet is expected to worsen the nutritional status (Arimond and Ruel, 2004). Therefore, even if self-sufficiency is met, the diet may be unsatisfactory in terms of nutrition. de Jager et al. (2018) found that in northern Ghana, with a similar agroecological zone as southern Mali, not all nutrient requirements could be met with the crops generally grown on farm. The availability of food and nutrients improved with greater agro-biodiversity, but this was not always reflected in the diet. Additionally, in order to bridge the poverty line most adequate strategies included cotton, leading to a trade-off between income and food production. Combining cotton with maize enabled to exceed the income threshold for all farm types on average and some of them passed the threshold even in a bad season. Recently the proportion of maize on farm cultivated land has been increasing, while the production of cotton, millet, and sorghum tended to decline in southern Mali (Laris and Foltz, 2011; Traore et al., 2014). Maize and cotton were the crops that require most fertiliser inputs, and thus resources from the farm.

We used the extreme poverty line (2.15 USD PPP / day / capita) in this study; the common benchmark used for Low and Middle Income Countries such as Mali (World Bank, 2022). An additional measure used for other countries is the poverty line of 3.65 USD PPP which would set the requirements for crop return even higher. Our analysis suggested that crop cultivation was insufficient to gain an income that can lift farmers out of poverty throughout all years. Indeed, several studies suggested that gaining income from other sources such as off-farm work and dairy production could help to exceed the income threshold (Falconnier et al., 2018; Ollenburger et al., 2019; Giller et al., 2021). Therefore, income from other sources could enable farmers to choose diversification strategies with lower variability. Trade-offs between high productivity level and high variability were often observed in Sub-Saharan Africa, and farmers may have different objectives as obtaining a higher productivity, or rather investing in the reliability and stability of production (Descheemaeker et al., 2020). Our results indicated that farmers needed to be willing to take some risk to go beyond the income threshold.

Diversification of crop land showed benefits related to increased stability and several strategies were meaningful for farms, yet the results were not uniformly in favour of diversification as (i) in various combinations the lower yielding asset was pushed out and all land was allocated to the higher yielding crop, and (ii) the more stable options were often not adequate to cross the income threshold. In literature there is also mixed results when it comes to the impact of diversification. Ochieng et al.

(2020) conducted a literature study on climate variability as driver of crop diversification and found no conclusive results whether variability and diversified crop management as an adaptation strategy were positively correlated. For example, some studies showed that farm size was positively related to crop diversity in areas where drought related hazards were common (Ashfaq et al., 2008; Makate et al., 2016). On the other hand, there are examples where income portfolios did not become more diversified throughout time (Lay et al., 2009). Farmers in southern Mali engage in different farm components and value chains, which were related to each other for example via crop-livestock interactions (e.g. fodder and manure production, draught power) or through the cross-overs between the cereal and cotton value chains. This led to positive feedback loops in good years and negative feedback loops in bad years (Dissa, 2023). Or in other words, diversity on these farms had potential to buffer for hazards, but as farm components were not independent from each other, the magnitude of the buffering was also limited by certain hazards.

4.4.3 Methodological considerations

When the objective of farmers is achieving food self-sufficiency, cereal production remained an important contributor and many diversification strategies had a stabilisation benefit. When income was added as a target for farmers, the number of adequate diversification options were limited. So the potential of other diversification options which include other crops and activities should be assessed, or the potential of specialisation in other farm activities could be investigated, which was outside the scope of this paper.

Our approach allowed an exploration of farm-level effects of diversification not only in terms of crops, but also in terms of other management practices (variety, fertiliser rates). Additionally, we assessed different indicators of return (yield, energy and economic) and compared it with food self-sufficiency and income benchmarks for different farm types. Although with a limited set of assets, we addressed knowledge gaps associated with quantifying the effect of diversification in coping with risk for different farm types (Paut et al., 2019).

Nevertheless, our approach also had some limitations. For simplicity, we only addressed two assets in the combination, while in real life there are many options for diversification. The reference point included land allocation to 3 or 4 crops. Follow-up research could allow for more combinations in the assets, rather than only pairwise combinations. Additionally, it would be good to include other types of crops, such as legumes.

The simulated yields we used were only influenced by weather variability, and therefore higher than the yields that farmers obtain on their farms. Measured observed yields in the area were around 2 t/ ha maize, 0.9 t / ha sorghum and 0.8 t / ha millet (Falconnier et al., 2016) versus 3.4 t / ha for maize, 1.7 t / ha for sorghum and 1.3 t / ha for millet in our simulation. Many other factors that were not accounted for play a role in the variability and return (pests and diseases, management and labour, access, market prices). For cotton we used observed yields, although these were obtained under optimal, on-station management, so carefully controlled for pests and diseases. On-station experiments of maize and millet in the same region by Traore et al. (2015) recorded gross margins of 100,000-150,000 FCFA / ha for maize and 50,000-250,000 FCFA / ha for millet depending on the fertiliser treatments. Converted to USD PPP, this equals 474-3554 USD PPP / ha for maize and 237-1182 USD PPP /ha for millet. The economic returns we calculated in this research were conform that range.

We used the PPP conversion rate as it is a useful tool to compare between countries, yet it is not without its critics. For instance, the PPP conversion rate is based on the cost of a specific basket of goods in a country, yet it is hard to uniformalise such a common set of commodities (Taylor, 2006). Using the PPP instead of the market exchange rate, as is regularly used in agricultural studies as well, resulted in greater gross margin. With the market conversion rates (with 615.5 XOF to 1 USD, the average conversion rate in the same year 2020), the average gross margin per ha was 527, 286, 301 and 562 USD / ha for baseline maize, millet, sorghum and cotton respectively.

Other hazards related to for example market were not included in the analysis. Weather variability and grain prices might be correlated, with lower prices in years with good weather production. In addition to interannual fluctuation, the cereal price is variable within a year because of the poor storage capacity. The price is typically lower right after the harvest and higher before the harvest season (Brown et al. 2009). Storage capacities and price setting might be different for the different crops, which would influence the variability reduction of the combinations.

4.5 Conclusion

We explored diversification of crop land allocation, taking into account the main crops (cereals and cotton). In terms of energy levels, all farm types were able to reach the required food self-sufficiency thresholds, yet a limited set of allocation strategies were able to provide for the income requirements. The strategies that had potential to bridge the poverty line, entailed risks because of their large variability. The strategies that provided a higher variability reduction often did not have an adequate mean return to exceed the poverty line. Millet and sorghum in asset combinations contributed to stability, while adding maize and cotton increased the mean return. The combination of cotton and a cereal had a relatively strong stabilisation benefit, as there was a low correlation between cotton and the different cereals in their response to weather circumstances.

In this research, the yields were only influenced by weather variability, as data was obtained from simulations and well-managed on-station trials in which pests and diseases were controlled. The returns were therefore higher than what can be expected on-farm where several other environmental and market factors increase the variability of the return. Even in the optimal circumstances as depicted in our research, crop production was too risky to provide for an income exceeding the poverty line. This led us to conclude that diversification had the potential to increase stability and that cereal and cotton contributed significantly to the income and food production when allocated strategically. However, crop production alone was not sufficient to provide a balanced livelihood, and diversification with (or focus on) other crops (legumes etc) for nutrition, livestock and/or complemented with off-farm income would be essential.

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5 Knowledge, productivity, diversification: Drivers of farmers' choices of sustainable intensification options in participatory co-learning cycles

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Abstract

Sustainable intensification options to deal with the many challenges of farming in West Africa need to be tailored to the local context of farmers. In a participatory co-learning process, on-farm trials were expanded with farmers' try-out fields where farmers implemented options at a larger scale on their own field without guidance from researchers. In six villages in the Koutiala region of Mali 538 on-farm trials were installed between 2012-2020, as well as 243 farmer 'try-out' fields between 2017-2020. All farm types were represented in the activities, but an age and gender gap existed among the participants, who were more often male and from the older segments of the population. Farmers defined the options they were keen to test: intercropping patterns, varieties of cereals and legumes, increased fertiliser rates, types and application, bio-pesticides, and relatively new crops such as soyabean. The options that were not explored further in the try-out fields were mainly those that demanded more labour or required more inputs. The iterative and adaptive experimentation and co-evaluation yielded a diversity of options farmers wanted to test and facilitated co-learning. Organising try-out fields with farmers in addition to classic agronomic trials contributed to refining the relevant options for farmers, and revealed the importance of e.g. labour requirements, market opportunities, previous experience, fodder production and taste. Grain yield remained an important criteria for farmers in their choice of options. Farmers valued diversity and flexibility of farm and field management. This requires a conducive socio-economic environment, with well-functioning input and output markets and secured access to inputs and/or credit.

Key words

on-farm trial, try-out field, legume, cereal, southern Mali, participatory design, Farmer Research Network (FRN), risk

5.1 Introduction

Sustainable intensification (SI) is seen as a promising pathway to deal with the many challenges farmers face in West Africa, as long as options are tailored to the local context (Gerard, 2020; Silva et al., 2021). Smallholder farmers often rely on agriculture for their food and nutrition self-sufficiency as well as income, but are challenged by a growing population pressure, declining natural resources and stagnating yields (Tittonell & Giller, 2013; Falconnier et al., 2015). These challenges are accompanied by a plethora of risks (Huet et al., 2020), some of which are expected to be aggravated by climate change (Schmitt Olabisi et al., 2017). SI is defined as management that “increases production, income, nutrition or other returns on the same amount of, or less, land and water with efficient and prudent use of inputs, minimising greenhouse gas emissions while increasing natural capital and the flow of environmental services, strengthening resilience and reducing environmental impact, through innovative technologies and processes” (The Montpellier Panel, 2013). SI options can be implemented at field level entailing changes in crop or animal management, or at farm/household and community/landscape level taking into account value chains and policies. To increase the impact and relevance, the options need to match the local context (Descheemaeker et al., 2019).

Nevertheless, in the past, farmers’ uptake of SI options developed through research has been low and slow, and as such disappointing (Wossen et al., 2015). Productivity increase (at field level) is a widely evaluated criterion in the targeting of technologies (Baudron et al., 2021b), but the adoption potential depends on several additional characteristics of and interaction between the option itself, the farmer, and the external environment (Sumberg, 2005; Meijer et al., 2015; Coe et al., 2019). Some characteristics that are often omitted in technology development and promotion are returns to labour, cost and period to return of investment, cultural or historical barriers, access to inputs or the impact at farm level instead of field level (Drechsel et al., 2005; Descheemaeker et al., 2016; Glover et al., 2016; Montes de Oca Munguia et al., 2021). Evaluating a broad spectrum of technology characteristics in relation with its environment, helps to tailor a basket of options to the diversity of farmers’ local contexts (Glover et al., 2019; Ronner et al., 2021). Additionally, farmers’ intrinsic characteristics play a role in the decision-making process, and involve farmers’ knowledge, perception and attitude, and this topic only recently gained research interest (Meijer et al., 2015). For example, the perception of risk (Montes de Oca Munguia et al., 2021) and access to knowledge (Marinus et al., 2021) play a key role in the decision-making process of farmers. As such, the uptake of technologies is not a linear process but calls for continuous trying out, learning, and adapting (Meijer et al., 2015; Glover et al., 2016; Ronner et al., 2018).

For individual learning, Kolb (1984) emphasises the importance of experiential learning where a learner (in this case a farmer) follows the steps of experiencing and conceptualising before deciding and acting, and which may be enhanced by mechanisms of feedback (Loeber et al., 2007). Forms of social interaction also influence farmers’ learning processes. For instance, farmers may spontaneously see a neighbour’s field they appreciate and decide to copy (Glover et al., 2019). The concept of social learning goes one step further, and refers to learning as a collective process (Blackmore, 2007). By encouraging social learning in agricultural research projects, both farmers and researchers can benefit from exchanging knowledge and experiences. Crucial is a shared understanding and trust between farmers and researchers (Ramisch, 2014; Hunecke et al., 2017), which requires time to build (Marinus et al., 2021).

Several approaches have been developed to involve farmers in agricultural research on SI options, and to foster social learning. First, the analysis of technological innovations itself can entail different levels of farmers' engagement. Purely biophysical performance can be well studied on-station (Type 1 trial: research designed and managed), while local and social conditions can be incorporated in on-farm trials (Type 2 trial: research designed and farmer managed), and farmers' choices can be studied when there are no strict protocols to follow (Type 3 trial: farmer designed and managed) (Franzel & Coe, 2002). Second, apart from trial implementation, the development of the overall research process can have several gradients of farmer engagement. For example, Farmer Field Schools are participatory extension meeting places that have been implemented since the 1980's, and have also comprised technology development with farmers in some cases (Nelson et al., 2001). Since then, participatory processes evolved to include more input from farmers in the design and sharing of knowledge. Some examples are iterative co-design processes where farmers form innovation platforms involved in the design and evaluation of innovative options (e.g. Husson et al., 2016; Andrieu et al., 2019; Ronner et al., 2019). Other projects tracked innovations that were already executed by some farmers, and scrutinised the options in a participatory trial trajectory (Salembier et al., 2015; Perinelle, 2021). Similar approaches are employed in Farmer Research Networks (FRN), which are groups of farmers that aim at matching options to the local context by sharing (research) information, data and technical support through cooperation with research and development organisations (Richardson et al., 2021). Three principles guide FRN research processes: (i) "diverse farmers participate in the whole research process" , (ii) "the research is rigorous, democratised and useful" providing practical benefits to farmers, and (iii) "networks are collaborative and facilitate learning".

In southern Mali, an iterative co-learning project with a focus on on-farm trials has been running since 2012 (Falconnier et al., 2016; Falconnier et al., 2017) by following the four phases of the DEED approach: Describe-Explain-Explore-Design (Descheemaeker et al., 2019). Experimental trials and model studies conducted during the research cycles identified several promising options. For example, crop-livestock integration is an important aspect of the system. By introducing more legumes, mostly cowpea, in the rotation, the quality and quantity of fodder could be increased (Falconnier et al., 2016). This fodder can be used for stall-feeding cattle in the dry season and benefit milk and manure production and collection (Sanogo, 2010; de Ridder et al., 2015). The manure is then used as organic fertiliser. Next, legumes such as cowpea (in intercropping) and soyabean (replacing sorghum) could contribute to increased income and food self-sufficiency at farm level when targeted to the right niche and farm type (Falconnier et al., 2017). Moreover, fine-tuning cereal field management showed increased yields after augmenting fertiliser rates and adapting the variety in relation to the planting date (Traore et al., 2014; Freduah et al., 2019; Adam et al., 2020), and in certain circumstances lowered the risk of yield loss (Huet et al., 2022). Overall, technological options contribute to eliminating poverty when aligned with farmers' priorities and context (Ollenburger, 2019; Ollenburger et al., 2019), but by themselves, technological options are insufficient for farmers in southern Mali to escape poverty (Falconnier et al., 2018) indicating an additional need for off-farm employment and market opportunities (Assogba et al., 2022). This stresses the importance of aligning SI options with farmers' decision-making processes and understanding where farmers are most willing to invest their limited resources, in order for the technology to reach its best potential.

Therefore, in order to investigate farmers' exploration of options, the on-farm trials in southern Mali were expanded with farmers' try-out fields where farmers implemented and experimented with SI options at a larger scale on their own field without guidance from the project. Previous learning cycles of the project focused on how farmers adapted the on-farm trials (Falconnier et al., 2017), yet there was no monitoring of how farmers applied (parts of) these options outside of the trials. Thus, over time and guided by the FRN principles, the research process evolved towards a stronger involvement of farmers. By stimulating co-learning cycles and by taking a qualitative research approach of monitoring what farmers did on try-out fields, we traced where farmers invested resources and how farmers perceived performance of the options for criteria additional to yield. This assessment addressed the following questions: (i) What are the dynamics of participation by farmers over the years? (ii) What options are chosen in the trials and try-out fields and how does this relate to the perceived multi-criteria performance of these options? (iii) What goals and criteria are most important for farmers when implementing an option? Based on the answers to these questions, we discuss on a broader level the lessons for implementation of participatory agricultural research.

5.2 Methodology

5.2.1 The approach included a co-learning cycle

Since 2012 the project "Pathways to Agroecological Intensification of Crop-Livestock Farming Systems of Southern Mali" conducted several activities in a yearly repeated co-learning cycle between farmers and researchers. Project activities involved several farming components such as crop cultivation, animal husbandry, farm planning, value chain development and the interactions between them. In this paper we focus on the crop component.

An iterated cycle of activities intended to stimulate individual learning as farmers themselves implemented trials and try-out fields and were asked to give feedback (experiential learning). Social learning was stimulated both among farmers and between farmers and researchers through village planning and evaluation meetings and field days (Figure 5.1a). Such discussions gave more insights in constraints and opportunities of the technologies. For the village discussion all farmers interested were encouraged to participate, with specific efforts to involve women and obtain a fair representation of different generations as well as of farm types (Falconnier et al., 2015). The same objective of inclusiveness guided the selection of participants for the on-farm trials. As try-out fields were organised without any involvement of the project, there was a constant communication with farmers to ask whether the project could monitor the fields, but there was no active encouragement to participate.

Before the start of each growing season, on-farm trials were designed together with farmers (Figure 5.1a). The trials had the intention to expose farmers to new options and to evaluate whether these were adapted to the local context. In village meetings farmers gave input on SI options that they were interested in to experiment with. Based on farmers' input, researchers designed trials and provided inputs and monitored outputs (additional information on the trials and co-learning cycle can be found in Falconnier et al. (2016); Falconnier et al. (2017)). These researcher-designed trials were implemented on-farm by the farmer, under research guidance (Type 2 trial) (Figure 5.1b). During the growing season, farmers visited trials and exchanged experiences during "farmer field days". At harvest, each farmer made an individual qualitative evaluation of his or her own trial. The average yield of each treatment was presented in village meetings to spark a plenary discussion. This discussion served as input for defining and refining the trial design according to farmers' wishes and observations, and thus initiated a new co-learning cycle.

Since 2017, the on-farm trials in southern Mali were expanded with a new form of experiments: farmers' try-out fields (Figure 5.1 a, b) to observe how farmers use and adapt previously tested options according to their circumstances and constraints. Here farmers themselves designed and implemented options at larger scale on their own field (Type 3 trial). Labour and input costs were provided by the farmer, but access to inputs was facilitated by the project if needed. The choice of SI option was recorded, as well as how it was adapted, the objectives for implementing the option and the evaluation of performance. More detailed information on the design of trials and try-outs is given below.

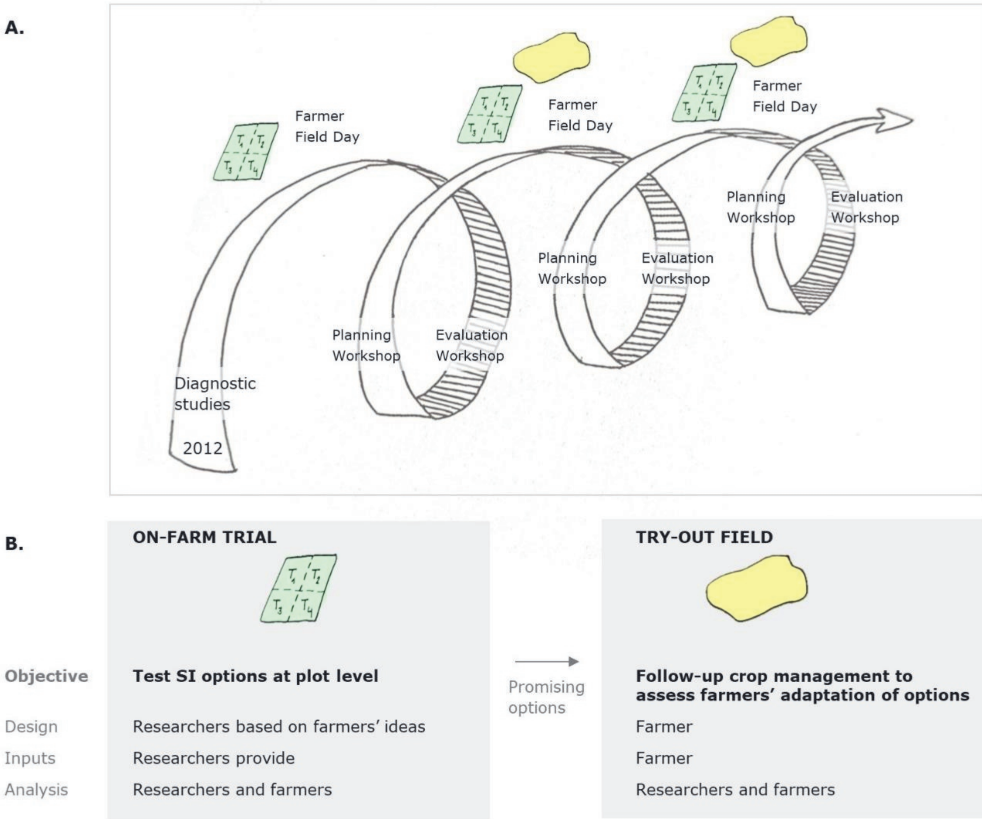

Figure 5.1 A) Overview of yearly activities that fed co-learning cycles from 2012 onwards. The evaluation of trials also indicated the start of a new cycle since the discussion served as input for adaptation of the trial design, and as inspiration for farmers to apply options in try-out fields. **B)** gives a more detailed overview of the objective and responsibility sharing between research and farmers in the design, input provision and analysis of trials and try-out fields.

5.2.2 Study area

The project started in three villages, Nampossela, Nitabougoro and M'Peresso (12°19'00"N, 5°32'30"W, elevation 350 m), in the Koutiala region in southern Mali. Since 2016 a second phase of the project initiated in three additional villages, N'Tiesso, Signé and Deresso, north of Koutiala (12°31'31"N, 5°20'20"W, elevation 340m). A total of 724 farm households (Coulibaly et al., 2013; Coulibaly et al., 2017) lived in these six villages, who can be classified into four farm types depending on resource endowment: High Resource Endowed farms with a Large Herd (HRE-LH), High Resource Endowed (HRE), Medium Resource Endowed (MRE), and Low Resource Endowed (LRE) farms (Falconnier et al., 2015). These farm types are not present at equal rates in the Koutiala region with a distribution estimated at 16% HRE-LH, 34% HRE, 40% MRE and 10% LRE (Falconnier et al., 2015).

Farmers target food self-sufficiency through the cultivation of maize, millet and sorghum (Bosma et al., 1999; Kanté, 2001; Falconnier et al., 2015), complemented with the cultivation of legumes as cowpea and groundnut. Agriculture is the main source of income, obtained mainly through cotton cultivation, next to the sales of cereal surpluses (mainly maize and millet). Fertiliser is generally targeted to cotton and maize. Livestock plays an important role in the farming system, since cattle are used for ploughing, a source of manure and income, and to a lesser extent milk (Van Dijk et al., 2004; de Ridder et al., 2015).

Farming in this area is confronted with biophysical constraints and risks. Pressure on land is big since most land suitable for agriculture is cultivated or used for (communal) grazing (Benjaminsen, 2002; Soumaré et al., 2008). The rainy season is unimodal with an average rainfall of 863 mm/year ranging between 500 mm and 1250 mm (Traore et al., 2013; Huet et al., 2022).

Overall households achieve food self-sufficiency, and about half of them reach a living income (Giller et al., 2021c). These households are large and include several generations. In such large entities, decision-making is a complex process where the end responsibility in general lies with the eldest men, the head of the household. The household head can delegate certain tasks on organising labour to another male of the household, the 'head of labour' (Kanté, 2001; Guirkinger et al., 2015).

5.2.3 On-farm trial set-up

Each year (2012-2020) a set of five to six types of trials were developed, where farmers' practice was compared with treatments that embraced SI options. Plenary trial co-evaluations by farmers and researchers led to trial designs that were updated yearly based on the lessons learned. On-farm trials were implemented following a strict protocol. However, depending on the yearly evaluation, treatments could be adapted, a type of trial could be discarded or a complete new type of trial introduced. More details on the protocols and the statistical analysis of the 2012-2014 trials can be found in Falconnier et al. (2016). For some types of trials, treatments were adapted substantially throughout the years, which complicates a general statistical analysis.

The trials were designed based on farmers' ideas and input, but some SI principles guided the development of options in the co-learning discussions (The Montpellier Panel, 2013). Overall, the options should: (i) make efficient use of resources, (ii) stimulate equitable improvements of livelihood, and (iii) pursue economic, environmental and social sustainability. Within this farming system, this translated into a focus on crop and variety diversity with attention to the role of legumes, integrated soil fertility management and integrated pest management.

5.2.4 Try-out fields

Try-out fields were introduced as 'ladegueli foro' to farmers (2017-2020), meaning 'fields of imitation' in Bambara. Farmers were asked whether they were interested in trying (a part) of an option in their own fields, and whether they would welcome the project to follow this up. As a guidance, an overview of all the treatments of the on-farm trials throughout the years were presented in the village meeting before the season. The names of farmers that were interested were listed together with the crop and option they wanted to implement. However, farmers' planning is a dynamic process. Close contact with the farming community was continued throughout the season in order to keep track of farmers that changed their plans (abandoning the idea of installing a try-out field, or trying-out some options without communicating as such in the planning meeting). Informal communication also indicated that some farmers tried out options outside of the project. In such cases farmers were asked whether the project was allowed to also monitor these fields. The dynamics of planning and communication crystallised over time, and so the data recorded of the try-out fields does not contain the same amount of detail each year. For example, in the process of following-up the try-out fields and understanding farmers' interests in options, it became clear that recording the reason for adapting plans was also important, next to farmers' initial objectives. In 2019-2020 follow-up was more thoroughly by recording the reason for cancelling a try-out field.

Improved crop varieties used in (earlier) on-farm trials could be ordered by farmers via the project. Nevertheless, the options for the try-out fields were not limited to what was already tested and the project facilitated the access to requested input where possible (seeds, fertiliser, inoculant, bio-pesticide etc.). However, input costs were always covered by the farmers themselves.

5.2.5 Evaluation criteria and objectives

The farmer field days and village evaluation meetings were platforms where farmers were encouraged to exchange and have open discussions based on their observations of the fields. Average crop and fodder yield and a cost-benefit analysis of the on-farm trials were presented in the village meetings to incite discussion. For each crop some specific questions were prepared based on the design of the treatments and results. For example, when different varieties of soyabean were tested, we asked farmers to evaluate the cycle of these varieties. Or, if in one village the yield was much larger than in others, we asked farmers why that could be the case. In each village a couple of farmers gave a testimony on their try-out fields. At the end of each village meeting, we asked what was new to farmers and what they would like to implement in their own fields. These discussion platforms served as a learning moment for both farmers and researchers, to define the criteria important to farmers when assessing an option, and to design the options to be tested the following year in on-farm trials.

At harvest each participating farmer gave an individual evaluation of their field(s) (on-farm trial and try-out) by scoring the performance (good, medium, bad) of the option following a predefined list of criteria. The criteria were defined based on farmers' observations that surfaced during village evaluation meetings in the earlier phase of the project, as well as on criteria that are mentioned in literature as important for farmers decision-making (Michalscheck et al., 2018; Ronner et al., 2019). The list of criteria included quantity and quality of grain and fodder yield, labour requirement (sowing, weeding and overall), resistance to pest and diseases, resistance to drought, effect on soil fertility, cost and access of inputs, quality of inputs and cycle of the variety. For some types of trials a specific criterion, that appeared relevant in earlier group discussions, was added. For example, taste seemed an important criterion when evaluating the introduced millet varieties. In addition, the try-out farmers were asked to state the biggest constraint when implementing the option.

The list of criteria did not only serve to evaluate tried-out options, but also to assess the objectives of farmers when utilising an option in the try-out fields. From the list of criteria, farmers picked the three most important criteria for the option at the start of the season for which they expected to reach a benefit when implementing that option. Farmers were asked whether they intended to sell (all or part of) the produce, and under what circumstances (individually or in group, and when).

5.2.6 Data analysis

The tested options were categorised (Table D.1) according to the field management components explored: crop, crop configuration (sole, inter- or relay cropping), variety (grain, fodder, dual-purpose, hybrid, enriched nutritional qualities, short cycle, other), sowing (pattern, density, timing), fertiliser (application method, type, rate), other inputs (inoculant, bio-pesticide). The category 'crop' refers to cultivating a crop that the farmer was less familiar with, mainly soyabean, or to cultivating cowpea as a sole crop while the farmer is normally intercropping the cowpea. So the categories 'configuration', 'crop' and 'variety' are intertwined and often overlapping in the same fields.

Some characteristics of participating farmers were recorded: farm type, gender and age. The age of farmers was recorded only for those implementing try-out fields. The age of the overall population, and the number of adults active in agriculture (spending over 50% of their time on agriculture) served as a point of comparison (data obtained from a household survey described in detail in Huet et al. (2020)).

5.3 Results

The result are organised by first evaluating who participated in trials and try-outs. Secondly, we describe the options designed for the trials and how farmers evaluated these. Next, farmers' considerations for selecting options in the try-out fields are reported, before concluding with farmers' evaluation of the try-out fields.

5.3.1 Dynamics of farmers' participation

Between 2012 and 2020 a total of 161 different farms participated in on-farm trials (Figure 5.2a), which is 22% of all farms present in the target area. The number of participating farms in trials started small (Figure 5.2b), but increased in the course of the project, while also the study area expanded. Try-out fields were only introduced in 2017; an activity in which 101 farms participated, being 14% of all farms in the targeted villages. More farmers participated in try-outs over the years when the project shifted to a more balanced focus on both trials and try-out fields. The participating farms represented all four farm types (Figure 5.2a). The higher resource endowed farms (HRE-LH and HRE) participated relatively more compared to their abundance in the Koutiala region, while MRE farms participated less often in the trials (30%) and try-out fields (27%) compared to their relative distribution in the area (40%) (Table 5.1). Many farms participated for several years in both activities (Figure 5.2c, d), although about 45% and 50% of participating farms, in trials and try-outs respectively, did so only once (Table D.2). Among the 24 farms that participated in a try-out field without ever having implemented a trial first, LRE's were relatively well represented (5 farms).

Since households are large, different household members of the same farm implemented a trial or try-out field in the same year, so the total number of trials and try-out fields and individual farmers is larger than the number of participating farms. In total 538 on-farm trials and 243 try-out fields were installed (Table D.4). In the planning phases (May-June) farmers indicated their intentions for try-out fields, after which sometimes plans changed or unforeseen hazards occurred forcing farmers to adapt their field management to the new circumstances. For the 64 cancelled try-out fields in 2019 and 2020, farmers indicated a lack of financial capacity (or willingness) to invest, a lack of access to land, followed by a lack of access to inputs as main reasons (Table 5.1). In 2019 the rainy season started late, and several farmers mentioned a late onset of the rainy season as a reason for having to change plans. Most cancelled fields were from HRE farmers, while there were no fields from LRE cancelled, and relatively few from MRE.

Of the on-farm trials 80% were managed by a man and 20% by a woman. Of the planned try-out fields, 85% were managed by a man and 15% by a woman, while of the installed try-out fields, 88% were managed by a man and only 12% by a woman, which indicates that woman canceled their try-out fields relatively more often than men. Only 8% of try-out farmers were younger than 35; 41% of farmers were 36-45 years old, 38% between 46-55 and 13% of farmers were older than 55. The age pyramid of adults active in agriculture is inverted to this situation, with over 50% younger than 35 years, and 5% older than 55 (Table D.3).

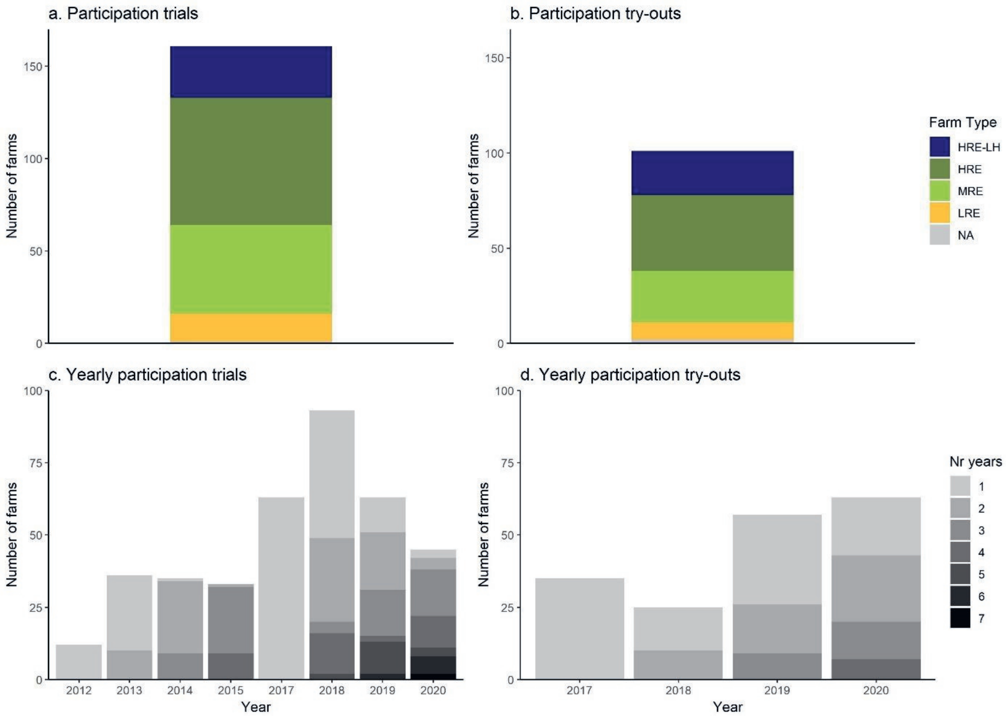

Figure 5.2 a) Number of farms that participated in trials between 2012-2020 per farm type (HRE-LH: High Resource Endowed with Large Herd, HRE: Large Resource Endowed, MRE: Medium Resource Endowed, LRE: Low Resource Endowed). **b)** Number of farms that participated in try-outs between 2017-2020 per farm type. **c)** Number of farms per year participating in trials. **d)** Number of farms per year participating in try-out fields.

Table 5.1 Number of farms implementing trials and try-out fields (2012-2020) according to their farm type, compared to the relative distribution of these farm types in Koutiala. The number of cancelled try-out fields (in 2019 and 2020) are also organised per reason for cancelling

Farm Type		**LRE**	**MRE**	**HRE**	**HRE-LH**	**Na**	**Total**
Distribution of farm types Koutiala*	*%*	*10*	*40*	*34*	*16*	*-*	*100*
Farms participating in trials	Number farms	15	48	69	25	1	161
	%	*9*	*30*	*43*	*16*	*1*	*100*
Farms participating in try-out	Number farms	9	27	40	23	2	101
	%	*9*	*27*	*40*	*23*	*2*	*100*
Try-out fields canceled (data 2019, 2020)	Number fields	0	9	34	13	8	64
	%	*0*	*14*	*53*	*19*	*14*	*100*
Reason for canceling try-out fields	Number fields						
Lack of financial capacity		0	2	9	1	4	16
Lack of access to land		0	2	3	6	0	11
Lack of access to inputs (seeds or fertiliser)		0	1	5	1	2	9
Late onset of rains		0	1	6	1	0	8
Lack of labour		0	1	4	1	0	6
Farmers lost contact with project or forgot		0	1	1	1	0	3
Lack of draught animal		0	0	2	0	0	2
Farmer deceased		0	0	2	0	0	2
Bird damage of seedlings		0	0	1	0	0	1
No timely preparation of compost		0	0	0	0	1	1
Unknown		0	1	1	2	1	5

*Falconnier et al. (2015)

5.3.2 Choice and evaluation of trials

The village meetings offered a platform for farmers to discuss novelties in management, including new crops with which farmers had little experience. A detailed overview of the trial options, including the number of trials and the years in which they were executed, is given in Table D.4. Ideas for introduction of new crops were limited; only soyabean was regularly included in the trials as a relatively new crop for many farmers. During the discussions farmers expressed most interest in testing new varieties and diversifying input application rates. Debates were often focusing on cereal crops (maize, sorghum, millet) and legumes (cowpea, groundnut, soyabean), whether in intercropping or as sole crop.

The trials introduced varieties, intercropping patterns, input rates and application methods, as well as sowing patterns and dates (early or late sowing). Introduced varieties served a diversity of objectives such as feed production and quality, shorter cycles or increased nutritional benefits (Figure 5.3). Varieties used several years were Soumbatimi and Wulibali, a dual-purpose sorghum and cowpea variety respectively, Dunanfana, a cowpea fodder variety, and NKOxTC1, a millet variety recommended for its nutritional value as it is enriched with Fe and Zn. Maize was mostly tested when intercropped with a legume following different patterns or timing of intercropping. Fertiliser was always added on maize and soyabean trials. In millet and sorghum trials different fertilisation strategies were experimented: rates, application methods (microdosing or spreading) and type (mineral, organic or combined). Soyabean treatments covered sowing density and different varieties. Cowpea suffered from insect damage which led to the inclusion of treatments with a bio-insecticide made from the neem tree; either purchased neem oil or a home-made emulsion made from neem leaves. Village discussions also instigated other treatments with cowpea including varying the sowing date. Farmers speculated that in some years grain production was limited if flowering coincided with heavy rainfall which they thought more likely to happen when sowing early. The third legume of interest, groundnut, was compared for two varieties and sowing patterns (broadcasted, which is the farmers' practice, versus in lines).

Overall, farmers evaluated the treatments in the different trials as good, according to several evaluation criteria (Figure 5.4, Figure D.2). All treatments of millet and sorghum cereal trials, which had a similar design, were evaluated positively by individual farmers as well as during the village meetings. Farmers did not spot large differences in yields between different fertiliser applications, yet labour requirements were judged excessive for the microdosing treatments. The lack of distinctive differences in yields between different fertiliser rates, led to increased application rates in the later years of trials. The introduced varieties were appreciated for specific characteristics but not necessarily for the yield potential. For example, many farmers liked the stover quality for cattle feed and short cycle of the sorghum Soumbatimi variety, although the taste of the grains was less appealing for human consumption. Likewise, the nutritional quality and shorter cycle of NKOxTC1 were seen as potential benefits. Farmers appreciated this short cycle variety in the light of climate change, but when not cultivated by many farmers such varieties would be more prone to bird damage; losses would be concentrated in a single field that matures before the neighbouring fields, while the damage would be spread among the later and simultaneously maturing fields. For both millet and sorghum, farmers emphasised the importance of maintaining local varieties, because of their adaptation to the local conditions. Regarding the intercropping trials of maize-cowpea, farmers were somewhat disappointed with the production of grain and stover, as well as with the labour requirement. Nevertheless, they stressed the benefits of intercropping in the conservation of soil humidity and net benefit of producing two crops (Land Equivalent Ratio (LER)>1, Falconnier et al. (2016)) although an important objective was to minimise maize grain loss. Delayed sowing of cowpea was flagged to potentially counteract maize grain loss, and was added as a treatment in the trial.

Farmers' evaluation of the legume trials was nuanced, although generally positive (Figure 5.4). Cowpea grain production was not always positively rated, which is not surprising since part of the trials specifically focused on fodder varieties, and quality of the Wulibali seed was rated as disappointing in 2019. Cowpea suffered from insect damage, as the neem treatments were not very effective (Figure D.2) and regarded as labour demanding when prepared at the homestead or hardly accessible when to be bought. Farmers debated that targeting sole cowpea for fodder is sometimes seen as a "waste of good land for food production", hence its lower score regarding cultural acceptance, although some participating farmers specifically emphasized the benefit for animal feed. Varieties that produce both fodder and grain were valued. Some villages were less familiar with the cultivation of soyabean, and therefore appreciated learning on the management of this crop in the trials, although some farmers found the cultural acceptance doubtful. Farmers appreciated the grain production of soyabean, as well as the benefits of the biomass production for animal feed or for soil fertility when left on the field. Nevertheless, the lack of market for soyabean and the absence of a structure for soyabean processing was mentioned as a constraint, even though the soyabean grain price was well appraised. Farmers appreciated different varieties tested, but observed that the germination rate of soyabean went down when conserving the seeds for more than a year. Farmers expressed the difficulty of using di-ammonium phosphate (DAP) because it was more expensive than other fertilisers. Seed inoculation was abandoned after trying it out for a few years because a significant yield benefit was not observed (Falconnier et al., 2016) and the inoculant was not easily accessible in the region.

When farmers perceived their own practice could not be improved anymore or curiosity for an option was low, that type of trial was no longer pursued. Farmers did not see any benefit in changing the variety of groundnut, nor for sowing in lines which they perceived as labour intensive, so groundnut trials were no longer included from 2018 onwards. Maize-legume intercropping trials stopped in 2020, because outcomes were consistent. Although many intercropping practices exist for different objectives, generally the additive pattern with a fodder or dual-purpose cowpea variety sown some weeks after maize to prevent smothering of maize seedlings, was evaluated as most beneficial.

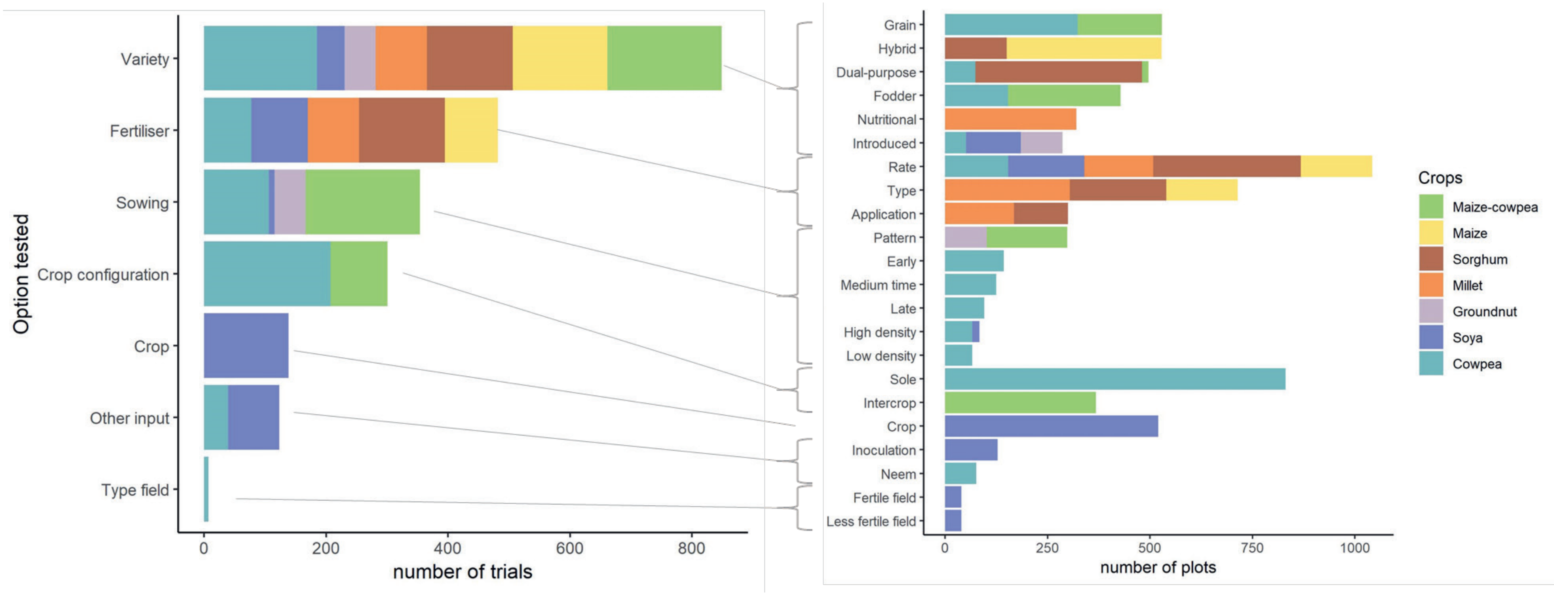

Figure 5.3 Options tested in trials between 2012-2020. **a)** For each category the number of times that they were implemented as a factor of a trial are counted on the x-axis, with the colour scheme indicating the crop on which these options were applied. **b)** The categories are broken down in more detail. On the x-axis the number of plots of the trials each treatment was implemented.

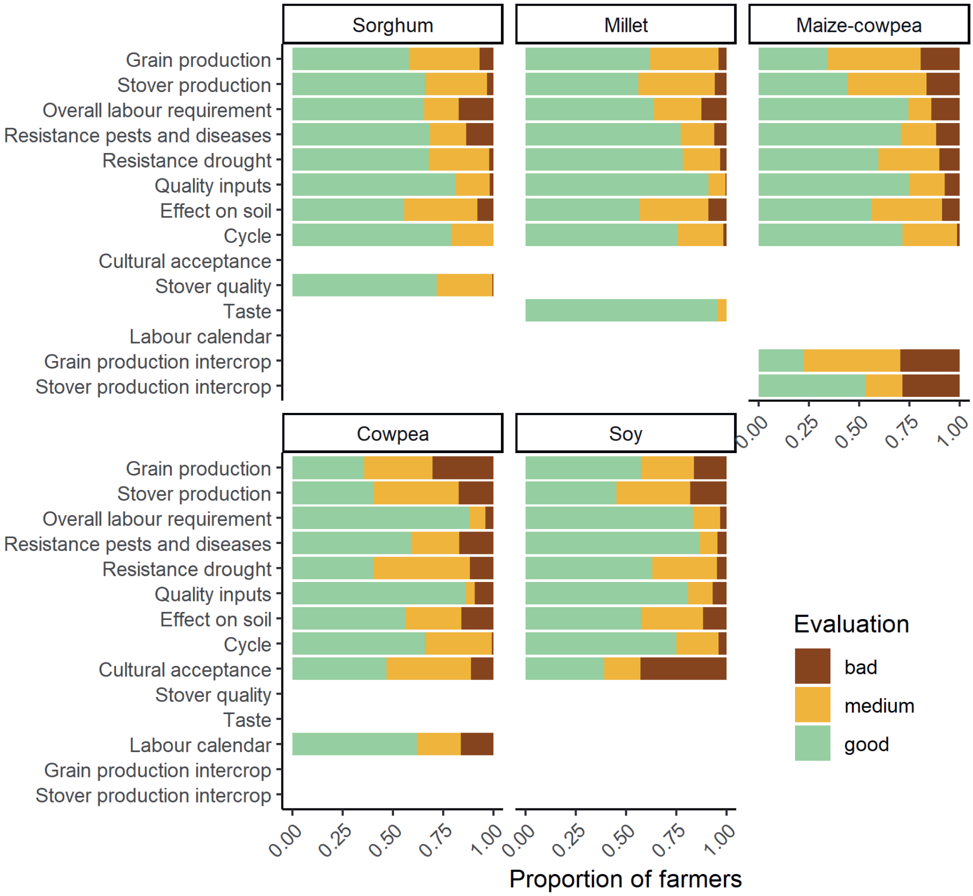

Figure 5.4 Farmers' evaluation of the different treatments, organised per crop of the trial. The proportion of farmers that assessed different evaluation criteria of the plot as 'bad', 'medium', or 'good' are represented. Data is averaged over 2018, 2019 and 2020.

5.3.3 Farmers' considerations for choosing options to try out

In try-out fields, farmers picked several aspects from the trials but almost never fully reproduced a treatment (Figure 5.5, Table D.4). Altogether, improving grain production was the main reason for implementing a specific option in a try-out field (Figure 5.6a). Additionally, stover production and quality were also very important considerations especially for the intercropping options, and to a lesser extent the grain quality. Optimising labour requirements, targeting crop cycles or assuring the quality of inputs were important aims as well, especially for the sole cropped fields. To a lesser extent, the resistance to droughts and pests, the access to inputs and the cost played a role in the selection of an option to try out. Assuring access to good quality of inputs was mentioned when the farmers bought seeds via the project (Figure D.1a). Millet, sorghum, cowpea and soyabean were largely cultivated for consumption, although most farmers foresaw to at least sell a part of the production of the field. All farmers targeted at least a part of their maize, groundnut and sesame field to the market. A minority of farmers intended to sell all the sorghum and soyabean of the try-out field (Figure D.1b).

From the choice of options to try out, some key insights could be deduced that confirm the evaluation of the trials. Farmers were inclined to explore new varieties, mostly of legumes and often in combination with intercropping (Figure 5.5). Farmers were intercropping maize or sorghum with cowpea, mostly with application of mineral fertiliser, to produce cereal grain and fodder from both cowpea and the cereals and to preserve the humidity of the field. Diversifying cowpea varieties seemed an important driver for farmers, with special attention for fodder varieties. Similar as in the trials, groundnut was not a crop of interest in choosing try-out options. For soyabean, there were large differences in interest between participating villages. If grown on a try-out, farmers cultivated it on small fields with application of mineral fertiliser. Farmers mentioned that apart from selling the grains and using the leaves for fodder or mulch, soyabean grain was mainly used for the production of the condiment 'soumbala' which is traditionally made from the African locust bean or néré tree (*Parkia biglobosa*). In villages where the néré tree was less present, farmers showed more interest in cultivating soyabean in trials and try-out fields. Farmers found it hard to access good seeds of soyabean and mostly recycled seeds. Overall, farmers used seed material from a previous year or from another farmer (Figure D.1a). In over half of the cowpea and millet (introduced variety) try-out fields, farmers used formal channels of seed supply (either the market, the project or other organisations). Options that required a lot of labour, for example applying a neem pesticide or microdosing, were not or rarely implemented by farmers. Farmers did not see the necessity to spray any insecticide on cowpea fodder varieties, and thought it only worthwhile for grain production. Each year some farmers adapted the microdosing options to their local preferences in a try-out field, yet the number of farmers remained very few.

Some contradictions in choice of try-out options and trial evaluation were noted: although the introduced millet and sorghum varieties were appreciated in the trials, few farmers implemented the sole millet or sorghum options in their try-out fields. While farmers mentioned that cultivating sole cowpea for fodder had a low cultural acceptance, a relatively large share of the try-out fields were grown with a fodder variety of sole cowpea, suggesting that there might have been a shift in perception taking place, giving more importance to cultivating fodder for feeding animals. Less often farmers chose options that focused on management aspects, such as changing fertiliser application methods and rates, or changing sowing time or density. In certain cases, farmers also extended beyond the options presented in the trials, for example by intercropping two legumes or millet with a legume.

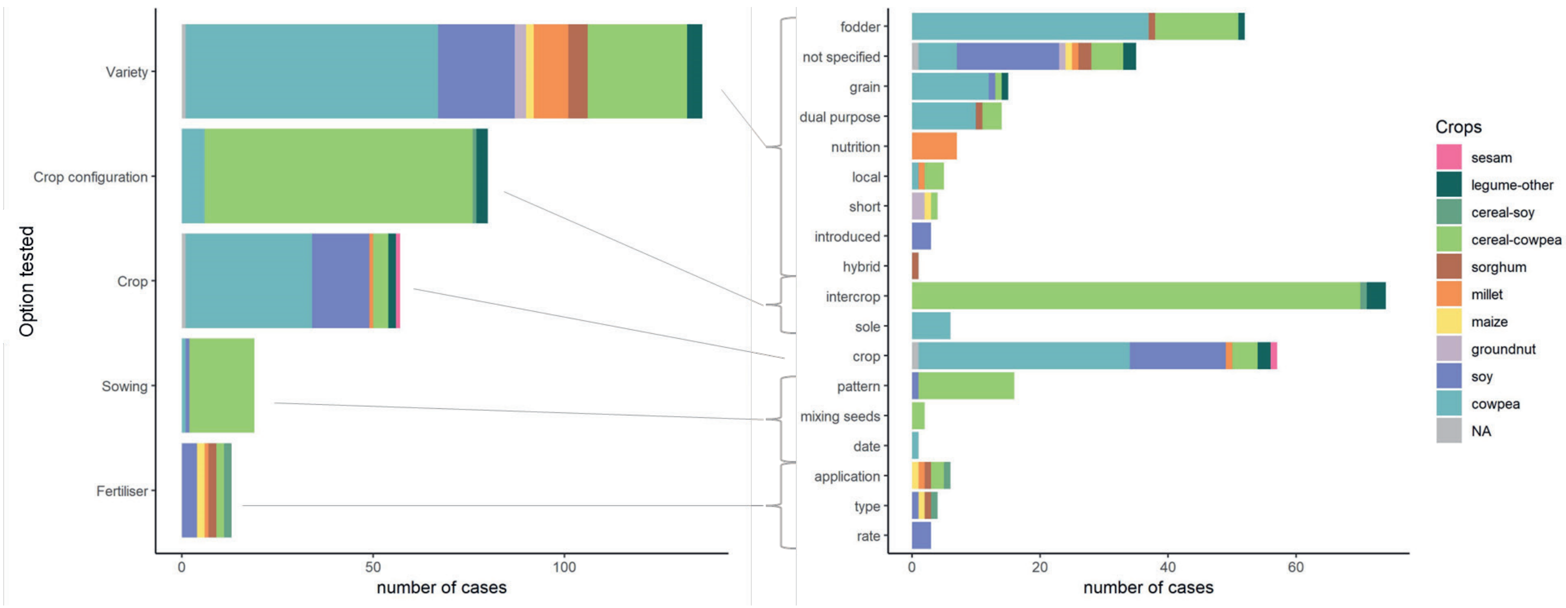

Figure 5.5 Try-out options implemented in try-out fields between 2017-2020. **a)** For each category the number of times it was implemented in a try-out field (and followed up) on the x-axis, with the colour-scheme indicating the crops on which these options were applied. **b)** The number of cases as presented in a, with the categories broken down in more detail

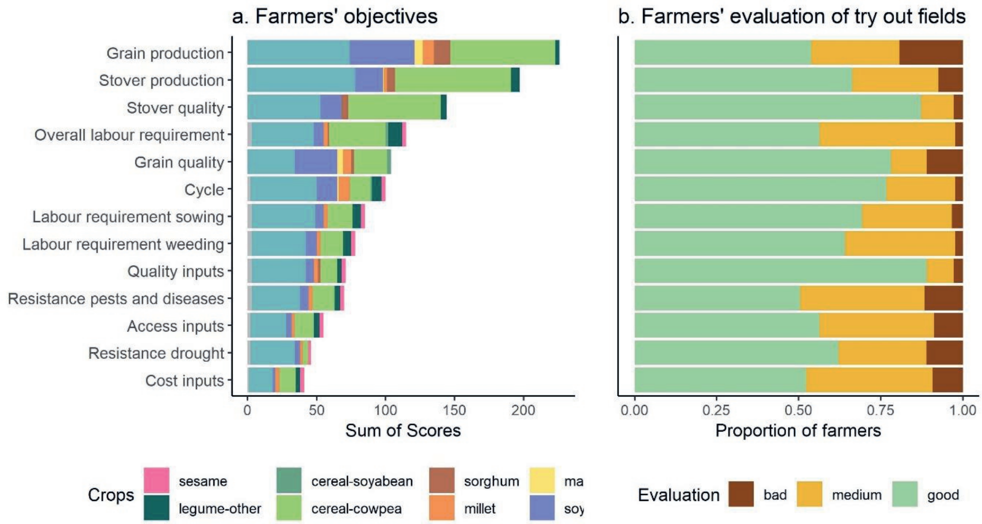

Figure 5.6 a) The objectives of farmers' when implementing their try-out fields, organised per crop. **b)** The proportion of farmers that rated their try-out field as 'good', 'medium' or 'bad' according to different criteria, across all the tested options.

5.3.4 Farmers' evaluation of try-out fields

In general farmers evaluated the options on their try-out fields as relatively positive for different criteria (Figure 5.6b, Figure 5.7). Although grain production was an important consideration for farmers' choice of option, the options did not always fulfill these expectations. Stover quality and production were assessed more positively. As in the trials, the appreciation of cowpea grain production was relatively low, which was expected since most farmers focused on the fodder variety Dunafana (Figure 5.4). In addition, some farmers also assessed the cowpea fodder production as relatively bad. The sole cowpea was seen relatively sensitive to pests, diseases, and droughts, compared to other sole crops. The taste of the millet NKOxTC1 variety was appreciated (Figure 5.7e). Soyabean and groundnut were assessed negatively or neutrally on several criteria, especially on costs and labour requirements (Figure 5.7g,h). For groundnut this was in line with abandoning the trials. For soyabean this could be linked to it being a relatively new crop, for which farmers still needed to learn the best management. Also, farmers mentioned that DAP is expensive, and that there was no institutional support to get fertiliser for soyabean. For most farmers the cost of inputs (seed and fertiliser) was a bottleneck, yet it was not seen as the most common constraint (Figure D.3). Labour-related constraints remained an important issue in the try-out fields, especially for intercropped fields, followed by bio-physical field properties and events (hazardous rainfall, animal damage, low soil fertility, pests and diseases). Quality of inputs on the other hand, was assessed as good, potentially because access of new varieties was foreseen via the project.

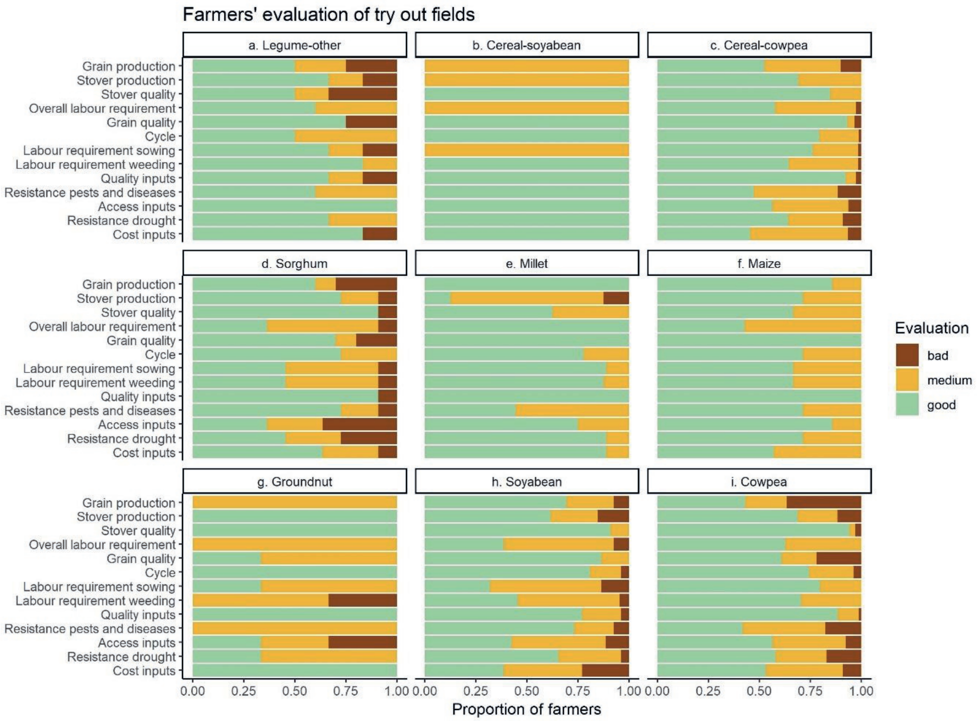

Figure 5.7 The proportion of farmers that rated their try-out field as 'good', 'medium' or 'bad' according to different criteria, organised per crop combination on the field.

5.4 Discussion

As our research approach was inspired by Farmer Research Networks, we use its principles of including farmer diversity, facilitating learning and knowledge sharing in collaborative networks, and supporting democratic, rigorous, and useful research (Richardson et al., 2021) as a skeleton for answering the research questions: the qualitative information on multi-year trials ran by numerous farmers provided insights on participation dynamics, the overall learning and research process, and the tailoring of options by farmers.

5.4.1 Local tailoring of the agronomic options

Farmers' choices and feedback provided lessons on the usefulness of options. Farmers operate in a variable environment, in which planning ahead is not an easy task. This could also be observed from the many changes farmers made between the planning stages of the try-out fields, the implementation of the fields and sometimes even during crop growth. From the dynamic planning of farmers we can conclude that maintaining flexibility and adaptability remained important at farm level, regardless of the options explored at field level. These are common, and needed, characteristics of farming systems in variable environments, such as those of the Sudano-Sahelian zone of West

Africa (Andrieu et al., 2015; Huet et al., 2020; Huet et al., 2022). Options that require high investments, long-term planning or have specific requirements that don't allow for diversification or adaptation, are less suitable.

Although cereals are crucial in the southern Malian farming system for consumption and income (Losch et al., 2012) and in the trials these crops received prominent attention, farmers were less interested to experiment with millet, sorghum and maize as sole crops on their own try-out fields. The reasons for not choosing these options in try-out fields were not indicated by farmers directly, but we deduct two hypotheses from literature and field experience. Firstly, the sole cereal options in the trials partly focused on an increase of fertilisers, while farmers struggled with limited financial capacity and poor access to inputs. Farmers indicated that they primarily intend to invest in agriculture in case of financial slack, but the gained benefit when using small amounts of additional fertiliser may not have been large enough for farmers to invest in cereal fertilisation. Secondly, the limited number of cereal try-outs could be related to the main differences between trials and try-outs: scale and cost. In the try-out fields farmers not only benefit the potential gains, but also carry the potential losses. The latter are limited in trials since these are small fields where inputs are provided by researchers. Farmers in West Africa are known to be rather loss averse (Feyisa et al., 2023). Because of the importance of cereal crops in the system, we hypothesise that farmers were less willing to take risks and/or already finetuned the management according to the maximum of their available resources. For relatively new crops, such as soyabean, the experience differed a lot between farmers and villages, and although farmers remained interested to include it in trials and try-outs, they mentioned that the poorly developed input and output market influenced their choice.

In the occasions where cereals were targeted in try-out fields, farmers' objective was mainly to diversify the varieties, be it of the cereals themselves or of intercropped legumes. Additionally, stover quantity and quality were important considerations for farmers when choosing an option, indicating the importance of crop-livestock integration on the farm. Livestock remains important in the system, yet pressure on natural grazing lands (Van Dijk et al., 2004; Soumaré, 2008) calls for additional feeding strategies (Sanogo, 2010; de Ridder et al., 2015). Farmers' interest for amplifying the number of varieties, for intercropping and for producing fodder for livestock all indicated an inclination towards diversification, not only on-field but also on-farm.

It should be kept in mind that the call for new varieties could also reveal a market bottleneck, apart from the choice to diversify. The project provided access to most inputs, including to varieties that farmers would otherwise not have had access to. The soyabean seeds for example were brought from outside the region since they were not available in Koutiala or neighbouring markets. It would not be surprising that farmers used that service to gain access to seeds that they plan to recycle, and therefore prioritised the implementation of new varieties in trials and try-out fields.

Options that increased rates of inputs or labour, were not covered in try-out fields. Increased labour requirement also obstructed the implementation of options aimed at reducing input quantity, such as microdosing. Equally, Sirrine et al. (2010) observed large differences in ex-ante appreciation and ex-post adoption of options, partly attributable to the labour requirements, alongside the time lapse between practice and benefit of options. This opposes the ladder approach by Aune and Bationo

(2008), that presented a pathway towards agricultural intensification that starts with steps of labour intense technologies before climbing the ladder to technologies that require financial investment, as for example increasing fertiliser, cultivating cash crops or animal fattening. The farmers in the region of Koutiala seemed to have plateaued on the ladder when it comes to crop management, as they did not have the means or desire to intensify labour (anymore), yet also had difficulty to apply options in the try-out fields that required a financial investment, even when these options were assessed promising during the trials.

5.4.2 Lessons from a Farmer Research Network Approach

5.4.2.1 Diversity among participating farmers

Eight years of iterative cycles formed a steady base for building trust between researchers and farmers, which is seen as a requisite for co-learning (Hunecke et al., 2017; Marinus et al., 2021). First, a representative proportion of the farms with different resource endowment in the target villages participated in at least one activity, implying that the process triggered interest of all farm types. Second, alongside a group of regular participants, there were also farmers who joined in and opted out throughout the different co-learning cycles. It suggests farmers felt free to (not) take part in the activities, stressing the democratic nature of the process.

Nevertheless, our results also indicated challenges to 'leave no-one behind' (a prerequisite for reaching the Sustainable Development Goals (United Nations, 2015)): the trials and try-outs were mostly conducted under the responsibility of the older and male household members, who are generally the people with most decision power in Malian households (Kanté, 2001). Participation shifted even more to the male population in the try-out fields. Additionally, women were more likely to drop out after the planning phase of the try-out fields. Thus, the project process has the potential to comprise the inter- and intra-farm diversity, but struggled with the latter. Our process reinforced the literature describing a gender and age gap in adoption of technologies (Theriault et al., 2017; Rao et al., 2020). In a participatory search for agronomic innovations in Burkina Faso by Périnelle et al. (2021) a similar underrepresentation of women was recorded. Although it is well described that within West African households access to inputs, labour and decision power is complex and unevenly divided between age and gender (Guirkinger et al., 2015), this does not necessarily mean that youth and women cannot benefit indirectly. Our results only describe the direct reach of the activities, and not the impact of potential benefits (Thuijsman et al., 2022).

Still, it is important to understand contextual social specificities within research work to be able to adapt options to different contexts and users in a changing socio-economic environment (Thuijsman et al., 2022). In the context of southern Mali, we suggest that an approach that is truly intersectional and gender-inclusive should include the dynamics of access to land and financial capital, as the lack of these two resources were the main reasons why farmers dropped a try-out.

5.4.2.2 Facilitating co-learning and knowledge sharing in collaborative networks

The dynamics of participation and the continuous tweaking of options in trials and try-out fields revealed insights on the set-up of participatory research and the learning that accompanied it. After implementing trials, farmers adapted these options in their try-out fields, pointing out a process of individual experiential learning (Loeber et al., 2007). Additionally, signs of social learning manifested itself through farmers who did not follow this order of steps (Blackmore, 2007). Such farmers, who implemented try-out fields without first having a trial, could have gained knowledge on the options through village meetings, other project activities or peer-to-peer communication. The exchange of, and access to, knowledge was stimulated in the village meetings and field visits, which potentially influenced farmers' intrinsic factors in the decision making processes on trying out a technology (Meijer et al., 2015). For example, a farmer mentioned that he only realised the potential of soyabean cultivation, after he saw a lush field of another farmer during the farmer field days. Additionally, options with a relatively low cultural acceptance in trials (sole fields of cowpea and soyabean) were implemented in try-out fields as well, which could be a step towards a shift of perception.

5.4.2.3 Iterative participatory co-learning cycles supported rigorous, useful research

The introduction of the try-out fields was grafted onto a co-learning process that already provided meaningful insights on the potential future of farming through an ex-ante modelling exercise (Falconnier et al., 2017). The introduction of try-out fields gave additional information by looking at what farmers are actually doing in their own fields (ex-post) when the risks are carried by them. Try-out fields can provide insight in the missing link between on-farm participatory studies and adoption studies (Ronner et al., 2018), as they provided an opportunity to tweak the basket of options along the way according to criteria farmers found important. Ergo, this process is expected to increase the goodness-of-fit between option and potential user (Sumberg, 2005). The non-linear process including try-out fields aimed to finetune options, as well as to increase farmers' capacity to innovate, which according to Douthwaite and Hoffecker (2017) are two self-reinforcing pathways influencing the impact of a research project.

The contribution of farmers in all our steps from conception phase, to analysis, to feedback and to implementing farmer-controlled trials, added rigor and legitimacy to the options that were coming forward. The drawback of such an approach is firstly that a lot of time needed to be invested by researchers or extension workers to build a close relationship and trust between farmers and researchers, and secondly that researchers should be attentive to observe and record changes in field management where it may not be initially expected.

5.4.3 Research benefits and challenges of introducing try-out fields

Apart from the FRN approach, there are similarities between our approach and Mother and Baby Trials (MBT) where farmers test a subset of technologies of their choice (baby trial) simultaneously to a larger research-controlled mother trial that includes a wide range of technologies (Snapp et al., 2019). Yet research processes where farmers explicitly organise and design their own trials (type 3) are relatively rare (Franzel & Coe, 2002) with exceptions, such as use-as-you-learn 'tryouts' by Misiko and Tittonell (2011) or farmers' adaptation trials described by Périnelle et al. (2022) or Ronner et al. (2018). In these last two examples, farmers remained interested in options seen as promising in earlier research, but for very different individual reasons, and a vast majority of farmers still adapted these options.

Since the design of trials started from farmers' input, the options were often building on current farmers' practice. In the trials, options were compared with a control that represented a farmers' practice as discussed in village meetings. Nevertheless, there is a vast diversity among farmers and a single farmers' practice does not exist (Kool et al., 2020), so the options that were new for some farmers, were close to common practice for others. More radical innovations, that also encompass processes beyond the technological, were less likely to be included within such a participatory process (Meynard et al., 2017).

5.5 Conclusion

The iterative co-learning helped to identify characteristics that are important to farmers and fostered a learning environment for a diversity of farm types. It remained a challenge, however, to reach all farmers across different age and gender groups. The benefit of organising try-out fields on top of trials contributed to the goodness-of-fit of a relevant basket of options for farmers by showing the importance of labour requirements, market opportunities, previous experience, fodder production and taste next to grain yield, which remained an important criterion for farmers in their choice of an option. In general, many findings from the choices made on try-out fields were in line with the evaluation of trials by farmers. Yet additional insights on the interaction between option, environment and farmers came forward, from which we can deduct some suggestions for research and policy. Firstly, in order to fit options to farmers' characteristics in southern Mali, research should focus on technologies that reduce labour requirements (or at the very least do not increase labour burdens), and make sure that options are assessed based on multiple criteria, including yield. Secondly, options with higher financial input requirements were less often chosen in try-out fields, although farmers expressed interest in new and more varieties. This requires a market approach and policy can play a role in the development of input and output markets and facilitate access to seeds, other inputs and credit, and strengthening farmer organisations. Interventions and research however, should take into account the complex and diverse reality of farming systems. As our research showed, continued and thorough interactions with farmers yielded a huge diversity of responses and a variety of technologies tested which were of farmers' interest.

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6 General Discussion

The main aim of this thesis was to increase understanding on suitable strategies in coping with the highly variable environment in which farming takes place in southern Mali. In this general discussion, I reflect on the main findings on farmers' perceptions of risks and management options, linked to quantifications of impact of hazards and mitigation management. Combining insights at farmer, field and farm scale improved understanding of the context to tailor suitable on-farm options (Figure 1.4) and to express the needs for an enabling environment.

In the first section I focus on the risks that influence southern Mali's farming system, by juxtaposing my findings with some recent hazards that people were exposed to. Second, I zoom in to the drivers for decision-making that were deemed essential by farmers. Third, I use these findings to formulate characteristics of promising on-farm options, followed by a section on recommendations for measures outside the farm that contribute to resilient farming systems. Finally, I conclude with some reflections on the methodologies used in this thesis and ideas for further research.

6.1 What are the farming risks in southern Mali: Perception and Quantification of hazards

Rainfall variability creates major uncertainty for crop production in semi-arid environments, such as southern Mali (Cooper et al., 2008; Akumaga & Tarhule, 2018). However, when farmers were asked about the uncertain events they were concerned about, several other hazards besides climate variability, came forward (Chapter 2). These hazards originated both in the biophysical and the socio-economic domain. One of farmers' main concerns was related to the health of family members as it impacts the labour availability for farming next to the households' wellbeing. Health of livestock came second, since livestock has its own value but also contributes to crop management (draught power), indicating the strong interactions between crops and livestock.

The variety of identified risks was based on farmers' perceptions, which are influenced by many personal and historical factors. Perceptions of the hazards therefore also differed between (groups of) individuals. When it comes to estimating the frequency of an event, people tend to be confident in their probability judgement, regardless of potential biases, which can lead to an under- or overestimation of risks in decision-making (Hardaker et al., 2015). For some of the hazards mentioned by farmers, the frequency in the past could be quantified based on long-term weather data (Chapter 3) and compared with farmers' perception. In the specific cases of a low total amount of rainfall and a late onset of rains, the perception of less than half of farmers was in line with the quantification of the frequency (Table 6.1). Dry spells happened more often over the course of the last 49 years than what farmers estimated. This could be due to either an underestimation by farmers of the frequency, or on a mismatch between farmer definitions of hazardous years and the translation to mathematical formulas applied to the weather data.

Several risks that farmers mentioned could be classified as day-to-day risks which are relatively probable to happen but have moderate impact (5-15% of losses). Few of the risks mentioned were so extreme that the impact could be classified as catastrophic (over 50% losses). Nevertheless, the broad range of hazards mentioned implicates that farmers may have to deal also with an accumulation of hazards. First, some hazards can spark other hazards to happen as well, as often they are not independent of each other (Brooks, 2003). For example, flooding could increase prevalence of malaria (Boyce et al., 2016). Second, farm components are interdependent, leading to positive feedback loops in good years, and to cascading negative outcomes in bad years (Dissa, 2023). For example, high yields provide enough fodder to feed the cattle, which will (more likely) be strong enough the next season to provide draught power.

In the book 'The Black Swan' on the importance of extreme events (Taleb, 2010), a swan metaphor is introduced that can be applied to risk analysis. The origin of the metaphor finds itself in European history where ample observation of white swans lead to the belief that *all* swans were white; which then became a truth based on empirical evidence. One single surprising observation of a black individual in Australia disrupted this idea. Taleb (2010) describes black swan events as unpredictable extreme events; outliers that are unexpected but potentially shape the world. Following this analogy, black swan events stand for unexpected hazards while the white swan events are 'known risks' that are expected and can be prepared for.

In this research, focus lay on identifying a ballet of white swans and on how farmers prepare and cope. Nevertheless, during the course of this thesis, a worldwide black swan arrived, shaped as the COVID-19 pandemic[2]. The pandemic had a direct and dramatic impact on the health of many, but also provoked several indirect effects. As such, the pandemic induced unexpected consequences within the Malian farming system. Firstly, increased budget spendings of the Malian government to deal with the pandemic put a severe strain on other government expenditures and led to a delay in the distribution of subsidised fertiliser (Koné et al., 2020b). Secondly, the pandemic decreased the demand for cotton on the international market and as a result the price collapsed steeply in 2020, while international prices already had known a downward trend since 2018 (WTO, 2021). In Mali, this meant that CMDT had to lower the guaranteed farmgate price for cotton in the 2020-2021 cropping season in comparison to 2019. Initially, the price was reduced by 30% (from 275 to 200 FCFA / kg) in April 2020, and after negotiations with farmers' cotton cooperatives, the government added cotton price subsidies resulting in a final price set in June 2020 that still included a 9% reduction for farmers (from 275 to 250 FCFA / kg) (IPC Mali, 2020a, 2020b), while a cut of the fertiliser subsidies remained (from 11,000 FCFA to 18,000 FCFA for a bag of 50 kg). Regardless of the negotiations, many farmers protested and decided not to cultivate cotton, which also meant they had no/less access to subsidised fertiliser as the quantity that can be claimed for is tied to the area of cotton cultivated. At country level, the production of cotton dropped by an estimated three quarters (from an average of 290,000 tonnes to around 62,000 tonnes). Nevertheless, the cotton

[2] I describe the COVID-19 pandemic in the context of Malian agriculture as a black swan. During the initial stages, the COVID-19 pandemic was often referred to as a black swan. Nevertheless, whether the COVID-19 pandemic classifies as a true black swan event is contested, among others by Taleb himself. He emphasised that the pandemic was predictable, and that it reached this impact partly because the crisis was mal-managed. The world is very connected, and several warnings, reports and simulations on the potential spreading of (corona) viruses existed already (e.g. Avishai, 2020; Sweeney, 2022). Of the three attributes defining a black swan, the last one would not stand: (i) must be considered an outlier, (ii) must have an extreme impact, and (iii) must be *retrospectively* predictable. Sweeney (2022) summarised that the COVID-19 pandemic both is and is not a black swan, depending on the perspective and context used to look at it. He stated that an additional question to answer should be: 'For whom might the COVID-19 pandemic be a black swan?'. In this light, I concluded it is legitimate to use the metaphor from a perspective of farmers in southern Mali, especially given the resulting speed, timing and severity of interruptions on the global cotton market.

crisis only lasted one year as the following season prices and production bounced back up to above the level of 2019-2020 (Theriault et al., 2021; WTO, 2021).

Farmers in the Koutiala region, who generally depend for a large part on cotton for their income, shifted their resources to other farming activities during the crisis (Dissa et al., forthcoming). Farmers earned some of their income with sales of livestock and livestock products, off-farm income, while the main share remained crop production. They shifted the land allocation mainly to cereals and to a lesser extent to cowpea. Farmers decreased their fertiliser use and since farmers primarily target fertilisers to maize, the area allocated to maize decreased in comparison to sorghum and millet. While in previous years all farmers used some amount of mineral fertiliser, in the 2020 season 15 % of farmers did not use any mineral fertiliser. Regardless of these shifts, cereal crop yields were not significantly lower in 2020 than in the previous seasons. Potential clarifications could be (i) a strategical distribution of manure, (ii) a carry-over effect from nutrients applied the previous year, or (iii) good weather conditions for cereals (Dissa et al., forthcoming). In regular years, only small amounts of mineral fertilisers were applied on sorghum and millet already, and sorghum performed relatively well without fertiliser (Chapter 3). Likewise, the cotton crisis did not seem to have an effect on the food self-sufficiency levels or income per capita of farms (Dissa et al., forthcoming). Farmers in southern Mali show potential to be food self-sufficient, yet it was more challenging to cross the poverty line (Chapter 4). Nevertheless, at national level Theriault et al. (2021) assessed that during the first phase of the pandemic, about a quarter of rural and urban households experienced a decline in their income, and a third reported a drop in quality and quantity of food. In other countries of West Africa, similar market disruptions and decreased access to inputs or labour was noticed, which in Senegal seemed to lead to a decrease in yields (Jha et al., 2023). The suggested reasons being a limited access to inputs and a limited mobility hindering planting and market activities. During previous epidemics in West Africa, such as the Ebola outbreak in Guinea, Sierra Leone and Liberia in 2013-2016, the effects on agriculture were so that farm lands were left uncultivated and cereal prices increased (Ali et al., 2020).

The COVID-19 impact on the farming system is a good example of how events cannot be predicted, but still can be prepared for. In 2000 farmers already went on a 'cotton strike' because of low market prices (Dietz, 2004). However, in the assessment of farmers' risk perception, conducted before the COVID-19 pandemic, market risks did not emerge as highly relevant to farmers. The hypotheses for this result were that (i) farmers usually have a certainty on the price of cotton well-before the growing season, and (ii) farmers are relatively independent of the market for their basic food needs. Farmers' food self-sufficiency levels, and the market infrastructure of CMDT possibly buffered some of the market risks farmers would otherwise be exposed to. The COVID-19 pandemic disturbed this situation, yet it seemed that in this particular case, farmers' adaptive capacity was such that they could shift activities which limited the impact on food self-sufficiency and income (at least for one year) showcasing resilience of the system. The participation of farmers in different types of markets for different value chains (organised by CMDT for cotton, spot markets for cereals), contributed to meet livelihood objectives, and to balance the flexibility and security of sales (Dissa et al., 2022). It should be noted that the rainfall pattern during the 2020 growing season was beneficial for cereal growth (Ali et al., 2020). Although it has been indicated in literature that crop cultivation in southern

Mali is limited by nutrients rather than water (e.g. Bationo et al., 2012), it remains to be seen if farms would have been able to withstand the combination of unfavourable market conditions (no access to mineral fertilisers) and equally challenging weather conditions.

Farmers mentioned to overcome the challenges partly by selling livestock and animal products (Dissa et al., forthcoming), which was a commonly mentioned as a reactive risk coping strategy (Chapter 2). During the COVID-induced cotton crisis farmers applied a range of risk management actions in different domains (agronomic, livestock and socio-economic) (Chapter 2): a change of land allocation (crops), a change in quantity of inputs used (field), a change in livestock management (animal), calling on the negotiation power of farmers' cooperatives (social) and increasing off-farm activities (labour). Additionally, the 2020 example also emphasises the different roles crops have in the farming system, as maintaining a diversity of crops could be seen as a preventive risk management strategy. Sometimes the contribution of each crop can be dormant, until they take up different roles in case of disturbances. In Chapter 4, it was indicated that cotton and maize are important crops in their contribution to the household income because they were high-yielding (expressed in economic return), even when this also implied a high variability. These results reflected average and stable market prices, but included weather variability. Allocating parts of land to millet and sorghum mainly contributed to increasing stability. The benefit of allocating land to millet or sorghum became more pronounced when access to fertilisers was reduced (Dissa et al. (forthcoming), Chapter 3) and the market changed as during the 2020 growing season.

The above example allowed me to compare the cascading consequences and management of a recent Black Swan event with the results of the risk analysis studies conducted in this thesis. When looking at the future, it is worthwhile to notice that farmers in Koutiala operate within a region that has seen increasing political instability and unrest since 2012, with the strongest intensity in the country's north and central regions, and a growing number of spillovers to the southern part. A body of literature posits a reinforcing negative feedback loop between low available resources, climate shocks and conflict (Warren & Khogali, 1992; Homer-Dixon, 1999), while others contest this by arguing that the Malian population has developed resilience in dealing with weather extremes and conflicts throughout history (D'Errico et al., 2021). In the survey results of this thesis farmers did not mention political unrest or conflict as a hazard for their individual farms. Yet it is not unlikely that the national conflict has or will provoke(d) hazards that affect Malian agriculture. For example, following a military coup, on January 9, 2022 the Authority of Heads of State and Government of the Economic Community of West African States (ECOWAS) decided to apply sanctions on Mali that included trade restrictions and border closures with ECOWAS member states, and exclusion of Mali from the decision-making bodies. The restrictions were loosened on July 2022. There is still limited information on the direct impact on agriculture. However, during 2022, it was reported that access to fields was hampered in some Malian localities reducing the area of cultivated cereal, while the availability of fertilisers was low throughout the country (FAO, 2022). In such a volatile environment, building or maintaining farm resilience, including adaptive capacity, is all the more relevant. As Taleb (2010) states it: "Black Swans being unpredictable, we need to adjust to their existence, rather than naively try to predict them. There are so many things we can do if we focus on what we do not know." The next section reflects on what farmers do to cope with the uncertainties related to hazards.

Table 6.1 For three hazards that were of concern for farmers, farmers' perception of the frequency (Chapter 2) could be compared with the quantified frequency based on long-term term weather data (Chapter 3).

Hazard	**Perception** (Nr of farmers estimating frequency level)	**Quantification**
Low total amount of rainfall	33% of years: 4 20% of years: 6 10% of years:1	35% of years
Late onset	33% of years: 3 20% of years: 3 10% of years:1	18% of years
Dry spells and irregular distribution of rain	33% of years: 5 20% of years: 2 10% of years: na	71% of years

6.2 Insights in decision-making processes of farmers

Chapter 2 and Chapter 5 focused on the decisions farmers make, first on how to prepare for and cope with risks, and second on the (crop-related) sustainable intensification options they find promising within that variable environment. Although a wide variety of risk coping management actions were applied by farmers (linked to risk reduction, transfer and avoidance strategies), at the same time risk acceptance was common. The latter means that many farmers did not deal with hazards specifically, or when they did, it was targeted to short-term management (Chapter 2). Similarly, a wide variety of options came forward in village discussions and were tested on-farm. Nevertheless, the selection taken up by farmers in their own try-out fields was more limited. I will discuss the potential and interest of specific options in the next section (section 6.3), and will first focus on the overall drivers of farmers for making these farm management choices.

6.2.1 Visions on past and future of farms: Additional insights from RHoMIS

A broader reflection on farmers' general ambitions for farming can contextualise the observations on decisions on individual SI solutions and risk management. Farmers responded to questions regarding satisfaction of life and farming via an add-on to the RHoMIS survey. The RHoMIS household survey (van Wijk et al., 2020) was done on 80 farms in 2018 who were also participating in the other activities presented in this thesis. Out of the respondents, usually an elder male of the family, 37.5 % did not benefit any form of education, and only 13.8 % followed formal schooling (primary, secondary or post-secondary). The remaining 48.7 % of respondents were involved in religious schooling or some forms of training as an adult. Zossou et al. (2020) determined that in the process of acquiring agricultural knowledge, a range of drivers seemed to influence farming practices of rice farmers in West Africa, including training, household size, and formal and information sources, and community socioeconomic status. Formal education was not a significant determinant in this study, although other studies give examples of formal education contributing to agricultural knowledge and eventually leading to increased food security (Njura et al., 2020). Education, learning and training in rural areas are seen as critical elements to overcome poverty and food insecurity in many studies. Personal experiences and access to formal and informal knowledge sources are crucial (Zossou et al., 2020).

In the region, around three quarters of farmers are poor (Falconnier et al., 2017; Giller et al., 2021b). This might influence the level of satisfaction people have with their life. In the RHoMIS survey, over a quarter of farmers was unsatisfied with their lives, yet for the HRE-LH farmers, another quarter was very satisfied. Of the participants with children, 17% said that all of their children wanted to become farmers, while for 78% some of the children envisioned farming, and 5% answered none of their children aspired to become farmers. More specifically about farming, farmers indicated changes in the history and expected future of the farm. The changes over the last four years that were most common (experienced on over half of the farms) were an increased production of animal feed, the use of inputs and the number of crops cultivated, while over half of the farmers reduced the number of animals (Figure 6.1). Similarly, the farmers elaborated on the components were they would like to see change in the five years ahead: in situations when there is spare cash available, farmers were more willing to invest in the farm than to buy more food or possessions, followed by the interest to save money or invest in people. When asked for intentions for the coming five years, all farmers intended to apply or stimulate some changes: increase materials, increase livestock, increase crops and land, sell more or have more off-farm activities. Just a few farmers wanted to decrease the cultivated land.

Figure 6.1 Answers of 80 farmers in the RHoMIS survey (2018) about the history and future of their farm: **A)** In what direction changed the different farm components over the last four years (now less, equal or more)? **B)** In what do you invest in the case you have some spare cash available? **C)** What are your plans for the farm in the coming five years related to the farm components?

6.2.2 Diversity and flexibility: Drivers for management choices

When it comes to current farm management: farmers keep their options open. Farmers . Farmers cultivated a broad portfolio of crops, diversified field management, engaged in different value chains and maintained crop-livestock interactions. The benefit of diversifying came forward in each chapter. In Chapter 2, we learned that farmers applied a wide range of activities in dealing with hazards. In chapter 3, we confirmed that crops responded differently to weather hazards, and in Chapter 4, the potential for stabilising return through diversifying land allocation was indicated. In discussions with farmers the interest for a great diversity of SI options came forward (Chapter 5). On top of that, farmers intended to increase the number of crops in the future (Figure 6.1). Diversification is seen as a longer term strategical choice to be prepared for hazards (Mubaya & Mafongoya, 2016). Indeed, in a comparative study over 22 countries of sub-Saharan Africa, crop diversification came forward as a stabilising and profit enhancing strategy (Djoumessi, 2021), and in other studies diversification effectively mitigated everyday risks farmers face (Brouwer et al., 2007). Nevertheless, the benefits of diversification in southern Mali should also be approached with some caution. First, the farm components are dependent of each other, so the buffering capacity of the diversity is also susceptible to the hazards (Dissa, 2023). Second, in order to exceed the poverty line farmers had to take risks by pursuing high yielding options, that also have a high variability (Chapter 4)[3]. Or as Ochieng et al. (2020) stated it: 'crop diversification is not a one-size-fits-all strategy'. Their literature study found that crop diversification yielded most benefit in areas with small farm sizes, low input use, low income and little off-farm opportunities. These characteristics are valid in southern Mali, with exception of the first as farm sizes are relatively large compared to other areas in sub-Saharan Africa (Giller et al., 2021b).

Partly as a result of the diversity, farmers maintained an operational flexibility. Farmers regularly adapted their planning according to changing circumstances, as was demonstrated in the changes on try-out fields between the planning and execution phases (Chapter 5). Reactive risk management actions took place in the operational time scale, going from a few days to weeks, or the tactical time scale, over a timescale of a few months. Many of these measures were also described by Nissan et al. (2019) in dealing with climate variability: adapting planting dates, change harvest timing or selling livestock as operational activities. Tactical management actions included shifting crop allocation and variety choice.

Hazards guide crop management decisions to either maximise or stabilise yields (Khumairoh et al., 2018; Descheemaeker et al., 2019), since higher returns are often associated with higher variability. In some studies farmers deemed flexibility more important than optimizing farm profit (Darnhofer et al., 2010). Arguments for both of these orientations can be drawn from this thesis. On the one hand, the most important driver for farmers remained to achieve high yields on their fields (Chapter 5), and for the future, farmers envisioned to increase the number of livestock and input use (Figure 6.1) On the other hand, farmers had to cope with a broad variety of risks, which they accepted (i.e. did

[3] Our exercise was done by only including the return of crop production, while farms have other sources of income as well: selling some livestock products and to a limited extend off-farm income. However, crop production remained the income contributor (Dissa et al., forthcoming), and other studies have indicated the limited overall income of farmers (Falconnier et al., 2018).

nothing specifically), or reacted to with short-term risk reduction or informal risk transfer options (Chapter 2). Farmers diversified to spread the risks and valued flexibility. Moreover, after a hazard had impacted the farm, farmers often relied on their limited productive assets to fill the gaps, which were then no longer available for investments, which potentially induces a poverty trap (Hansen et al., 2019; Wichern et al., 2023). It seemed to be a double-edged sword: farmers had limited resources and so many different hazards to deal with, that spreading risks and adding stability seemed good strategies. But at the same time, farmers need to target inputs carefully and aim for some higher-yielding options to escape poverty.

6.2.3 Linking farmers' coping strategies to a resilience framework

Resilience captures the ability of farms in dealing with risks. Following the framework of Meuwissen et al. (2019), the resilience concept combines three capacities: robustness, adaptability and transformability. Diversity is seen as an attribute that enhances resilience. By creating buffers and spreading risks it contributes to robustness. By creating opportunities to react to unexpected circumstances it contributes to adaptability. Two different forms of diversity (Carpenter et al., 2012) are accomplished by farms in southern Mali: (i) functional diversity since farmers combine various farming activities (providing different functions) and farmers apply this diversity to overcome losses (chapter 2), and (ii) response diversity since farmers combine different crops with similar objectives but different responses to hazards (Chapter 3-4). Next to diversification, Darnhofer et al. (2010) recognised two other strategies that support the adaptive capacity of farms: ensuring flexibility in farm organisation and experimental learning and monitoring. The latter was stimulated through the participatory co-learning cycles between 2012-2020 (Chapter 5).

Another resilience enhancing attribute relates to system reserves (Meuwissen et al., 2019) that can serve as buffer. Such system reserves can include social networks or precautionary savings. Farmers in southern Mali relied heavily on informal social interactions, but in case of spare cash tend to invest in the farm and its members first, next to saving (Figure 6.1). However, in this region, livestock could be seen as a substitute for savings. A minority of farmers maintained a stable number of cattle over the last four years (Figure 6.1), which could indicate that cattle are a common asset to sell in case of hazards. Indeed, in southern Mali farmers used such productive assets to cover for losses, indicating that the system reserve was limited for farms with few animals.

Without having the intention to conduct a full resilience analysis, I conclude that some of the attributes that strengthen resilience of farms are available to farmers. For example, farms were robust enough to withstand the impact of the COVID-19 pandemic. On the other hand, to overcome the impact of hazards, some farmers consumed less diverse food than they preferred, consumed less, or consumed food that they had planned to sell for income, leading me to hypothesise that even moderate losses may surpass farmers' reserves. So resilience of farms could probably still be improved, through measures on and outside the farm.

6.2.4 Differences within and among farms

When it comes to differences in risk perception between household members, gender differences were not prominent (Chapter 2). However, women implemented less on-farm trials and try-outs, and when they did, they were more often abandoning after the planning phase. A lack of land and a lack of financial means were the main reasons mentioned (Chapter 5). This confirms Tschakert (2007), who stated that differences between concerns of men and women were more related to constraints than risks. Moreover, in a study of (Smale et al., 2019), individual fields of women were smaller than those of men and targeted different objectives. Women tended to focus on legumes for increased nutrition of the family, but did not exclude (intercropped) cereals. Individual fields of men were larger and cropped with cereals, often including maize which received more fertiliser.

Although farm resource endowment differs between LRE and HRE farms, the amount of land per person is similar. The amount of land per person of LRE and HRE farms is less than that of MRE and HRE-LH farms. This is a plausible driver for LRE and HRE farms having a higher risk concern (Chapter 2), as well as higher income and food self-sufficiency requirements (Chapter 4). LRE farms also obtained the lowest yields (Falconnier et al., 2015), making their situation more precarious. As HRE farms are larger, their scale may give them the benefit of targeting more resources, for example cattle, to deal with risks. It was the higher resource endowed farms (HRE and HRE-LH) who were mostly implementing trials and try-out fields (Chapter 5).

6.3 On farm: Suitable SI options matching farmers' coping strategies

The suitability of on-farm management options was explored by looking at: (i) the current risk management practices applied by farmers (Chapter 2), (ii) the response of field management options to hazards (Chapter 3), (iii) the farm-level return of crop diversification options (Chapter 4), and finally iv) the choice of sustainable intensification options experimented with by farmers in participatory co-learning cycles (Chapter 5). From these different perspectives some general characteristics of suitable options emerged, together with some contradicting results.

Farmers cultivated numerous crops on their farm, each for different reasons. The objectives included risk mitigation since different crops had different sensitivities to hazards (Chapter 3), and crop combinations helped to maintain a more stable production through time (Chapter 4). Specifically, legumes were of interest for farmers for their nutritional qualities and fodder production (Chapter 5). Cereal-legume intercropping was a traditional and common practice (Ganeme et al., 2021) and although fields targeted solely to fodder production were seen 'as a waste of good land' by some farmers, sole cowpea production gained interest during the co-learning cycle. The interest in soyabean differed between villages and farmers as well. Soyabean was a relatively new crop, with little market presence. Crop selection goals may not always be evident at first sight. For example, one farmer mentioned that for him one of the main benefits of producing groundnut was that it was harvested earlier than other crops. The harvest coincided with the start of the school year, and he used the cash obtained from the first sales of groundnut to pay the school fees for his children.

Farmers indicated an interest in diversifying varieties as well, for example through using short duration varieties in response to climate hazards (Chapter 2, 5). Short duration varieties of maize and sorghum showed potential (Chapter 3). Farmers stressed that they saw these introduced varieties as a potential addition to their portfolio, not as a replacement of the locally used ones. Farmers in Mali previously expressed the preference for combining late and early varieties to spread risks (Omanya et al., 2007). Furthermore, in Niger there were examples of farmers implementing this practice for up to five different crops (Ceccarelli et al., 1994). Nevertheless, in the try-out fields, farmers did not continue with as many varieties of cereals as offered. For cowpea however, the different varieties were appreciated (grain, fodder or dual-purpose). The drivers for choices in variety were plural, and included production, taste, fodder quality, crop cycle duration. Some farmers mentioned additional constraints, for example, for diversifying millet varieties. First, millet is stored in traditional granaries on the panicle and not in bags. As farmers do not want to mix varieties, it is hard to keep them separate in the granary. Second, millet is prone to bird attack when it matures (Omanya et al., 2007). When a single farmer has a field that matures earlier than the surrounding fields, bird losses will be concentrated in his field, or he would need to invest in labour to chase birds. When fields mature at the same time, the risk is spread. As such, the village level plays its role in farm-level crop diversity.

Increased N application on cereals showed potential to increase yields while maintaining some stability (Chapter 3, 4). Maize and millet responded well to an increase in N rates. While sorghum did not have a strong response to additional N, sorghum yields were higher than those of maize and millet when no N was applied. When fertiliser was added, maize yielded higher than sorghum and millet at all N rates (Chapter 3). Millet yields had less variability, and millet with a higher rate of N applied was a good option in diversifying land allocation (Chapter 4). During the co-learning cycles, farmers were interested to experiment with different types (organic and inorganic), application methods (spreading and microdosing) and increased rates of fertiliser on millet and sorghum (Chapter 5, Figure 6.1). Nevertheless, farmers did not continue fertiliser-related options in their try-out fields (Chapter 5). Was this due to a lack of access to fertiliser, a lack of investment capital, a return that is perceived too low, or lack of incentive as farmers were generally food self-sufficient? It is probable that constraints played a role. Labour was the most common constraint for farmers, which interfered with the interest of applying micro-dosing. Applying organic fertiliser is more labour intensive, while its quantity is dependent on the number of animals owned. Additionally, for most farmers the cost of inputs as seeds and mineral fertiliser appeared a bottleneck (Chapter 5). Most fertilisers are obtained on credit via CMDT at subsidised prices. It is difficult for farmers to get access to subsidised fertilisers outside the CMDT system (Koné et al., 2020b), and non-subsidised fertiliser was perceived to be too expensive. Farmers can only receive subsidised fertilisers if they are cultivating the DNA (Direction Nationale de l' Agriculture) target crops (rice, cotton, maize, millet and sorghum). The amount of subsidised fertiliser a farmer can claim depends on the area a farmer plans to cultivate of each target crop. For cotton and maize, a farmer can request 100% of the fertiliser rate recommended by IER (Institut d'Economie Rurale) and CMDT, while for sorghum and millet only 35% of the recommended rate for sorghum and millet can be subsidised (Theriault & Smale, 2021). The applied N rates (via fertilisers) by an average farm (data from Chapter 3, 4) did not exceed the N rates of the maximum quantity of subsidised fertilisers that farmers can claim via

CMDT (Table 6.2). Moreover, applied rates were close to the recommended rates. The N applied on cotton fields, was somewhat below the recommended rate. This is in line with earlier findings that CMDT is also a vehicle for farmers to gain access to (cotton) fertiliser, which is then shifted to other crops (Coulibaly et al., 2015; Sidibé et al., 2018; Dissa et al., 2022). Aside of farmers' benefits in gaining access to cheaper fertiliser, Theriault and Smale (2021) also critiqued this system that links access to subsidised fertiliser to target crops. They state it reduced crop diversity, favouring cotton (a non-food crop) and cereals over other crops that could contribute to food- and nutrition security. Indeed, for example, on-farm trials of soyabeans were appreciated but the cost of applying the DAP (diammonium phosphate, a source of P and N) was seen too high by farmers, as this fertiliser is not subsidised for soyabean (Chapter 5).

A relevant strategy in risk management appeared targeting the correct planting dates. Early sowing optimised yields, especially of sorghum (Chapter 3). Our findings confirmed other literature on the importance of timely sowing while trying to avoid dry spells right after the first rains (Wolf et al., 2015). Nevertheless, labour hazards were common and the resulting delayed sowing impacted cereal yields (Chapter 2, 3). In one fifth of years, farmers adapted field management by re-sowing as an answer to several hazards tampering initial crop development (Chapter 2). There are examples of farmers in southern Africa spreading risks by sowing as much land as possible and re-sowing up to six times after each rainfall event in the start of the season (Milgroom & Giller, 2013). Such strategies require the possibility to follow a planning that can be adapted to changing circumstances. It implies the need for flexibility, meaning that seeds, potentially of different varieties, need to be available. Moreover, the sowing period often goes hand in hand with a peak in labour demand. Nevertheless, it was a consistent finding in different chapters of this thesis that labour availability was an important factor in risk management (Chapter 2) and labour requirements remained a constraining factor in the choice of options by farmers (Chapter 5). As crop management is largely dependent on manual labour, this leads to high drudgery and makes farming unattractive to youth (Baudron et al., 2015; Aune et al., 2017). As mentioned above, 95% of the RHoMIS respondents with children answered that at least one of their children wanted to proceed in farming.

To conclude, farmers were dealing with a diversity of hazards to which they responded with a variety of actions using different farm components. For this, it is deemed important that both a broad and deep basket of options for farmers are presented during the continuous process of technological change, as initiated by the co-learning cycle (Chapter 5). The basket of options stands for a range of agricultural technologies from which farmers can pick those that suit them best. The depth of a basket of options refers to the number options related to a hazard, constraint or opportunity, while the breath of the basket refers to the number of different hazards, constraints or opportunities addressed (Ronner et al., 2021).

Above I focused on the crop component by summarising learnings on crops, varieties, input use and sowing. Nevertheless, options related to other farm components are equally valuable in the system. Farmers stressed the importance of crop-livestock interactions. For example, improved feeding regimes for cattle showed potential for increased milk production (Sanogo, 2010; de Ridder et al., 2015). This activity still encountered a lot of constraints. While talking with farmers, it became clear that production levels were still low and transport maintaining a cold chain is complicated. Other potential options to explore could be sheep-fattening, efficient composting, transformation of products, trees such as cashew etc. Not all of the options that could contribute to risk mitigation or poverty relieve target sustainable intensification, i.e. to increase the production per unit of land without harming the environment or conversion of non-agricultural land. Ollenburger et al. (2019) stressed that in regions further south in Mali (Bougouni), the biggest impact on poverty would come from increased ability to benefit from peak market prices of groundnut, searching off-farm employment or even expanding land. The latter would not be possible in Koutiala as pressure on agricultural land is high already (Benjaminsen, 2002; Van Dijk et al., 2004; Soumaré, 2008). Also in the social domain, there might be opportunities to explore further. For example, farms with cattle used those animals as buffer to overcome losses. Yet, farms without those resources, relied more on social interactions and solidarity (Chapter 2). The social networks called upon for risk transfer were mostly informal. Nevertheless, during the COVID-19 pandemic, the negotiating power of the cotton cooperatives lead to changes in governmental decisions (section 6.1). Formalised networks, and strengthened capacity, for example through co-learning cycles (Chapter 5), could also contribute to a resilient farming system (Darnhofer et al., 2010).

Some of the options suggested by farmers in the co-learning cycles have already been suggested some decades ago, and cannot be called innovations. For example, in 1995 a research report came out on ‘Production Soudano-Sahelienne’ (PSS project) where recommendations were made how to increase productivity in a sustainable way including the Koutiala area (Teme et al., 1996). Research vocabulary has changed since then, but some of the mentioned recommendations and constraints were still valid today. They referred to the potential of fodder crops for improved feeding regimes of livestock, and intensifying through adding fertiliser or compost and stress the constraints of high investments costs. In the last decades, farming practices have changed, although slowly. For example, Traore et al. (2015) described that around ten years ago, farmers did not allocate mineral fertiliser to millet and sorghum. In our 2018 survey they did do so, albeit in very low quantities (Chapter 3). Nevertheless, pressures and hazards are expected to rise. It is not sure if tailoring on-farm SI options is sufficient in speed and in impact to assure wellbeing of farmers. Constraints pertaining beyond the farm need to be addressed simultaneously to create an institutional environment that enables change (Descheemaeker et al., 2016)

Table 6.2 The kg N / ha obtained via mineral fertiliser that is recommended (by CMDT and IER), subsidised, and applied by farmers for different crops in the area of Koutiala.

	Unit	Cotton	Maize	Millet	Sorghum	References
Recommended fertiliser rate	kgN/ha	44-51	53-80	40	40	Falconnier et al. (2016), IFDC/AFAP (2018), Westerberg et al. (2020), farmers’ discussions
Subisdised recommended rate	%	100	100	35	35	Theriault and Smale (2021)
Potential amount subsidised	kgN/ha	44-51	53-80	14	14	
Farmers’ practice (2018-2019)	kgN/ha	33	53	16	11	Database used Chapter 3-4

6.4 Beyond the farm: Recommendations for a resilient farming system

The perception and effects of risks on farms and farm management were the primary focus of this thesis. However, many hazards originate beyond the farm's borders, and the availability of certain coping mechanisms are also affected by external factors. These external factors may influence the probability severance of some hazards, while others could affect the impact of the hazards on farms. Below I describe some institutional conditions that could support a resilient farming system, and remove some constraints that hinder farmers to apply the options they prefer. Diwakar and Shepherd (2022) stressed the relevance of an enabling environment as part of the pathway for households to escape sustainably from poverty especially in hazardous contexts. Some of the critical context-specific measures they addressed were livestock insurance and universal health coverage.

Highly relevant hazards for farmers in southern Mali, however, were connected to the physical health of household members, as well as the health of cattle (Chapter 2). Good healthcare would be an important contributor to limiting both the probability of people falling sick (through preventive care) and the impact of this hazard (through proper care targeting thorough recovery without high costs). Community health centres (CSCOM, Centre de Santé Communautaire) provide health care in rural Mali, but several obstacles made it hard for people to receive good quality care: (i) it is a fee-for-service system and although fees are kept low, people had difficulty to afford the treatments; (ii) the transport to a CSCOM and more specialised secondary health facilities (often further away) was challenging because of the distance and the cost; and (iii) the CSCOM is dependent on the income it gains from the fees, and experienced difficulties to cover expenses. As a result, quality of care remained low, with less emphasis on prevention (Koenig & Diarra, 2023). Overall health of farm animals is challenged by seasonal feed shortages and a high disease burden, while the current vaccination strategies and veterinary services are poorly established throughout the country. Dione et al. (2017) recommended to increase the number of trained veterinarians and community health workers, to strengthen regulatory bodies and traceability services to combat poor quality medicines and to provide better extension services to livestock value chain actors.

Aside from the fact that a good health is an essential contributor to a fulfilling life, and that farm animals have important roles as buffers for capital availability or manure production, unhealthy household members and draught animals also affect crop management planning and practices. Access to mechanisation and improved infrastructure, in addition to labour-saving technologies, could help lessen the burden. Several studies confirmed that mechanisation contributes to a timely land preparation (Baudron et al., 2015; Silva et al., 2019). There is debate about suitable and sustainable forms of mechanisation for land preparation in sub-Saharan Africa, with different voices promoting the use of animal power, two-wheel tractors and/or four-wheel tractors. Previously, many state-supported schemes to promote tractors have failed (Daum et al., 2022), yet it is argued that such failures were linked to supply-side constraints rather than demand (Diao et al., 2020). In Mali, institutional support for mechanisation has been declining over the past few decades, putting more emphasis on a transfer to the private sector. The cotton and rice zones maintained more support through CMDT and the Office du Niger respectively. Nevertheless, it appeared that both the commercial and institutional channels were insufficient due to a lack of coordination and capacity of the former, and low knowledge levels of distributors, imperfect supply services and large time lapses for delivery of the latter. In both cases the cost and availability of spare parts remained barriers for farmers. In recent years, the Malian government subsidised tractors for 50% (1000 in 2014 and 500 in 2018). Farmers that procured a tractor, often were not only farmers, but also active as civil servant, trader, politician etc (Kergna et al., 2020). This could point towards elite capture, which was one of the reasons contributing to the failure of past state-organised mechanisation initiatives across sub-Saharan Africa (Daum & Birner, 2017).

Next to facilitating land preparation, mechanisation and infrastructure improvement could also contribute to improving storage facilities and transport of, for example, organic fertiliser. Livestock is kept near the homestead at night where droppings are collected and mixed with crop residues. When the growing season arrives, this organic fertiliser is collected and taken to the fields by donkey carts. During my stay in the villages, I observed that accompanying the transport was often done by young children. The manure is bulky and sometimes large distances need to be covered over poor and narrow roads. Improvements in material or roads could also reduce the labour burden.

Infrastructures like (communal) storage facilities can be used within the warehouse receipt system. This system gives farmers the opportunity to be flexible in their objectives. Farmers deposit cereals as collateral in the warehouse at harvest time when prices are low. With the receipt they can get a loan to fulfill their urgent cash needs, without immediately jeopardising the quantity of cereals they might need for consumption during the year or foregoing the benefit of better prices later in the year (Coulter & Onumah, 2002). In two of the target villages of this thesis such storage facilities had recently been installed. The law on warehouse receipt systems was installed in 2018 and related activities by farmer cooperatives are supported by the 2013 law on cooperatives (Uniform Act on Cooperatives, OHADA) (Dissa et al., 2022). During discussions farmers mentioned to appreciate the system for the buffering opportunities, but also brought up the high investment costs of the warehouse.

When it comes to markets, farmers make use of different types of value chains: for cotton there is a fixed annual price and a single offtake moment by CMDT, while other crops are commonly traded at spot markets with seasonal price fluctuations (Dissa, 2023). Hence, farmers do not only diversify in the farm activities and crops, but also in the type of value chains they interact with. When the conditions of CMDT became unfavourable for farmers, the presence of both types of markets allowed farmers to balance and shift towards cereal sales. Overall, the presence of CMDT seemed to provide a certain degree of security for farmers, as also suggested by Giller et al. (2021b), who looked at poverty rates and food self-sufficiency rates across different farming systems in sub-Saharan Africa. Farmers in the cotton zone in southern Mali were doing relatively well compared to other areas. They attributed a higher land over people ratio of the farms and state support to the cotton production to this relatively better situation of Malian farmers.

Market hazards were of relatively little concern for farmers (Chapter 2). But markets also play a role in the access and possibility of coping strategies by farmers. When farmers intend to target additional crops, varieties and fertilisers, these need to be available on the market. Introduced varieties had a potential for risk reduction (Chapter 3 and 4). Nevertheless, varieties, with the traits farmers preferred, cultivated in on-farm trials (Chapter 5), were often absent on the local market. Especially soyabean seeds needed to be sourced outside the region. Also the neem oil and legume inoculant were not locally available.

This list of institutional interventions is not exhaustive. Other options could be: to invest in weather forecasts what potentially helps both agricultural as healthcare planning (Simon et al., 2018), improving access to finance, ameliorate education, establishing insurance schemes, or strengthening social networks. The short-term action frame of farmers also implies that research and intervention strategies should not only focus on long-term projections and scenarios (e.g. of climate change) but support the flexibility of farmers as well (Nissan et al., 2019). Regardless of what drives what: agricultural production driving overall development, or the other way around - investments outside agriculture could contribute to mitigating farming risks.

But even if constraints would be alleviated, would farmers be willing to close the yield gap? Koutiala is part of the breadbasket of Mali and provides food for the rest of the country (Segnon et al., 2020), making an increased and sustainable food production even more pertinent. Nevertheless, individual ambitions of farmers might be different than the overall country's need. There are several studies that indicate that narrowing the yield gap by itself would not be enough to escape poverty (e.g. Ollenburger, 2019; Marinus et al., 2023). The results of Koutiala confirmed this. Nevertheless, risk seemed an important driver in farmers decision-making for resource allocation. A crop model study on yield gaps in Zambia, contributed around a quarter of the gap to risk-reducing management (Gatti et al., 2023). So mitigating risks through institutional measures could lift some of farmers' constraints and potentially contribute to increased production.

6.5 Reflections on participatory and future research

Collaboration and stakeholder participation in the design and implementation of agricultural options can be enriching both for researchers and stakeholders. For example, experiential learning and outcome monitoring could contribute to adaptive capacity of farmers (Darnhofer et al., 2010). For researchers, it increases understanding on farmers' needs and objectives that refine the tailoring process of options. But such co-learning processes also bring challenges for communication because of differences in language, culture, education level and objectives (Klerkx et al., 2010). In the project, we attempted to assure an information flow in two directions. It took time and attention for me to find a common language for understanding and be understood. Although I am convinced that I missed out on nuances in the debates, a few factors contributed to clarifying communication. First, the village meetings and field visits were facilitated by the local NGO AMEDD, who has established a solid reputation in the region (Figure 6.2). Second, visualisations are helpful for conveying information (Mikhailovich et al., 2015). Trial results, i.e. average yields and gross margins, were presented using the visualization schemes as they were introduced at the beginning of the co-learning cycle in 2012 (Falconnier, 2016). In a region with a high level of illiteracy (section 6.2.1), we anticipated that farmers would have limited experience with interpreting graphs. Nevertheless, as an exercise, we aspired to discuss the relations between treatments in a trial via a graph (Figure 6.3a). The yield level on the y-axis was compared to the potential height of a granary that could be filled with that particular level of cereal production. By adding clarifying visuals, and taking the time to explain, we observed that farmers posed relevant questions and a lively discussion followed. Third, in addition to visuals, metaphors helped to convey relatively complex information. From each on-farm trial, a soil sample was taken. The soil analysis results of farmers' own fields were handed out, and their meaning was discussed collectively. For this, we used the conceptualisation of Tittonell et al. (2008) and Marinus et al. (2021) who compared the soil nutrient composition to a plate of food. Each type of food of a Malian meal (e.g. cereal, sauce, vegetables) represented a different soil component (Figure 6.3b), which should be present in different quantities for balanced plant nutrition, in analogy to a healthy human diet. Finally, attention was given to find the right word in the local language (Bambara and Minyanka) for the important concepts. After all, researchers have been discussing the definition of risk for decades as well. After discussions with the team, 'farati' was decided to describe risk the best, which translates to 'danger'. For the try-out fields, the name was decided after discussions with farmers and the AMEDD team after a first year of implementation. According to farmers and AMEDD 'ladeguali foro', or 'imitation field', best reflected the objective of such fields.

I aimed to list the risks that interfered with farm management, but some of these risks also affected my personal research process. The unrest and conflict in northern and central Mali made it challenging to plan for extended visits to the villages. Later the COVID-19 pandemic made it impossible to travel at all. Again, the local partner was essential for information gathering and activity planning. And although the project still continues in a third phase, the participatory process of the specific topics I focused on, is in my view incomplete. I would have loved to share the conclusions of my chapters with farmers, and to get their feedback.

The options designed and evaluated through the participatory process, remained close to farmers' practice. Partly because of the nature of the project design: options had to be feasible for farmers to implement. Therefore, one of the three components of resilience by Meuwissen et al. (2019) was not addressed in this research: transformability. Transformability is the capacity to significantly change the structure of the farm (Table 1.1). A next step in the (participatory) research could be to explore the potential of more transformative changes, given the constraints farmers have and the risks they are dealing with. For example, in the Bougouni area of Mali an agent-based model simulation indicated the income potential of targeting cashew production as a transformative option (Ollenburger, 2019). This option entailed an expansion of cultivated land, something that is not in line with the SI definition, and not feasible in the Koutiala area as land pressure is too high. Nevertheless, other suitable options could arise through evaluating the potential of transformative scenarios.

Figure 6.2 Iterative and participative village meetings were organised between 2012-2020 to discuss the options to be tested in the coming season, and to evaluate the performance of the on-farm trials and try-outs in the previous cropping season. Credits: E.K. Huet, March 2019

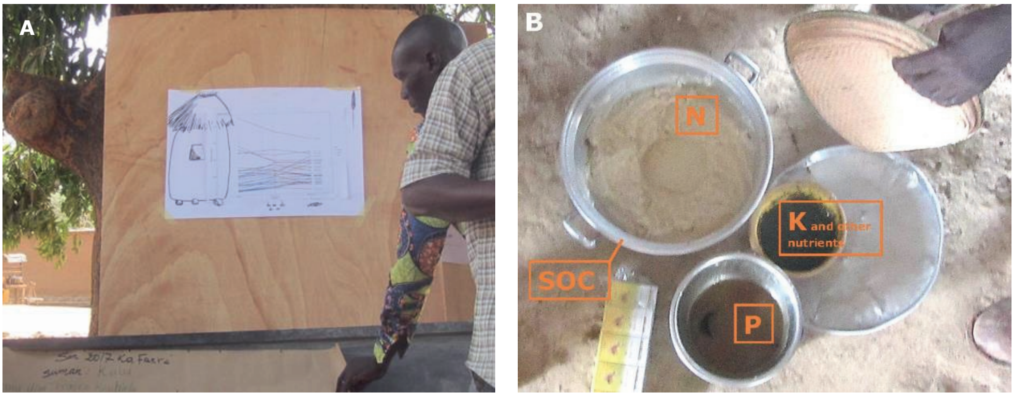

Figure 6.3 A) Visualisation of a graph used during interactive village meeting. The yield level (y-axis) is represented by the potential height to which a traditional cereal granary could be filled with that particular level of production. On the x-axis the different treatments of the experiment were visualised (a bag of fertiliser and a pile of manure). **B)** Illustration used with farmers to explain the analogy between soil nutrients and a plate of food. In Mali, the food is typically served as a shared dish for many people. The plate that carries the food represented the soil organic carbon (SOC) that holds the nutrients. 'Tô' (mashed maize, millet or sorghum) is the main ingredient of a meal, representing N in the soil. The proteins (meat, fish, soyabean or cowpea) represented P, while the leafy sauce or vegetables represented K and other nutrients. The glass of water accompanying the meal represented the soil texture, as this soil characteristic influences the water holding capacity of the soil. After Tittonell et al. (2008) and Marinus et al. (2021).

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Appendices

A. Supplementary to chapter 2: Diversity in perception and management of farming risks

B. Supplementary to chapter 3: Coping with cereal production risks due to the vagaries of weather, labour shortages and input markets through management

C. Supplementary to chapter 4: Risk reduction by diversification at farm level

D. Supplementary to chapter 5: Drivers of farmers' choices of SI options in participatory co-learning cycles

A. Supplementary to chapter 2: Diversity in perception and management of farming risks

Table A.1 The average values of farm components that determine farm type, as well as the distribution of the farm types in representative villages and in the survey

Farm Type	Unit	HRE-LH	HRE	MRE	LRE
		High Resource Endowed – Large Herd	High Resource Endowed	Medium Resource Endowed	Low Resource Endowed
Averages of farm components					
Herd	TLU*	30	12	8	2
Cropped area	Ha	20	13	9	4.5
Active labour force	AME**	23	16	7	5
Draught tools	Nr	6	4	3	1
Distribution farm types in villages					
Koutiala district 2006***	%	13	28	40	19
Risk perception survey	Nr	9	20	23	6
Risk perception survey	%	16	34	40	10

* Tropical Livestock Unit
** Adult Male Equivalent
*** Falconnier et al. (2015)

Table A.2 List of hazards with their explanations

Hazard	Explanation	Time in relation to rainy season
Animals damaging crops	Livestock, mainly cattle, damaging crops	End
Bad market price	Bad price for selling or buying farm products	End
Bad quality fertiliser	The quality of fertiliser appears bad. Farmers mentioned to observe this when fertilisers do not dissolve in water and/or when there are having no visible effects on young plants.	During
Bad quality pesticides	The quality of pesticides appears to be bad	During
Bad quality seed	The quality of seed appears bad	Start
Bad rainfall distribution	Bad distribution of rain during the season. Often this includes longer dry spells (1-3 weeks) during the growing season.	During
Empty granaries lean season	Granaries are empty before the end of the lean season, so they are not sufficient to feed the family	During
Health hazard from pesticides	Health problems due to high or wrong (no protective gear) use of pesticides.	During
Lack of access fertiliser	Lack of access to fertiliser (with importance of the time aspect of access)	Start
Lack of access seed	Lack of (timely) access to seeds	Start
Lack of access to equipment	Lack of (timely) access to farming equipment	Start
Lack of access to pesticides	Lack of (timely) access to pesticides	Start
Lack of rain	Not enough rain overall	During
Late start rains	Late start of rains	Start
Migration	Active family member leaving during the growing season	During
Misunderstandings	Misunderstandings between family members during planning of agricultural activities	Start
Pests and diseases	Incidence of agricultural pests and diseases	During
Post-harvest losses	Post-harvest losses, mostly related to storage	End
Sickness animals	Animals of the herd are weak or fall sick	Start
Sickness labour force	Family members fall sick	Start
Soil erosion	Soil erosion (heavy incidences of erosion in combination with a slow gradual process)	During
Theft	Theft of farm products or materials	End
Too much rain	Too much rainfall overall	During
Unforeseen sales	Selling farm products because of an urgent need for cash, without this being planned for	End

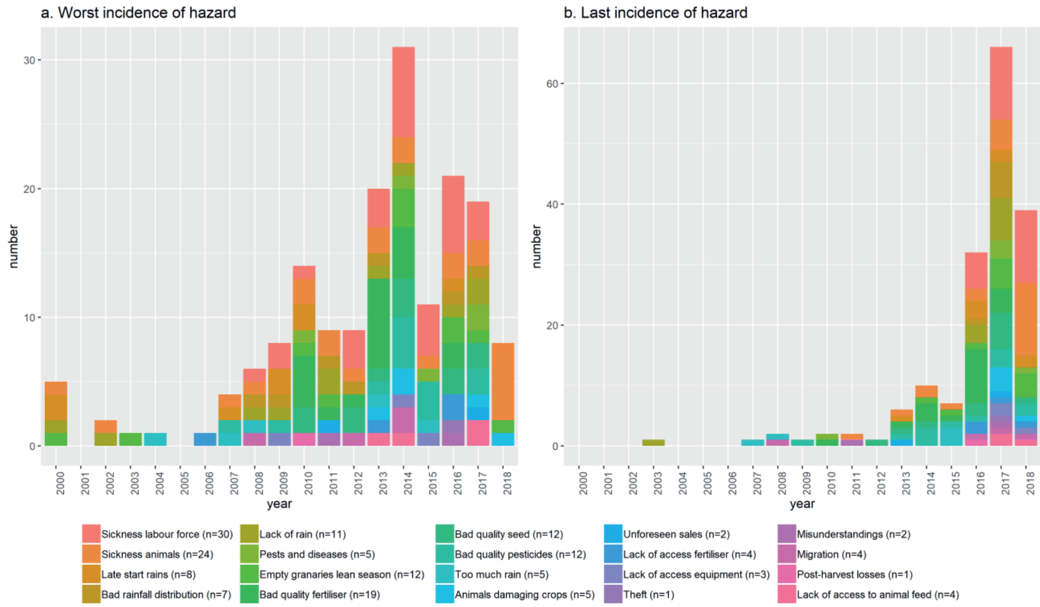

Figure A.1 The number of times the hazards occurred over the last 20 years, as mentioned by farmers. **a)** Farmers mentioning the worst incidence of the hazard, and **b)** the last time it occurred on their farm.

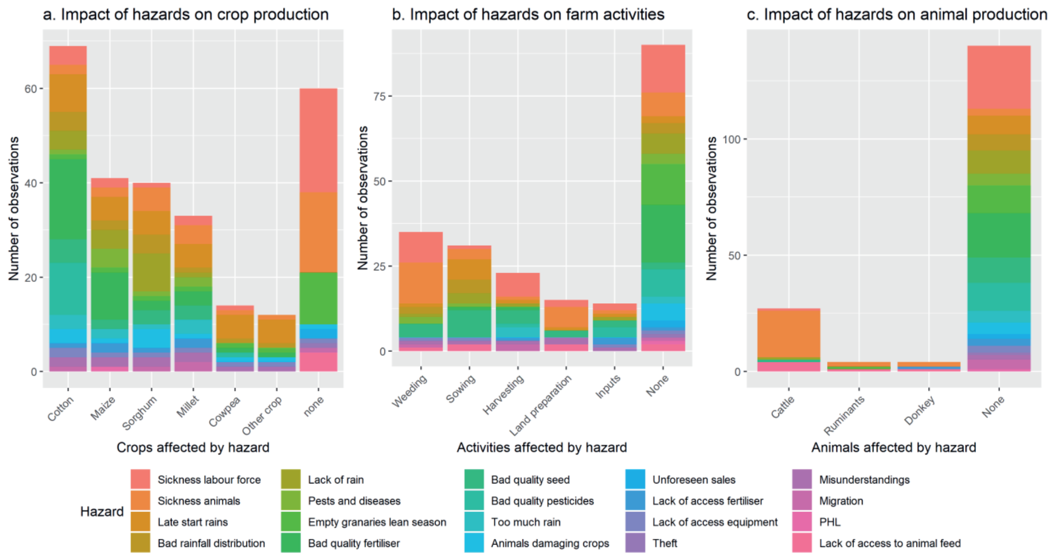

Figure A.2 a) Affected crops, **b)** activities and **c)** livestock by incidence hazards

Table A.3 The number of cases described by farmers classified by risk level (high, medium, low) and farm type, calculated based on the perceived frequency of the hazard and the impact on income (Income risk) or food availability (Food availability risk).

Farm Type	Income risk				Food availability risk				Total
	High	Medium	Low	NA	High	Medium	Low	NA	
HRE-LH	7	19	1	0	1	24	1	1	27
HRE	11	40	3	3	5	45	4	3	57
MRE	14	48	7	0	7	55	7	0	69
LRE	8	8	2	0	6	10	2	0	18
Total	40	115	13	3	19	134	14	4	171

NA = not available

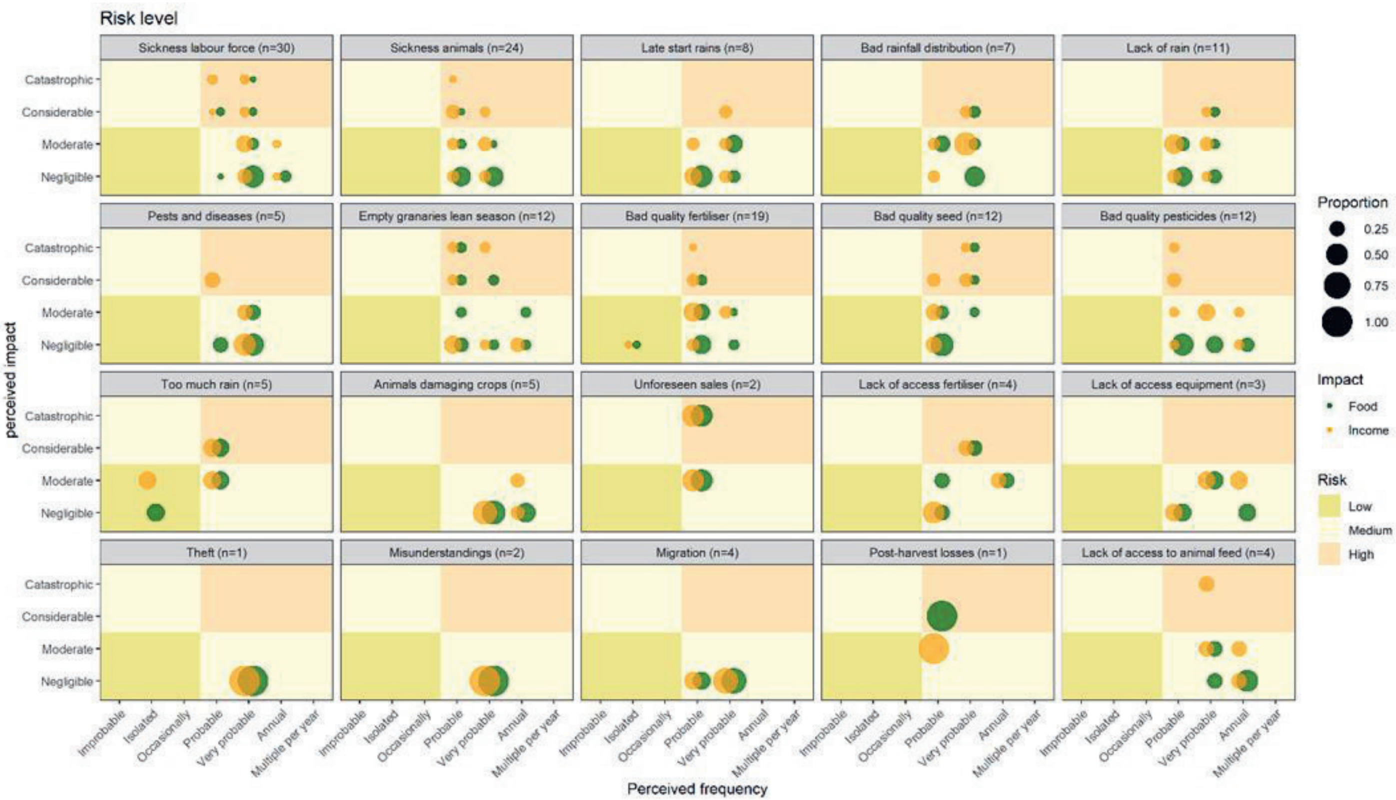

Figure A.3 Perceived frequency and impact on food availability and income of the hazards. The size of the dots indicates the proportion of farmers who mentioned this combination of frequency and impact. The background colour of the quadrants represent the risk level. Impact scores are: none or negligible (losses <5%), moderate (losses 5-15%), considerable (losses 15-50%), catastrophic (losses >50%). Frequency is indicated as follows: improbable (every 40 years), isolated (every 20 years), occasionally (every 10 years), probable (every 5 years), very probable (more or less every 3 years), annually, and multiple times a year.

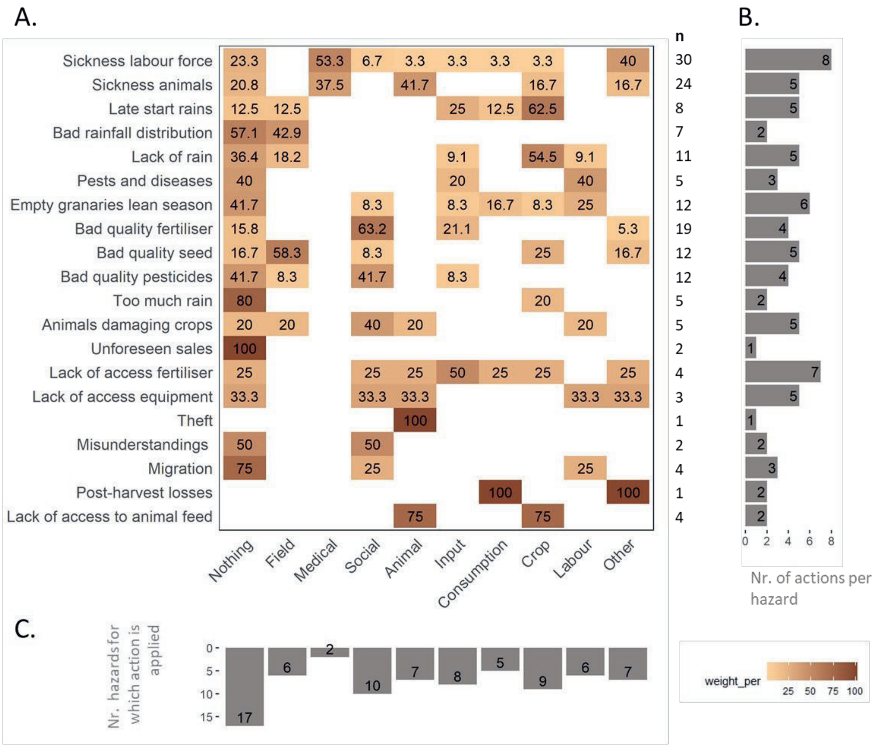

Figure A.4 A) Heatmap of the actions applied as preventive management to the different hazards, with the intensity of the colour representing the abundance of an action to deal with a hazard. The number in the boxes represent the percentage of cases that a specific action was applied out of the number of hazard cases described by farmers (n). Several actions could be applied simultaneously by the same farmer, so that the sum of the rows is 100% or more. The hazards are ordered according to farmers' ranking, and the actions are ordered according to the number of times they were applied (total count). **B)** The bar chart on the right represents the number of actions that have been applied for every hazard. **C)** The bar chart on the bottom shows the number of hazards for which that action has been applied.

B. Supplementary to chapter 3: Coping with cereal production risks due to the vagaries of weather, labour shortages and input markets through management in southern Mali

Table B.1 Characteristics and DSSAT parameter values for sand, gravelly and black soils

	Layer (*cm*)	Lower limit (*m³/m³*)	Drained upper limit (*m³/m³*)	Saturated water content (*m³/m³*)	Root growth (*0-1*)	Saturated hydraulic conductivity (*cm/h*)	Bulk Density (*g/cm³*)	Organic C (*%*)	Clay (*%*)	Silt (*%*)	Coarse fraction (*%*)	Total N (*%*)	pH (water)	Initial N NH4 (*g[N]/Mg[soil]*)	Initial N NO3 (*g[N]/Mg[soil]*)
DSSAT		SLLL	SDUL	SSAT	SRGF	SSKS	SBDM	SLOC	SLCL	SLSI	SLCF	SLNI	SLHW		
Sandy	0-25	0.079	0.184	0.405	1	2.848	1.58	0.47	12	31	2	0.023	5	0.1	0.8
	25-50	0.2	0.315	0.42	0.472	0.287	1.54	0.22	33	21	2	na	na	0.1	0.8
	50-100	0.263	0.387	0.454	0.223	0.074	1.45	0.16	44	20	7	na	na	0.1	0.8
	100-150	0.257	0.381	0.45	0.082	0.067	1.46	0.10	43	21	25	na	na	0.1	0.8
Gravelly	0-10	0.095	0.184	0.42	1	1.664	1.54	0.89	14	20	52	0.026	5.1	0.2	1.2
	10-30	0.231	0.349	0.438	1	0.095	1.49	0.50	38	19	50	0.026	5.1	0.2	1.2
	30-50	0.236	0.357	0.441	0	0.062	1.48	0.46	39	20	64	na	na	0.2	1.2
Black	0-20	0.051	0.137	0.4	1	4.863	1.59	0.30	8	25	3	0.028	5.3	0.1	0.8
	20-50	0.234	0.358	0.441	0.497	0.138	1.48	0.24	39	23	6	na	na	0.1	0.8
	50-100	0.251	0.376	0.449	0.223	0.098	1.46	0.13	42	22	1	na	na	0.1	0.8
	100-160	0.251	0.376	0.449	0.074	0.098	1.46	0.08	42	23	0	na	na	0.1	0.8

Table B.2 DSSAT parameters for maize, sorghum, and millet varieties

	Variety	Ecotype code	Thermal time seedling emergence to end juvenile phase	Thermal time end juvenile phase to tassel initiation (degree days)	Critical photoperiod at which development occurs at max rate (h)	Extent phasic development is delayed above P2O	Thermal time end of tassel initiation to anthesis	Thermal time end flag leaf expansion to anthesis	Thermal time anthesis to grain filling	Thermal time grain filling to maturity	Phylochron interval (degree days)	Scaler relative leaf size	Scaler partitioning assimilates to panicle	Tillering coefficient			Potential grain size (mg)	Reference DSSAT parameters
DSSAT		ECO#	P1	P2	P2O	P2R	PANTH	P3	P4	P5	PHINT	G1	G2	GT	G3	G4	G5	
Maize	Obatampa	.IB0001	280.0	0.0						837.0	40.00		540		7.50			Freduah et al. (2019)
	TZEEY-SRBC5	.IB0001	250	0.0						720.0	55.00		850		8.00			Freduah et al. (2019)
	SUWAN 1-SR	.IB0001	300	0.5						640	55.00		850		8			Falconnier et al. (2020)
Sorghum	CSM335	.IB0002	400.0	252.0	12.80	1000	617.5	252.5	81.5	400.0	60.00	10.0	3.0					Adam et al. (2018)
	CSM63E	.IB0003	300.0	102.0	12.80	100	647.5	142.5	61.5	450.0	55.00	16.0	3.0					Adam et al. (2018)
	IS15401	.IB0002	500.0	300.0	12.80	1800	640.5	300.5	81.5	350.0	55.00	0.5	2.0					Adam et al. (2018)
MIllet	CIVT	.IB0001	365.0		12.00	260.0				285.0	43.00	0.60		1.00		0.60	11.0	Singh et al. (2017)
	CIVT-10%	.IB0001	328.0		12.00	190.0				223.0	43.00	1.00		1.00		0.60	11.0	Singh et al. (2017)
	CIVT+10%	.IB0001	401.0		12.00	340.0				317.0	43.00	1.00		1.00		0.60	11.0	Singh et al. (2017)

Table B.3 Characteristics of the maize, sorghum, and millet varieties

	Variety	Local name	Duration	Photoperiod sensitive	Genetic nature	Days to maturity	Yield potential (t / ha)	Maintainer	Characteristics	Reference
Maize	Obatampa	Dembagnuman	Baseline	Insensitive	Open pollinated variety	105-110	5	CIMMYT/CRI	White grain, 1.75 m height	Traore et al. (2014)
	TZEEY-SRBC5		Short	Insensitive	Open pollinated variety			IITA / NARS Senegal	Yellow grain	Oikeh et al. (2003); MacCarthy et al. (2021)
	SUWAN 1-SR	Sotubaka	Long	Insensitive	Open pollinated variety	11-120	7	IITA-CYMT, Mali IER (1985)	Yellow grain, resistant to maize streak virus, 2.5-3 m height	Traore et al. (2014); et al. (2017)
Sorghum	CSM335	Tiéblé	Baseline	Sensitive	Improved population, Guinea landrace group	105-135	2.5	ICRISAT, IER (1999)	Intermediate height, high biomass, low grain, traditional local variety	Akinseye et al. (2017)
	CSM63E	Jakumbé	Short	Insensitive	Improved population, Guinea landrace group	85-100	2	IER (1984)	Intermediate height, relatively low biomass	Akinseye et al. (2017)
	IS15401	Soumalemba	Long	High sensitivity	Improved population, Guinea landrace group	110-160	2	IRAT, ISRA (Mali, 2002)	Improved traditional tall variety, high yielding dual purposes	Akinseye et al. (2017)
Millet	CIVT		Baseline	Low sensitivity	Improved population	90-95	2-2.5	INRAN (Niger, 1978, Burkina Faso, 1980)	CIVT (Composite Inter-Varietal de Tarna), tolerant to lodging and stem borer, susceptible to striga	Comité National des Semences (2014); Singh et al. (2017)
	CIVT-10%		Short			81-86		NA	Hypothetical variety	Singh et al. (2017)
	CIVT+10%		Long			99-105		NA	Hypothetical variety	Singh et al. (2017)

Table B.4 Overview of DSSAT treatments

Management factors	Factor levels Maize	Factor levels Sorghum and Millet	Total nr simulations per crop
N fertiliser	0, 10, 20, 40, 50, 60, 70, 80, 100, 120, 160, 200 kg N/ha (34% at 15DAS, and 66% at 45DAS)	0, 5, 10, 15, 20, 40, 60, 80, 100, 120, 160, 200 kg N/ha (34% at 15DAS, and 66% at 45DAS)	*12*
Planting density	62,000 plants/ha	50,000 plants/ha	*12*
Sowing date	10/5 until 2/8 with 5 day intervals (18 levels)	10/5 until 2/8 with 5 day intervals (18 levels)	*18*12=216*
Varieties	3 varieties (long, medium, short)	3 varieties (long, medium, short)	*216*3=648*
Soil	3 soil types : sandy, gravelly, black	3 soil types : sandy, gravelly, black	*648*3=1944*
Years	55 years (1965-2019)	55 years (1965-2019)	*1944*55=106,920*

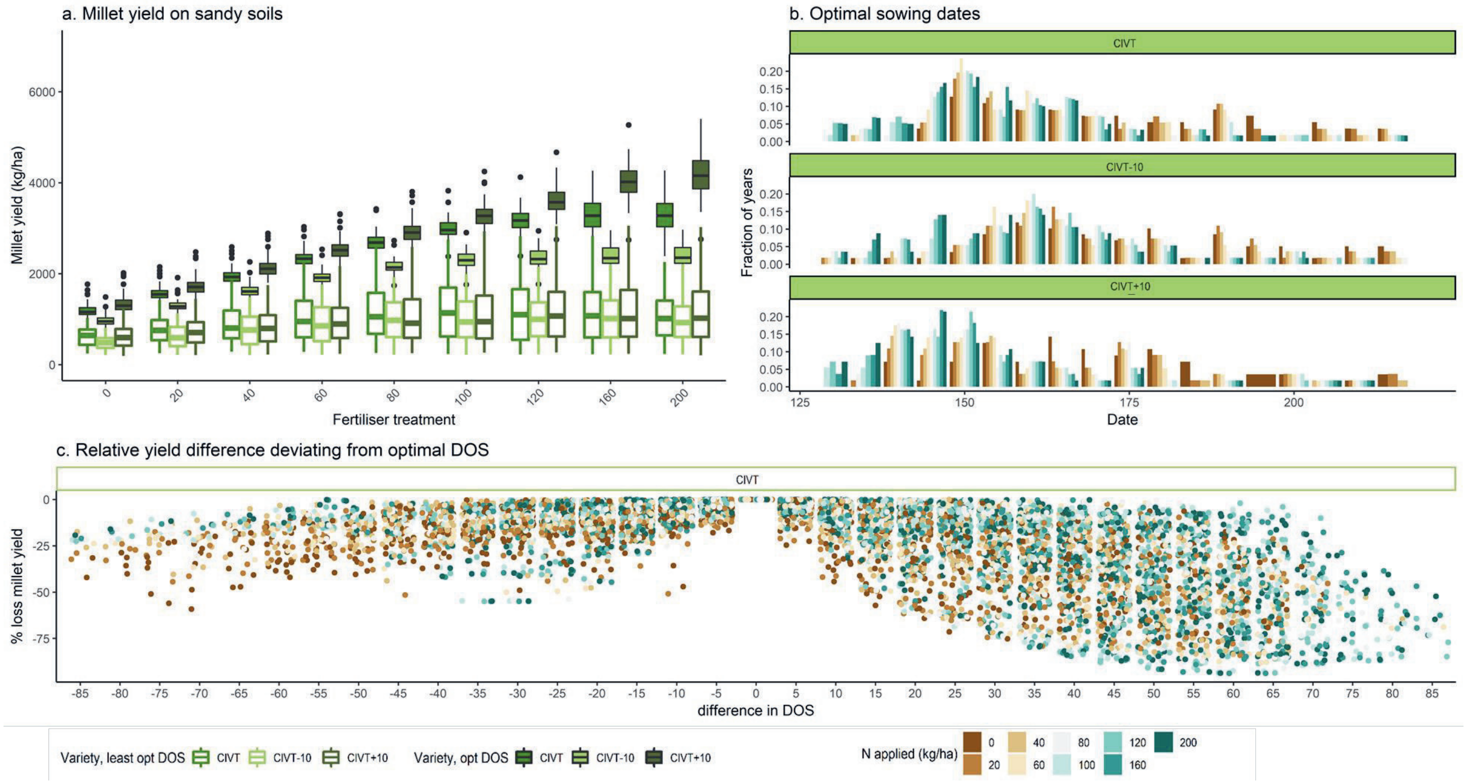

Figure B.1 a) Millet yield for different fertiliser rates and varieties on sandy soils, for the defined optimal sowing date (DOS) of each year (filled boxplots) and the least optimal DOS of each year (open boxplots). **b)** Histogram of the optimal sowing dates for the different years and **c)** Relative yield loss when deviating from the optimal sowing date for the baseline variety. Nine N rates (0 kg N / ha - 200 kg N / ha) and three varieties are represented.

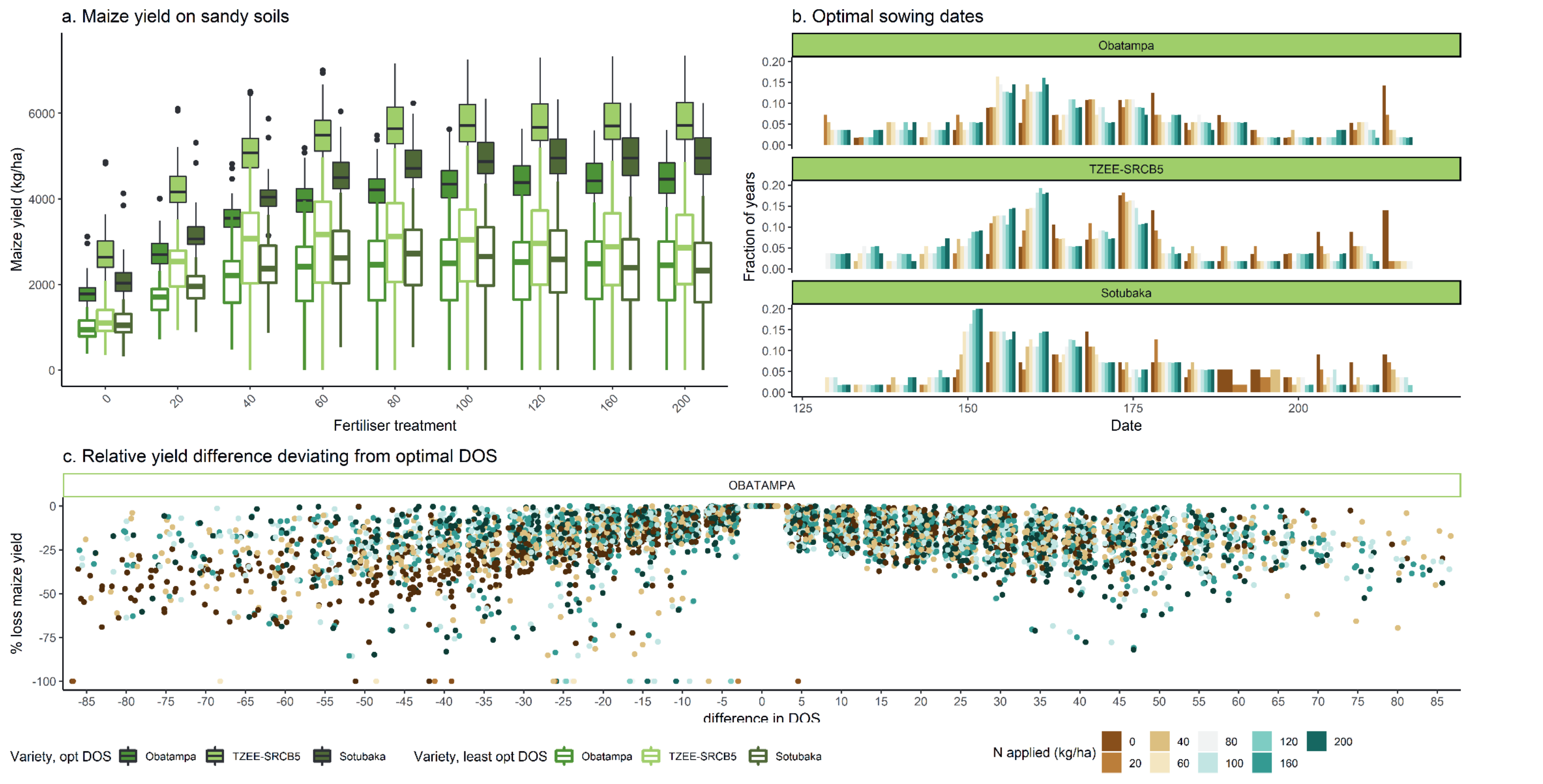

Figure B.2 a) Maize yield for different fertiliser rates and varieties on sandy soils, for the defined optimal sowing date (DOS) of each year (filled boxplots) and the least optimal DOS of each year (open boxplots). **b)** Histogram of the optimal sowing dates for the different years and **c)** Relative yield loss when deviating from the optimal sowing date for the baseline variety. Nine N rates (0 kg N / ha - 200 kg N / ha) and three varieties are represented.

C. Supplementary to chapter 4: Risk reduction by diversification at farm level

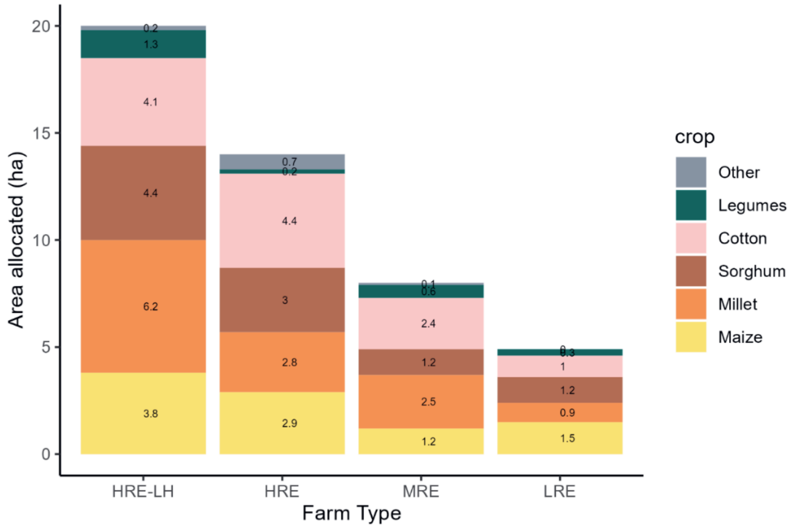

Figure C.1 The average cultivated land (ha) per farm type allocated to different (types of) crops

Table C.1 Summary of parameters used to calculate returns of the assets

Asset Management				Economic parameters					Energy parameter	Return					
Crop	Variety	Fertiliser rate (kg N/ha)	Asset code	Fertiliser cost (USD PPP/ha)	Seed rate (kg/ha)	Seed price (USD PPP/kg)	Seed Price (USD PPP/ha)	Grain Price (USD PPP/kg)	Energy (raw dry grains) (kcal/kg)	Mean yield (kg/ha)	sd yield (kg/ha)	Mean Economic return (USD PPP/ha)	Sd economic (USD PPP/ha)	Mean energy return (10^6 kcal/ha)	Sd energy (10^6 kcal/ha)
Maize (MZ)	**Obatampa**	**50**	**MZ-LV-LF**	152 [(a)]	30 [(b)]	0	0	0.50 [(c)]	3650 [(d)]	3372 [(e)]	466 [(e)]	1534	233	12.30	1.70
		70	MZ-LV-HF	212 [(a)]	30 [(b)]	0	0	0.50 [(c)]	3650 [(d)]	3613 [(e)]	544 [(e)]	1595	272	13.19	1.99
	TZEE-SRBC5	50	MZ-SV-LF	152 [(a)]	30 [(b)]	2.37 [(b)]	71	0.50 [(c)]	3650 [(d)]	4674 [(e)]	679 [(e)]	2114	340	17.06	2.48
		70	MZ-SV-HF	212 [(a)]	30 [(b)]	2.37 [(b)]	71	0.50 [(c)]	3650 [(d)]	4877 [(e)]	767 [(e)]	2156	383	17.80	2.80
Millet (ML)	**CIVT**	**15**	**ML-LV-LF**	45 [(a)]	9.5 [(b)]	0	0	0.66 [(c)]	3780 [(d)]	1330 [(e)]	220 [(e)]	832	145	5.03	0.83
		100	ML-LV-HF	303 [(a)]	9.5 [(b)]	0	0	0.66 [(c)]	3780 [(d)]	2720 [(e)]	425 [(e)]	1492	281	10.28	1.60
	CIVT-10	15	ML-SV-LF	45 [(a)]	9.5 [(b)]	4.1 [(b)]	39	0.66 [(c)]	3780 [(d)]	1100 [(e)]	138 [(e)]	642	91	4.16	0.52
		100	ML-SV-HF	303 [(a)]	9.5 [(b)]	4.1 [(b)]	39	0.66 [(c)]	3780 [(d)]	2110 [(e)]	264 [(e)]	1050	175	7.97	1.00
Sorghum (SG)	**CSM335**	**10**	**SG-LV-LF**	30 [(a)]	6.5 [(b)]	0	0	0.52 [(c)]	3290 [(d)]	1742 [(e)]	856 [(e)]	876	445	5.73	2.82
		80	SG-LV-HF	242 [(a)]	6.5 [(b)]	0	0	0.52 [(c)]	3290 [(d)]	1951 [(e)]	1067 [(e)]	773	555	6.42	3.51
	CSM63E	10	SG-SV-LF	30 [(a)]	6.5 [(b)]	2.52 [(b)]	16.4	0.52 [(c)]	3290 [(d)]	2326 [(e)]	352 [(e)]	1163	183	7.65	1.16
		80	SG-SV-HF	242 [(a)]	6.5 [(b)]	2.52 [(b)]	16.4	0.52 [(c)]	3290 [(d)]	2710 [(e)]	602 [(e)]	1151	313	8.92	1.98
Cotton (CT)	**CMDT cultivar**	**17**	**CT-LV-LF**	52 [(a)]	na	na	4.9 [(f)]	1.23 [(g)]	na	1376 [(h)]	544 [(h)]	1635	669	na	na
		40	CT-LV-HF	121 [(a)]	na	na	4.9 [(f)]	1.23 [(g)]	na	2036 [(h)]	617 [(h)]	2379	759	na	na

In bold the baseline management (as defined in Huet et al. (2022))

(a) Expert knowledge, Ripoche et al. (2015)
(b) Trials in McKnight project 2017-2020 (Huet et al. under review)
(c) OMA (2016)
(d) USDA (2019)
(e) Huet et al. (2022)
(f) Coulibaly et al. (2015)
(g) Dissa (2021)
(h) Traore et al. (2013)

Table C.2 Overview of the number of assets and the possible combinations in the different steps of the MPT analysis

Component diversification	Explanation	Number of assets	Number possible combinations
Crop	Combining baseline management of four crops	4 crops	6
Fertiliser	Combining baseline with increased fertiliser rates for each crop	2 for 4 crops	4
Variety	Combining baseline variety with a short-duration variety for each cereal crop	2 for 3 crops	3
All cereals	Combining all management components for the cereals	12	66
All	Combining all possible management components for all crops	14	91

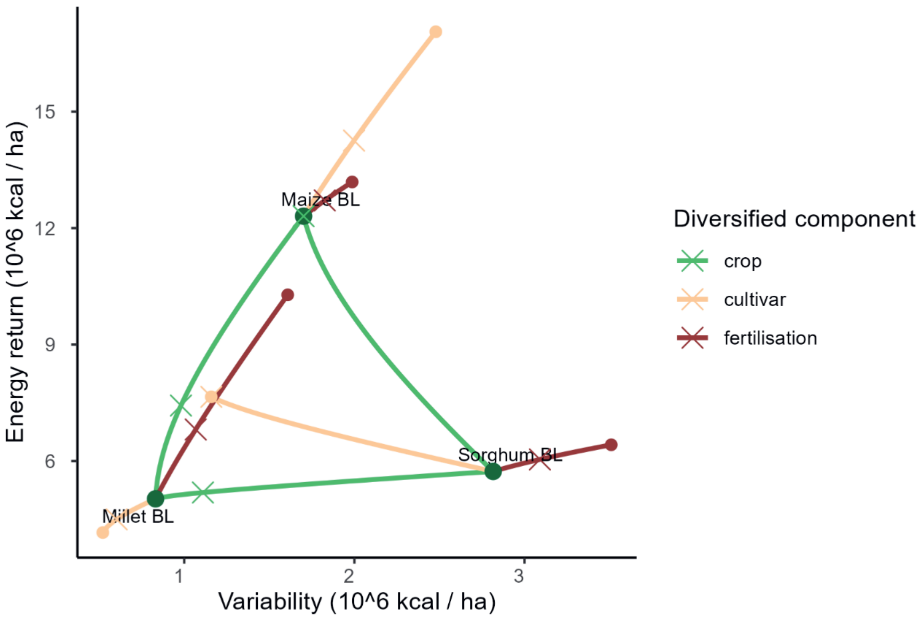

Figure C.2 The farm-level energetic return (kcal / ha) and variability (kcal / ha) for the points were all land was allocated to a cereal baseline (BL) management (Maize BL, Sorghum BL, Millet BL). For each of these three points the Modern Portfolio Curve was drawn when one asset component was diversified (crop, fertilisation level, cultivar). The crosses determine the optimal points on each diversification curve.

Table C.3 MPT parameters of the baseline strategies expressed in yield and food (energy) return (F)

Diversification component	Strategy		Farm-level return at optimal point: YIELD (Y)								Farm-level return at optimal point: ENERGY (F)						
	Asset 1	Asset 2	Corr	Prop 1	Prop 2	Yield	sd	Rel Δσ	Rel ΔY	ΔY	Prop 1	prop 2	Energy	sd	Rel Δσ	Rel ΔF	ΔF
						kg/ha	*kg/ha*	*%*	*%*	*kg/ha*			*10^3 kcal/ha*	*10^3 kcal/ha*	*%*	*%*	*10^3 kcal/ha*
cultivar	MZ-LV-LF	MZ-SV-LF	0.96	**0.59**	**0.41**	3906	547	1	16	768	**0.59**	**0.41**	14256	1998	1	16	2803
cultivar	ML-LV-LF	ML-SV-LF	0.76	**0.39**	**0.61**	1190	159	6	11	140	**0.39**	**0.61**	4497	603	6	11	530
cultivar	SG-LV-LF	SG-SV-LF	0.73	**0**	**1**	2326	352	0	0	0	**0**	**1**	7654	1159	0	0	0
fertilisation	MZ-LV-LF	MZ-LV-HF	0.99	**0.54**	**0.46**	3483	500	0	4	130	**0.54**	**0.46**	12713	1826	0	4	476
fertilisation	ML-LV-LF	ML-LV-HF	0.90	**0.66**	**0.34**	1802	282	3	34	918	**0.66**	**0.34**	6813	1067	3	34	3468
fertilisation	SG-LV-LF	SG-LV-HF	0.95	**0.55**	**0.45**	1836	939	1	6	115	**0.55**	**0.45**	6041	3090	1	6	378
crop	MZ-LV-LF	ML-LV-LF	0.54	**0.32**	**0.68**	1983	262	12	41	1389	**0.33**	**0.67**	7429	981	12	40	4878
crop	ML-LV-LF	SG-LV-LF	0.49	**0.8**	**0.2**	1412	299	14	19	330	**0.77**	**0.23**	5189	1110	14	9	543
crop	SG-LV-LF	MZ-LV-LF	0.74	**0**	**1**	3372	466	0	0	0	**0**	**1**	12308	1701	0	0	0

Table C.4 MPT parameters of the baseline strategies expressed in economic return (E)

Diversification component	**Strategy**					**Farm-level return at optimal point: ECONOMIC**				
	Asset 1	**Asset 2**	**Correlation**	**Prop 1**	**Prop 2**	**Mean return**	**sd**	**Rel Δσ**	**Rel ΔE**	**ΔE**
						USD PPP/ha	*USD PPP/ha*	*%*	*%*	*USD PPP/ha*
cultivar	MZ-LV-LF	MZ-SV-LF	0.96	**0.57**	**0.43**	1730	279	1	43	319
cultivar	ML-LV-LF	ML-SV-LF	0.81	**0.38**	**0.62**	705	124	5	62	105
cultivar	SG-LV-LF	SG-SV-LF	0.76	**0**	**1**	1100	213	0	100	0
fertilisation	MZ-LV-LF	MZ-LV-HF	0.99	**0.54**	**0.46**	1513	265	0	46	27
fertilisation	ML-LV-LF	ML-LV-HF	0.93	**0.67**	**0.33**	1009	227	2	33	406
fertilisation	SG-LV-LF	SG-LV-HF	0.95	**1**	**0**	769	442	0	0	0
crop	MZ-LV-LF	ML-LV-LF	0.57	**0.41**	**0.59**	1088	179	11	59	401
crop	ML-LV-LF	SG-LV-LF	0.48	**1**	**0**	809	172	0	0	0
crop	MZ-LV-LF	SG-LV-LF	0.79	**1**	**0**	1490	245	0	0	0
crop	CT_LF	MZ-LV-LF	-0.02	**0.27**	**0.73**	1529	251	30	73	107
crop	CT_LF	ML-LV-LF	0.16	**0.2**	**0.8**	975	206	24	80	661
crop	CT_LF	SG-LV-LF	0.04	**0.4**	**0.6**	1116	384	28	60	520
fertilisation	CT_LF	CT_HF	0.65	**0.53**	**0.47**	1985	647	9	47	394

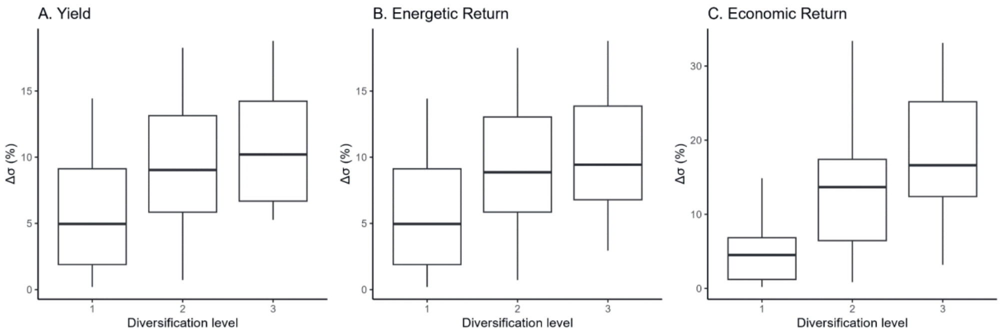

Figure C.3 Boxplots for the Δσ values of the optimal points for strategies with different diversification levels: one component (crop, variety or fertiliser levels) of the combined assets is different (1), two components differ (2), or all components differ (3). The Δσ are represented for the different indicators: **A)** weighted farm-level yield, **B)** the energetic return and **C)** the economic return.

D. Supplementary to chapter 5: Drivers of farmers' choices of SI options

Table D.1 Overview of the categories and levels for agricultural options that were explored in trials and try-out fields in Koutiala

Option category		Category levels
Field	Crop configuration	Sole
		Intercrop
		Relay
	Crop	
Management	Fertiliser	Type
		Rate
		Application method
	Sowing	Sowing density
		Timing
		Pattern
	Variety	Other introduced
		Double purpose
		Fodder
		Hybrid
		Short cycle
		Nutritional
	Other	Bio-pesticides
		Inoculant

Table D.2 The number of farms that participated in the trials and try-out fields, organised according to the number of years that they participated within the period 2012-2020

	Trials	Try-outs
Nr of years	Nr of farms	Nr of farms
1	72	51
2	21	28
3	32	15
4	20	7
5	8	na
6	6	na
7	2	na
Total	161	101

Table D.3 The number of farmers per age class that were responsible for a try-out field, compared to the number of adult farmers per age class active in agriculture (defined as spending more than 50% of their time in agriculture). The data of the latter is obtained from a household survey in 2018 in the same villages described in Huet et al. (2020).

Age class	Farmers with a try-out field		Farmers active in agriculture	
	%	*Nr*	%	*Nr*
0-15	Na	*Na*	Not included	*Not included*
16-25	0.5	*1*	42	*204*
26-35	7	*15*	25	*122*
36-45	41	*85*	20	*97*
46-55	38	*79*	7	*35*
56-65	11	*23*	4	*18*
>65	3	*6*	1	*6*
Total	100	*209*	100	*482*

Table D.4 Evolution of the options explored in on-farm trials and try-out fields 2012-2020. The options are organised per crop and per management factor that was explored in the trial or try-out field and that differed from general farmers' practice. The design of the trials was discussed with farmers, as well as the results. After these discussions trial design was adapted allowing the options of interest to evolve. The years in which each management factor was explored in trials is given, together with the number of farmers who implemented such a trial. The try-out fields are also organised per crop and management factor that was explored in the trials, and complemented with farmers' additions (or partial implementation of the trial design). The years in which each management factor was explored by farmers in try-out fields is given, together with the number of fields.

Field	Crop	Explored factor					Years of trials	Nr of trials	Years of try-outs	Nr of try-outs	Description options in trials	Description options in try-outs
		Fertiliser	Sowing	Variety	Other input	Niche						
Intercrop	Maize-cowpea		Pattern	Fodder, Grain			\`12, \`13, \`14, \`19	42	\`17,\`18,\`19,\`20	18	Additive pattern; varieties of cowpea: Dunanfana, Wulibali	
			Pattern	Fodder			\`17, \`18	24			Additive pattern; variety of cowpea: Dunanfana	
		Application						0	\`19, \`20	2		Adaptation of option: microdosing fertiliser
			Pattern					0	\`17,\`18,\`19,\`20	30		Partial option: additive pattern with local cowpea variety
	Sorghum-cowpea		Pattern	Fodder, dual-purpose			\`13, \`14	4	\`20	8	Additive pattern; varieties cowpea: Dunanfana, Wulibali	Adaptation: the introduced variety Soumbatimi is cultivated in intercrop, not as a sole crop
		Application						0	\`19	1		Adaptation : microdosing fertiliser
			Pattern					0	\`17,\`18,\`19,\`20	18		Partial: additive pattern with local cowpea variety
	Millet-cowpea		Pattern					0	\`18	1		Additional cereal-legume option
	Cowpea-sesame /dah		Pattern					0	\`18, \`20	2		Additional intercrop option
Relay	Groundnut-cowpea						\`14	11		0	Relay cropping cowpea (Dunanfana, Wulibali) after Groundnut (ICGV)	
Sole	Maize	Type, Rate		Other			\`13, \`14	37		0	variety: Bofonda	
				Other			\`15	25		0	varieties: Bofonda, DK910, Sotubaka	
		Type, Rate						0	\`19	1		Partial option: adapting fertiliser application with local maize variety
								0	\`17	4		na
	Sorghum	Rate		Hybrid			\`13, \`14, \`15	17		0	varieties: Seguetana, Pablo, Djiguikala, Soumba, Zalatimi	
				Hybrid				0	\`20	1		Adaptation: variety Fadda (but seeds recovered from own field)
		Type, Rate, Application		Dual purpose			\`17, \`18, \`19, \`20	70		0	microdosing organic fertiliser; variety: Soumbatimi	
		Type, Rate, Application						0	\`20	1		Adaptation: microdosing (adapting to chicken manure) with local sorghum variety
				Dual purpose				0	\`20	1		Partial option: farmers practice with variety Soumbatimi
				Other				0	\`18, \`20	3		Additional: different varieties

Field	Crop	Explored factor					Years of trials	Nr of trials	Years of try-outs	Nr of try-outs	Description options in trials	Description options in try-outs
		Fertiliser	Sowing	Variety	Other input	Niche						
	Millet	Type, Rate, Application		Nutrition			`17, `18, `19, `20	84			microdosing organic fertiliser; variety: NKOxT1	
		Type, Rate, Application						0	`18	1		Adapatation: microdosing chicken manure
				Nutrition				0	`18,`19,`20	7		Partial: farmers practice with variety NKOxTC1
				Other				0	`18, `20	2		Additional: varieties Boboni and local
	Cowpea	Rate		Fodder, Grain			`13, `14	12		0	varieties: Dunanfana, Wulibali	
			Timing, Density				`15	3		0		
			Timing	Grain, Fodder			`15, `19, `20	38	`19	1	2 or 3 sowing windows; varieties: Wulibali, KVX309, Dunanfana, Korobalen, Sangaraka	Adaptation: variety Fackson
				Grain	Bio-pesticide		`17, `18	41		0	Neem treatment; variety: Wulibali	
								0	`17,`18,`19,`20	12		For these farmers it is new to grow sole cowpea (varieties: local, Dunanfanan, Sangaraka, Wulibali)
				Fodder, grain, dual purpose				0	`17,`18,`19,`20	65		Adaptation: farmer practice with varieties Korobalen, Wulibali, local, Dunanfana, Niban
	Groundnut		Pattern	Other			'15, '17	31		0	sowing in lines; variety: ICGV8612	
				Other				0	`18	3		Adapatation: Ganipia, kanbianne locale
								0	`18	2		na
	Soyabean	Type, Rate			Inoculant		'13, '14	32		0	Soyabean is a relatively new crop; variety: Houla, +DAP	
		Type, Rate				fertile field	'15	6		0	Soyabean is a relatively new crop; variety: Houla, +DAP	
		Type, Rate	Density				'17	9	`19	1	Soyabean is a relatively new crop; variety: G196, high sowing density	
				Other			'18, '19, '20	52	`19,`20	17	Soyabean is a relatively new crop; varieties: G197, TGx 1951-3F, TGx 1835-10E, TGx 1987-62F, G115, G121 et G195	
		Type, Rate		Other				0	`19	2		Adaptation: combining trial treatments from different years
			Density	Other				0	`19	1		Adaptation: combining trial treatments from different years
								0	`17,`18,`20	7		Other
	Sesame							0	`19	1		Additional crop
Both	Stylosanthes	Rate	Pattern				'13, '14	na		0	Sole stylosanthes or intercropped with millet	
Total number of trials and try-outs							'12-'20	***538***	'17-'20	***223****		

**Number of try-out fields with complete recorded datasets (more have been installed)*

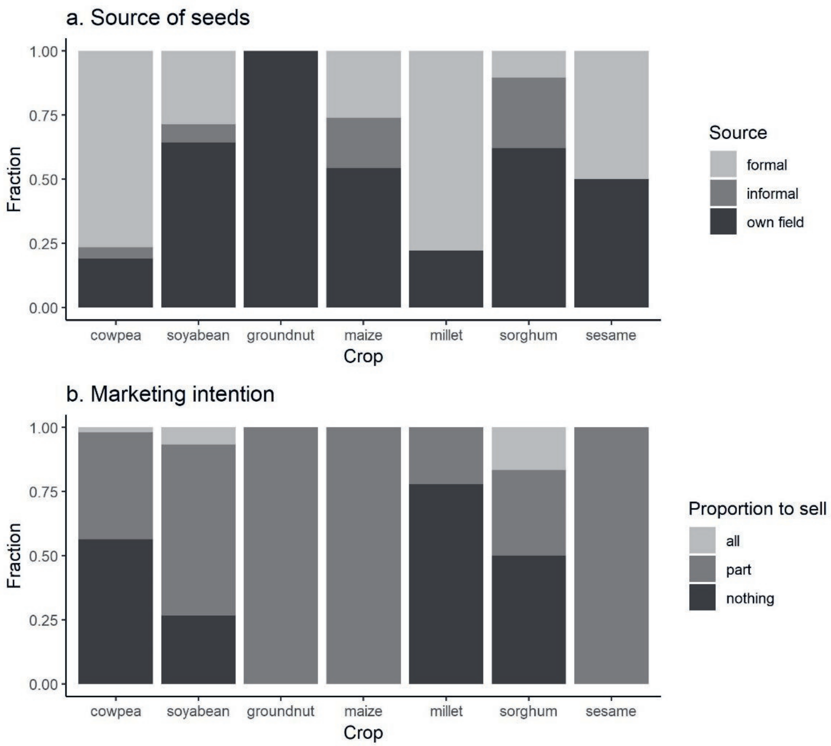

Figure D.1 Additional background on inputs and objectives of the try-out fields. **a)** For each of the crops, the fraction of the fields is given according to the source of the seeds: recycled from farmers' own fields ("own field"), informally obtained with another farmer ("informal"), or seeds more formally bought via the market, an NGO or other ("formal") (n=192). **b)** For each of the crops, the fraction of fields according to farmers' market intention of the obtained grain production. Farmers indicated whether they intended to sell all the production, only part, or nothing at all (consumption) (n=138).

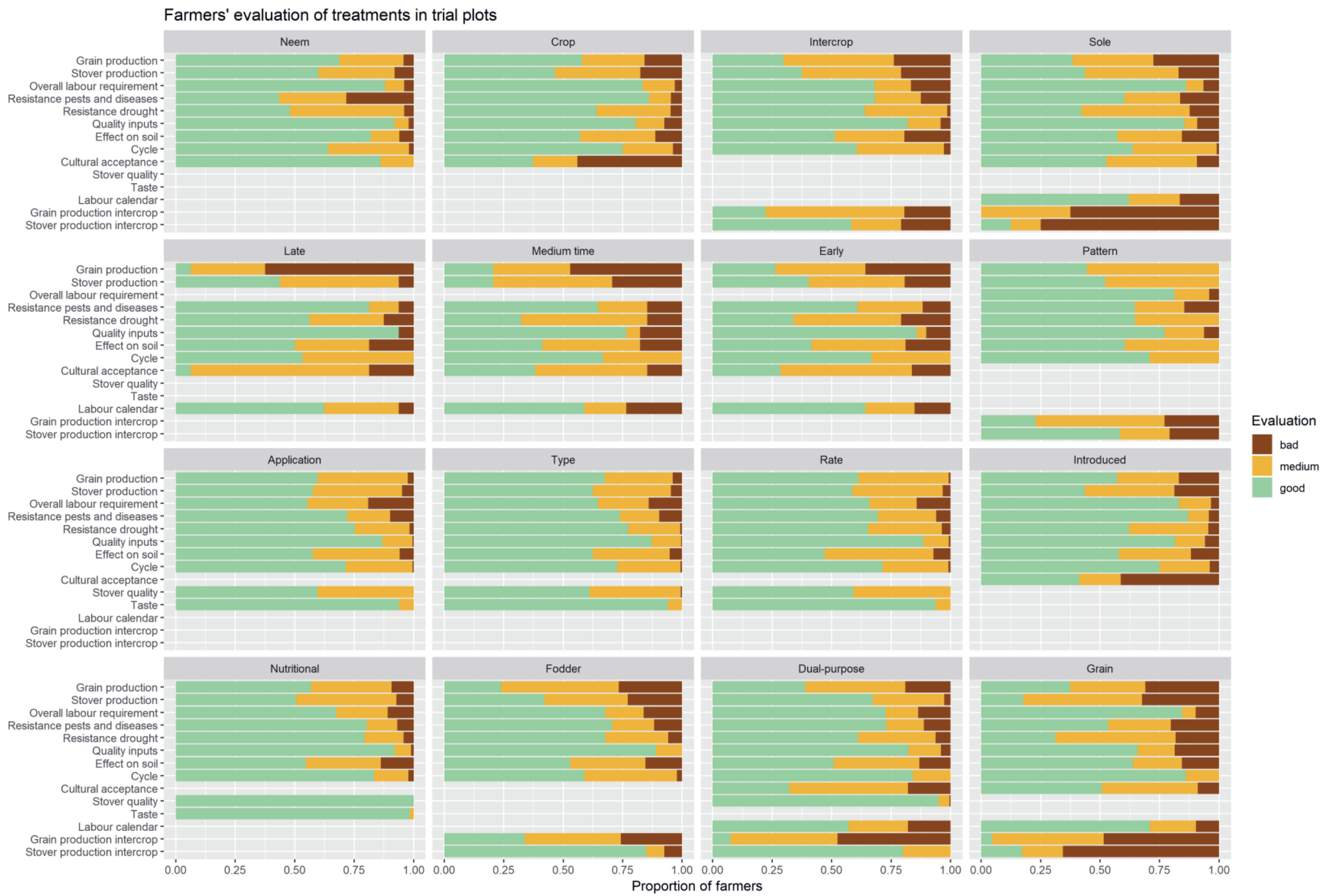

Figure D.2 The proportion of farmers that rated the different trial plots as 'good', 'medium' or 'bad' according to different criteria, organised for the different options tested in the plot. Data is averaged for 2018, 2019 and 2020.

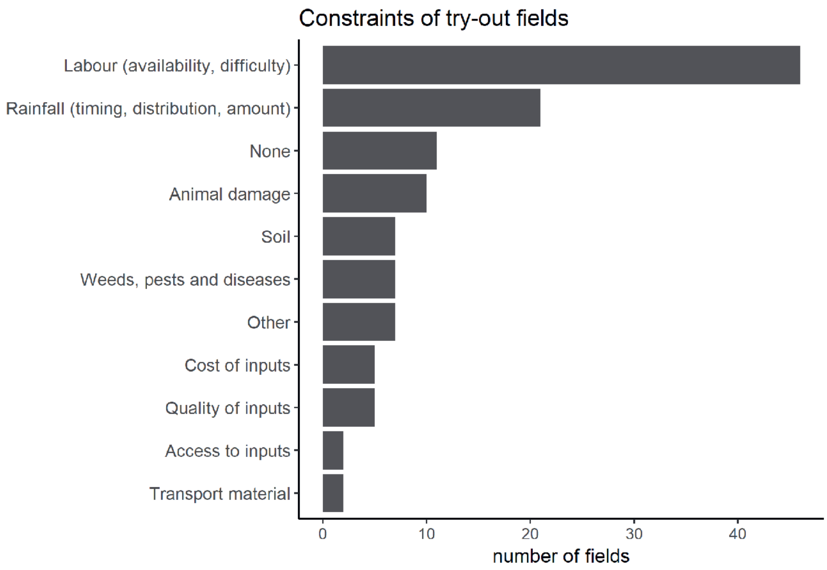

Figure D.3 The main constraints given by farmers when cultivating their try-out fields, collected from 229 try-out fields (some of which with multiple constraints).

Summary

Smallholder farmers in West Africa are challenged by a diversity of agricultural risks for both food production and income. Risks represent the negative impact of a hazard and the frequency with which a hazard occurs. Both elements are associated with uncertainty, resulting in difficulties for farmers to manage risk. Climate variability is a well-known source of risk that is expected to increase due to climate change. However, hazards are diverse and can be related to biophysical as well as to marketing, financial, legal and human resources. Ongoing population growth, declining natural resources and climate change further pressure the system. Farmers are often struggling to be food self-sufficient and to escape poverty.

The aim of this thesis was to understand farmers' strategies to cope within a variable and hazardous environment. A parallel objective was to analyse which sustainable intensification options could increase productivity and/or reduce risks within the socio-economic and biophysical context. The thesis was constructed around four specific objectives: (1) to analyse which risks farmers perceive to be important, how this perception differs between and within households, and how farmers manage their farm in a risky environment; (2) to quantify cereal crop yield losses at field level due to the interactions of different production hazards under varied management strategies; (3) to quantify the potential to mitigate variability in agricultural production by diversifying crop and management allocation at farm level; and (4) to learn how farmer-designed try-outs are evaluated by farmers and how they can be incorporated in agricultural participatory research projects.

I focused on the area of Koutiala, southern Mali, as a case study of the challenging farming conditions in West Africa. Agriculture, and mainly crop production, is the major source for food and income. Cereals (maize, millet sorghum) are grown first and foremost for consumption, as well as to provide an income. Cotton is the main cash crop and crop-livestock interactions are important. To analyse risk perception and suitability of on-farm options several data sources were combined: responses from individual surveys and focus group discussions, outputs from crop model simulations, long-term weather data and farmers' evaluations of on-farm trials and try-out fields. The research was embedded in an iterative participatory co-learning cycle that was carried out in six villages. The suitability of options was scanned for variability among farms as opportunities and constraints vary with the resource endowment of farms. Furthermore, as households are large, intrahousehold diversity may influence perceptions and risk management.

Chapter 2 described farmers' perception of risks and the management options they apply. A deeper understanding of how smallholder farmers perceive and manage risks is crucial to identify options that increase farmers' adaptive capacity. Information was gathered through focus group discussions and a survey with 250 people from 58 households. Farmers faced a diversity of risks, with hazards related to animal and personal health, and climate variability of highest concern. Within households, the differences in risk perception were mostly related to decision-power, not to gender. Household members with decision power worried most about risks. Between farms, differences in resource endowment were related to risk perception to a limited extent. Almost a quarter of described hazards occurred with a high frequency and led to a high impact on food availability and income. Low resource-endowed farms were more often exposed to high risks than other farm types. Farmers

applied a variety of actions to cope with hazards, yet in many cases farmers lacked a response. Generally, farmers managed risks by maintaining flexibility and diversity in the farm management which allowed them to react in the short-term when hazards happened. Farmers overcame losses by using productive assets, e.g. selling cattle, which could not be used anymore for farm investments. Medical actions were targeted to human and animal health hazards. Changes in field and animal management practices, adapted consumption rates and calls on social interactions, were combined for a diversity of hazards. By assessing the diversity of risks encountered by farmers and the diversity of risk management actions taken by farmers, this study goes beyond common risk research that focuses on a single hazard.

Chapter 3 quantified the frequency of the most relevant hazards and their impact on cereal production. Five most important (according to chapter 2) hazards were analysed: late onset of rains, insufficient total rainfall, dry spells, lack of access to fertiliser of good quality and sudden lack of labour. Cereal yield losses were calculated at field level under different management strategies: farmers' practice and optimised variety, fertiliser rates and sowing dates. The frequency and impact on yield of these hazards were assessed from simulation outputs combining a long-term weather database (1965-2019) with the DSSAT crop model. The prevalence of the weather hazards was common, with all of them occurring at least once every five years. Frequency of non-weather hazards were perceived to occur once every five years (labour hazards) and once every ten years (fertiliser hazards). Maize outperformed sorghum and millet, except when no N was applied. Maize responded relatively well to N application, and sorghum performed relatively well without added N. The benefit of millet resided in low yield variability, and its less sensitivity to the weather hazards. Changing management to optimise yields generally involved early sowing, increased N applications, and using short duration varieties. For millet the long duration variety was more beneficial. Increasing maize yields through management did not affect relative yield losses in case of hazards. Adapted millet management caused a trade-off between yield and hazard impact. Adapted sorghum management increased yield and mitigated hazard impacts simultaneously. The different interactions between hazards and management for the three cereals stressed the importance of maintaining farm diversity, as well as operational farm flexibility to respond to production risks.

Chapter 4 built on the same data to look at the potential of diversification at farm level. Modern Portfolio Theory (MPT) was used to evaluate the farm-level effects of diversified crop land allocation in dealing with weather variability. MPT is a tool frequently used in economic research to determine the variability and the mean expected return when two assets are combined, in order to assess the stabilisation benefit of diversification. We expressed the return in weighted farm-level yield, food (energy) and in economic terms. The assets that were combined on the farm land included different crops, varieties, and fertiliser rates of four main crops (maize, millet, sorghum, cotton). Cereal yields and variability were obtained from model simulation output (chapter 3). Cotton yields were observed in a long-term trial from 1965-1993. For each farm type the minimum food requirement to obtain food self-sufficiency at household level was calculated, as well as the minimum economic return to exceed the extreme poverty line. Allocating crop land to combinations of two assets had the potential to increase the farm-level stability and the combinations that diversified the crop component allowed for most stabilisation benefit (more than only diversifying varieties and fertilizer rates). Millet and sorghum contributed most to stability. Maize and cotton were important contributors to increased yields, energy and/or economic return. The combination of cotton and a cereal had a relatively strong stabilisation benefit, as cereals and cotton responded differently to weather conditions. Diversification strategies were constrained more by the income than by the food self-sufficiency thresholds for all farm types. For exceeding the poverty line farmers had to take risks and to target combinations with a high mean return and large variability. Crop production alone was not sufficient to provide a balanced livelihood, and diversification with other crops, livestock and/or complementation and other livelihood strategies would be essential.

In Chapter 5, I returned back to the farmers' level by analysing the choices that are made about sustainable intensification options, tailored to the local context. In a participatory co-learning process, on-farm trials were expanded with farmers' try-out fields where farmers implemented options at a larger scale on their own field without guidance from researchers. 538 on-farm trials were installed between 2012-2020, as well as 243 farmer 'try-out' fields between 2017-2020. All farm types were represented in the activities, but an age and gender gap existed among the participants, who were more often male and from the older segments of the population. Farmers defined the options they were keen to test: intercropping patterns, varieties of cereals and legumes, increased fertiliser rates, types and application, bio-pesticides, and relatively new crops such as soyabean. The options that were not explored further in the try-out fields were mainly those that demanded more labour or required more inputs (regardless of the potential benefits of increased input use (Chapter 3)). The iterative and adaptive experimentation and co-evaluation yielded a diversity of options farmers wanted to test and facilitated co-learning. Organising try-out fields with farmers in addition to classic agronomic trials contributed to refining the relevant options for farmers. Labour requirements appeared an important indicator in the choice of options, which was in line with the high concern for labour-related hazards (Chapter 2). Grain yield remained an important criterion for farmers in their choice of options, in addition to quality and quantity of fodder production for animal feed and taste.

Overall, risks were prevalent for farmers in Koutiala. Farmers valued diversity and flexibility of farm and field management. Maintaining a diversity of management strategies aimed to contribute to the adaptive capacity and resilience of farms to deal with hazards. For example, during the COVID-19 pandemic, which caused disruptions in the cotton value-chain, farmers appeared to maintain production levels by shifting between farm activities. In general, farmers were food self-sufficient, but had difficulty to exceed the poverty line. As resources were limited, and on-top of that productive assets were used to cover for losses, farmers did not have much room to invest. On-farm options need to be accompanied by institutional measures in the agronomic, market and health domain to strengthen a conducive socio-economic environment. Interventions should not focus on either agronomic or economic options separately, but combine both to strengthen well-being and agricultural production.

Résumé

Comment les risques influencent l'agriculture dans le sud du Mali

Les petits producteurs d'Afrique de l'Ouest sont confrontés à une diversité de risques liés à la production agricole, tant pour la production alimentaire que pour les revenus. Ces risques représentent l'impact négatif d'un aléa et la fréquence à laquelle il se produit. Ces deux éléments sont associés à l'incertitude, ce qui rend la gestion des risques difficile pour les agriculteurs. La variabilité climatique est une source de risque bien connue qui est prévu d'augmenter en raison du changement climatique. Cependant, les aléas sont divers et peuvent être liés à des facteurs biophysiques comme à des facteurs liés aux fluctuations du marché, des finances, de la législation ou des ressources humaines. La croissance démographique, la diminution des ressources naturelles et le changement climatique exercent une pression supplémentaire sur le système. Les agriculteurs ont souvent du mal à être autosuffisants sur le plan alimentaire et à échapper à la pauvreté.

L'objectif de cette thèse était de comprendre les stratégies mises en place par les agriculteurs pour faire face aux aléas d'un environnement variable. Un objectif parallèle était d'analyser quelles options d'intensification durable pourraient augmenter la productivité et/ou réduire les risques au sein du contexte socio-économique et biophysique. La thèse est structurée autour de quatre objectifs spécifiques : (1) analyser les risques perçus comme importants par les agriculteurs, comprendre comment cette perception varie entre les ménages et au sein même des ménages, ainsi qu'étudier comment les agriculteurs gèrent leur exploitation dans un environnement risqué ; (2) quantifier les pertes de rendement des cultures céréalières au niveau de la parcelle dues à différents aléas de production, en tenant compte de différentes stratégies de gestion ; (3) quantifier le potentiel d'atténuation de la variabilité de la production agricole par la diversification des cultures et des itinéraires techniques au niveau de l'exploitation agricole ; (4) apprendre comment les agriculteurs évaluent des essais qu'ils ont eux-mêmes conçus, et comment ce type d'essais peut être intégrés dans des projets de recherche participative en agriculture.

Les recherches se sont concentrées sur la région de Koutiala, dans le sud du Mali. Cette région se prête à l'étude des conditions agricoles difficiles en Afrique de l'Ouest. L'agriculture, et principalement la production de cultures, y est la principale source de nourriture et de revenus. Les céréales (maïs, le mil et le sorgho) sont cultivées pour la consommation alimentaire, et dans une moindre mesure, pour générer des revenus, tandis que le coton est purement une culture commerciale. De plus, les cultures et l'élevage sont fortement liés dans cette région. Pour analyser la perception des risques et l'adéquation des options à 'exploitation agricole, plusieurs sources de données ont été combinées. Cela inclut des réponses des enquêtes individuelles et des groupes de discussion, des résultats des simulations de modèles de cultures, des données météorologiques à long terme, ainsi que des évaluations des agriculteurs sur les essais agricoles. La recherche a été menée selon un processus itératif de co-apprentissage participatif dans six villages. J'ai pris en compte la variabilité entre les exploitations agricoles, car les opportunités et les contraintes diffèrent en fonction des ressources disponibles dans chaque exploitation. De plus, étant donné le grand nombre de ménages, la diversité au sein des ménages peut également influencer les perceptions et la gestion des risques. En intégrant

ces différentes sources de données et en considérant la diversité des exploitations agricoles, j’ai pu examiner la pertinence des options proposées pour faire face aux risques agricoles.

Dans le chapitre 2, je décris la perception des agriculteurs concernant les risques et les options de gestion qu'ils appliquent. Une compréhension approfondie de la façon dont les petits agriculteurs perçoivent et gèrent les risques est cruciale pour identifier les options qui augmentent leur capacité d'adaptation. Les données ont été recueillies dans le cadre de groupes de discussion ainsi que d’enquêtes auprès de 250 personnes, dans de 58 ménages. Les agriculteurs ont été confrontés à une diversité de risques, comprenant des aléas liés à la santé des animaux d’élevage et à leur propre santé, ainsi qu'à une préoccupante variabilité climatique. Au sein des ménages, les différences de perception des risques étaient principalement liées au pouvoir décisionnel, et non au genre. Les membres du ménage ayant le pouvoir de décision étaient les plus préoccupés par les risques. Entre les exploitations, les différences de dotation en ressources étaient liées à la perception des risques dans une mesure limitée. Près d'un quart des aléas décrits se produisaient fréquemment et avaient un impact élevé sur la disponibilité alimentaire et les revenus. Les exploitations agricoles disposant de peu de ressources étaient plus souvent exposées à des risques élevés que les autres types d'exploitations. Les agriculteurs mettaient en œuvre diverses actions pour faire face aux dangers, mais dans de nombreux cas, ils manquaient d'une réponse appropriée. Généralement, les agriculteurs géraient les risques en maintenant une flexibilité et une diversité dans la gestion de l'exploitation, ce qui leur permettait de réagir à court terme lorsque les aléas se produisaient. Les agriculteurs compensaient les pertes en utilisant des moyens de production, tels que la vente de bétail. Cependant, cela signifiait qu'ils n'étaient plus en mesure d'utiliser ces ressources pour investir dans leur exploitation agricole. Les mesures médicales étaient spécifiquement axées sur la gestion des risques sanitaires liés à la santé humaine et animale. Les changements dans la gestion de l’élevage et dans les itinéraires techniques, l’adaptation des taux de consommation et des interactions sociales (ou entraide) étaient combinés pour faire face à une diversité d’aléas. En évaluant la diversité des risques auxquels les agriculteurs sont confrontés et la variété des actions de gestion des risques qu'ils entreprennent, cette étude va au-delà des recherches classiques qui ne se concentrent que sur un seul aléa.

Le chapitre 3 quantifie la fréquence des aléas les plus importants et leur impact sur la production céréalière. Les cinq aléas les plus importants (selon le chapitre 2) ont été analysés : le début tardif des pluies, les précipitations insuffisantes, les périodes de sécheresse, le manque d'accès à des engrais de bonne qualité et les pénuries de main-d'œuvre. Les pertes de rendement des céréales ont été calculées à l’échelle des parcelles agricoles en fonction de différentes stratégies de gestion : les pratiques des agriculteurs contre une optimalisation des variétés, les taux d'engrais et les dates de semis. La fréquence et l'impact de ces aléas sur le rendement ont été évalués à partir des résultats de simulation combinant une base de données météorologiques à long terme (1965-2019) avec le modèle DSSAT. La fréquence des aléas météorologiques était forte, tous se produisant au moins une fois tous les cinq ans. La fréquence des aléas liés à la main-d'œuvre était perçue comme se produisant une fois tous les cinq ans, et celle des aléas liés aux engrais une fois tous les dix ans. Le rendement en maïs surpassait le sorgho et le mil, sauf en l'absence de fertilisation azotée. Le maïs répondait relativement bien à l'application d'azote, tandis que le sorgho se comportait relativement bien sans ajout d'azote. L'avantage du mil résidait dans sa faible variabilité de rendement et sa capacité à être peu sensible aux aléas météorologiques. Pour optimiser les rendements, les changement d'itinéraires techniques impliquait généralement un semis précoce, une augmentation des applications d'azote et l'utilisation de variétés à courte durée de croissance. Dans le cas du mil, la variété à longue durée avait un plus haut rendement. L'augmentation des rendements du maïs grâce à la l'adaptation de l'itinéraire technique n'a pas affecté les pertes relatives de rendement en cas d'aléas. La gestion adaptée du mil a entraîné un compromis entre le rendement et l'impact des aléas alors que gestion adaptée du sorgho a augmenté le rendement et a atténué simultanément les impacts des aléas. Les différentes interactions entre les aléas et la gestion pour les trois céréales soulignent l'importance de maintenir un diversité de culture au sein des exploitations, ainsi que la flexibilité opérationnelle des exploitations pour faire face aux risques de production.

Le chapitre 4 s'appuie sur ces mêmes données pour examiner le potentiel de la diversification au niveau de l'exploitation. La théorie moderne du portefeuille (TMP) a été utilisée pour évaluer les effets au niveau de l'exploitation d'une allocation diversifiée des terres cultivées pour faire face à la variabilité climatique. La TMP est un outil fréquemment utilisé dans la recherche économique pour déterminer la variabilité et le retour moyen attendu lors de la combinaison de deux actifs, afin d'évaluer les avantages de la diversification en termes de stabilité. Dans cette étude, nous avons exprimé le taux de retour en fonction de la production de cultures pondérés au niveau de l'exploitation, les rendements calorifiques liés à l'alimentation et des retombés économiques. Les actifs combinés sur les terres comprenaient différentes variétés et taux d'engrais de quatre cultures principales (maïs, mil, sorgho, coton). Les données de rendements des cultures céréalières et leur variabilité ont été obtenus à partir des résultats de simulation du modèle développé dans le chapitre 3. Les résultats d'un essai à long terme de 1965 à 1993 ont été utilisées pour obtenir les rendements en coton. Pour chaque type d'exploitation agricole, les besoins alimentaires minimums nécessaires pour l'autosuffisance alimentaire des ménages ont été calculés, ainsi que le rendement économique minimum permettant de dépasser le seuil d'extrême pauvreté. En allouant les terres cultivées avec deux itinéraires techniques, il était possible d'accroître la stabilité du retour au niveau de l'exploitation. Les combinaisons qui diversifiaient les cultures apportaient le plus de stabilité, plus que la simple diversification des variétés utilisées ou des taux d'engrais. Le millet et le sorgho contribuaient le plus à la stabilité. Le maïs et le coton contribuaient surtout à l'augmentation des rendements en grain, du rendement calorifique, et/ou des revenus économique. La combinaison de coton et d'une céréale présentait un avantage de stabilisation relativement fort, car les céréales et le coton réagissaient différemment aux conditions météorologiques. Les stratégies de diversification étaient plus contraintes par le revenu que par les seuils d'autosuffisance alimentaire pour tous les types d'exploitation agricole. Pour dépasser le seuil de pauvreté, les agriculteurs devaient prendre des risques et cibler des combinaisons avec un rendement moyen élevé et une grande variabilité. La production agricole seule (de maïs, millet, sorgho, coton) n'était pas suffisante pour assurer des moyens de subsistance équilibrés, et la diversification avec du bétail, d'autres cultures végétales, et/ou d'autres stratégies de moyens de subsistance serait essentielle.

Au chapitre 5, je suis revenu à l'échelle des agriculteurs en analysant les choix qui sont fait concernant les options d'intensification agricole durable, adaptées au contexte local. Dans le cadre

processus itératif et participatif de co-apprentissage deux types des essais ont été mis en place : des essais conçu par des chercheurs (essai agronomique classique), étendu avec des essais que les agriculteurs ont eux-mêmes conçus et gérés (try-out). Ces derniers ont donné aux producteurs l'espace pour mettre en place, a plus grande échelle, différentes options sur leurs propres terrains, sans être guidés par des chercheurs. Entre 2012 et 2020, 538 essais à la ferme ont été réalisés, et entre 2017 et 2020, 243 parcelles try-out ont été implémentées. Tous les types d'exploitation agricole étaient représentés dans ces activités. Cependant, les agriculteurs de genre masculin, issus des segments plus âgés de la population étaient représentés de manière plus importante. Les agriculteurs ont défini eux-mêmes les options qu'ils souhaitaient de mettre en place/tester dans les essais classiques: les schémas d'interculture, les variétés de céréales et de légumineuses tel que le soja (relativement nouveau pour la région), les taux d'engrais, les types et les modes d'application d'intrants, les bio-pesticides. Les options qui n'ont pas été explorées davantage dans les try-outs étaient principalement celles qui exigeaient plus de travail ou nécessitaient plus d'intrants (indépendamment des avantages potentiels d'une utilisation accrue des intrants (chapitre 3). L'expérimentation itérative et adaptative ainsi que la co-évaluation ont permis d'obtenir une diversité d'options que les agriculteurs souhaitaient tester et ont facilité le co-apprentissage. L'évaluation de parcelles d'essai gérées par agriculteurs, en plus des essais agronomiques classiques, a contribué à affiner les options pertinentes pour les agriculteurs. Les exigences en termes de main-d'œuvre sont apparues comme un indicateur important dans le choix des options, ce qui était conforme à la préoccupation élevée pour les aléas liés au travail (chapitre 2). Le rendement en grains restait un critère important pour les agriculteurs dans leur choix d'options, en plus de la qualité et de la quantité de la production de fourrage pour l'alimentation animale et du goût.

Dans l'ensemble, les risques étaient prévalent pour les agriculteurs de Koutiala. Les agriculteurs valorisaient la diversité et la flexibilité de la gestion des exploitations et des champs. Le maintien d'une diversité de stratégies de gestion visait à contribuer à la capacité d'adaptation et à la résilience des exploitations agricoles face aux aléas. Par exemple, pendant la pandémie de COVID-19, qui a entraîné des perturbations dans la chaîne de valeur du coton, les agriculteurs semblaient maintenir les niveaux de production en passant d'une activité agricole à une autre. En général, les agriculteurs étaient autosuffisants en termes d'alimentation, mais avaient des difficultés à dépasser le seuil de pauvreté. Les ressources étaient limitées et, de surcroît, les moyens productifs étaient utilisés pour compenser les pertes, limitaient par la suite les possibilités d'investissement. L'implémentation d'options à l'échelle de l'exploitation agricole doit être accompagnées de mesures institutionnelles dans les domaines agronomique, économique et sanitaire pour favoriser un environnement socio-économique favorable. Les interventions ne devraient pas se concentrer uniquement sur les options agronomiques ou économiques, mais combiner les deux pour contribuer à l'intensification durable de la production agricole et l'amélioration du niveau de vie des ménages

Samenvatting

Hoe landbouw in Zuid-Mali beïnvloed wordt door risico's

Kleinschalige boeren in West-Afrika worden uitgedaagd in zowel hun voedselproductie als hun inkomen door een verscheidenheid van landbouwrisico's. Het concept risico vertegenwoordigt de negatieve impact van een gevaarlijke gebeurtenis, en de frequentie waarmee deze gebeurtenis voorkomt. Beide elementen (impact en frequentie) dragen een onzekerheid in zich, wat resulteert in moeilijkheden voor boeren om risico's te beheersen. Klimaatvariabiliteit is een gekende bron van risico's. Zulke risico's zullen naar verwachting toenemen ten gevolgen van de klimaatsverandering. De landbouwrisico's zijn echter divers en kunnen hun oorsprong vinden in veranderingen van biofysische, markt-, financiële, legale en menselijke omstandigheden. Voortdurende bevolkingsaangroei, afnemende kwaliteit van natuurlijke hulpbronnen en klimaatsverandering zetten verdere druk op het systeem. Boeren worstelen vaak om zelfvoorzienend te zijn in voedsel, en om aan armoede te ontsnappen.

Met deze thesis wilde ik een poging doen om te begrijpen welke strategieën de boeren aanwenden om met een risicovolle omgeving om te gaan. Parallel hieraan maakte ik een analyse van mogelijke duurzame intensiveringsopties die de productiviteit kunnen verhogen en/of risico's kunnen verminderen binnen de sociaal-economische en biofysische context. Deze thesis is opgebouwd rond vier specifieke richtpunten: (1) analyseren welke risico's boeren als belangrijk beschouwen; hoe deze perceptie verschilt tussen en binnen huishoudens; alsook hoe boeren hun bedrijf beheren in zulke risicovolle context; (2) het kwantificeren van oogstverliezen op veldniveau van graangewassen ten gevolge van de interacties tussen risico's en het toegepaste veldbeheer; (3) het kwantificeren van het potentieel om de productievariabiliteit te verminderen door het diversifiëren van de gewassen en hun beheer op bedrijfsniveau; en tenslotte (4) het leren hoe door boeren ontworpen proefvelden (try-outs) worden geëvalueerd door boeren en hoe ze opgenomen kunnen worden in landbouwkundige participatieve projecten.

Mijn focus lag op de regio van Koutiala, Zuid-Mali, als een representatief gebied voor de uitdagende West-Afrikaanse landbouwomgeving. Landbouw, en dan vooral gewasproductie, is de voornaamste bron van voedsel en inkomen. Graangewassen als maïs, sorghum, en millet worden voornamelijk verbouwd voor consumptie, maar daarnaast ook om te verkopen. Katoen is het belangrijkste commerciële gewas. De wisselwerkingen tussen vee- en gewasteelt zijn essentieel in het systeem. Om de perceptie van risico's en de geschiktheid van beheersopties te analyseren, werden databronnen gecombineerd: antwoorden van individuele interviews, alsook groepsdiscussies, resultaten van simulaties met een gewasmodel, lange-termijn weersgegevens en evaluaties van boerderij-experimenten en try-outs. Het onderzoek was ingebed in een iteratieve en participatieve co-learning cyclus die werd uitgevoerd in zes dorpen. De geschiktheid van opties werd belicht voor de variabiliteit tussen boerderijen, aangezien kansen en beperkingen variëren met de beschikbare middelen van het type boerderij. Aangezien de huishoudens groot zijn, kan de diversiteit binnen huishoudens bovendien ook de individuele perceptie en beheer van risico's beïnvloeden.

Hoofdstuk 2 beschrijft de risicoperceptie van boeren, alsook het beheer dat zij toepassen. Een breder begrip van risicoperceptie en -beheer is cruciaal om geschikte opties te identificeren die bijdragen aan het aanpassingsvermogen van boeren. Enquêtes werden afgenomen bij 250 mensen uit 58 huishoudens. Die informatie werd aangevuld met discussies in groep. Hieruit bleek dat boeren verschillende soorten risico's liepen, waarbij de gevaren met betrekking tot de persoonlijke gezondheid van familieleden, en daarnaast die van hun dieren tot hun grootste zorg behoorden. Binnen huishoudens waren de verschillen in perceptie gerelateerd aan de beslissingsmacht van het familielid, en niet zozeer gendergerelateerd. Familieleden met beslissingsbevoegdheid maakten zich meer zorgen over risico's. De verschillen tussen boerderijen waren tot een beperkte hoogte gerelateerd tot hun beschikbare hulpbronnen. Ongeveer een vierde van de beschreven gevaren kwam voor met een hoge frequentie en leidde tot een hoge impact op de voedselbeschikbaarheid en inkomen. Boerderijen met weinig middelen waren vaker blootgesteld aan grote risico's dan andere types boerderijen. Boeren pasten een verscheidenheid aan maatregelen toe om met gevaren om te gaan, maar in veel gevallen ontbrak een reactie. Over het algemeen beheerden boeren risico's door flexibiliteit en diversiteit in het bedrijfsbeheer te behouden. Zo konden ze op korte termijn reageren wanneer zich een gevaar voordeed. De verliezen werden overwonnen door het inzetten van productieve activa, zoals bijvoorbeeld het verkopen van vee, waardoor deze hulpbronnen niet meer ingezet konden worden om te investeren. Medische maatregelen waren gericht op de gezondheidsrisico's voor mens en dier. Voor andere risico's werden maatregelen gecombineerd door onder andere het veld- en veebeheer aan te passen, consumptie te beperken, en in te zetten op sociale interacties. Dit onderzoek gaat verder dan het gangbare risico-onderzoek dat zich vaak focust op een enkel gevaar, doordat het de brede diversiteit in acht neemt van de zowel de beheersmaatregelen als de risico's waarmee boeren geconfronteerd werden.

In hoofdstuk 3 werd de frequentie en impact van de meest relevante risico's voor gewasproductie gekwantificeerd. De vijf belangrijkste gevaren (volgens hoofdstuk 2) werden geanalyseerd: een late start van de regen, onvoldoende regenval, droge periodes, het gebrek aan toegang tot kwalitatieve meststoffen en een plots gebrek aan arbeidskracht. Het verlies van de graanopbrengst werd berekend op veldniveau onder verschillende beheerstrategieën: de meest gangbare praktijk van boeren werd vergeleken met het gebruik van optimale variëteiten, meststofdoseringen en zaaidata. De frequentie en impact van de risico's werden beoordeeld aan de hand van een simulatie van oogstgegevens waarbij lange termijn weersdata (1965-2019) werd gecombineerd met het DSSAT gewasmodel. De gevaarlijke weersomstandigheden kwamen minstens één maal in de vijf jaar voor. De prevalentie van de andere risico's werd waargenomen als een keer per vijf jaar voor plotse tekorten van werkkrachten en een keer in de tien jaar voor onvoldoende toegang tot meststof. Over het algemeen presteerde maïs beter dan sorghum en millet, behalve wanneer er geen stikstof werd toegevoegd aan de bodem. Maïs reageerde relatief goed op stikstoftoevoeging, terwijl sorghum relatief goed presteerde zonder toegevoegde stikstof. Het telen van millet was voordelig doordat de opbrengst weinig variabel was en het een lage gevoeligheid voor negatieve weersomstandigheden had. Het veranderen van het beheer optimaliseerde de gemiddelde opbrengst over het algemeen door vroeg te zaaien, stikstoftoevoeging te verhogen en een variëteit met een korte cyclus te gebruiken. Enkel bij millet bleek de variëteit met een langere cyclus voordelig. Beheeraanpassingen om de maïsopbrengst te verhogen hadden geen invloed op het relatieve verlies in het geval een risico zich voordeed. Een aangepast beheer van millet zorgde voor een trade-off tussen een hogere gemiddelde opbrengst en grotere relatieve verliezen in het geval van risicovolle gebeurtenissen. Aangepast beheer van sorghum verhoogde de opbrengst en mitigeerde de gevaren. De verschillende interacties voor de drie graangewassen tussen de reactie op risico's en het beheer, benadrukte het belang van het behoud van diversiteit, evenals operationele flexibiliteit om te kunnen reageren op risico's.

Hoofdstuk 4 bouwt voort op bovenstaande gegevens, en keek naar de potentie van diversificatie op boerderijniveau. Modern Portfolio Theory (MPT) werd gebruikt om de invloed van weersevaluatie op de totale productie te evalueren wanneer combinaties van gewassen (en beheer) worden toegewezen aan het land. MPT is een veelgebruikte tool in economisch onderzoek om het stabiliserend voordeel en het gemiddelde rendement te bepalen wanneer twee of meer investeringen worden gecombineerd. Het rendement werd uitgedrukt als de gewogen opbrengst op bedrijfsniveau in graangewicht, voedsel (energie) en in economische termen. De combinaties in landbeheer omvatten verschillende gewassen (maïs, sorghum, millet en katoen), bemestingsniveaus en variëteiten. De resultaten van de DSSAT simulaties (Hoofdstuk 3) werden gebruikt om de jaarlijkse opbrengst en risico's van verschillende combinaties van graangewassen in te schatten. De katoenopbrengsten werden waargenomen in een langdurige veldproef tussen 1965 en 1993. Voor elk type boerderij werd de minimale voedselproductie berekend om zelfvoorzienend te kunnen zijn, evenals het minimale economische rendement nodig om de extreme armoedegrens te overschrijden. Het toewijzen van het land aan combinaties van twee soorten veldbeheer had het potentieel om de stabiliteit in productie te vergroten. De combinaties van twee verschillende gewassen bracht meer stabiliteitsvoordeel ten opzichte van wanneer enkel het beheer (van hetzelfde gewas) werd gediversifieerd. Millet en sorghum droegen meer bij tot stabiliteit. Maïs en katoen daarentegen leverden een belangrijke bijdrage aan hogere opbrengsten, energie en/of het economische rendement. De combinatie van katoen met een graansoort had een relatief sterk stabiliserend voordeel, aangezien granen en katoen verschillend reageren op weersomstandigheden. Geschikte combinaties werden beperkt door de inkomensvereiste, meer dan door de voedselvoorziening. Om aan de armoedegrens te voldoen zouden boeren risico's moeten nemen en zich richten op combinaties met een hoog gemiddeld rendement en een hoge variabiliteit. Daarom, gewasproductie (van graan en katoen) op zichzelf was niet voldoende om een evenwichtig levensonderhoud aan te bieden. Diversificatie met andere gewassen, vee of een aanvulling met ander inkomensactivititeiten zouden essentieel zijn.

In hoofdstuk 5 keerde ik terug naar het niveau van de individuele boer door zijn keuzes te analyseren in verband met intensiveringsopties aangepast aan de lokale context. In een participatief proces van co-learning werden veldproeven op de boerderij (door wetenschappers uitgetekend) uitgebreid met try-outs. Dit waren proefvelden waar boeren opties op grotere schaal op hun eigen veld implementeerden zonder begeleiding van onderzoekers. Tussen 2012-2020 werden 538 proefvelden op boerderijen geïnstalleerd, evenals 234 try-outs tussen 2017-2020. Alle bedrijfstypes waren vertegenwoordigd hierin, maar er bestond een leeftijds- en genderkloof onder de deelnemers. Deze deelnemers waren vaker mannelijk en uit de oudere segmenten van de bevolking. Boeren definieerden de opties die ze graag wilden testen: mengteelt, andere variëteiten van granen en peulvruchten, hogere bemestingsniveaus, -types en -toepassingen, bio pesticiden en relatief nieuwe gewassen voor de regio zoals sojabonen. In de try-outs werden niet alle opties verder verkend, voornamelijk deze die meer arbeid of inputs vereisten (ongeacht de potentiële oogstvoordelen). De iteratieve en adaptieve experimenten en co-evaluatie leverden een diversiteit aan opties op die boeren wilden testen en faciliteerden co-learning. Het organiseren van try-outs naast de meer klassieke agronomische proeven, droeg bij aan het verfijnen van relevante opties voor boeren. Arbeidsvereiste bleek een belangrijke indicator in de keuze van opties, wat strookt met de bezorgdheid van boeren voor arbeidsgerelateerde risico's (Hoofdstuk 2). Ook graanopbrengst bleef een belangrijk criterium voor boeren in hun keuze van opties, naast de kwaliteit en kwantiteit van de veevoederproductie en de smaak.

Globaal gezien, werden boeren in Koutiala blootgesteld aan vele risico's. Boeren waardeerden diversiteit en flexibiliteit van boerderij- en veldbeheer. Het in stand houden van en diversiteit in beheerstrategieën veronderstelt bij te dragen aan het aanpassingsvermogen en de veerkracht van landbouwbedrijven om met risico's om te gaan. Tijdens de COVID-19 pandemie bijvoorbeeld werd de katoen waardeketen verstoord en leken boeren hun productieniveaus op peil te houden door tussen verschillende bedrijfsactiviteiten te schakelen. Over het algemeen slaagden boeren erin om zelfvoorzienend te zijn in voedselproductie, maar hadden ze moeite om de armoedegrens te overschrijden. Aangezien hun middelen beperkt zijn, en bovendien hulpbronnen werden ingezet om verliezen door risico's te dekken, hadden boeren niet veel ruimte om te investeren. Bedrijfsopties moeten vergezeld gaan van institutionele maatregelen op agronomisch, markt- en gezondheidsgebied om een gunstig sociaal-economisch klimaat te versterken. Interventies moeten zich niet richten op ofwel agronomische ofwel economische opties afzonderlijk, maar gecombineerd om het welzijn en landbouwproductie te versterken.

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This thesis was centred around agricultural risk management. Yet, I also had to conduct personal risk assessments to be able to visit Mali as well prepared and safe as possible. I would like to thank colleagues as well as strangers, who took the time to share information and advice, whether it was officially or informal. For Mali, I hope times will get better.

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About the author

Eva grew up in the Pampa, in the quiet countryside in the north of Belgium. She studied Bioscience Engineering at the KULeuven, specialising in Forestry and Nature Management as well as Tropical Agriculture. In her MSc thesis, she analysed the relation between maize management, production, and the socio-economic status of farmers in the savannah of central Togo. After graduation in 2008, she went to Guatemala to visit family and to keep exploring smallholder agriculture. There, she got the opportunity to visit several villages with the NGO ADICI Wakliiqo to evaluate sustainable production of amaranth and cacao.

Her first job was with Vlaamse Landmaatschappij (VLM), targeting the strengthening of different functions of a landscape, for example, the integration of nature, tourism, agriculture, and other ecosystem services. Afterwards, she worked on bilateral and multilateral development cooperation projects on land use management, with a strong focus on learning and capacity building. First for Enabel in the Andes of Peru, working together with MINAM (the Ministry of Environment). Later as an M&E officer at the Technical Centre for Agricultural and Rural Cooperation between EU and the ACP countries (CTA), which led her to Wageningen. At the end of 2016, she embarked on a PhD journey at the Plant Production Systems (PPS) Group, from which she had once found inspiration during her MSc thesis. Parallel to the last phases of her PhD, she started to work as an agricultural advisor for the Royal Tropical Institute (KIT) in Amsterdam, focusing on seed sector development in Mali, Niger and South Sudan.

Her interests have always been on the frontier of agricultural, environmental and socio-economic challenges. Besides that, she loves hiking and drawing.

List of publications

Peer reviewed journal articles

Huet, E.K., Adam, M., Giller, K.E., Descheemaeker, K. (Under Review). Knowledge, productivity, diversification: Drivers of farmers' choices of sustainable intensification options in participatory co-learning cycles.

Huet, E.K., Adam, M., Traore, B., Giller, K.E., Descheemaeker, K. (2022). Coping with cereal production risks due to the vagaries of weather, labour shortages and input markets through management in southern Mali. European Journal of Agronomy, 140.

Huet, E.K., Adam, M., Giller, K.E., Descheemaeker, K. (2020). Diversity in perception and management of farming risks in southern Mali. Agricultural Systems, 184.

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Descheemaeker, K., **Huet, E.K.**, Dissa, A., Sanogo, O., Dembele, , O., Doumbia, S., Falconnier, G.N., Adam, M., Giller, K.E. (2021). Farmer research networks for co-designing agro-ecological intensification options in crop-livestock systems of southern Mali. 7th International symposium for Farming System Design, 20-23 March 2021.

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Huet, E.K., Adam, M., Giller, K., Traore, B., Coulibaly, S., Descheemaeker, K. (2019). Risk perception and management strategies in farming systems of southern Mali. 6th International Symposium for Farming Systems Design, 18-21 August 2019, Montevideo, Uruguay.

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Huet, E.K., Descheemaeker, K., Adam, M., Dembélé, O., Giller, K. (2018). Co-learning Through Agronomic Experiments with Farmers: Tailoring Agroecological Intensification to the Context of Southern Mali. 15th European Society for Agronomy Congress, Geneva, Switzerland.

Other

Huet, E.K. (2021, November 2021). Boeren in Mali zetten in op diversiteit. Ekoland, 2.

PE&RC Training and Education Statement

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/project proposal (4.5 ECTS)

- Farmers' choices in applying agroecological intensification options in the light of farming risk in southern Mali

Post-graduate courses (5.9 ECTS)

- Introduction to R for statistical analysis; PE&RC (2017)
- Design of experiments; PE&RC, WIAS (2017)
- Farming systems and rural livelihoods; PPS (2018)
- Basic statistics; PE&RC, SENSE (2018)

Invited review of journal manuscripts (1 ECTS)

- Agricultural Systems: participatory evaluation of on-farm innovations in in West-Africa (2020)

Deficiency, refresh, brush-up courses (6 ECTS)

- Quantitative analysis land use systems; PPS (2017)

Competence, skills and career-oriented activities (6.6 ECTS)

- Basic safety and security: hostile environment awareness training; Centre for Safety and Development (2017)
- Competence assessment; WGS (2017)
- Essentials of scientific writing and presenting; Wageningen In'to Languages (2018)
- PhD Masterclass challenges of fieldwork in high tension environments; WASS (2018)
- Project and time management; WGS (2019)
- Ethics for social sciences research; WASS (2019)
- Career assessment; WGS (2019)
- Scientific writing; Wageningen In'to Languages (2020)

PE&RC Annual meetings, seminars and PE&RC weekend/retreat (1.35 ECTS)

- PE&RC First years weekend (2017)
- PE&RC Carrousel (2019)
- PE&RC Last years weekend; online (2020)

Discussion groups/local seminars or scientific meetings (5.4 ECTS)

- Sustainable intensification of agricultural systems; Wageningen, the Netherlands (2016-2017)
- Annual project meetings and CCRP field visits: pathways to agroecological intensification in southern Mali; Koutiala, Mali (2017-2020)
- Africa rising planning and review meeting; Accra, Ghana (2019)
- Annual meeting of the west Africa community of practice of the McKnight collaborative crop research programme; Bamako, Mali (2019)

International symposia, workshops and conferences (4.1 ECTS)

- European society for agronomy conference; poster presentation; Geneva, Switzerland (2018)
- Farming systems design conference; oral presentation; Montevideo, Uruguay (2019)

Societally relevant exposure (0.3 ECTS)

- Boeren zetten in op diversiteit; Ekoland magazine (2021)

Lecturing/supervision of practicals/tutorials (4 ECTS)

- Supervising farm modelling practical (2018-2020)

BSc/MSc thesis supervision (6 ECTS)

- Potential of crop-livestock integration for agroecological intensification of mixed systems in southern Mali
- Exploring effective diversification strategies for agricultural risk reduction in southern Mali

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