Beyond Intensification: landscapes and livelihoods in Mali's Guinea Savannah

Mary H. Ollenburger

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Invitation

You are cordially invited to attend the defense of the PhD Thesis entitled:

Beyond Intensification: landscapes and livelihoods in Mali's Guinea Savannah

on Monday 15 April 2019 at 11 a. m. in the Aula of Wageningen University Generaal Foulkesweg 1a, Wageningen.

The ceremony will be followed by a reception in the Aula.

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Propositions

1. Since maize is not profitable in the USA, where yields are the highest in the world, claims that increased productivity will reduce poverty among smallholder farmers are disingenuous.
(this thesis)

2. Access to affordable fertilizer helps farmers maintain soil fertility in existing fields, reducing the need to clear new land.
(this thesis)

3. Research is not “more scientific” just because it involves more complicated math.

4. If you can’t measure what’s important, don’t try to make what you can measure into something important.

5. “Research for Development” requires skills more often taught to engineers than to scientists.

6. Researchers have ethical responsibilities to farmers they work with: “First, do no harm.”

7. It is impossible to do good agricultural research from behind a desk.

8. Dogma belongs in theology not agronomy.

Propositions belonging to the thesis, entitled

Beyond intensification: landscapes and livelihoods in Mali’s Guinea Savannah

Mary Helena Ollenburger
Wageningen, 15 April 2019

Beyond Intensification: landscapes and livelihoods in Mali's Guinea Savannah

Mary H. Ollenburger

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Thesis

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Abstract

For more than a decade, sub-Saharan Africa has been the focus of calls for a new Green Revolution. Like its predecessor, the African Green Revolution aims to increase the productivity of smallholder farmers, improving their own food security and income as well as that of the continent as a whole. This is to be done with minimum environmental damage, through "sustainable intensification." While sustainable intensification has shown potential in places where high population density precludes cropland expansion, evidence of its effectiveness in land-abundant, labor-limited areas is limited. One such land-abundant, labor-limited area is the Guinea Savannah region of West Africa, which the World Bank called a "Sleeping Giant" where agricultural development could drive economic growth both locally and at the national level. Within the Guinea Savannah region, we use southern Mali's Bougouni district as a case study to explore potential futures for smallholder agriculture in the area.

We explored the history of the area's agriculture using a panel data set for three villages, as well as remote sensing analysis and census data. Over the period of the panel data (1994-2012), agricultural change was minor. Cultivated area per household was highly correlated with household size and the number of draft animals a household owned. This relationship remained constant over the full period, suggesting little change in labor productivity. Yields of major crops remained stagnant, even as fertilizer input increased. Cropland expansion occurred in parallel with population growth, but up to the present, over half the arable land in the study villages was not cultivated.

Because uncultivated rangeland made up such a large percentage of the land, we characterized the productivity, management and use of these rangelands (Chapter 3). In two villages, we assessed biomass quantity and species composition at 2-month intervals, tracked a sample of village herds, and used remote sensing combined with regression analysis to map the productivity of herbaceous biomass in a woody savannah landscape. We found that rangelands produced a seasonal peak of 2-2.5 t/ha of herbaceous biomass, from a diverse mix of annual and perennial species, notably Andropogon gayanus and A. pseudapricus. Herds covered distances of 10-18 km each day, with distance and location variable based on the season. During most of the year, the forage supply far exceeded the demands of grazing herds, but in the late dry season forage becomes scarce and herders supplement grazing with cut tree fodders, or send herds on transhumance to the south. While rangelands are exploited for a variety of uses, local management has thus far maintained high levels of productivity and biodiversity.

In order to evaluate the potential of sustainable intensification to meet its goals of reducing poverty and improving food security, we explored the solution space of possible gains from intensification for farm households in three villages. With yields equivalent to the best farmers yields in the area, over 90% of households can achieve food self-sufficiency, and most can raise income levels above the threshold for extreme poverty. Reaching attainable yield levels, equal to those obtained in on-station trials, improved the picture further. However, agriculture must compete with other income generating options, which can be considerably more profitable. The average annual income for a gold miner in the area was $1225. Even at attainable yield levels, only 25% of households in the study villages could earn higher per capita incomes from their current cropped area. If we consider options beyond intensification, we find that expanding cultivated land area can

increase this fraction to 59%, while also timing crop sales to correspond to peak price points allows over 90% of households to earn more from agriculture than the average gold mining income. Dairy production has potential to provide high income to a few households with large herds, but would require large investments in infrastructure and improved market access. Production of small ruminants for meat, particularly rams sold at peak holiday prices, could raise incomes for a larger number of households, because initial costs are modest. While small ruminant production does not require the complex infrastructure of dairy marketing, current production potential is limited by a lack of veterinary services and limited market access.

Because of the limited gains from intensification, new options are needed for land-abundant, labor-constrained farming systems like those in southern Mali. We worked with local farmers in two villages to develop and analyze future scenarios. Scenarios were based on key drivers farmers identified: tractor availability and increased cashew production. These were explored further by developing a game in which the board represented the village territory, and players with varying initial assets could make decisions about planting trees, purchasing or renting tractors, and clearing new land. The agent-based model Mali-sene (Multi-agent land-use and intensification socio-ecological niche exploration) simulated behavior seen in the land use game, and was used to explore a wider range of scenarios, with different rates of tree planting as well as access to tractor rental and purchase. Scenarios with extensive tree planting resulted in high rates of land conversion, with the majority of cultivated land in tree plantations, and resulted in incomes of up to $1600 per capita. Scenarios where tractor rental was available but tree planting was minimal resulted in somewhat lower rates of land conversion, but converted land was planted to annual staple crops, while tractor rental without the introduction of cashew increased annual incomes to $400 per capita, still twice the initial value. It seems clear that cropland expansion is highly likely to occur in this area, and preventing expansion comes at a real cost to local farmers. Tractor availability and cashew planting both led to land conversion, but the environmental impacts of cashew, as a perennial tree crop, are likely to be lower than the impacts of annual staples. A holistic evaluation of sustainability that considers farmer livelihoods might therefore conclude that expansion is as sustainable as intensification.

The process of developing agricultural technology innovations in sub-Saharan Africa is generally led by scientists, but has many commonalities with engineering and product design methodologies. Increased attention to the steps in this process, from problem definition to developing design specifications to testing possible solutions, could help research for development projects develop more relevant technical solutions for farmers.

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Introduction

Background

Over the past decade, concerns over food price spikes, climate change, and rapid population growth have led to a renewed interest in agriculture and agricultural research (Giller et al. 2017). Institutions from the World Bank to the African Union to the Gates Foundation are investing in agriculture and agricultural research, promoting a new African Green Revolution as a means to both improve food security and to reduce poverty. These are large-scale strategic challenges, but the changes in agricultural practice needed to meet those goals are implemented in large part by African smallholder farmers. These farmers make decisions not based on global considerations, but on local and personal ones—the amount of land and labor they have available, their access to markets and to credit, and their own goals and priorities. It is by no means clear that the priorities of farmers will be compatible with the large-scale objectives of development institutions, donors, or the state.

In this thesis, the district of Bougouni, in southern Mali's Guinea Savannah, serves as a case study in the implementation of the African Green Revolution. I look at agriculture at the scale not of a continent but of households and villages, not as an isolated activity but as part of a set of livelihood strategies. Programs for achieving the strategic goals of sustainability, increased food production, and poverty reduction have promoted a set of sustainable intensification practices, while farmers themselves identify their own objectives and livelihood strategies for meeting them. The following chapters explore where farmer objectives and agricultural development strategy run in parallel and where they diverge, and what that implies for agricultural research.

The first Green Revolution succeeded in massively increasing food production, particularly in India and Southeast Asia. Green Revolution breeders developed widely adapted varieties that could be introduced to farmers across a range of agroecologies and social contexts (Baranski 2015). These new varieties were promoted alongside a package of agricultural practices, which was supported by subsidies and other policy support. The Green Revolution was highly beneficial to farmers in productive regions, who had access to the fertilizer, irrigation, and other components that made the new hybrids successful, and the resulting improvement in food security in the region helped spur more widespread economic growth (Sastry et al. 2003). However, many poorer farmers did not see the benefits of improved technologies. In some cases their land was degraded or unsuitable for irrigation, in others they were unable to access the package of inputs required to make the Green Revolution seeds productive. The new technologies thus increased rural inequality (Pingali 2012). In Africa, where state support to agriculture was limited and irrigated land was scarce, both ecological and socioeconomic conditions were incompatible with the Green Revolution. Yields stagnated over the second half of the 20th century (Mwangi 1996).

It was in acknowledgement of the limitations of the first Green Revolution that Kofi Annan, former UN Secretary-General called for a new "African Green Revolution" (Annan 2004). This African Green Revolution was to be more inclusive, more environmentally friendly, and more holistic in scope—considering not only agricultural production systems but also agricultural markets and financial systems (AGRA 2017). In response, donors including the Gates Foundation and Rockefeller Foundation (one of the forces behind the first Green Revolution), as well as bilateral and multilateral aid agencies, formed the Alliance for a Green Revolution in Africa in 2006. AGRA has as its aim "Putting the smallholder farmer at the center of the continent's growing economy" (AGRA 2017).

The first Green Revolution dramatically increased the use of fertilizer and pesticides, leading to criticism on environmental grounds. The new Green Revolution sought, therefore, to be more sustainable than its predecessor. This was to be done through the "sustainable intensification" of agriculture. While arguments continue over the definition of the term, as do efforts to change the phrasing (agro-ecological intensification, etc.), definitions the general idea that agriculture should maintain or improve its productivity while maintaining or its environmental impact (Petersen and Snapp 2015). In industrial agricultural systems, the focus is on maintaining productivity while decreasing use of inputs like irrigation water and N fertilizer through precision agriculture (Cassman 1999). In smallholder farming systems, sustainable intensification generally focuses on increasing yields per unit area, through efficient use of external inputs and improved on-farm nutrient cycling (Vanlauwe et al. 2014).

Food production worldwide will need to increase to accommodate increasing population and the added demand for animal products from the growing middle class (Tilman et al. 2011). At the same time, agriculture's adverse environmental impacts, including groundwater depletion or contamination as well as the loss of biodiversity and greenhouse gas emissions, are growing causes for concern (Clark and Tilman 2017). Finally, the majority of people living in extreme poverty worldwide are smallholder farmers. Since agriculture is a key source of their income, improvements in agricultural productivity could have a significant impact on global poverty (Hazell et al. 2010). Sustainable intensification of agriculture seems to address all of these issues. It is therefore not surprising that has been so widely embraced.

Like the first Green Revolution, the new one treats problems of food security and poverty primarily as technical challenges which have technological solutions. Agricultural researchers therefore focus on developing high-yielding crop varieties and determining best management practices with limited consideration of how those technologies interact with larger social, economic and political processes. Facilitating access to markets, promoting enabling policy environments, and considering barriers to adoption may be considered, but as part of a largely one-way process: once the best technology has been developed, policymakers and others are tasked with arranging the world such that the technology can be effectively deployed (Rhoades 2006).

The technology-driven approach to agricultural change is in marked contrast to interdisciplinary research approaches that embed agriculture in complex rural livelihoods as well as a network of political and economic influences at a range of scales. The technology-focused research of the Green Revolution treats the research process like a pipeline—technology is developed by scientists, promoted by extension workers, and adopted by farmers. But research processes can also be thought of as a more complex learning process, characterized by a network of multidirectional interactions among researchers, farmers, extension workers, and others (Chambers 2006). These participatory approaches recognize the value of local knowledge and facilitate opportunities for co-learning processes that include researchers, farmers, and other stakeholders involved in rural livelihoods. Inclusive research processes can empower farmers to help set research agendas and improve the quality and relevance of research, making it more likely to achieve development impacts (Sumberg et al. 2013).

Learning process research aligns poorly with large-scale strategic plans. While pipeline projects may assert that they are doing "demand-driven" research, that demand is often tightly constrained to fit within project or donor priorities. A farmer first approach requires that research plans be adapted based on needs expressed by farmers, displacing power to set priorities away from donors and scientists. Research questions, methodologies, and technology options developed and tested may all change as researchers better understand the context in which farmers operate. For institutions which have delineated mandates and scientists who have specific areas of expertise, engaging in truly demand driven research carries the risk that farmers' needs will be outside their capacities. In addition, co-learning processes are inextricably tied to specific places, making the conceit that agricultural research can develop "universal" technical solutions impossible to maintain (Giller et al. 2017).

Study Area

Research activities for this thesis were carried out under the auspices of the "Africa Research in Sustainable Intensification for the Next Generation" (Africa RISING) program. Africa RISING is the research component of the Obama Administration's "Feed the Future Initiative," a coordinated effort among United States government agencies and partners to improve food security and end chronic hunger (Feed the Future 2018). The district of Bougouni in southern Mali is one of the Africa RISING project's zones of intervention.

Bougouni is situated within West Africa's Guinea Savannah agro-ecological zone, and area which the World Bank in 2009 called "Africa's Sleeping Giant." They compared this area's high potential productivity and low population density to two areas where agriculture-driven economic growth had occurred in the recent past: the Cerrado region of Brazil, and areas of Northeast Thailand. These two areas followed very different pathways: in Brazil, production increases came from large-scale commercial farming, which provided jobs and overall increases in national income but has also increased inequality and displaced indigenous peoples. In Northeast Thailand, by contrast, agricultural growth was driven by improved smallholder production, leading to more broad-based growth and lowering inequality (Morris et al. 2009). Notably, both cases included both increases in yield (intensification) and cropland expansion.

The cercle (district) of Bougouni, in Mali's Sikasso region, has a population density of 24 people per square kilometer, and average rainfall of about 1200 mm/year, which comes during a single rainy season between May and October (INSTAT 2013). Farm households, which we define as "a group of people who manage land and resources together" (Beaman and Dillon 2012) range in size from small nuclear families to large, multigenerational and polygamous households of up to 80 people. The current cropping system was introduced by the Malian parastatal cotton company, the "Compagnie malienne pour le développement du textile" or CMDT beginning in the mid-1980s. This system is based on a rotation of cotton, maize, and groundnut, with draft oxen commonly used for traction. The CMDT provides credit for the purchase of agricultural inputs through cooperatives of cotton-producing farmers. Farmers' primary objective for agriculture is the production of food for the family; for cash income some rely on agriculture while others seek other income generating opportunities (Bingen 1998, Koenig et al. 1998).

Historical analysis was undertaken in three villages—Sorona, Banco, and Kodialan, where panel surveys had been carried out since 1994. Other work occurred in the villages of Flola, Sibirila, and Dieba, three of the sites selected by the AfricaRISING project (Figure 1).

Study Objectives and Methodology

What would it mean for Bougouni's farmers to be part of a new Green Revolution? At a national or global level, the answers have implications for food security and environmental sustainability. At a more local level, there are impacts on farmers' livelihoods and the landscapes in which they live. In alignment with the Africa RISING project goals, original research questions centered around sustainable intensification: what intensification options would work best given the local socio-ecological context? What might be the consequences of their adoption on the surrounding natural resources as well as on farmer livelihoods?

Bougouni, and West Africa's sub-humid Guinea Savannah generally, are not well-represented in agricultural literature. The first task, then, was to develop an understanding of the farming systems, land use and resources in the area. To do this, I used historical panel data, remote sensing, field trials and rangeland assessments to understand the

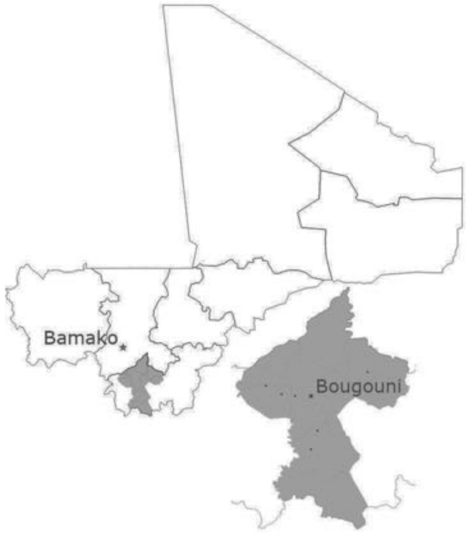

Figure 1. Map of Mali, showing the study area. Bougouni cercle (district) is shaded. The stars denote Bamako, the capitol of Mali, and Bougouni town. The black dots mark the study villages.

agroecology of the area. At the same time, focus group discussions, interviews, and conversations over on-farm trial observation allowed me to better understand the ways the complex socio-ecological systems of rural livelihoods functioned (Chapters 2 and 3).

As this process progressed, it became clear that farmers were not particularly interested in "sustainable intensification." They had access to abundant land, and saw little urgency for limiting the area they cultivated. They didn't expect agriculture to be profitable—their first goal was to provide food for their families. There were few obvious advantages to intensifying production beyond the current level.

This was inconvenient. There are obvious disadvantages to questioning the premise of a multi-million-dollar project while working within it. However, while research activities formed part of Africa RISING, this thesis was also part of a project supported by the McKnight Foundation's Collaborative Crop Research Program (CCRP). The CCRP, founded in 1983, works within the paradigm of participatory, farmer-focused research. As part of that project, I was encouraged to adapt my research plans to match local realities and farmer priorities.

Adapting to local realities meant expanding the research questions beyond intensification. The objective of this study remains to explore options that would allow farmers to improve their livelihoods while maintaining the natural resource base that supports those livelihoods. Those options are, however, not restricted to those which fit the definition of sustainable intensification. Chapter 4 of this thesis uses a simple optimization model to explore the potential impact of intensified crop and livestock production as well as cropland expansion and marketing strategies. In Chapter 5, a multi-step participatory process was used to explore possible futures developed in collaboration with farmers. Scenarios based on mechanization and cashew planting were constructed based on focus group discussions. These scenarios were then explored using a board game played by farmers and an agent-based model was used to evaluate impacts on land use and livelihoods. Through the process of doing place-based agricultural research anchored by farmer realities, this study also illuminated ways in which the African Green Revolution risks replicating the flaws of the first Green Revolution, and raised questions about the roles of agricultural scientists in development-oriented agricultural research. These broader issues are addressed in Chapter 6.

In order to explore options for the future, we must first understand the past and present. Specific objectives for this study were thus to:

1. Describe farming systems and land use change over two decades using panel survey data and remote sensing.

2. Characterize the current natural resource base by evaluating the productivity of non-cropped rangelands and the ecosystem services they provide, through repeated biomass sampling, livestock tracking, remote sensing, and farmer interviews.

3. Explore the potential solution space of existing sustainable intensification options, using survey data and statistical models.

4. Develop scenarios based on farmers' aspirations for the future, and explore these scenarios using a participatory land use game as well as an agent-based model.

Outline of the Thesis

Chapter 2 describes three villages in the district of Bougouni, using panel surveys and remote sensing data to show changes in cropping patterns and cropland expansion (Objective 1). In Chapter 3, an analysis of non-cropped rangelands illustrates the importance of rangeland resources to crop-livestock systems and presents a picture of a healthy but threatened ecosystem (Objective 2). Chapter 4 looks at near-term futures, and uses statistical modeling to delimit a solution space for intensification (Objective 3). Chapter 5 provides alternative future scenarios, where increased mechanization and tree crop production can dramatically change both farm livelihoods and village landscapes (Objective 4). The final chapter addresses the process of development-oriented agricultural research and presents an alternative, with implications for the roles of science and scientists.

Waking the Sleeping Giant: Agricultural intensification, extensification or stagnation in Mali's Guinea Savannah

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Abstract:

The World Bank argued that West Africa's Guinea Savannah zone forms part of "Africa's Sleeping Giant," where increases in agricultural production could be an engine of economic growth, through expansion of cultivated land in sparsely populated areas. The district of Bougouni, in southern Mali, falls within this zone. We used multiple data sources including a panel survey in three villages from 1994-2012, remote sensing-based land cover classification, population data, and farmer focus group discussions, to investigate whether the area is following a commonly-described pathway of agricultural intensification due to increasing land scarcity. We then use our understanding of historical change to explore plausible future pathways. Bougouni forms part of the expansion zone of the CMDT, which since the mid-1980s has provided support for intensive agricultural systems of cotton-maize rotations with animal traction and use of mineral fertilizer. In the period of the panel survey (1994-2012), cropped land increase at household level was closely linked to household size and equipment (R^2 values above 0.8). At the village level, cropped land increases varied with the amount of remaining available land and the importance of off-farm income. We see partial intensification in maize and cotton, and corresponding improvements in food self-sufficiency. However, yields remain well below national averages, and other crops are still grown in outfields relying on long fallows with limited nutrient inputs. Thus rather than either intensification or extensification the agricultural situation may be best described as stagnation with minimal change in agricultural production. This may be due to limited incentives to invest in agriculture when compared to opportunities such as gold mining or small businesses, which contribute significantly to household livelihoods in two of the three villages. Future scenarios include land expansion, which could lead to increased conflict between farmers and transhumant herders, and could lead to increased inequality at village level. Factors mitigating the tendency to land expansion include opportunities for off-farm income and migration, or market opportunities and capacity to produce high-value crops. This would preserve some remaining savannah area for grazing use and conservation purposes. Understanding household livelihood systems as part of a network of complex social and ecological factors allows identifying and exploring multiple viable pathways towards desirable futures.

Keywords: livelihood systems, land use change, off-farm income, mechanization, scenario analysis, smallholder

1. Introduction

The World Bank argued that the Guinea Savannah of West Africa forms “Africa’s Sleeping Giant” (Morris et al., 2009). Increases in agricultural production in these areas could be an engine of economic growth, driven either by transition to large commercial farms, as in Brazil’s Cerrado region, or by improved productivity on smallholder farms, as in Northeast Thailand. In both cases, expansion of cultivated land in sparsely populated areas improved incomes both in the region and nationally (Morris et al., 2009). The World Bank claims that both pathways can contribute to improved livelihoods, through direct employment or income gains, reduction in grain prices for consumers, and increased national income which can be used for social welfare programs. While large-scale commercial agriculture can provide stable jobs, it has been criticized for increasing inequality and displacing autochthonous people in Brazil (Morris et al., 2009). Such development may also lead to conflict between traditional and legal land tenure arrangements (Diallo and Mushinzimana, 2009). By contrast, improvements in smallholder agricultural productivity led to more broad-based growth and less inequality in the agricultural sector in Northeast Thailand (Morris et al., 2009). Enhanced productivity in the smallholder sector has the potential to reduce the rates of extreme poverty (Christiaensen et al., 2011), and can contribute to improving opportunities for rural non-farm employment.

Explorations of agricultural change using farming systems methodologies have described a variety of potential rural development pathways based on smallholder agriculture. These generally focus on induced innovation, particularly the ways in which farmers increasingly use mechanization and inputs in response to rising population and land pressure (de Ridder et al., 2004; Bainville and Dufumier, 2007; Demont et al., 2007; Aune and Bationo, 2008; Vanlauwe et al., 2014). De Ridder et al. (2004) describe a general pathway of intensification in West Africa from shifting cultivation, through increased use and recycling of organic resources and increased crop-livestock integration, ending with use of mineral fertilizers on crops and zero-grazing animal production. Aune and Bationo (2008) similarly describe a “ladder of intensification” for the Sahel, which provides a set of steps farmers can climb, moving from inexpensive, often labor-intensive strategies, to options requiring larger investments, including increased fertilizer use, improved crop-livestock integration, and finally commercially-oriented agriculture. Such innovations are supposed to counteract the long-term land degradation that is otherwise predicted to result of continuous cropping of ever-larger areas. Clearing of forest land as a result of the expansion of continuous cropping is observed in many areas in the savannahs of West Africa, generally driven by increasing population density (Seaquist et al., 2009; Oedraogo et al., 2010).

These explanations of agricultural development focus on linear pathways, which are seen as straightforward responses to a limited set of theorized drivers. In contrast, the analysis presented here aims to integrate how factors operating and interacting at different scales lead to a diversity of pathways toward rural development (Williams et al., 1999). Rural development pathways are generally centered on agriculture, but also consider the important contributions of both rural non-farm employment and remittances from migrated family members (Haggblade et al., 2010). Furthermore, rural development pathways also involve site-specific social and political factors that are not necessarily motivated by optimizing agro-ecological productivity or farm income (Crane 2010). Our approach to exploring pathways of agricultural change expands on typical farming systems analysis by placing more focus on interactions among levels, interactions that cross the boundaries of the farm system. We consider a range of factors, at multiple levels, as integral to our analysis. These range from field-scale fertilizer response, through farm level cropland

Figure 1. Location of study villages Banco, Sorona, and Kodialan; sub-districts (arrondissements) Sanso and Garalo; in Bougouni district (border shown by bold line), in Sikasso region, southern Mali.

allocation, household-level livelihoods indicators, to village level land use change and population growth. At larger scales we consider historical and institutional factors. We use multiple quantitative and qualitative data sources to analyze the complex interactions among these different factors and to consider multiple pathways of future change.

We focus on the Bougouni district in the Sikasso region of southern Mali as a case study situated within the "Sleeping Giant" Guinea Savannah zone, to explore the changes that have taken place in farming systems in the past 30 years. We seek to understand the complex network of causes that have led to those changes. More specifically, we investigate whether the district is following a pathway of agricultural intensification driven by increasing land scarcity due to population growth, such as commonly described in the literature? Or is the pathway one of extensification? The pathway of historical change that we identify informs our explorations of plausible future pathways, and helps us to investigate whether those pathways align with the kind of agricultural development envisaged by the World Bank.

2. Methods

2.1 Study area

The study site is the district ("cercle") of Bougouni, in the region of Sikasso, in the Guinea Savannah zone of Southern Mali. It has an average rainfall of about 1100 mm/year during a single rainy season from May to October, and population density of 24 people per square kilometer, thus placing it within the "Sleeping Giant" zone of high agricultural potential and low population density. Farm households, defined here as "a group of people who manage land and resources together" (Beaman and Dillon, 2012), are diverse, ranging from small nuclear family units to extended, often polygamous families of up to 70 people. Main crops are cotton, maize, groundnut, and sorghum, grown in rotation, with rice grown in low-lying areas. Cotton is the main cash crop, while groundnut is used both for home consumption and sale. Cropping is generally done both on home fields and bush fields. Home fields are continuously cultivated and receive mineral and organic fertilizers when planted to cotton or maize, while bush fields are fallowed regularly, and do not generally receive organic inputs, though they may receive mineral fertilizer when planted to cotton or maize. Cotton production is organized by the parastatal "Compagnie malienne pour le développement du textile" (CMDT), which has a monopoly on sale of seed and purchases of cotton and fixes prices at the beginning of the season. Through CMDT-associated cooperatives formed in the 1990s (Bingen, 1998), farmers are able to procure inputs on credit, with payment from cotton earnings at the end of the season. Cooperatives assume collective responsibility for defaults, which has been a recurring source of tension (Roy, 2010).

Three villages in the district of Bougouni were studied in more detail. Banco and Sorona are located in the sub-district (arrondissement) of Garalo, in the southern part of Bougouni district, while Kodialan is located in the sub-district of Sanso, in the eastern part of the district (Fig 1).

2.2 Data sources

We use a variety of data types to characterize change. Our focus is on the household level, paying particular attention as well to field- and village-level processes and interactions over which farmers exert the most influence. We thus collected information about a range of factors we thought would be key to understanding agricultural change. At the farm and household scale we rely on panel data from 1994-2012 from three villages, containing information about yields, input use, crop areas, livestock and draft equipment numbers, among other variables. For these same villages, we conducted focus group discussions to elicit farmer perceptions of agricultural change, focusing on the period 1980 to the present. We also analyzed Landsat images to assess land use change at the village level. At larger scales, we analyze census data from 1976-2009 to identify changes in population density, and rainfall data for the nearby town of Bougouni to assess changes in rainfall amount and distribution.

We use long-term panel survey data collected by the Malian Institute d'Economie Rurale (IER), known as the SEP (Suivi et Evaluation Permanent; Permanent Monitoring and Evaluation), which was collected annually between 1994 and 2012 in the three villages of Banco, Sorona, and Kodialan. Twenty-three households were selected based on a previously established farm typology which classified households into types A, B, C, and D, based on numbers of oxen, draft tools, and herd size (Table 1). Over the course of the survey, four households split, and in each case both resulting households were followed. Two households were added in 1998. Thus by 2012, the final year of the survey, 29 households were followed (Table 1). Surveys were conducted annually by extension agents at each site. A complementary survey in 2012 asked the same households about income-generating activities beyond agriculture, including tree crops, rural non-farm employment, and migration.

In the SEP survey, information was collected on cultivated areas, crop yields, input use, livestock and draft animals, as well as household size and age structure. Economic indicators including gross margins were calculated based on local prices and assuming all crop production was sold. CFA Francs were converted to US dollars using World Bank exchange rate data for the years of the survey (http://data.worldbank.org/indicator/PA.NUS.FCRF). Conversions to constant 2005 US dollars was done using the US consumer price index (http://stats.areppim.com/calc/calc_usdlrxdeflxcpi.php), as a Malian real effective exchange rate was not available.

Focus group meetings were held in each of the SEP villages in April 2014 to discuss farmer perceptions of changes in land use, cropping patterns, rainfall, and farming practices. Participants in these meetings were older men and women involved in agriculture. Transects were conducted with one of the IER extension agents who participated in the SEP surveys, and with men from hunters' cooperatives and from the founding families of the villages. These provided information on past land use across the village territory from 1975 to 2013. This information also provided ground-truthing for remote sensing analysis.

While panel data provided information on land use at household level, this was complemented with land use/land cover classification of Landsat imagery for each of the SEP villages. Banco and Sorona were found in the same Landsat frame, while Kodialan was located in an adjacent frame. Images were analyzed from 2013 (Banco and Sorona: 23 October Kodialan: 30 September), as well as from 14 November 1986 for Kodialan and 16 October 1984 for Banco and Sorona. Cloud-free images were not available from the same year in this period. Images were processed and classified in ENVI 5.0 (Exelis Visual Information Solutions, Boulder, Colorado). Principal components were calculated from all available bands, and were combined with NDVI for visual discrimination of land use. Classification used four land cover classes: Cropped land and land in short, grassy fallows was classified as agricultural land. Long shrub and tree dominated fallows, as well as primary and secondary open forest was classified as savannah. Bare outcrops and riverbeds were classified separately. Classification for 2013 was based on ground-truth land use data collected in each village, complemented by observational classification of DigitalGlobe imagery from February and May 2013 in Google Earth (as described in Baudron et al., 2011). For 1984/86, classification was based on recalled land use by villagers and visual identification of the land use type in the Landsat images. Final classification was performed using supervised maximum likelihood classification as described in Richards (2013). Village area boundaries are often difficult to define precisely, and customary village areas may differ from legally defined boundaries, so we estimated areas used by each village based on maps drawn in focus group discussions. We then analyzed rectangular areas covering the use areas described. These varied by village, with a total of 570 ha at Kodialan, 876 ha at Banco and 975 ha at Sorona.

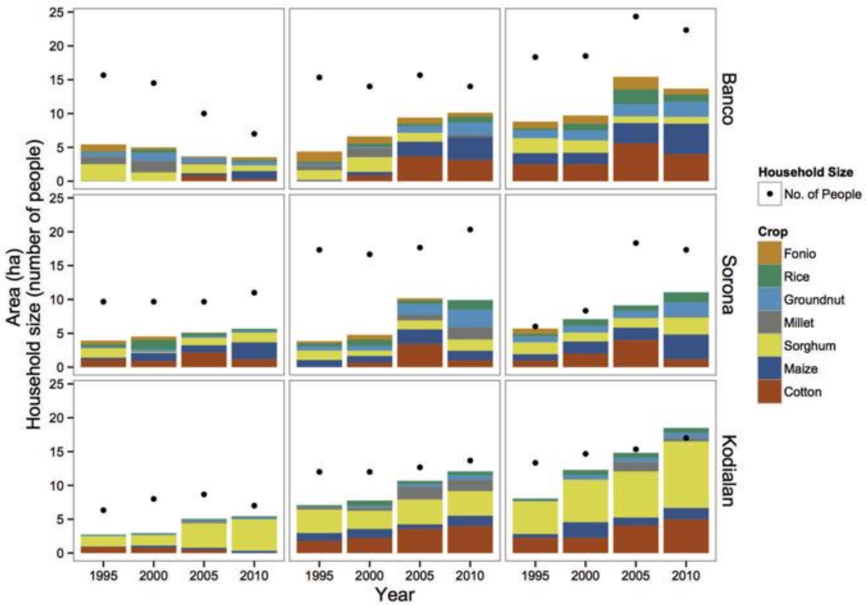


Figure 2. Crop area allocation (ha), total farm size (ha), and farm household size (no. of people) for the villages of Banco, Sorona, and Kodialan, in Bougouni district, Sikasso region, Southern Mali. Each panel represents one farm, with crop areas averaged over three years centered on the year listed on the x axis. Three farms were selected to illustrate different pathways in each village.

Table 1. Description and classification of farm types identified by CMDT across three SEP villages.

Type	Description	Percent of surveyed households in 1994	Percent of surveyed households in 2012
A	At least 2 traction teams*, at least 6 head of cattle	5%	41%
B	1 traction team, less than 6 head of cattle	50%	41%
C	Incomplete traction team, with experience in traction	14%	18%
D	Non-equipped, no traction experience	32%	0%
	Total households	23	29

*a traction team consists of two oxen and a plow (descriptions from Tefft, 2010 p138)

Census data was used from 1976, 1987, 1998 and 2009 (Institut National de la Statistique, 1976, 1987, 1998, 2009). This data was collected at several administrative levels. In 1976 and 1987 these included cercle (here translated as "district"), and arrondissement ("sub-district"). Mali underwent a process of decentralization in 1996 (Lalumia and Alinon, 2010), in which the sub-districts were transformed into one or more communes. In the case of our study sites, the sub-district of Garalo simply became the commune of Garalo, while the sub-district of Sanso split into 4 communes: Debelin, Domba, Sanso, and Wola. The study site of Kodialan is now located in the commune of Debelin. Due to this change, 1998 and 2009 census data was grouped by district and commune. When analyzing census data, we re-aggregated commune-level data to follow the population growth in the area of the former arrondissement of Sanso from 1976 to 2009. For 1987, 1998 and 2009 village-level population information was also available.

We used long-term rainfall records collected by the National Meteorological Agency (L'Agence Nationale De La Météorologie) in the town of Bougouni to examine trends in rainfall amounts and seasonality for the area. This record runs continuously from April 1921 through August 2006. In addition to examining rainfall quantities and number of rain days we also looked at dates for the beginning and end of the rainy season. The start date was defined as the first date after 1 April where cumulative rainfall over 2 days was greater than 20 mm, with no dry spells of 10 days or more in the following 30 days. The season end date was defined as the last day in the calendar year with less than 10 mm cumulative rainfall over the previous 10 days and less than 5 mm cumulative rainfall in the following 10 days (Stern and Cooper, 2011; Traore et al., 2013; Akinseye et al., 2015).

Statistical analysis of population, rainfall, and SEP panel data was conducted in R (R Development Core Team, 2015), and graphics produced using ggplot2 (Wickham, 2009). To describe trends in data we used LOESS regressions, which are localized polynomial regressions (Cleveland et al., 1992). For each point x in the dataset, a proportion (in our case 75%) of points are used in the regression, with a tricubic weighting relative to their distance from x. Fitting is by weighted least squares. Where noted we also used linear regression models in R calculated using the lm function (Chambers, 1992) and further details of these regressions are noted in the results.

3. Results and Discussion

Here we describe the results from each analysis, before synthesizing these into a broader description of system change. We begin with some historical background, focusing on key institutions. We then characterize the farming systems and their changes over time, and describe the broader economic strategies that make up household livelihoods. From there we shift to increasing spatial scales and decreasing farmer influence, to describe population growth at village, sub-district, and district level. Finally we characterize changes in rainfall patterns, a factor that is completely exogenous. In most cases, we begin with farmer perceptions, which are then complemented by quantitative data analysis.

3.1 Historical and institutional background

Historically, the sub-humid zone of southern Mali had a very low population density, due to factors including endemic river blindness and trypanosomiasis and wide depopulation due to slave raiding until the early 1900s (Peterson, 2004). After about 1910, political stability under the colonial government allowed farmers to expand bush-field cultivation in areas farther from villages. Colonial taxes could be paid in either cash or in cotton. This encouraged cash cropping of cotton to pay taxes directly, or the cultivation of groundnut as a cash crop. Seasonal migration, mainly to coastal areas of Côte d'Ivoire or to Senegal's groundnut basin was also a common way to earn cash to pay taxes (Dufumier, 2005). Cotton production continued to be encouraged, first by the CFDT, then, following

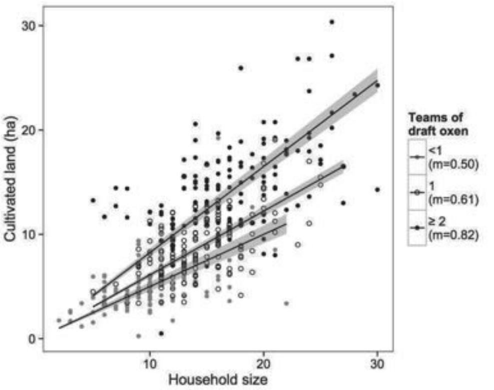


Figure 3. Cultivated area (ha) per household member in the villages of Banco, Sorona, and Kodialan, Bougouni district, Sikasso region, Southern Mali. Each point represents a single observation from one farm in a given year of the period 1994-2012 (n = 455). The lines represent linear regressions (y = mx) for less than one (R2 = 0.83), one (R2 = 0.93), or two or more (R2 = 0.93), spans of oxen; the shaded area shows one standard error above and below the regression line.

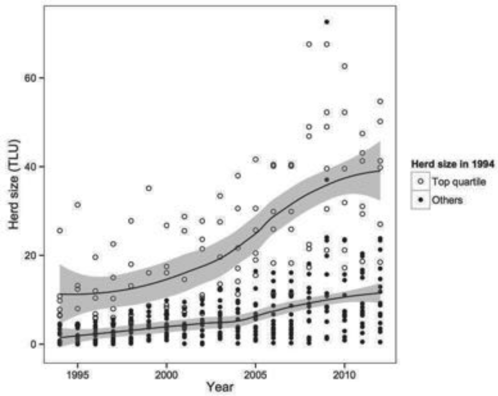


Figure 4. Herd size (TLU per household) over time for households grouped based on herd size in the villages of Banco, Sorona, and Kodialan, Bougouni district, Sikasso region, Southern Mali. The upper line represents households in the highest quartile of livestock ownership in 1994; the lower line represents all other households. The trend lines are LOESS regressions and the shaded area is one standard error above and below the regression line.

Malian independence, by the newly formed CMDT.

Bougouni cercle is considered part of the "expansion zone" of the CMDT. The first office in Bougouni was opened in 1976 and the first cotton growing cooperative in the area was formed that same year (Beaudouin, 2005). From there cotton cultivation expanded throughout the district during the 1980s. It was at this point that the cotton/maize rotation system currently common in the area was introduced, along with widespread use of animal traction and chemical fertilizers (Bainville and Dufumier, 2007). This lead to a shift in farming practices away from the traditional systems based largely around sorghum and millet, to a system with home fields devoted to continuous maize/cotton cultivation supported by inputs of mineral fertilizers provided through the CMDT. The period of CMDT expansion can be considered finished by about 1990, at which point the CMDT-supported cotton/maize based system was widespread.

The CMDT entered a period of crisis that can be variously dated to farmers' strikes and financial trouble in 1998-2001 (Roy, 2010), or the bankruptcy of the CMDT in 2004 (Falconnier et al., 2015). In the early 2000s, CMDT reduced support for extension, literacy, and road maintenance. CMDT was unable in some cases to make payments as promised. For example, very late payment for the 2008 season meant that fewer farmers grew cotton in 2009, and access to inputs was disrupted (Theriault and Sterns, 2012).

Legal and customary land tenure and natural resource management arrangements coexist and sometimes come into conflict (Lalumia and Alinon, 2010). Most notably during the 1980s, under President Moussa Traoré, cutting of forests and setting of bush fires were banned. The forest service (Service des Eaux et Forêts) levied steep fines on individuals and villages that violated the law (Benjaminsen, 2000). Following Traoré's departure in a coup d'etat in 1991, Mali began a process of decentralization. Following this reform, formal legal responsibility for natural resource management rests with the rural commune, with the forest service remaining responsible for enforcement of a more liberal Forest Law passed in 1995 (Benjamin, 2008; Benjaminsen, 2000). However, village-level arrangements governing de facto use are common. In all three of the study villages, farmers could identify customary conventions regarding timber use, land clearing for agriculture, and grazing, although the degree of enforcement varied. While some effort has been made to formalize local natural resource management conventions in the area (Cissé and Samaké, 2012), farmers who participated in focus groups were unaware of the existence of such formal conventions. Farmers do not have formal land tenure, no livestock corridors were identified for use of transhumant livestock, and lumber concessions have been granted by the Malian state to private enterprises, in ways that conflict with local customary use.

3.2 Farming system change

Farmers trace back major changes in cropping systems to changes in the engagement of the CMDT. Prior to 1980, the cropping system in both Banco and Kodialan was based on sorghum and millet, while in Sorona rice and yam were also important crops. The CMDT promoted cotton-maize rotations, especially in the southern part of the cotton zone where climatic conditions were most suitable for maize, by facilitating access to improved maize and cotton seeds, fertilizer, and animal traction equipment. While in the past farmers could only request fertilizer for cotton, currently farmers can request fertilizer for up to two hectares of maize for each hectare of cotton produced (Fuentes et al., 2011).

We observe the continuation of these trends in the long-term data set, although our data begins after the CMDT expansion period was largely complete. The shift to cotton and maize is clearest in Banco and Sorona, although cropping systems have remained quite diverse (Fig. 2). In Kodialan, sorghum has remained the most important food crop by area. In all three villages, cotton areas increased up to the 2004 cotton crisis, then generally declined, consistent with country and region-wide trends reported elsewhere (Vitale et al., 2009; Serra, 2014).

Expansion of the cultivated area has taken place both in land previously uncultivated and due to reductions in fallowing. Farmers recall that when they were young fields were cultivated for 6-10 years, depending on the soil's fertility, then left fallow for up to 20 years at a time. In comparison, current fallow times have been reduced to 2-5 years, and fields may be cultivated continuously for up to 20 years at a time. In Kodialan and Banco, most available land, including fallowed fields, belongs to one of the founding families of the village, who may give others permission to cultivate fallowed areas. In contrast, in Sorona, opening new land used to require authorization from the village chief, but now uncultivated land is cleared by autochthonous villagers without such authorization. Farmers thus worry that land left fallow will be used by others. This has led to an increase in establishment of cashew plantations as a way to maintain ownership of fallow land, also described in Dufumier (2005). This difference appears as well in a 2012 survey of tree crops, where nine

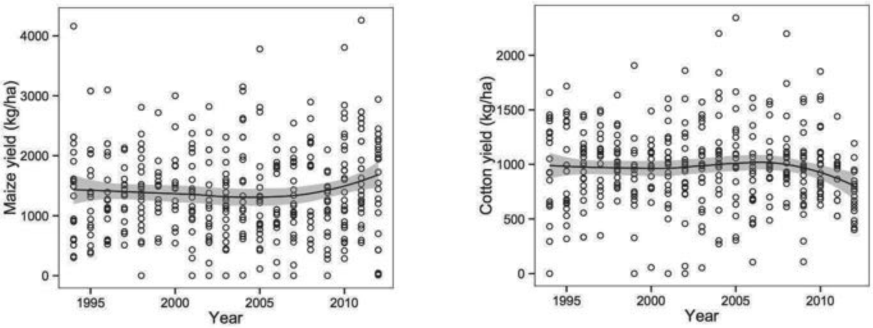


Figure 5. Maize (left) and cotton (right) yield in kg/ha from 1994-2012 in the villages of Banco, Sorona, and Kodialan, Bougouni district, Sikasso region, Southern Mali. Each point represents one farm. The trend lines are LOESS regressions and the shaded area is one standard error above and below the regression line.

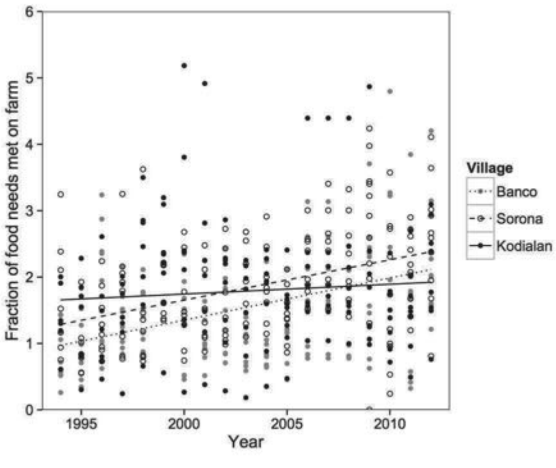


Figure 6. Food self-sufficiency status, as determined by the fraction of household calorie requirements produced on farm, assuming all production is consumed. Data presented from 1994-2012 in the villages of Banco, Sorona, and Kodialan, Bougouni district, Sikasso region, Southern Mali. Each point represents one farm. Lines are linear regressions. Slopes of the lines for Banco and Sorona are significantly positive (P<0.05), while the slope of the line for Kodialan is not significantly different from zero.

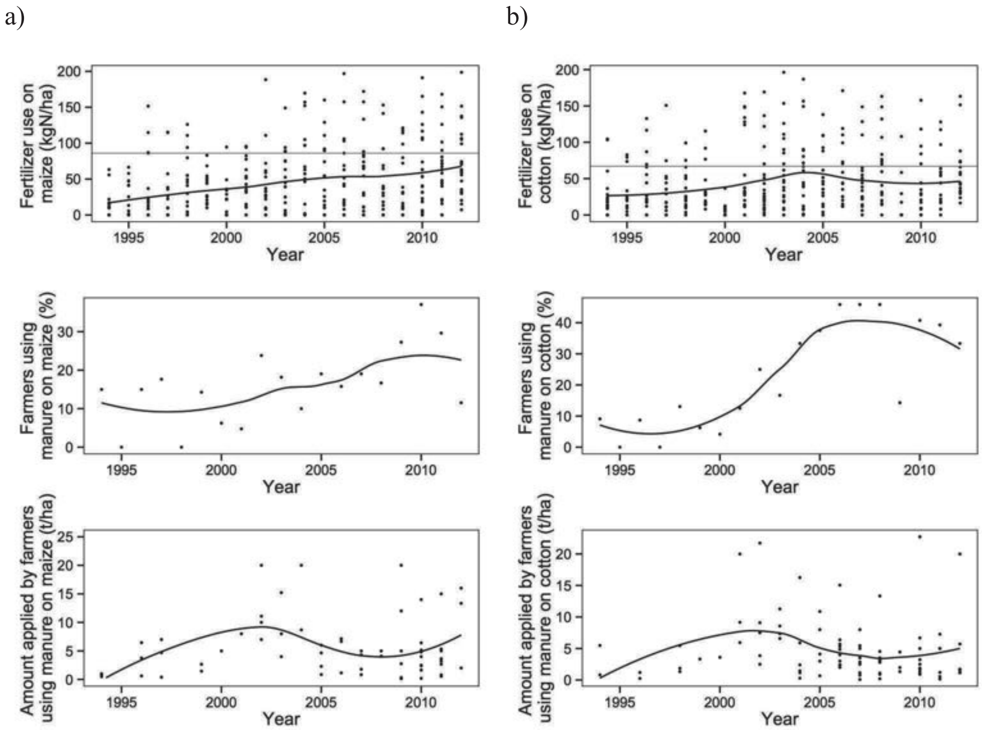


Fig. 7. Mineral fertilizer and manure use on a) maize and b) cotton in the villages of Banco, Sorona, and Kodialan, Bougouni district, Sikasso region, Southern Mali. Top panels show rates of fertilizer (in kg N /ha). Middle panels show the percentage of farmers who apply manure. Bottom panels show the dose (t/ha) of manure applied by those farmers who use manure. The trend lines are LOESS smooth regressions.

out of ten farms in Sorona had cashew plantations, compared to four (out of nine) households in Banco and none in Kodialan.

Analysis of the SEP monitoring data confirmed farmers' perceptions of an increase in the amount of land cultivated by each household. These increases, as seen in Fig. 2, were generally correlated to household size. Availability of draft animals and traction equipment are key factors for improving labor productivity and increasing the amount of land that can be cultivated. Cropped area per family was thus related directly to the number of teams of animals and the family size. Households with less than a full team of oxen cultivated 0.50 (± 0.021) ha per household member, households with one full team (2-3 oxen) cultivated 0.61 (± 0.012) ha, and households with two or more full teams (≥4 oxen) cultivated 0.82 (± 0.019) ha (Fig. 3). These values did not change substantially over the period for which data was available, although the number of families who have draft animals increased over time.

Herd sizes also increased over the monitoring period. Farmers linked this trend to the increased importance of draft animals, which then led to increased interest in livestock in general. While herd expansions thus began in the 1980s, they continued through the period of the SEP. Households with initially large herds increased their herd sizes most strongly (Fig. 4).

Table 2. Non-farm sources of income for farm households in Banco, Sorona, and Kodialan villages in Bougouni district, Sikasso region, Southern Mali, from 29 households surveyed in 2012.

Activity	Village	Revenue earned per year (US$, farmer estimate)			Number of individuals participating
		Mean	*Max*	*Min*	
Gold mining	Banco	490	490	490	1
	Sorona	-	-	-	-
	Kodialan	1273	7843	4	15
	Total	*1224*	*7843*	*4*	*16*
Small businesses	Banco	49	49	49	1
	Sorona	310	686	49	3
	Kodialan	317	588	20	3
	Total	*276*	*686*	*20*	*7*
Charcoal making and sales	Banco	608	980	196	5
	Sorona	490	490	490	1
	Kodialan	-	-	-	-
	Total	*588*	*980*	*196*	*6*
Harvest and transformation of forest products	Banco	-	-	-	-
	Sorona	-	-	-	-
	Kodialan	97	127	47	5
	Total	*97*	*127*	*47*	*5*
Buying and trading farm products	Banco	399	490	235	3
	Sorona	-	-	-	-
	Kodialan	-	-	-	-
	Total	*399*	*490*	*235*	*3*
Other	Banco	637	980	49	3
	Sorona	242	392	29	6
	Kodialan	-	-	-	-
	Total	*374*	*980*	*29*	*9*
Percentage of income from sale of all crops	Banco	85%	99%	71%	9
	Sorona	92%	100%	65%	10
	Kodialan	65%	98%	30%	8
	Overall	81%	100%	30%	*27*
Percentage of income from cotton	Banco	27%	54%	8%	9
	Sorona	16%	33%	0%	10
	Kodialan	23%	34%	7%	8
	Overall	*22%*	*54%*	*0%*	*27*

Table 3. Migration by destination from Banco, Sorona, and Kodialan villages in Bougouni district, Sikasso region, Southern Mali, from 29 households surveyed in 2012.

		Migrants traveling:		
		Within Mali	Within Africa	To Europe
Kodialan	Total	4	1	0
	Per Household	0.5	0.1	0
Banco	Total	7	9	2
	Per Household	0.8	1	0.2
Sorona	Total	9	4	2
	Per Household	0.9	0.4	0.2

3.3 Intensification of crop production

Laris et al. (2015:11) used the same panel data set used here to show increases in maize yield in Sikasso region as a whole, and concluded that "From the perspective of grain production…the story is one of agricultural intensification par excellence." A more detailed analysis of data from Bougouni specifically leads us to question this assertion. Maize grain yields increased slightly over the period of the study (Fig. 5a), and this, combined with shifts from other crops to maize, led to significant improvements in average food self-sufficiency ratios and the numbers of farmers attaining food self-sufficiency in Banco and Sorona, but not in Kodialan (Fig. 6). Fertilizer use increased more strongly than yields (Fig. 7a), suggesting that the use efficiency of fertilizer is declining. Despite these increases, the median fertilizer rate on maize is only 67 kg N/ha in 2012, 77% of CMDT recommended rates (86 kgN/ha).

Laris et al. (2015) attribute the increase in maize yields and fertilizer use on maize to a shift away from investing in cotton. Median fertilizer use on cotton declined from its peak of 61 kg N/ha in 2004 to a low of 17 kg N/ha in 2009-2010, when CMDT payments to farmers arrived after planting. Fertilizer rates have since recovered; the median rate in 2012 was 57 kg N/ha, 85% of the CMDT recommended rate for cotton (67 kg N/ha) (Fig. 7b). Variability in rates of fertilizer used on cotton is larger than that seen for maize. Thus farmers do not seem to have shifted fertilizer systematically away from cotton but rather to have prioritized fertilizer application on maize when less was available, while fertilizer rates over the entire study period increased for both crops. The clearest shift is in the number of farmers using organic manure on cotton and maize, which increased from about 10% for both crops to between 30% and 40% by the end of the study period. Among farmers using manure, no trend was observed in the amount of manure used.

Increases in overall fertilizer rate, maize yield and land devoted to maize provide some evidence of intensification. Farmers are clearly taking advantage of the technological package provided by the CMDT, but neither maize nor cotton yields correlate well with fertilizer application rates. Yields remain poor, with average maize yields of 1800 kg/ha —well below the national average of 2960 kg/ha (FAOSTAT, 2015). These are also smaller than smallholder yields reported in Koutiala by Falconnier et al. (2015), which were generally above two tons per hectare.

a)

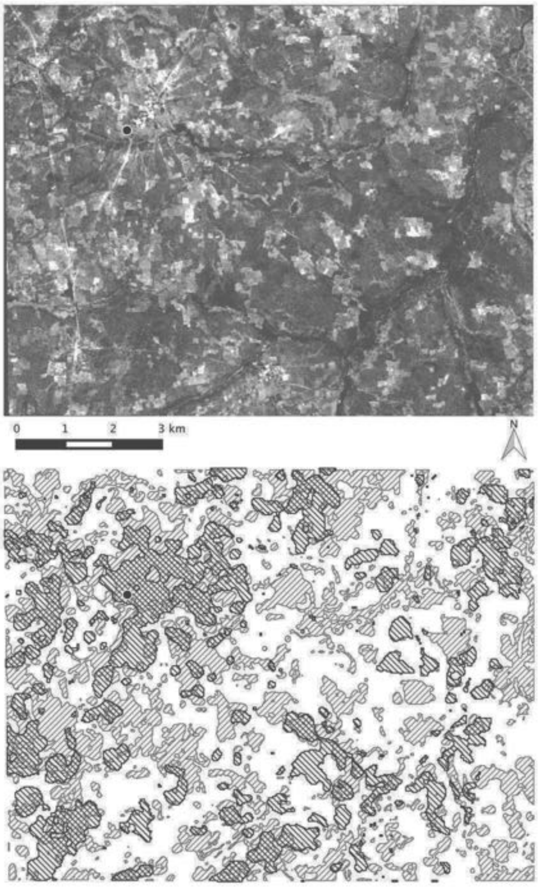
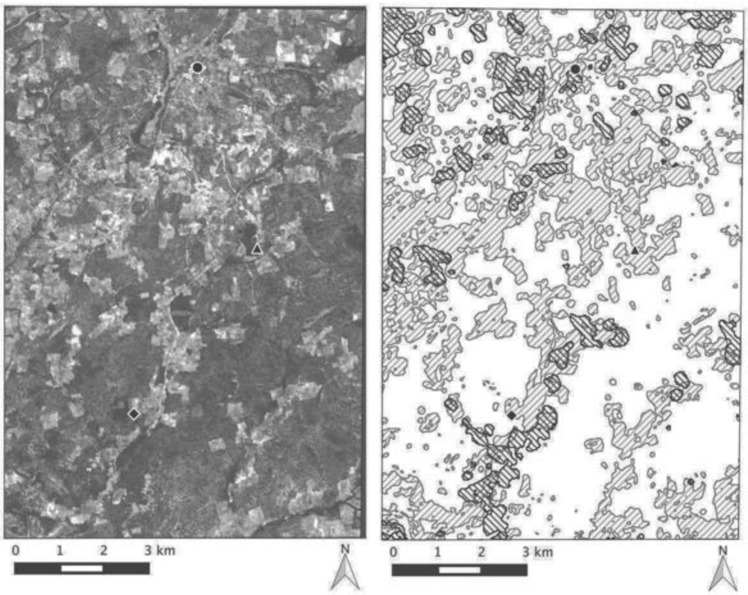
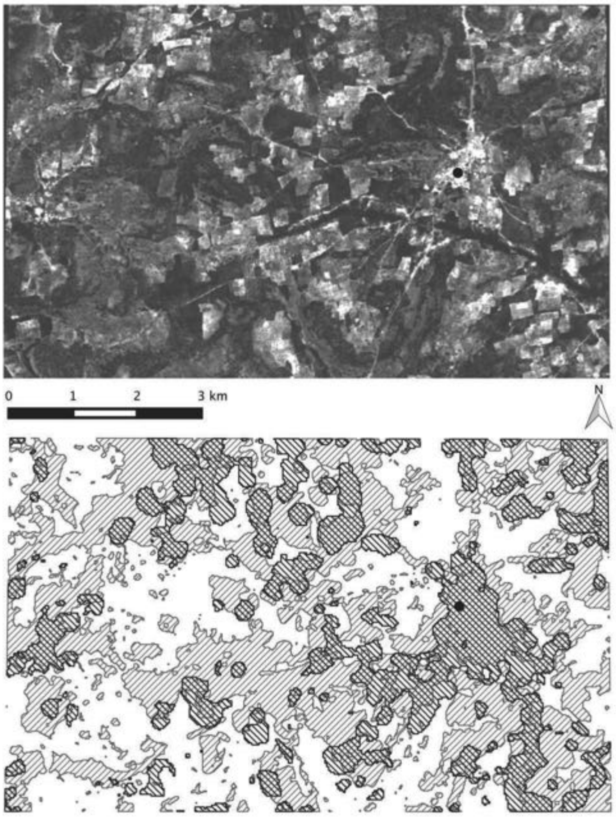


Figure 8. Landsat images from 2013 and corresponding agricultural (cultivated and short-term grass fallow) land in the villages of (a) Banco, in 2013 (grey), and 1986 (black), (b) Sorona, in 2013 (grey), and 1986 (black), and (c) Kodialan, in 2013 (grey), and 1984 (black). Circles mark current village locations. In (b), the triangle marks the location of Sorona village from c.1900-1970, while the diamond marks the pre-colonial village location. White areas correspond to savannah, bare outcrops and riverbeds

b)



c)



3.4 Household economic strategies

Farm income in the study villages is derived from both crop production and non-farm employment. Gross margins for crop production overall increased over the survey period, from an average of 204 USD per hectare in 1995 to 259 USD per hectare in 2012 (in constant 2005 USD). Mean gross margins for both cotton and maize also increased, but margins on cotton flattened and began to decline during the period of CMDT crisis.

The three villages differed in the importance of non-farm employment. In Kodialan, most households were involved in gold mining, as well as other activities (Table 2). In Banco, several households were involved in charcoal making, while households in Sorona had the least involvement in off-farm activities. Reported incomes from these activities varied widely, as did their relative importance compared with total household earnings. In Kodialan, three out of eight households earned more than half their income from off-farm activities and the remaining five all earned more than 25% of their income off-farm. In Banco and Sorona, all families earned at least half their income from crop production, and only one family in each village earned at least 25% of their income from off-farm activities. Data on amounts of remittances from migration are not available, but migration was more common in Banco and particularly in Sorona than in Kodialan (Table 3).

Labor exchanges also took place in Banco and Sorona, for weeding and harvest, as well as, in Sorona, for small-scale gold mining. Women in all households used nuts collected from shea (Vitellaria paradoxa) trees on crop fields as well as in non-cropped areas to produce shea butter for home use and sale. Income from sales of shea butter remained with women in all but one reported case.

3.5 Land use change

Laris et al. (2015) analyzed land cover at district scale, using a Landsat scene covering approximately 50% of Bougouni district, including two of the study villages. Their analysis showed land in agriculture (crops and short fallows) increasing from 40,000 ha in 1975 to 89,000 ha in 2010, a change from 7% to 15.6% of the total land area. They defined continuously cropped areas as those areas classified as agricultural in two consecutive images. For the period 1975-1986, 14% of land in agriculture was continuously cropped, while 33% was continuously cropped for 1999-2010. The total land in agriculture over the area analyzed increased by 123% over the period 1975-2010, comparable to the district-wide population increase of 129% from 1976 to 2009.

Our village-scale analysis showed major differences among the three villages in the percentage of agricultural land in the 1980s as well as in the rate of change up to 2013 (Table 4, Fig. 8). In Sorona, the amount of agricultural land tripled, while population doubled. In Banco and Kodialan, population growth was faster than growth in agricultural land: while population grew by 150% and 200% respectively, growth in agricultural land was 66% and 118% (Table 4). In Kodialan in particular, the land use change analysis confirmed farmers' concerns about land saturation— in 2013 only 0.6 hectares of savanna land remained uncultivated for each hectare of agricultural land. In contrast, in 2013 Banco and Sorona still had 1.6 and 1.7 hectares of savanna respectively for each hectare of agricultural land. Banco had the largest growth in population, but interestingly this did not result in a large increase in agricultural land. This may be due to its position along a road to the larger town of Garalo, and eventually to Côte d'Ivoire. Growth of commercial activity in the area along the road reduced the economic pressure for expansion of agriculture. Banco and Sorona were also located in an area where the villages are more widely spaced than around Kodialan, so more land was available for expansion (Fig. 8).

Uncultivated land should not be understood as unused land. Local herds rely on these areas for grazing, especially during the rainy season, and tree fodders are commonly used in the dry season. In addition, Bougouni district is a key transhumance transit area, and increases in cropped area, combined with increased local herd sizes, have led to tension between resident and transhumant herders (Turner et al., 2011). Herds move through from the Sahelian zone to dry-season grazing areas, generally in northern Côte d'Ivoire (Cissé

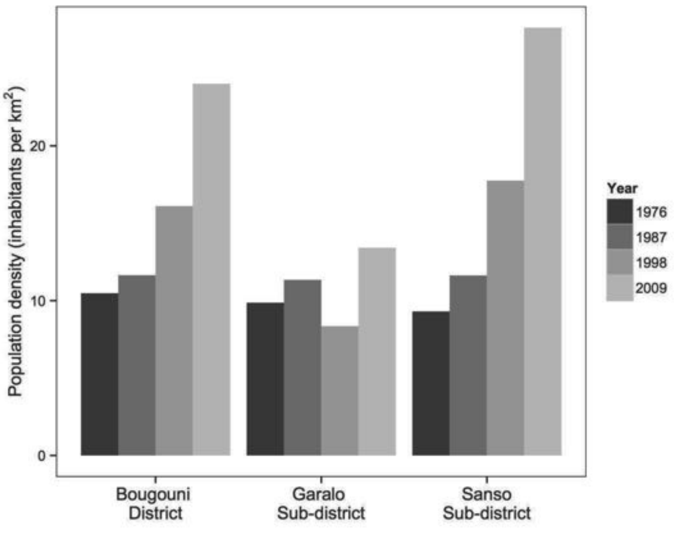


Figure 9. Population density (inhabitants per km^2) for the district (cercle) of Bougouni and the sub-districts (arrondissements) of Garalo and Sanso. Census data from 1976, 1987, 1998 and 2009 (source: INSTAT).

Table 4: Agricultural (cultivated and short-term grass fallow) and savannah (non-cultivated and long tree fallows) land use change, compared with village population growth in Banco, Sorona, and Kodialan villages in Bougouni district, Sikasso region, Southern Mali. Land use analysis based on Landsat images from 2013 in all villages, from 1986 in Sorona and Banco, and from 1984 in Kodialan. Village population from census data (INSTAT 1987, 2009).

	Sorona	Banco	Kodialan
Percent agricultural land 1984/6	8%	23%	22%
Percent savannah 1984/6	80%	60%	67%
Percent agricultural land 2013	35%	35%	48%
Percent savannah 2013	61%	57%	31%
Village population 1987	464	913	396
Village population 2009	838	2244	1179
Village population increase	81%	146%	198%
Increase in agricultural land area	321%	54%	118%

and Samaké, 2012). While these herds move south in December, after most crops are harvested, they move north during the May/June planting season, and crop destruction is a widespread problem.

3.6 Increasing population pressure

Farmers in all three study villages noted increases in population from 1980 to the present, due to both endogenous population growth and in-migration. Migrants arrived from the old cotton zone in and around the district of Koutiala in Sikasso region, and from the regions of Koulikoro and Segou, to the north of Bamako. In all three villages migrants could be granted access to land by the village chief with a gift of 10 kola nuts and a chicken. In Kodialan, in-migration has slowed because most of the suitable land is occupied.

Census data shows that population increased at national, district, and local levels between 1976 and 2009 (Fig. 9). However, the population density of Bougouni district as a whole was only 24 people per square kilometer in 2009 – much less than areas in Mali's old cotton basin such as Koutiala, where population density is 70 people per square kilometer (Falconnier et al., 2015). Population density in Garalo arrondissement, which is relatively isolated due to poor infrastructure, is below the district average and its growth is slower. In contrast, Sanso arrondissement is more densely populated and has experienced rapid growth due in part to small-scale and industrial gold mining. At the Bougouni district level, about 25 percent of the residents moved there from outside the district, with just over 10% having moved in the past 5 years. These rates were the same in 1987 and 2009, the dates for which data is available, although given the increase in population over that time, this corresponds to an acceleration in the number of people moving to the Bougouni district.

3.7 Changes in rainfall patterns

In focus group meetings, farmers in all three villages reported experiencing delays in the start of rains since 1980, when they were able to plant in late April or early May. They also reported increasing uncertainty around start dates. The delayed start is supported by analysis of rainfall data through 2006. Taking rainfall data from 1980 to 2006, we found a linear increase in start date despite high variability, with an intercept in 1980 of Julian day 119 (April 29) and a slope of 1.15 days/year, significant at $p<0.05$. There was no significant change in the end date of the season (Fig. 10).

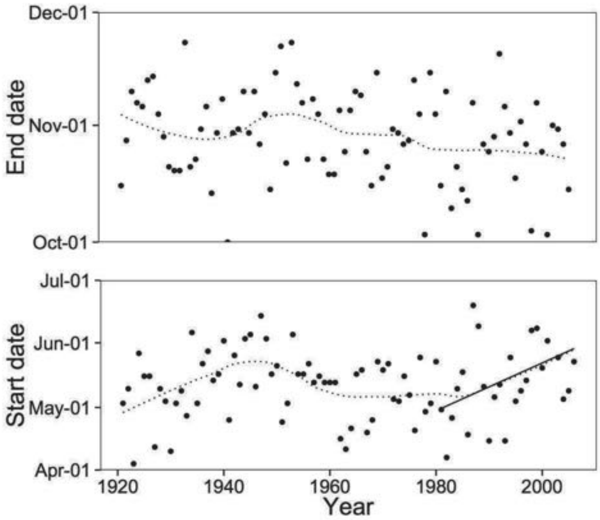


Figure 10. Start and end dates of the rainy season for the town of Bougouni, Sikasso region, southern Mali. The start of the rainy season was defined as the first date after 1st April where cumulative rainfall over two days was greater than 20 mm, with no dry spells of 10 days or more in the subsequent 30 days. Season end date was defined as the last day in the calendar year with less than 10 mm cumulative rainfall over the previous 10 days and less than 5 mm cumulative rainfall in the subsequent 10 days.

As is commonly observed in the region (de Ridder et al., 2004; Jalloh et al., 2013), more annual rainfall was received prior to the mid-1970s than currently found. Since 1980, however, total yearly rainfall has remained steady at an average of 1100 mm/year, about 95% of which falls in-season. This contradicts some farmer perceptions of decreases in total rainfall, perceptions which may be based on the shortening of the rainy season. Ongoing climate change means that rainfall patterns will continue to shift. Projections from climate models vary for this area—temperatures are projected to increase by 1-4 °C, while precipitation projections range from 100 mm increase to 100 mm decrease (Jalloh et al., 2013).

4. Synthesis: where are we now?

Farming systems in Bougouni district changed most dramatically in the 1980s with the increased involvement of the CMDT. Use of animal traction and access to mineral fertilizers in an area with low land pressure altered the pathway taken by farms in Bougouni from the standard intensification trajectory (de Ridder et al., 2004). Bougouni district falls at the low end of the range of population densities described in de Ridder et al. (2004), for which low rates of manure and no use of mineral fertilizer would be expected. Yet we observe that farmers used relatively high rates of mineral fertilizer, while organic fertilizer is used by less than half of farmers surveyed. Both mineral and organic fertilizers were used to maintain the productivity of more intensively cultivated home fields, while bush fields continued to be managed with long fallows.

In the period 1994-2012 covered by the SEP data, the farming system was relatively stable. There was a gradual intensification in cotton and maize production, as farmers invested more land and inputs in these crops. Yet, this was not mirrored by increasing yields. The change in cropping system varied significantly among the three villages. Banco and Sorona shifted towards the maize-cotton system, although farmers maintained diversity. In particular, the area under groundnut increased in recent years. In Kodialan, sorghum remains the dominant grain crop, helping to explain why grain calorie production has remained nearly constant, though from a higher baseline. In Kodialan, households have largely diversified out of farming, while households in the other two villages continue to rely mainly on farming for income as well as food self-sufficiency. We see greater crop diversity in these villages: in annual crops and in diversification into tree plantations. Besides securing land through tree plantations, diversification may also be a hedge against increasingly uncertain climate conditions, as farmers say they are no longer sure when the rains will start (Fig. 10). Diversifying household income sources from cotton, either into other potential cash crops such as groundnut or horticultural crops, or into increased off-farm employment is an important risk management strategy given the uncertainty around the functioning of the CMDT. Privatization has been scheduled but delayed since 2004, and while fertilizer subsidies and prices are currently favorable to farmers, this follows only a few years after serious payment delays (Serra, 2014).

At farm level, cultivated land per person has remained constant—in an area where land is abundant, this suggests that farm size is labor limited. Labor-saving technical improvements, such as 2- or 4-wheel tractors and increased use and efficiency of herbicides may help relieve this constraint. In the past, agricultural innovations have largely been diffused through the CMDT, but given the current institutional uncertainty, and tighter focus on cotton purchasing and input provision, it is likely that new avenues for dissemination of these technologies will need to be found.

Expanding the scope of analysis to longer term social, political and technological change helps to complement analysis of change at the farm-level. The observed increase in population density has led to cropland expansion at village and higher levels, due to a trend toward larger farm households as well as more farms. Moving forward this trend will result in land scarcity. Increasing urbanization may moderate rural population growth and thus slow cropland expansion. The World Bank estimates that by 2024 60% of Mali's population will be urban, compared to 33% in 2004 (Cartier, 2013). However, in terms of absolute numbers both rural and urban populations continue to grow at rapid rates, and much rural-urban migration within Mali is circular, either seasonally or for periods of several years.

5. Synthesis: where to from here?

As the situation continues to change, a variety of agricultural pathways are possible, falling along a spectrum from large-scale commercial development to smallholder intensification. It is likely that households will continue to follow a range of these pathways, depending on each family's constraints and opportunities. We see this already in the case of herd size: those with larger herds are able to more quickly increase their herds and the number of draft animals they own. Should this trend continue, the few farms able to invest more heavily in labor-saving technologies such as tractors and herbicides could capture an disproportionately large fraction of the remaining land, leading to increased inequality in land distribution in rural communities. Access to credit and to technology itself is likely to determine which households, and how many, can take advantage of such technologies, with smaller farms continuing to rely on draft animals or contracting equipment from service providers or larger farms. Increases in mechanization could provide additional labor demand for semi-skilled repair work, as well as for hired labor in non-mechanized farming activities such as the harvest of cotton. In the 1980s, the CMDT catalyzed widespread use of animal traction with loans known as the "Pret Premier Equipment", which assisted farmers in the purchase of their first draft team (Sangaré and Traoré, 1990). A similar program for small tractors could allow a wider subset of farmers to expand their area, potentially leading to a more equitable land distribution than other potential development pathways, such as the one outlined above.

Land expansion pathways would accelerate land scarcity, with both environmental and social consequences. Perceived scarcity of pasture already leads to conflict between transhumant herders and residents, which will be aggravated as resources decline. Decreasing fallow periods requires increased investment in fertilizer and manure to maintain soil fertility on continuously cropped fields. Charcoal making, an important income source for men, and forest products such as shea nuts, an important food and income source for women, rely on non-cropped areas. Charcoal making is possible during periodic clearing of bush fields, while long fallows improve natural regeneration of shea trees. Intensification on existing cropland has often been suggested as an alternative to cropland expansion, but intensification generally occurs only once land is scarce (de Ridder et al., 2004). When it does occur in land-abundant areas, intensification may lead to cropland expansion (Byerlee et al., 2014). Given the already relatively high rates of input use, our study area is unlikely to be an exception, unless protected areas are established and enforced, either through customary or formal legal means. Such protection is unlikely to be effective unless it is implemented with engagement from local people, and with their participation in enforcement. Given the current population growth rate of 2.6% per year and the land utilization value of 0.82 ha/person calculated for families with multiple teams of draft animals, half of the total land area in Bougouni district would be used as cropland by about 2050, and the whole area would be cultivated by 2075. Of course, not all the land in the district is equally suitable for agriculture, so such an extrapolation would result in land scarcity within the next 30-40 years. At this point, patterns of land use and land use change will no longer be an outcome of farming practices, but a cause of changes in those practices. This has been seen in Koutiala, where increasing land scarcity has made fallowing rare and has lead to more intensive use of inputs (Benjaminsen et al., 2010).

Another potential alternative is to diversify farm production into higher value horticultural or tree crops. These require stronger market linkages than currently exist, and institutional and infrastructural challenges would need to be addressed. In particular, poor potential for irrigation limits the off-season production of vegetables, as well as the establishment of many types of fruit trees. However, as urban populations grow, and higher-income consumers demand fruit, vegetables, and animal products in higher quantities, market opportunities could quickly develop. These could be opportunities for smallholders to increase their profits from farming without relying on land expansion.

Not all households rely on farming: indeed very few rely solely on crop production, and several derive the bulk of their income from non-farm employment (Table 2). As land becomes scarcer, non-farm income will become more important. As noted by Haggblade (2010), rural non-farm employment can evolve along two major paths. If agriculture is productive and profitable, at least for some farms, it can support a lively non-farm sector in rural areas—the "pull" scenario. However, if people turn to off-farm sources of employment because they are pushed out of an unproductive agricultural sector, the off-farm economy is likely to also be marginally profitable at best—the "push" scenario. The fact that most families in our study villages are meeting their food needs from agricultural production suggests that the non-farm sector tends toward the "pull" scenario, as does the prevalence of service-providing activities (e.g. trading, small businesses, Table 2) in Sorona and Banco. Further development of this sector could provide an alternative for some households to move out of agriculture, thus avoiding increasing land scarcity and the less desirable push scenario associated with low-return activities. Migration will play a part in either scenario, but the "pull" scenario provides rural people with a wider range of options.

6. Conclusions

"Awakening the Sleeping Giant" in Brazil and Thailand required a combination of cropland expansion and intensification of input use, facilitated by favorable institutional environments and opportunities for off-farm income generation (Morris et al., 2009). In Bougouni, there has been both intensification and cropland expansion over the past 35 years, but the farm-level agricultural situation since 1994 is best described as stagnation. This may represent a 'holding pattern' while population and land pressure remain so low that there is little incentive for farmers to invest in increasing agricultural productivity, and land expansion is limited by the technology available. In this situation, income is more likely to be invested in non-agricultural activities, either goods such as motorcycles or other household items, or in small businesses.

Livelihood strategies in the Bougouni district will continue to change, as people adapt to increasing land and population pressure, uncertainty in climate and markets, changes in institutional support, and changing technologies. Interactions among these factors are complex. For example, changes in farming practice will impact land pressure, as will in- and out-migration. Farmers also participate in the governance of institutions, from customary rules for land use at village level to strikes and advocacy for change in the CMDT. Identifying the complex ways in which these factors interact helps us build a more nuanced understanding of the household livelihood systems within a network of shifting social and ecological factors. This allows us to inform decisions made by farmers, village authorities, and policy makers by identifying multiple viable pathways toward desirable futures.

Acknowledgements

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Forest, pasture, fallow: Using and conserving rangelands in Mali's Guinea Savannah

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Abstract

Woody savannah rangelands in sub-humid West Africa are key sources of forage for livestock and provide a variety of other ecosystem services to farming systems in the region. However, detailed information about Guinea Savannah ecosystems is scarce. This study describes rangeland in two villages in southern Mali using a variety of methods. First, the quantity of biomass available from rangelands and its seasonal variability was characterized through repeated field measurements. A regression analysis method based on remotely sensed tree cover was developed to further explore the spatial variability of herbaceous biomass. Herbaceous and ligneous species were identified, and species composition was combined with secondary forage quality data to estimate energy and protein supply. Herds were tracked using GPS to quantify grazing practices, which then allowed us to calculate the feed demand throughout the year. We identify important constraints to livestock productivity and, based on this situation analysis, we identify key rangeland resources and suggest strategies for maintaining and strengthening their sustainable use.

Rangelands in the study area are highly productive, with peak biomass yields of up to 4 t/ha. Over 80 herbaceous and 70 ligneous species were identified, including perennial and highly palatable grasses, suggesting that grazing pressure is not excessive. Despite high productivity, seasonal forage deficits occur in the late dry season. Herders mitigate forage deficits by choice of grazing area, using tree fodders, or in some cases sending herds further south. However, dry season forage deficits limit possibilities for intensification of livestock production, and supplemental feed sources could both improve incomes and increase the value of rangelands. In addition to providing feed for livestock, rangelands are important sources of shea (Vitellaria paradoxa) nuts and other wild fruits, firewood and timber. While there are no signs of rangeland degradation at present, increasing population and crop area expansion will put increased stress on rangeland resources, requiring management to adapt to prevent future degradation.

Keywords: rangeland management, grazing patterns, remote sensing, species composition, woody savannah

1. Introduction

Rangelands in the sub-humid Guinea Savannah are key resources for livestock production in West Africa. While west Africa's Sahelian zone has typically been considered to be the area of primary importance for grazing livestock, the number of animals in more humid areas has increased dramatically in recent years (Bassett and Turner 2006). Improvements in animal health, notably the development of vaccines for trypanosomiasis; increasing population in sub-humid areas; and increasing interest in livestock among local farmers for use as animal traction have all contributed to the growth in animal numbers. While population density is still low (24 people/km2), the Guinea Savannah is also undergoing expansion of crop production area as population increases and farming technology improves (Bainville and Dufumier 2007, Tefft 2010). As livestock rely on grazing, rangelands provide the primary source of forage for cattle and small ruminants. However, whereas rangelands currently exist in abundance, they are under increasing pressure. While there is a large body of literature characterizing Sahelian grasslands (Hiernaux 1998, Schlecht et al. 2006, Hein et al. 2006), similar studies for the Guinea Savannah are limited (Nacoulma et al. 2011). Information about rangeland productivity in the Sahel and methods for studying grasslands do not transfer well to the woody savannah that dominates the Guinea Savannah (Leloup and Mannetje 1995). Remote sensing techniques for estimating grass biomass in the Sahel take advantage of low tree cover (usually less than 5%) which allows green vegetation to be treated as a single canopy (Jarlan et al. 2008). Even at low tree densities, accounting for tree cover significantly improves estimates of net primary productivity (Fensholt et al. 2006). In a recent review of remote sensing research in the region since 1975, no studies of herbaceous biomass were found south of the Sahelian zone (Karlson and Ostwald 2016). The increased complexity of woody savannah vegetation, with multiple canopy levels and widely varying phenologies makes remote sensing analyses difficult (Eisfelder et al. 2012). As a result, both the current status of Guinea Savannah rangelands and their potential response to changes in management and use intensity are uncertain.

While cropped area is expanding, woody savannah still covers the majority of the land area in many parts of southern Mali's Guinea Savannah (Laris et al. 2015, Ollenburger et al. 2016). Even when not cleared for crops, savannah areas are managed and used. Fallows with naturally regenerating vegetation comprise a significant portion of this land, which may be returned to cultivation as needed. In addition to timber for construction and fuelwood, many wild tree species produce valuable non-timber products, most notably the shea tree (Vitellaria paradoxa Gaertn. f.), and others which provide food, fodder, and medicine (Faye et al. 2010). Grasses such as Andropogon gayanus Stapf. are used for thatching roofs and making mats.

The most important use of rangelands is for grazing by livestock. In the sparsely populated southern parts of Mali, abundant rangelands provide a valuable source of forage. This contrasts with more densely populated areas farther north, where crop area has expanded such that remaining grazing areas are located on the poorest soils, and are so heavily grazed that the most nutritious species have become rare (Bagayoko et al. 2006). The Guinea Savannah may face the same future, given rising population density and trends toward cropland and livestock herd size expansion. In addition to local livestock, transhumant herds also utilize rangelands in the Guinea Savannah. These may originate from densely populated areas, where animals cannot freely roam in the rainy season

(Bagayoko et al. 2006), or belong to Fulani herders passing through or remaining in Mali's Guinea Savannah during the dry season (Turner et al. 2014). These transhumant herds increase the demand placed on sub-humid rangelands to provide forage. Animal production can be an important source of income, particularly as markets improve and production strategies intensify (Ollenburger et al., in press). However, appropriate management strategies are needed to ensure sustainable animal production on rangelands.

Because few studies have characterized woody savannah in West Africa, it is difficult to determine how productive these areas are, in terms of providing palatable grasses for livestock as well as other resources used by local communities, including timber, medicinal plants and wild fruits. Furthermore, the response of woody savannah ecosystems to more intensive use is uncertain. Increased grazing pressure on decreasing areas of available rangeland may lead to soil degradation and loss of biodiversity (Powell et al. 1996). However, the interactions between grazing intensity and environmental factors like drought are complex and varied, and fluctuations in rangeland productivity due to drought may have greater impact than stocking density (Vetter 2005). Tree populations may be maintained in parkland systems even as agriculture intensifies (Augusseau et al. 2006) and the heterogeneity of grazing areas may promote biodiversity (Nacoulma et al. 2011). Characterizing current conditions and management practices is therefore an important first step towards identifying appropriate and sustainable land use and animal husbandry strategies.

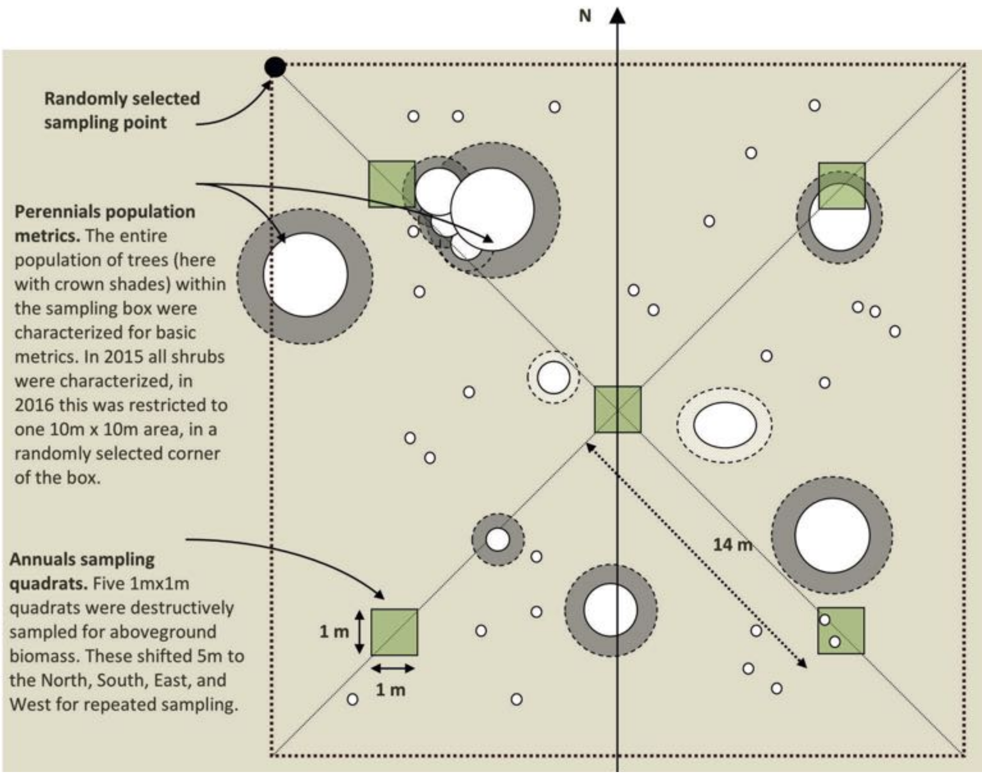


Figure 1. Biomass sampling box

Rangeland areas in two villages in the district of Bougouni in southern Mali were used as case studies for the Guinea Savannah rangelands which cover over 200,000 km2 in 11 countries in West Africa, including Nigeria, Ghana, Guinea and Burkina Faso, as well as much of southern Mali (Morris et al. 2009). We aimed to characterize these rangelands by quantifying the productivity of key resources, particularly herbaceous biomass available for grazing, to describe current uses of rangelands, and to assess the multiple ways in which rangelands contribute to local farming systems and farmer livelihoods. A holistic understanding of current practices and their interaction with the rangeland ecosystem provides a basis for sustainable management.

2. Materials and Methods

Characterizing rangeland status and use in a holistic way required a combination of different methods. First, we characterized the quantity and quality of biomass available from rangelands and its seasonal variability, through repeated field measurements and species identification combined with secondary data on feed quality. We developed a regression analysis method based on remotely sensed tree cover to explore the spatial variability of herbaceous biomass at landscape scale. We used focus group discussions and informal interviews to investigate customary regulations on the use of rangeland resources, including grazing livestock, timber and fuelwood, forest products, and other ecosystem services provided by rangelands. In addition, we reviewed legal regulations including Mali's Code Forestier. Herds were tracked using GPS to quantify grazing practices. This allowed us to calculate livestock feed demand throughout the year, and to identify key constraints to livestock productivity. Finally, based on this situation analysis, we identify key rangeland resources and suggest strategies for maintaining and strengthening their sustainable use.

2.1 Study area

Our study sites are the villages of Sibirila and Dieba, in the district of Bougouni, in the Guinea Savannah zone of southern Mali. Population density in the district is approximately 24 people per km^2, less than other agriculturally productive areas of Mali. The study villages are in the western part of the district, and both have populations of around 1000 people. Mixed crop-livestock systems predominate, with cropping systems based around cotton-maize rotations introduced and promoted by the Malian cotton parastatal "Compagnie Malienne pour le développement du textile" (CMDT). The CMDT facilitated increased cattle ownership in the area with the promotion of animal traction in the mid-1980s, and cotton income allowed successful farmers to increase their herd size (Bainville and Dufumier 2007). In 2013, basic information was collected on all households in the study villages. The result was an agricultural census that included information on household size, cultivated area (by crop), livestock holdings, draft animals and equipment (Ollenburger et al. 2018). In this survey 62% of farm families owned cattle. Rangelands are a key source of forage for these animals.

2.2 Rangeland biomass assessment

Mapping exercises were conducted in both villages through community meetings to identify village territories, locate landmarks, and distinguish land use types. We focused then on non-cultivated areas, which we call rangelands here. Uncultivated land cannot accurately be called "unused," even when it appears to be, as most has been cultivated at some point. During the community meetings we identified four types of rangelands, including very recent grass-dominated fallows, relatively recent fallows near to the village, old fallows in more distant areas, and plateaus. Very recent fallows, last cultivated within the past 1-5 years, were interspersed within cropland, and excluded from our analysis. Plateau areas occur on laterite outcrops and are nearly treeless, with shallow soils. We identified relatively recent fallows near to the village, old fallows in more distant areas, and plateaus in both villages. In Dieba, we also specifically sampled a designated pasture zone, where cropping has been forbidden for over 50 years. Land use types were delineated in Google Earth. We sampled 12 locations in each village territory, distributed evenly among the rangeland types. Twenty points were identified using stratified random sampling in QGIS (QGIS Development Team 2018), from which we took the first twelve that were within 1.5 km from a location accessible by vehicle.

At each of the 12 selected points we established a 30 m x 30 m sampling box. Within the box were five 1 m x 1 m sampling quadrats, placed systematically as illustrated in Figure 1. Destructive sampling of herbaceous biomass was done approximately every two months, from October 2013 to April 2016, with a dry-season break between October 2014 and May 2015, in quadrats displaced by 5 m in a different direction each time (Fig. 1). The three dominant herbaceous species in each quadrat were identified, as well as the estimated percentage cover provided by each species. In year two fresh weights were also recorded for each of the three dominant species separately. Samples from each quadrat were oven-dried to determine dry matter content. After one year of sampling, the boxes were noticeably disturbed, and thus new boxes were randomly selected within 500 m of the original boxes and within the same land use type.

Tree measurements were taken yearly. These measurements included diameter at breast height (DBH), trunk height, tree height, two perpendicular crown diameters, and a visual estimate of leaf cover density. In 2015 all shrubs were measured for basal diameter, height, and two crown diameters. In 2016 this was restricted to one 10 m x 10 m area, in a

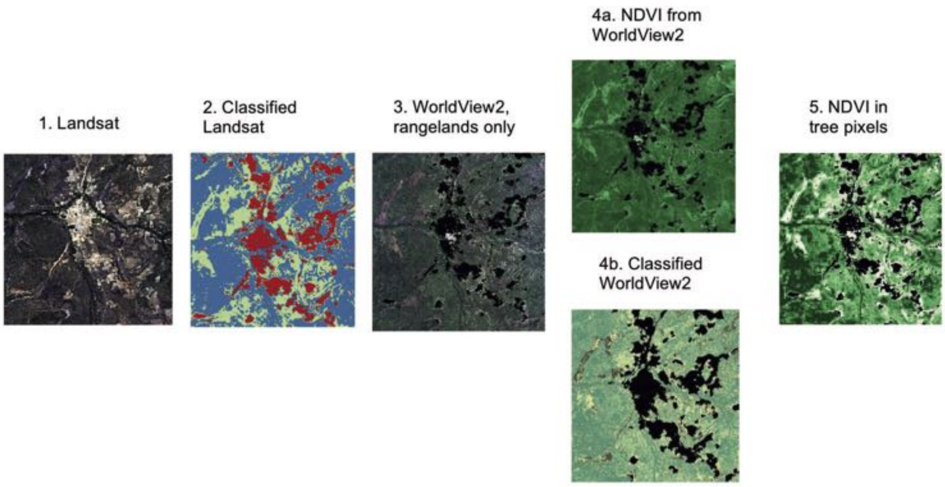


Figure 2. Process for extracting tree cover from WorldView2 images. A classified Landsat image is used to mask cropland and built-up areas from the high resolution image, which is then classified. NDVI is also calculated for the WorldView2 image, and these are combined to extract the NDVI values in tree pixels only.

randomly selected corner of the box. Trees and shrubs were identified by species. Tree cover was calculated using crown diameter and a visual estimate of the density of cover, ranging from 0 (bare branches) to 1 (fully opaque).

When analyzing biomass data, we found that the differences between recent, near and old, distant fallow areas were minimal: species composition was similar and there was no significant difference in biomass quantity. Thus herbaceous biomass data is presented for three categories: Savannah (all fallows), plateaus and designated pasture. Herbaceous biomass for these categories was computed as the mean of all quadrats. Regression models of tree cover and grass biomass were calculated using the lm function in R (R Core Group 2016).

2.3 Herd tracking and rangeland management

Herds were tracked using a Garmin Astro 320 handheld GPS linked to four DC-50 collars. This allowed tracking four herds at a time for three days before the collars had to be returned for charging. Four herds in each village were selected in October 2015 in order to cover a wide area based on typical grazing patterns. These four herds were followed for three days in October 2015 and January 2016. In April 2016, only three herds per village could be tracked, as the remaining herds were unsupervised. Information was collected on each herd tracked, including the animals' owners, the herders' names and ages, the sex and age category (calf or adult) of each animal, and the total number of animals in the herd. Focus group meetings were conducted in each village in October 2015 to elicit details on herd management practices, preferred tree and grass species for feeding livestock, and customary regulations on the use of local rangelands. Participants were cattle owners in the village, who tended to be older, wealthier men. In addition, informal interviews with herders were conducted during herd tracking in October 2015.

2.4 Remote sensing image analysis

While field data allowed estimating average herbaceous biomass production, the limited number of sampling points could not capture the spatial variation at the larger landscape scale. In grasslands, this is typically assessed using remotely-sensed vegetation indices, of which the most common is the Normalized Difference Vegetation Index (NDVI). In humid or temperate forests, other methods have been developed to estimate total aboveground biomass (Lu 2006). However, in our case trees cover a large percentage of the land, but we are more interested in herbaceous biomass. This required the development of a new methodology (Fig. 2) that combines land cover classification and NDVI analysis from remote sensing on the one hand with an empirical relation between field-measured herbaceous biomass and a proxy for tree cover derived from remote sensing imagery on the other hand. Image analysis was based on two sources. Landsat imagery from 16 December 2015 was used for large-scale land use classification (Fig. 2.1 and 2.2). Supervised classification was performed using a supervised Bayesian maximum likelihood classifier in Orfeo toolbox (Christophe and Inglada 2009). Classes used for Landsat images were crop fields, savannah, plateau, built up areas, and tree plantations. Classification was compared to ground truth data from 2013 and 2015, complemented by observational classification of WorldView2 high-resolution imagery (Fig. 2.3). Landsat classification accuracy was good (κ = 0.97). WorldView2 images were acquired for the estimated village territory area on 8 October 2015 in Sibirila and 16 October 2015 in Dieba. These images were pan-sharpened to a resolution of 0.65m using the raster package in R, and classified as tree, bare soil, crop, grass (savannah), tin or thatched roofs, riverbed, cloud or shadow, using a supervised

Table 1. Common rangeland grass (a, above) and crop and weed species (b, opposite) and parameters used to calculate fodder quality

a)

Species	Crude Protein (%)			Metabolizable Energy (MJ/kg)			
	Vegetative	Mature	Senescent	Vegetative	Mature	Senescent	Source
Andropogon pseudapricus Stapf [a c]	7.50	3.75	1.88	11.4	7.9	7.2	1
Andropogon guayanus Kunth	12.5	5.63	1.88	9.3	6.9	5.5	1
Fimbristylis ferruginea (L.) Vahl [a d]	5.34	4.01	2.67	10.1	7.8	7.1	2
Loudetia togoensis (Pilger) C. E. Hubbard	8.13	5.63	2.5	10.9	6.1	5.5	1
Commelina diffusa Burm. f.	40.6	18.8	9.38	11.8	11.0	9.8	1
Brachiaria ramosa (L.) Stapf [a d]	20.3	15.2	10.2	10.1	7.8	7.1	2
Microchloa indica (Linn. f.) P Beauv. [b c]	9.38	6.25	3.13	11.4	7.9	7.2	1
Cochlospermum planchonii Hook. f. [a d]	16.4	12.3	8.19	10.1	7.8	7.1	2
Ctenium villosum Berh. [a d]	11.4	8.57	5.71	10.1	7.8	7.1	2
Pennisetum pedicellatum Trin. [d b]	9.375	6.25	3.125	11.4	7.8	7.2	1

a ME values for generic perennial grass
b ME values for generic annual grass
c CP values for generic annual grass
d estimated seasonal values
Sources:
1. Breman and de Ridder (1991)
2. SSAFeed database (Duncan et al., 2011)

b)

Crop species	Common name	Crude Protein (%)	Metabolizable Energy (MJ/kg)
Pennisetum glaucum (L.) K. Schum	Pearl millet	7.40	7.1
Sorghum bicolor (L.) Moench	Sorghum	1.88	6.5
Zea mays L.	Maize	5.28	8.6
Oryza sativa L.	Rice	13.74	11.2
Arachis hypogaea L.	Groundnut	12.79	9.5
Vigna unguiculata (L.) Walp.	Cowpea	17.78	9.8
Digitaria exilis (Kippist) Stapf	Fonio	7.40	9.1
Common weed species			
Digitaria chevalieri Stapf.		5.83	8.1
Ipomoaea triloba L.		18.75	12.2
Aspilia africana (Pers.) C. D. Adams		6.06	7.7
Borreria scabra (Schum. & Thonn.) K. Schum.		Not palatable	Not palatable
Mitracarpus scaber Zucc.		Not palatable	Not palatable

Source: SSAFeed database (Duncan et al. 2011), except Ipomoaea triloba L. from Essiett and Ukpong 2014

maximum likelihood classifier and ground truth data as for Landsat. Classification accuracy of WorldView2 images was good (κ = 0.94 for Dieba, κ = 0.97 for Sibirila) with misclassification occurring most often between crop and grass classes (3% misclassified). We corrected crop/grass misclassifications in the high-resolution image classification by changing crop-classified pixels to grass pixels in the savannah areas (as determined by Landsat classification). NDVI was calculated for the full WorldView2 image areas (Fig. 2.4a).

Gridded shapefiles were created to cover the WorldView2 image areas, with a grid size of 60 m x 60 m chosen to approach the 30-m resolution of Landsat images while limiting processing time. Grid squares corresponding to crops, plantations, and built up area in the Landsat classification were excluded from further processing, while savannah and plateau rangelands were used for additional analysis. Within each grid cell, the WorldView2 classification was used to create masks for tree pixels and for grass pixels. These masks were then applied to the NDVI data to create one file with NDVI from grass-classified pixels only, and another with NDVI from tree-classified pixels only. These values were then summed for each grid square to produce aggregate grass-only NDVI and tree-only NDVI values. Initially, we intended to use grass-only NDVI to estimate herbaceous biomass. However, because most grid squares had very low percentages of grass pixels, these values were not meaningful. Instead, because field data showed a correlation between tree cover and herbaceous biomass, we used aggregate tree-only NDVI as an indicator for tree cover. We then estimated herbaceous biomass based on a linear regression established between measured herbaceous biomass in sampling boxes and the tree NDVI values in these locations.

2.5 Forage supply

Total grass biomass available from rangelands was estimated in each village based on area estimates of each rangeland type, and biomass calculations as described above. Crop residue and weed biomass was estimated for maize, cotton, sorghum, and groundnut fields in 2013 as part of a detailed farm characterization survey conducted with 12 farm families in each village. For each family, one field of each crop was selected, when possible the main family field for that crop. Fields were outlined using Trimble handheld GPS units, and five sampling quadrats were identified within that area by tracing an X across the field area and sampling at the center and along each arm of the X at approximately two thirds of the distance from the center to the corner. At harvesting, total grain, stover, and weed biomass was weighed in the field, and a sample of each was dried in order to estimate the dry matter content. Yield estimates obtained from this data were extrapolated to total village area for that crop, as collected in a basic farm survey in 2013 (Ollenburger et al., 2018). For other (minor) crops harvest indices and local yield estimates were used to calculate stover biomass, whereas weed biomass was estimated from the weed measurements in the other crop fields. Cotton residues were excluded, as they are typically rejected by livestock. Survey-based estimates of cropped area were 20-25% lower than estimates based on Landsat classification, similar to errors reported elsewhere for self-report estimations (Carletto et al. 2016). Because crop residues provided a relatively small percentage of total forage, we did not attempt to correct for this.

Information on forage quality was derived based on crude protein and metabolizable energy content for each species. For rangeland herbaceous biomass, we used a weighted average of values for the component species, based on their proportional contribution by

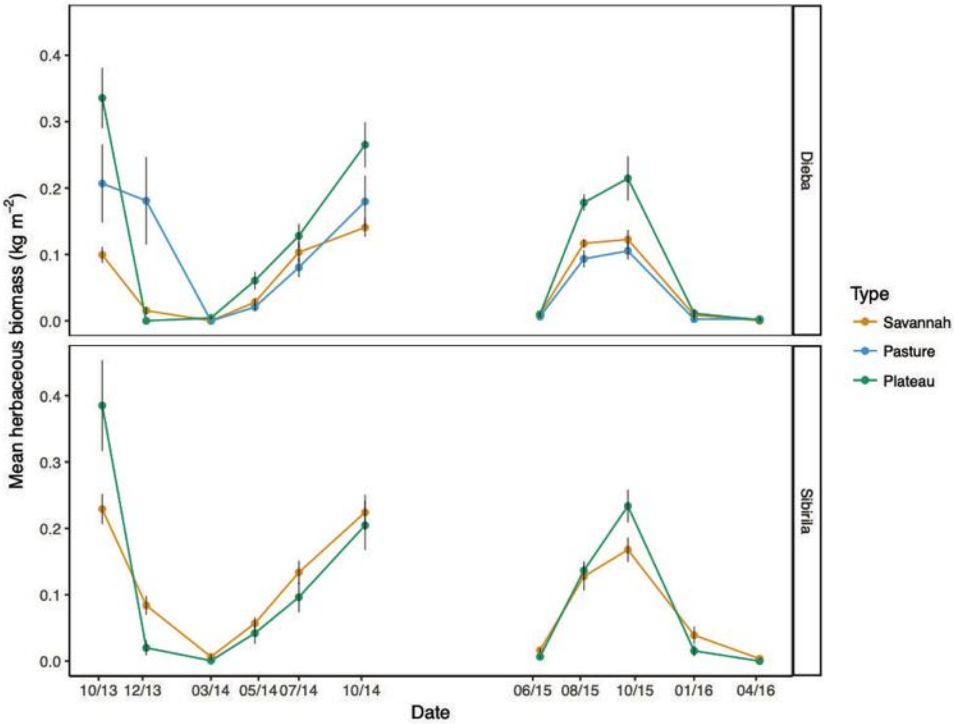


Figure 3. Total herbaceous biomass over time, by land type and village. Error bars show one standard error above and below the mean.

weight. In crop fields, weed species were ranked but not weighed, so quality estimates for weed biomass allocated weights of 50% to the first species, 30% to the second, and 20% to the third. Parameters and their sources are listed in Table 1. We were unable to accurately estimate the amount of tree fodders used, so these were excluded.

We expressed the supply of forage in dry matter, metabolizable energy (ME) and crude protein (CP) of the biomass produced in rangelands and croplands. For rangeland species, three quality values were estimated, for vegetative, mature, and senescent stages. Because cropland provides a small contribution to overall forage availability, we used constant

Table 2. Common tree species, local names, and uses

Percent of all trees surveyed	Species	Local name	Uses
14.1	*Detarium senegalense* JF Gmelin	N'Tabacoumba	Fruit
7.7	*Erythrina senegalensis* DC.	Blen	Medicinal, leguminous
6.9	*Crossopteryx febrifuga* (Afzel.) Benth.	Balenbo	Medicinal, timber
6.9	*Terminalia macroptera* Guill. & Perr.	Wolo	Timber, medicinal
6.8	*Combretum glutinosum* Perr. Ex DC.	Tiangara	Traditional medicine, firewood, tools
5.5	*Pteleopsis suberosa* Engl. & Diels	N'Tereni	Traditional medicine
5.2	*Isoberlinia doka* Craib & Stapf	Chô	Timber, leguminous
4.2	*Lannea acida* A. Rich	Surukupeku	Fruit, traditional medicine, textile dyes
3.8	*Lannea microcarpa* Engl. & K. Krause	M'Peku	Fruit, textile dyes
3.6	*Piliostigma reticulatum* (DC.) Hochst.	Gnama/Niama	Leguminous, traditional medicine
3.4	*Vitellaria paradoxa* Gaertn. f.	Chi	Shea butter
3.0	*Annona senegalensis* Pers.	Mande Sounsoun	Fruit, animal fodder
3.0	*Daniellia oliveri* (Rolfe) Hutch. & Dalz.	Sana	Traditional medicine, timber
2.6	*Entada africana* Guill. & Perr.	Samanere	Traditional medicine, fish poison
2.6	*Pericopsis laxiflora* (Benth.) Van Meeuwen	Kolokolo	Fodder, medicine, timber
2.1	*Grewia mollis* Juss.	Na nakifnininka	Fodder, medicine, timber

values for metabolizable energy and crude protein for both crop residues and weeds. This is likely to overestimate ME and CP because forage quality declines as the dry season progresses.

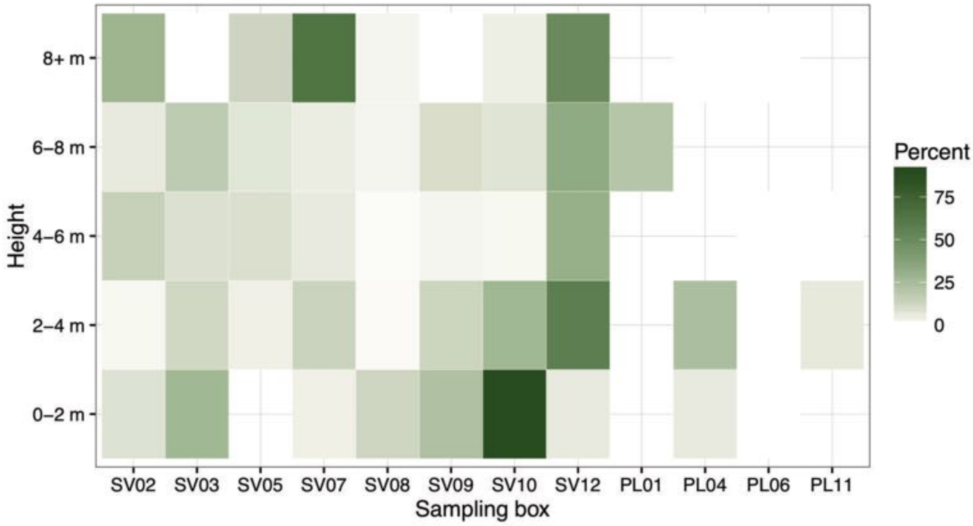
Forage demand was based on total village cattle herd size as recorded in the 2013 basic farm survey. Herd composition was estimated from records of herds tracked and the ARBES survey conducted by IFPRI in 2015 (Howard et al. 2016). In both sources, animals were classified by age and sex. Estimated weights were assigned to each class based on AFRC (1993), and the herd size was converted to tropical livestock units (TLUs). Because of its large sample size, ARBES data was used to calculate an overall conversion factor of 0.74 (+/- 0.005) TLUs per head of cattle. This was compared with values calculated for tracked herds to confirm that it was accurate for these specific villages. Energy demand was calculated with formulas for basal maintenance requirements and additional energy requirements for walking from Konandreas and Anderson (1982). Similarly, protein requirements for maintenance were calculated using formulas from AFRC (1993) and did not include adjustments for walking distance. Both energy and protein demand was calculated on a per-TLU basis, assuming a body weight of 250 kg. As milk production is negligible, we did not include additional requirements for lactation. Average walking distances in each season were derived from the herd tracking data.

3. Results

3.1. Herbaceous biomass

Grass biomass, as expected, varied strongly throughout the seasons (Fig. 3). After its peak at 2-4 t/ha it declined within two months to less than 1 t/ha, and approached zero in March and April, near the end of the dry season. The decline was particularly pronounced in the plateau areas. This was due to the prominence of relatively early-maturing annual grasses, shallow soils which do not retain water, and exacerbated by the fact that plateau areas are almost all burned early in the dry season. All plateau sampling boxes showed evidence of burning by the December sampling time, while 75% of savannah boxes were burned, and no pasture boxes. Pasture biomass thus declined more slowly than either of the other types.

The three rangeland types differed both in amount of herbaceous biomass and in species composition. In October, at the end of the rainy season, average savannah biomass was 0.17 kg/m^2. Pasture biomass was similar, at 0.16 kg/m^2, and plateau biomass was highest, at 0.27 kg/m^2. However, plateau biomass declined most quickly so that in December, plateau biomass was lowest, at 0.013 kg/m^2, while savannah biomass was 0.040 kg/m^2, and pasture biomass was highest at 0.095 kg/m^2. Biomass continued to decline through the dry season, until new growth appeared in June. As the rainy season began, savannah and plateau biomass were similar, at 0.029 kg/m^2, while pasture biomass lagged behind, at 0.014 kg/m^2. Savannah and plateau biomass were still similar in August, at 0.12 kg/m^2 for savannah and 0.13 kg/m^2 for plateaus, while pasture biomass continued to lag, at 0.087 kg/m^2. Species composition also varied. Plateaus were dominated by the annual grasses Andropogon pseudapricus and Loudetia togoensis, while the low-growing Microchloa indica and Fimbristylis ferruginea fill in below. In contrast, the savannah and pasture areas were both dominated by the perennial Andropogon gayanus, with annual grasses A. pseudapricus, Pennisetum pedicellatum, F. ferruginea, and M. indica also common, as well as the perennial herb Commelina diffusa. C. diffusa and the perennial grass Brachiaria



SV05 SV10 PL06

Figure 4. Percent tree cover by height for sampling boxes in Sibirila, 2015. Sampling boxes are listed on the x axis, where box numbers preceded by SV are savannah and box numbers preceded by PL are plateau. Percent cover for each box at a given height is represented by shading. Three examples are shown in photos: Box SV05 is dominated by large trees, SV10 is dominated by shorter shrubs, and box PL06 is treeless.

ramosa were more common in pasture than in savannah. In total, over 80 species were identified. Pasture and savannah rangelands had similar species composition and level of diversity, while plateaus were less diverse. At the end of the rainy season, based on species composition, pastures had the highest average mass-fractions of crude protein (6.5%), followed by savannah (5.6%), while plateau areas had the lowest (4.8%). However, on an area basis, plateaus provided the largest amounts of both metabolizable energy and crude protein due to their greater productivity (Fig. 3).

3.2. Tree cover

This area of sub-humid Guinea savannah is characterized by relatively dense tree cover. Our boxes ranged from treeless plateau areas to shrub-dominated secondary regrowth to large tree dominated forest (Fig. 4) with tree cover percentages ranging from 11% to 120%. Grass biomass was negatively correlated with total tree cover, with $p < 0.001$ and multiple R^2 of 0.22. Separating cover by height did not provide any additional explanatory power.

Table 3. Estimates of energy requirements based on distance walked. Protein requirements were assumed constant, at 144.6 g CP/TLU daily.

		Average daily distance (km)	ME/TLU (MJ/day)		
			Maintenance	Walking	Total
Dieba	January	12.4	23.6	6.5	30.2
	April	18.7	23.6	9.8	33.5
	October	10.1	23.6	5.3	28.9
Sibirila	January	9.4	23.6	4.9	28.6
	April	9.8	23.6	5.1	28.8
	October	13.0	23.6	6.8	30.5

Over 70 different tree species were represented in the sampling areas. Sixteen species make up 80% of those sampled, and these are listed in Table 2. The most common species was Detarium senegalense , a fruit-producing tree. Several leguminous species are common, including Isoberlinia doka Crain & Stapf, which is a preferred source of timber for construction. V. paradoxa comprised 3.4% of the trees sampled, and is also commonly found within crop fields. Nearly all common tree species are used in traditional medicine, while several provide fruit and fodder or provide soil fertility benefits through nitrogen fixation.

3.3 Spatial variations in tree cover and herbaceous biomass

Remote sensing analysis confirmed the high degree of tree cover over the larger study area (Fig. 5). In a gridded shapefile covering all savannah and plateau areas, pixels classified as tree comprised on average 52% of pixels in each grid square in Dieba, and 49% in Sibirila. By contrast, grass pixels only made up an average of 20% of pixels per grid square in Sibirila and 26% in Dieba.

The densest tree cover is found in Dieba's pasture areas, where cultivation has not occurred in at least 60 years (Fig. 5a). This area has relatively steeper slopes and is fairly rocky, making it less suitable for cultivation. Areas to the north of the village are similar, but were cultivated 30-40 years ago, prior to the widespread use of animal traction. Tree density in Sibirila is lower overall, with areas of high tree density concentrated in low-lying areas, and to the north of the village. There are remains of old mud brick buildings to the northeast of the village, indicating that this land was in active use at some point, but village elders estimated this to be nearly 100 years ago (Fig. 5b). Tree cover tends to be less dense near the villages, where crop production is also more intensive.

We derived the following relationship between remotely-sensed tree cover (as represented by NDVI in tree pixels) and ground-measured grass biomass:

$$\textit{Grass biomass (kg/m}^2\textit{)} = 0.29 - 4.1 \times 10^{-6} \times \textit{NDVI in tree pixels}$$

This relationship had an R^2 value of 0.32 and $p < 0.001$ and was used to map grass biomass for the area. Total grass biomass for the two villages' rangelands as estimated using regression analysis (29711 tons) not significantly different from the estimate based on sampled biomass (21411 tons).

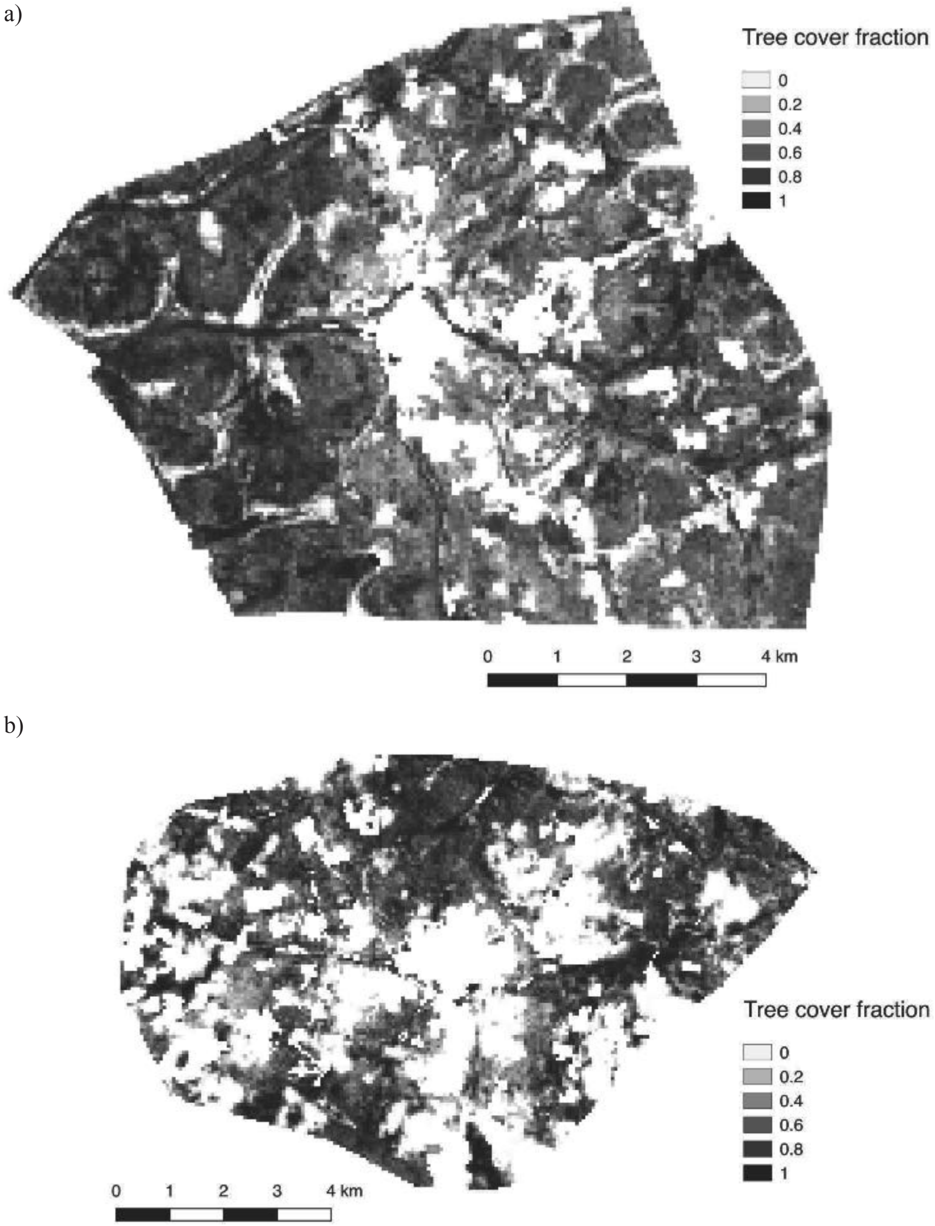


Figure 5. Tree cover, defined as the percentage of pixels classified as trees in VHRI images of village territories in a) Dieba and b) Sibirila. Tree cover estimates are made for rangeland only, so cropped area is masked out of these images.

Based on tree density, we tend to find higher peak grass biomass near the villages (Fig. 6). While villagers could not provide precise ages of fallow, they suggested that areas near the village had been in fallow for about 30-40 years. These near, recent fallows tend to have fewer, younger trees and thus allow for higher productivity of grasses. Very short, grassy fallows and plateau areas show the largest grass biomass in the regression analysis. These very short fallows are interspersed with crop fields and thus were not included in rangeland biomass sampling, which may account for the greater peak biomass estimate from regression analysis when compared to sampling-based estimates. Riverbeds, by contrast, have dense tree cover and thus less grass biomass.

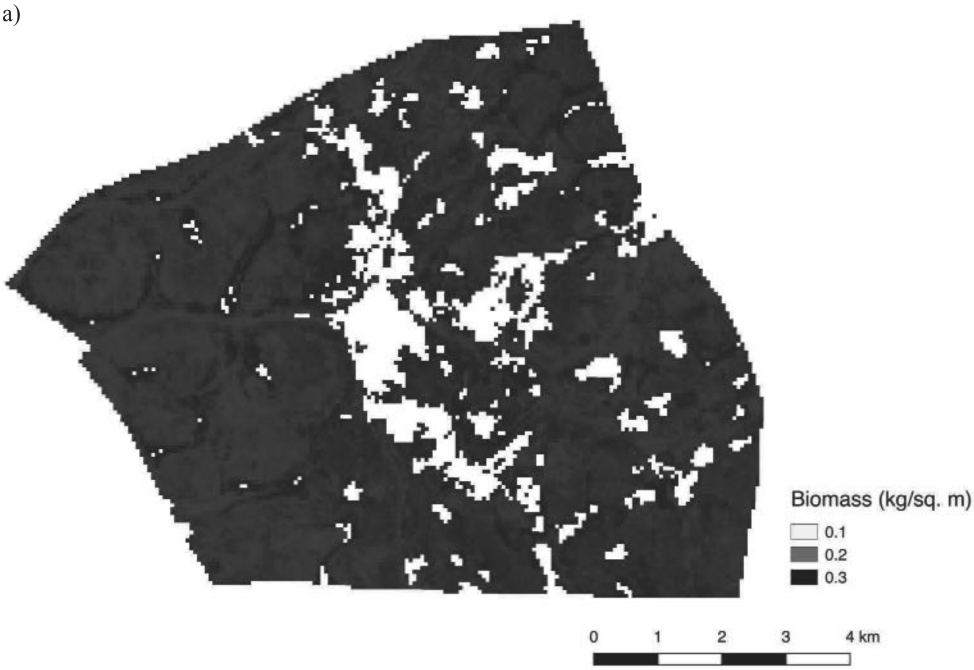
3.4. Herding practices

Stocking density in both villages was low: 0.11 TLU/ha in Sibirila and 0.076 TLU/ha in Dieba (9.5-13 hectares per TLU). Cattle were generally herded in family groups. Households with large herds grouped their animals if the household heads were related, while those with only a few animals usually entrusted these to another family's herder. Tracked herd sizes ranged from 35 to 61 animals in Sibirila and from 53 to 67 animals in Dieba. In October, during the rainy season, herds covered wide rangeland areas, including some territories of neighboring villages. In January, herds spent a considerable amount of their time in crop fields, while continuing to graze in rangelands as well. In April, most herds stayed near riverbeds, where they could find water, and where grass most often remained available (Fig. 7).

Herding practices also varied by season: In the rainy season, animals were actively herded to keep them from destroying crops and returned to corrals at night. Grazing periods amounted to 10-11 hours. Herders were usually young men, often family members, who are not paid for herding, but entitled to the milk produced by the animals. This amount is minimal and is usually consumed by the herders themselves. If the herders are not family members, in addition to any milk produced, a payment is made either on a per-month or per-animal basis. In the dry season, grazing periods lengthened to about 12 hours, and some herds (two in Sibirila and one in Dieba) were allowed to graze continuously, including at night. During the dry season, animals are generally not intensively herded. They may be left alone to graze, or may be followed by a child, whose job is to keep track of animals, not to direct them. In both villages, savannah and fallow areas were open to all village herds, and neighboring villages often shared the use of rangeland. Crop fields were also available to all village herds once harvest is completed, but herds tended to stay in the vicinity of the owner's fields. Average daily walking distances reflected seasonal and village differences. Herds in Dieba travelled further each day, with a maximum of 18.7 km in April, the late dry season, and a minimum of 10 km in October, at the end of the rainy season. In Sibirila, herds traveled furthest in October (13 km) and covered smaller distances in January and April (9.4 and 9.8 km) (Table 3).

Transhumant livestock passed through the area regularly, moving to the south in November and December and returning to the north in May. Relationships between transhumant herders and village residents differed between the two villages. In Sibirila, after serious conflicts 10-15 years ago, transhumant herders were not permitted to camp anywhere in the village, although they sometimes passed through. In Dieba, by contrast, certain village families had ongoing relationships with families of herders, who may camp on their land for periods ranging from a few days to a few months. In some cases, village residents had dug wells in specific fields to entice transhumant herders to camp there, in

a)



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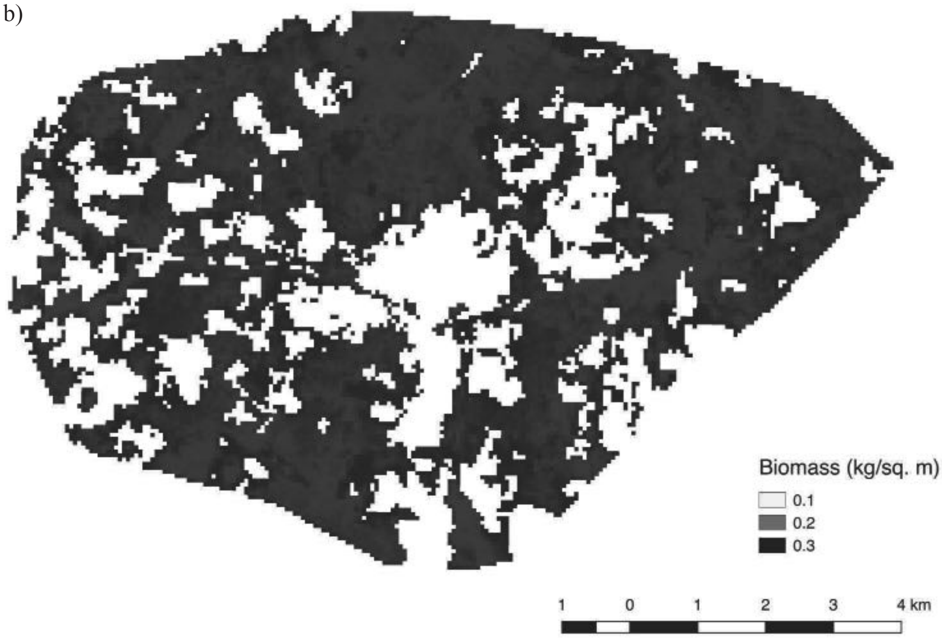

Figure 6. Estimated herbaceous biomass based on the correlation between remotely sensed tree cover (NDVI in tree pixels) and measured peak biomass for the locations of the boxes. (Multiple R2: 0.32, p-value < 0.001) in a) Dieba and b) Sibirila

order to benefit from the manure left by their animals. While tensions did exist in Dieba, these were considered manageable.

Some herds from Dieba participated in dry season transhumance, traveling south toward the region of Yanfolila or the border with Côte d'Ivoire. The decision to move the herd was largely a matter of preference as it entails trade-offs. Animals benefited from better grazing, but managing distant herds could be costly, since they were accompanied by three people: a paid herder, a family member to supervise, and a second family member with a motorcycle for supplies and potential problem solving. Herds in Sibirila did not travel far beyond the village. In the past, animals ranged more widely from Sibirila, but are now forced to stay nearby. Villagers cited recent droughts and the lack of surface water during the dry season as reasons for the change. They also noted an increase in forage availability within the village due to the exclusion of transhumant livestock, and the increasing tensions around transhumance in areas where they previously sent livestock.

3.5. Forage supply and demand

Forage demand varied throughout the year along with the distance herds travelled. The greatest energy demand occurred in Dieba in the late dry season, when long walking distances increased energy need from an overall average of about 30 MJ per TLU per day to a maximum of 33.5 MJ per TLU per day (Table 3). Forage supply was abundant on an annual basis—total livestock requirements were less than 10% of peak herbaceous rangeland biomass. However, availability varied greatly throughout the year, with a period of forage deficit in both villages in the late dry season (Fig. 8). In Dieba, both ME and CP availability were insufficient, while in Sibirila CP was also deficient, but ME available was approximately equal to demand. Herds in Dieba walked nearly twice as far during this period as those in Sibirila, contributing to the deficit there. Deficiencies resulted in large part from the lack of total biomass, which was notably reduced by burning, as well as reduced quality of grass straw. During the hot dry season, herders often used cut tree branches as supplemental fodder. Tree species preferred for dry season fodder included Pterocarpus erinaceus, a nitrogen-fixing legume (Diabate et al. 2005); Afzelia africana and Cassia nigricans, non-nodulating legumes (Diabate et al. 2005); and Strychnos innocua. The climbing vines Baissea multiflora and Dioscorea prehensilis were also preferred supplemental fodder. All of these were found in our tree census, with S. innocua being the most common of the trees mentioned, followed by P. erinaceus. These trees often showed evidence of recent pruning. Stockage of crop residues was limited, though more common in Dieba, where rice straw and groundnut haulms were often stored for use during the dry season. Some villagers also purchased concentrates, particularly cottonseed cake, although this was more common ten years ago, when the cottonseed cake was subsidized for cotton growers. Prices for cottonseed cake in the villages in 2015 were between 10 and 15 thousand CFA francs (US$ 16-24) per 50 kg sack, making the use of cottonseed cake too expensive for most villagers. Concentrates, stored crop residues, and tree fodder were given preferentially to draft oxen to ensure they were in good condition for land preparation at the beginning of the rainy season.

3.6 Ecosystem services and their management

Beyond serving as the predominant feed source for livestock, rangelands serve three major roles, providing soil fertility restoration in long-fallow rotation systems; non-timber products, notably shea nuts; and timber and fuel. While rangelands are not managed as intensively as croplands, they are managed in various ways.

a)

b)

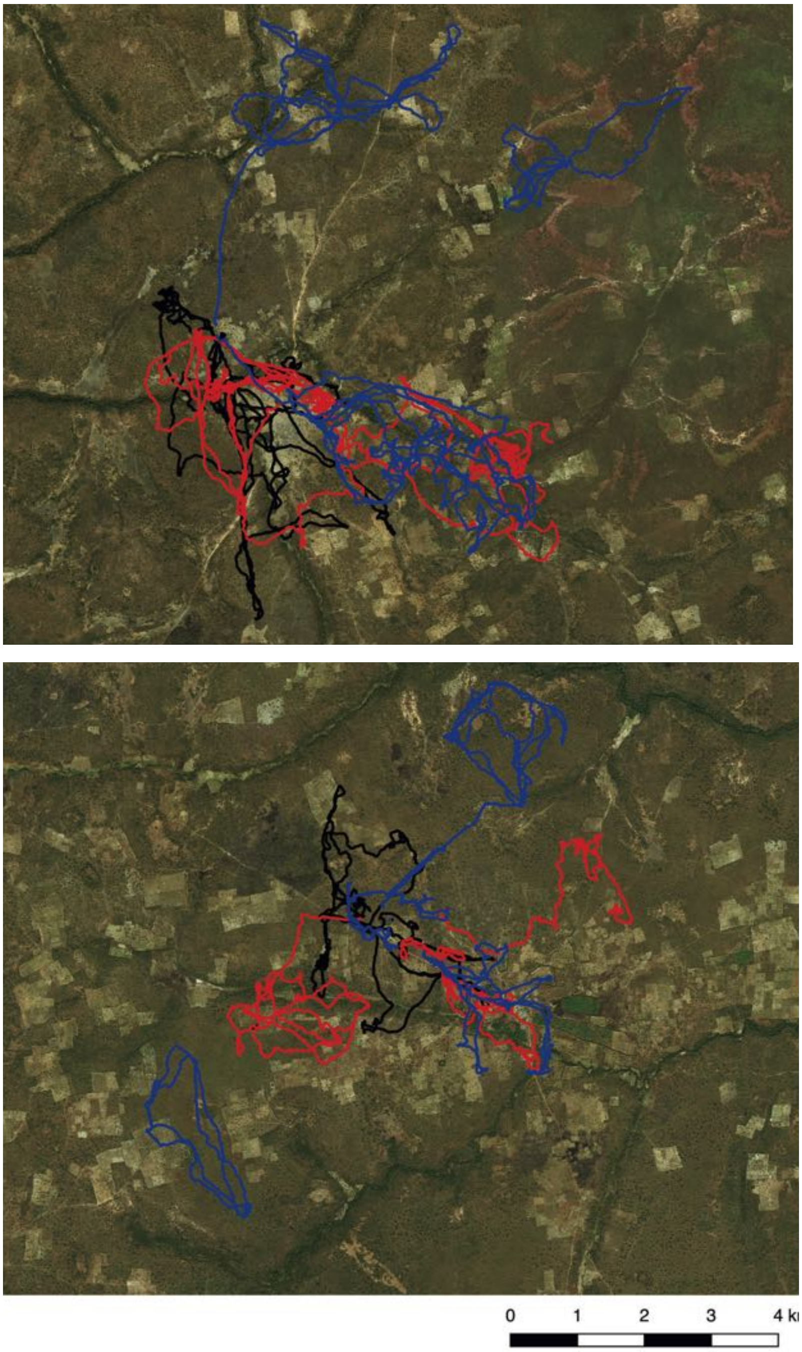

Figure 7. Herd tracks in a) Dieba and b) Sibirila. Blue lines are during the rainy season (early October), red lines are during the cold dry season (January) and black lines are during the hot dry season (April). During the rainy season, cattle range widely in rangeland areas. In the early dry season they spend more time in cropped areas, while in the late dry season they concentrate in dry riverbeds where water and grass are available longer.

Fire is an important management tool. Between 25 and 80% of rangelands in the Sudan and Guinea savannah zones of West Africa are burned each year (Laris 2002). In the study villages, it is common to burn plateau areas early in the dry season, as was apparent from the herbaceous biomass sampling reported above. Burning in savannah areas was less common but tolerated, while burning in designated pasture areas was prohibited. Intentional fires are set early in the dry season, sometimes by hunters wanting to clear high grass that can obscure animals, or by herders who anticipate the flush of new growth that occurs after such fires. These early fires contribute to the rapid decline in standing biomass, but by eliminating large amounts of poor-quality grass and promoting new growth, they improve the quality of what remains (Savadogo et al. 2007). Fires may also be set in the early dry season to reduce the fuel load and prevent larger, more destructive fires in the late dry season. Finally, fires are set deliberately late in the dry season mainly to clear new fields, and brush is often piled deliberately around trees the farmer wishes to remove (Laris 2002).

Fallow periods are key to the regeneration of diverse tree species. On crop land, young trees are vulnerable to accidental destruction during plowing or by grazing animals (Ræbild et al. 2007, Haarmeyer et al. 2013). Long fallow cycles facilitate the establishment of preferred tree species like V. paradoxa (shea), which are preserved when areas are cleared (Kelly et al. 2004). Shea trees are a critical rangeland resource, especially for women, who process nuts from these trees into shea butter for household use and for sale. Wild fruits, while they make a minor contribution to overall diets, are also appreciated, as are the medicinal properties of a variety of trees and herbs. Village customary law allows anyone to harvest shea nuts and wild fruits from rangelands. They continue to be widely available, as seen in the abundance of fruit trees like D. senegalense, L. microcarpa, and A. senegalensis (Table 2).

Harvesting trees for timber or as fuelwood is regulated both by customary law and by the Malian state. Prior to 1995, Mali's Forest Code prohibited land clearing or cutting trees without a permit from the state (Code Forestier 1986). This law was changed as part of a process of decentralization in 1995. Since then, land clearing is allowed except in specific protected areas including protected watersheds and areas with steep slopes, and harvesting of trees for home use is no longer regulated. Sale of fuelwood and timber, however, continues to require authorization, and trees with important economic value are still protected, including V. paradoxa and P. erinaceus (Code Forestier 1995). In the study villages, cutting firewood for sale or making charcoal is prohibited by customary law, as is sale of timber. Firewood is collected for home use, but this is usually from downed branches and dead trees, especially from newly cleared fields. Trees may be cut when clearing a new field, for timber if it is needed for construction within the village, or occasionally for firewood. Limitations on tree harvesting appear to be largely precautionary, as good timber species (e.g. Isoberlina doka) remain common (Table 2).

4. Discussion

The Guinea savannah rangelands in West Africa are of increasing importance to regional livestock production, but because woody savannah rangelands contain heterogeneous mixtures of trees, grass, and shrubs, characterization is more complex than in Sahelian grasslands or humid forests. To describe this complex ecosystem we relied on a combination of methodologies: ground data collection on herbaceous biomass, tree cover fractions, and species composition; remote sensing image analysis; herd tracking using

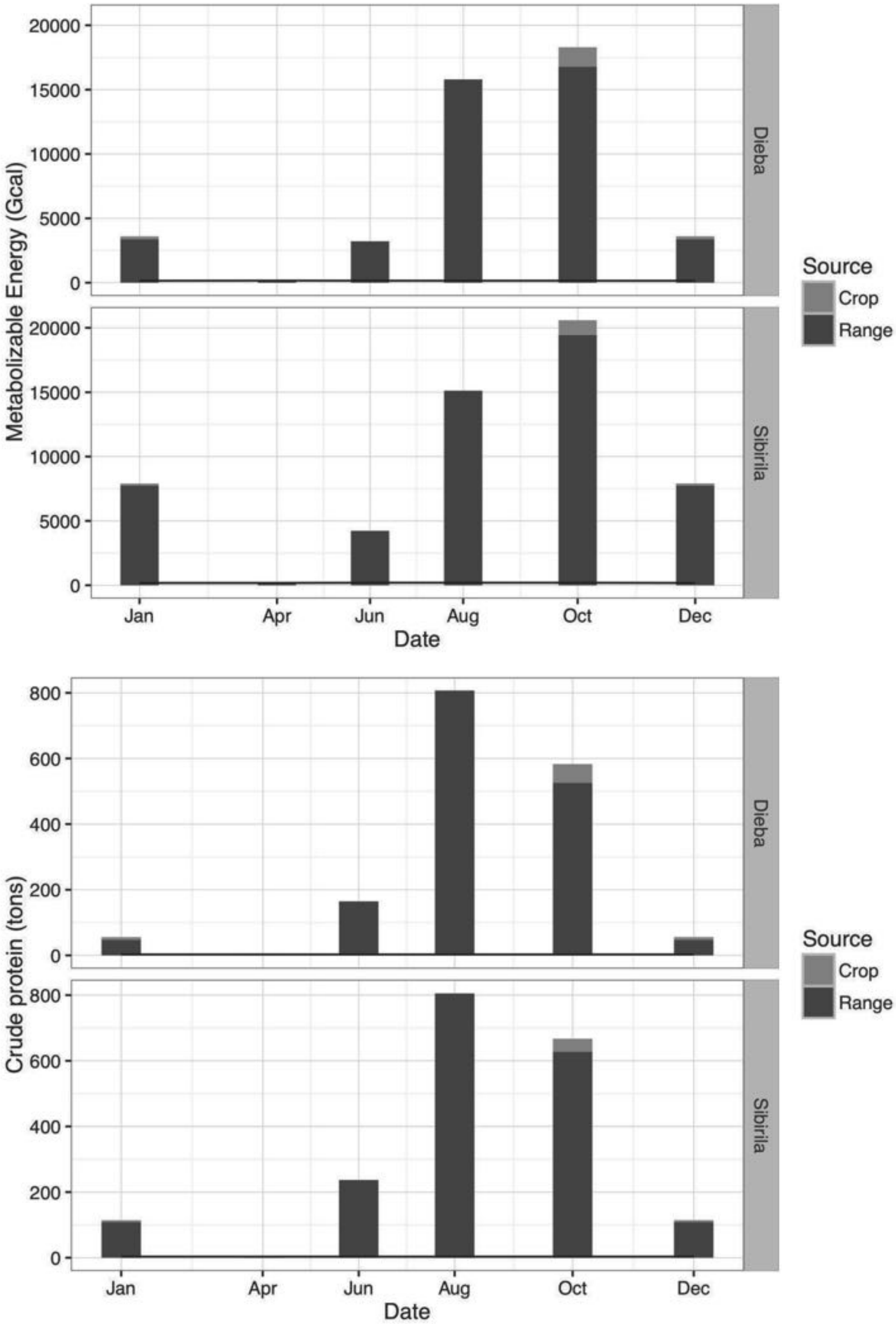

Figure 8. Total metabolizable energy (top) and crude protein (bottom) supply from village cropland and rangeland, and demand by village herds (2 month averages).

GPS and participatory techniques for community mapping and to characterize rangeland management.

Labor-intensive ground-based data collection can be extended beyond limited study areas using remote sensing techniques like those described here. The regression analysis we use is less precise than biomass estimates based on vegetation indices, but it does provide a straightforward way to estimate the spatial distribution of herbaceous biomass where other methods are not appropriate, due for example to tree presence as in this case. Moreover, the resulting estimates are similar to those obtained from field measurements. Similar methods could be used in other woody savannah ecosystems, and because the regression analysis requires only herbaceous biomass quantity, it could be done using simple ground data collection methods.

The system we characterize here is relatively non-stressed: livestock densities are low, and cropland expansion has not restricted rangelands to marginally productive areas. The current characterization can therefore serve as a baseline against which to measure changes that occur as demands on rangeland resources increase. Protected areas are often seen as the most effective way to conserve rangeland ecosystems (Bruner et al. 2001). Yet here we describe a managed system with few restrictions on grazing that shows no evidence of degradation. Indicators of overgrazing have been described as decreased species diversity, lowered abundance of perennial grasses such as A. guyanus, which are more sensitive to repeated grazing than annuals, and disappearance of palatable annuals like P. pedicellatum, which are preferentially consumed by grazing animals (Vetter 2005). Our study area retains high diversity, and both perennial grasses and palatable annuals are prevalent, suggesting that overgrazing is not present. This conclusion is reinforced by estimates of a large surplus of available biomass during the growing season (Fig. 8). Tree cover densities of 50% of total area in remote sensing images suggest that deforestation within rangelands is of limited concern.

In practice, the use of rangelands is governed under customary law as enforced by village chiefs and elders. While the Malian state has enforced a variety of forestry regulations in the past, the current system of use and management owes little to formal regulations. Under this local management, rangelands continue to be productive, with biomass production comparable to that measured in researcher-managed rangeland experiments in Burkina Faso (Savadogo et al. 2007).

Despite high peak productivity, the seasonal variation in rangeland biomass availability still leads to forage deficits at the end of the dry season (Fig. 8). The deficit is likely larger than described here, as our calculations assume 100% of biomass is available to animals. In reality, 30-50% of the total biomass produced each year is lost to trampling, burning, or other destructive processes, and is thus not available to grazing livestock (Breman and de Ridder 1991). Such a reduction would not result in deficits during the rainy season but would lead to more severe feed shortages during the late dry season.

Adoption of supplemental dry-season feeding, if combined with improvements in market access, could make livestock production a viable income generating strategy, with potential benefits that compare favorably to alternatives like intensifying crop production (Ollenburger et al., 2018). Several options already exist to fill the dry season feed gap; however each involves costs and trade-offs for farmers. Storage of crop residues for later feeding would be more efficient than the current practice of allowing herds to graze in harvested fields, and would spread the availability of these residues over a longer time period (Bosma et al. 1997). Groundnut, a common crop in the area, would be a good source of fodder due to the high protein content of groundnut haulms (Table 1). Hay could also be harvested from rangelands and stored for later feeding. However, both of these activities would take place prior to the end of the rainy season, also a time of peak labor demand for harvesting and transporting other crops. Roofed hangars would allow cut fodders to be stored effectively, but expenditure on such structures is difficult to justify while labor constraints are a limiting factor.

Tree fodders are already commonly used as a supplemental feeding strategy, and this practice could be extended. Agroforestry projects implementing "fodder banks" of leguminous trees have been widely promoted, but failures in establishment are common (Chakeredza et al. 2007) . In the study villages, Gliricidia sepium hedges were introduced about 15 years ago by the newly formed "Mouvement Biologique Malien" to surround and protect mango plantations, and have been successfully established in several other areas since then. Gliricidia, while well-accepted by most livestock when dry, is relatively unpalatable when fresh, ameliorating the challenge of protecting young trees from being destroyed by overgrazing before they are securely established. Use of supplemental feed during the dry season could also reduce the long walking distances for herds during this period, which would reduce forage demand.

Rangeland resources are most likely to be conserved where they are seen as valuable. Many tree species are valued for their use in traditional medicine, and thus tree biodiversity has often been maintained even as land use intensity increases (Nacoulma et al. 2011). Rangelands provide a range of other ecosystem services, but their value is usually discounted when compared to the immediate return of a harvested crop. Protecting rangelands from degradation or conversion to cropland thus requires that they provide material benefit to local farmers. Potential mechanisms for this exist—livestock production, non-timber forest products like shea nuts, and even moderate wood harvest could be compatible with sustainable rangeland management. The constraints on these enterprises are largely economic, social and political: livestock production is hampered primarily by a lack of access to veterinary services that results in high animal mortality. Markets for wild fruits are sparse, and markets for shea nuts and shea butter are either only marginally profitable, in the case of local markets, or require organization and certification, in the case of fair trade or organic markets. Pragmatic strategies for managing rangelands could combine efforts to ease constraints around sustainable income-generating activities with planning that is focused on maintaining the ecosystem services rangelands provide, even while cultivation expands.

5. Conclusions

Projections for southern Mali suggest that rural population will continue to grow rapidly (INSTAT 2013), and the increase in cropped area that implies will come at the expense of rangelands. In addition, increases in human population density are usually correlated with increases in livestock density, further increasing the demand for grazing resources as the area of supply declines (de Ridder et al. 2004). In more densely populated parts of Mali, cropland expansion has restricted rangelands to areas which are unfavorable to crop production. These are generally areas of low rangeland productivity, further exacerbating forage shortages which now persist even during the rainy season (Coulibaly et al. 2009).

It is difficult to imagine future pathways where southern Mali's rangelands are not placed under increasing stress. Management practices will therefore need to adapt, in order to avoid the degradation and disappearance of rangelands seen elsewhere. Such management should be informed by an account of existing rangeland resources and their value. This study provides a description of a rangeland ecosystem that has largely been conserved through local management. In addition, the combination of ground-based and remote sensing methods used here to estimate herbaceous biomass in woody savannah ecosystems could be applied to the large areas of Guinea savannah in West Africa.

Southern Mali's rangelands are not pristine natural ecosystems but rather evolving components of a dynamically managed landscape. Sustainable management that preserves the ecosystem services rangeland provides depends on local people's appreciation of the value of those services. Livestock production with dry-season supplementation and managed grazing would minimize the degradation of grazed rangelands, while earnings from livestock would increase the perceived value of uncultivated land. Mixed use systems that include livestock and tree crops in addition to staple grains could increase local incomes while reducing the environmental impact of expanded production. Land in southern Mali will inevitably change and evolve with the people who manage it. Understanding the current landscape is a key step towards considering its possible futures. Exploring those futures and their consequences can in turn provide guidance for the present.

Acknowledgments:

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Chapter 4

Are farmers searching for an African Green Revolution? Exploring the solution space for agricultural intensification in southern Mali

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Abstract

Development actors, including the African Union, the Alliance for a Green Revolution in Africa, and bilateral donors, promote a technology-driven sustainable intensification of agriculture as a way to feed a growing world population and reduce rural poverty. A broader view of smallholder agriculture in the context of rural livelihoods suggests that technological solutions alone are unlikely to meet these goals. Analysis of the solution space for agricultural interventions in a high potential area of southern Mali shows that intensification can lift most farm households out of extreme poverty and guarantee their food self-sufficiency. However, the most effective options do not fit the usual definition of sustainable intensification, increasing production per unit land while protecting the natural environment. Cropland expansion combined with the good yields seen in on-station experiments can nearly eliminate extreme poverty, while the biggest impact may come from taking advantage of peak seasonal prices for crops like groundnut. Other profitable alternatives can include meat production with small ruminants or sales of milk from cows. However, off-farm employment opportunities like gold mining outperform currently attainable agricultural options in terms of profitability. Options for rural households should fit within the households' socio-ecological niches and respond to their priorities in order to be successful. Given the relatively low impact of (sustainable) intensification technologies alone, a rethinking of the role of agricultural research in development is needed in order to align interventions with farmer priorities and meet development goals.

Keywords: Sustainable intensification, food security, optimization, livelihoods, income/ gross margin

Introduction

There is widespread consensus among development actors that Africa needs a "Green Revolution" in order to feed its growing population and reduce rural poverty. The African Union's Maputo Declaration in 2003 committed governments to allocate at least 10% of national budgets to supporting agriculture, in an effort to improve food security and reduce poverty on the continent. Supporting this prioritization of agriculture, the Alliance for a Green Revolution in Africa (AGRA) bases its strategy on the principle that technological improvements in agriculture and value chains will lead to increased agricultural productivity for smallholders, assuming that this in turn will lead to widespread economic development and reductions in poverty (Toenniessen et al., 2008). The United States Government's Feed the Future program similarly focuses on improved agricultural technologies for sustainable intensification to "end hunger and poverty" (USAID, 2011).

Like the first Green Revolution, its African counterpart was to be based on the development and dissemination of new technologies, adapted to the various agroecologies of the continent. However, while the Maputo Declaration made agriculture a priority of national governments, the prevailing neoliberal political and economic climate led to an emphasis on private sector involvement in agricultural development, from input provision to extension services, and reduced state subsidies and other support to farmers. Thus in contrast to the first Green Revolution, during which state support of agricultural research and development was prominent, this African Green Revolution increasingly relies on donor organizations and the private sector. The increasing emphasis on the private sector, along with increasing concern for environmental impact and an emphasis on participatory approaches, has contributed to increasing contestation in agronomy (Sumberg et al., 2013).

Agricultural development projects in the tradition of the Green Revolution perceive low productivity of smallholder agriculture as a largely technological problem (Sanchez et al., 2009; Toenniessen et al., 2008). This leads them to seek broadly-applicable technology-focused solutions from agricultural research — such as improved crop varieties and "best practice" fertilizer application methods and rates. The African version has been accompanied by a focus on smallholder farmers' integration into private-sector value chains (AGRA, 2015; USAID, 2011). A more nuanced view sees smallholder agriculture as embedded in and inseparable from complex rural livelihoods. Farmers make decisions not only based on yield and profit margin, but try to meet a complex set of objectives shaped by diverse social pressures, ranging from local traditions to recommendations by government agencies or changes in commodity prices on a regional or global scale (Koenig et al., 1998). For example, the introduction of cotton to the Kita area of Western Mali by the parastatal "Compagnie malienne pour le développement du textile" (CMDT) represented a substantial upheaval in the political, social, and even physical environment. Because the CMDT was conceived as not only a cotton enterprise but a rural development organization, upon its arrival in Kita CMDT agents organized village credit associations, began providing functional literacy training, and improved road infrastructure (Koenig, 2008). Farmers engaged in cotton cultivation as much out of a desire to access these secondary CMDT services as because they saw cotton as their most profitable option. Given these additional roles that cotton plays in farmers' livelihoods, the recent decline in cotton yields in some areas of southern Mali can be linked both to local, physical causes, and to a casual chain encompassing tensions within local cooperatives (Lacy, 2008), the withdrawal of secondary services by the CMDT, and international financial institutions which encouraged privatization and restructuring of the CMDT (Serra, 2014). Political ecology, by focusing on these types of causal chains, identifies the ways in which farmer decision making is shaped by extra-local political economic drivers (Blaikie, 1989). Political ecology analyses also open problem identification and definition to questioning, by recognizing that environmental management is by its very nature contested, by people and groups who may define problems very differently (Blaikie, 1995; Fabinyi et al., 2014).

Natural scientists have often used a framework and vocabulary of system dynamics to analyse socio-ecological systems, including farming systems (Collinson, 2000; Crane, 2010; Darnhofer et al., 2012; Giller et al., 2006). Agronomists (among others) have used this framework to consider the effects of larger social, economic and political forces on farmers' constraints and opportunities (Fabinyi et al., 2014). However, the simplification inherent in system dynamics-based models and analyses often fails to account for human agency, resulting in highly mechanistic and depoliticized representations (Crane, 2010). The concept of a "socio-ecological niche" has been used to recognize the social factors in which farming systems are embedded. The term was first used by ethnographers to describe cultural behaviour in terms of relationships within the human (social) and biotic (ecological) community (Frake, 1962). It has come to be used by agronomists, including to describe the physical environment and social conditions for which a given crop variety is suited (Brush et al., 1988), and to match technical options with the farmers who are best placed to use them (Ojiem et al., 2006; Descheemaeker et al., 2016). Defining a socio-ecological niche can be a helpful tool for tailoring agronomic research, by ensuring that research is directed in ways that meet farmers objectives within both their ecological and social frameworks. Defining these niches requires inter-disciplinary research to understand farm-level physical dynamics (Falconnier et al., 2016), interactions between agriculture and off-farm income sources within the household (Haggblade et al., 2010), as well as the ways farm households interact with their surrounding environment at different scales. It also requires the inclusion of smallholder farmers in research processes, as they are the only ones who can truly speak to the 'appropriateness' or usefulness of a technology. Participatory methods have for years been advocated as a means to engage smallholder farmers in technology development processes, in part as a means to better identify and address their concerns (Chambers and Ghildyal, 1985; Sumberg et al., 2013). However, the socio-cultural drivers and incentives that shape scientists' actual practices in the context of participatory technology development have rarely been critically examined as factors that explain outcomes (Crane, 2014; see also de Roo et al. in this issue for an example of where this has been done effectively).

Participatory and inter-disciplinary research centred on fitting technologies to local context does not lend itself to projects with pre-determined pathways such as "sustainable intensification" and which aim for continental or global-scale results. Nevertheless, agronomists, development agencies, and donors tend to use a set of common themes when arguing for the importance of agricultural research in developing countries: the need to narrow yield gaps in order to feed a growing population (Tilman et al., 2011; Pretty et al., 2011), or that improving the productivity of smallholder farmers will reduce poverty in rural areas (Denning et al., 2009; Sanchez et al., 2009). While there is some macro-level evidence that improving agricultural productivity can reduce rates of absolute poverty (Christiaensen et al., 2011), Harris and Orr (2014) have shown that even the best technologies for staple crop production are rarely sufficient to lift smallholder farming households above the poverty line. Agronomists thus find themselves in an invidious position. Research priorities are defined by states or international bodies who prioritize specific technologies or pathways and direct funding accordingly, but the results of agronomic research are meant to be applied by smallholder farmers, who have their own priorities and agendas which do not necessarily align with those of funders. Agronomists, as a group, possess a wide range of political opinions, professional skill sets, and personal inclinations and their agency as actors in the system cannot be discounted. However, the political bodies that set development priorities and funding organizations that determine how and where research investments flow represent the institutional context within which particular approaches and modes of engagement, as well as individual agronomists, are evaluated, rewarded or marginalized, even shaping they ways that research is conceptualized and operationalized (Crane et al 2016). As such, they establish clear pathways of upward accountability regardless of farmers' priorities and evaluation criteria. Agricultural researchers interested in contributing to development outcomes must therefore walk a thin line between the often conflicting goals of diverse stakeholders, with whom they have markedly different power relations.

We use the case of Bougouni district, in southern Mali, to explore the limitations of agricultural research for development that is based on technology transfer and focused on specific and limited sets of possible interventions. The relative ineffectiveness of sustainable intensification options in changing household poverty and food self-sufficiency status, which we demonstrate here, underlines the need for researchers, donors, and policymakers to move beyond the conception of low productivity as a technical problem with standardized, widely applicable technical solutions. Instead, low agricultural productivity is best treated as embedded in socio-ecological systems, implying the need for an interdisciplinary and farmer-focused research process both to define problems and to find solutions.

Southern Mali has long been a key agricultural production zone both for cotton, Mali’s second largest export after gold (Simoes et al., 2015), and for cereals. Increasingly, as land becomes scarcer in the “old cotton basin”, expansion of agriculture to meet growing food needs is occurring in the west and southernmost part of the country, including the district of Bougouni. Bougouni forms part of the sparsely populated Guinea Savannah zone that the World Bank described as “Africa’s Sleeping Giant,” a potential engine of economic growth because of its high agroecological potential and low population density (Morris et al., 2009). For this to happen, agricultural production would need to increase markedly. This could happen by means of large commercial ventures or through increasing the production of smallholder farmers, and while both options potentially contribute to economic growth, smallholder-led growth is generally considered to result in a more equitable distribution of benefits (Ollenburger et al., 2016). In part because of its assessment as a high-potential area, Bougouni forms a priority research zone for the Feed the Future project in Mali, itself a high priority country for both Feed the Future and AGRA. The Malian government is largely concerned with increasing staple crop production to improve national food security, and increasing cotton production as an important source of state revenue. A variety of projects have introduced options for “sustainable intensification” which, as generally defined, refers to increasing productivity on existing land while protecting the natural environment (e.g. Godfray et al., 2010; Pretty et al., 2011). Donors are also concerned with improving human nutrition and increasing smallholder incomes, expanding the notion of sustainability beyond the environmental dimension (USAID, 2011). These projects turn to agricultural research to provide “best bet” technologies which larger-scale projects can promote to meet their development goals.

Where agricultural intensification has occurred, it is because conditions either make intensification economically attractive (Netting, et al., 1989) or because land is no longer available for expansion and farmers must intensify to feed their families (Boserup, 1965). Bougouni district's low population density means that the second condition is not a major factor in farmer decision-making. In order for intensification options (sustainable or otherwise) to be adopted, they must fit into this socio-ecological niche, characterized by land abundance as well as alternative sources of income. Thus it is important to understand how the benefits of intensification compare to potential gains from other activities. We explore the potential benefits of agricultural intensification by defining a "solution space" for agricultural development in Bougouni. The idea of a solution space is borrowed from the mathematical definition: the set of possible solutions to (typically) an optimization problem. The concept has been applied to agricultural modelling to describe the set of outcomes possible via improving management practices, closing yield gaps, or eliminating inefficiencies (Groot & Rossing, 2011). In our case, we identify the solution space for intensification by evaluating the possible impact of closing yield gaps and optimizing land use for maximum profit. We then compare this to other options, including land expansion. As indicators we use household food self-sufficiency and incomes, because these are stated goals of smallholder farmers in Bougouni and allow us to consider impacts on the development goals of national food security and poverty reduction. The ability of sustainable intensification options that are outcomes of agricultural research to meet the sometimes contradictory development goals of farmers, donor organizations and the state has important implications for the role of agricultural research in development, and in turn how agronomists can engage practically in solutions-oriented research

Methods

Study Area

Bougouni district, located in southern Mali, has a population density of approximately 24 people per km2. Our study sites are the villages of Flola, Sibirila, and Dieba, to the west of the town of Bougouni (11.54°N 7.93°W – 11.42°N 7.62°W). They range in size from 500 inhabitants in Flola to 1200 in Dieba. Cropping systems are organized around cotton-maize rotations introduced and promoted by the CMDT, which has monopoly control of cotton seed distribution and the purchase of cotton. Cotton prices are fixed at the beginning of the growing season, and farmers can access credit for cotton and maize inputs through village-level cooperatives. Farmers in this area generally follow one of the two strategies described by Koenig et al. (1998): either they use agriculture as a source of both food and cash income, or they rely on agriculture for food while seeking other income generating opportunities. While it is notoriously difficult to estimate off-farm income accurately, previous studies in the area suggest that most families rely on at least some off-farm income, most commonly from local small shops or from remittances from family members working most often in seasonal employment elsewhere in Mali (Howard et al., 2016).

Scenario development

In order to explore the solution space for staple crop agriculture, we evaluate the impact on food self-sufficiency and gross margin of three intensification levels, represented by typical yields, best farmer yields, and attainable yields. Typical and best farmer yields were defined as median and 90th percentile yields from household surveys in the area. Attainable

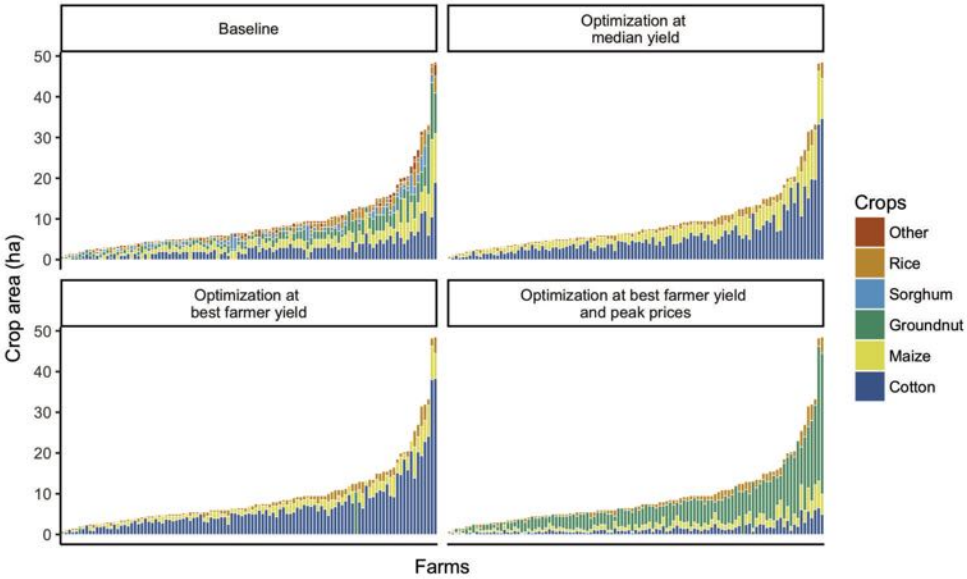


Figure 1. Land allocation to each crop in four scenarios. Farms are ordered by total land area. Other crops (orange in the baseline scenario) include sorghum, millet, fonio, and cowpea. Optimization scenarios are based on maximization of gross margins after accounting for 80% of the household's required calories from staple grains (maize, sorghum, millet, and rice).

yields represent "the maximum yield achievable by resource endowed farmers in their most productive fields" (Tittonell & Giller, 2013), for which we use yields from researcher-managed trials following best management practices. Yields at each intensification level are combined with three land use scenarios: (1) Current crop allocation; (2) crop allocation optimized for maximum gross margin, and; (3) optimized crop allocation plus a 50% expansion in cultivated land, resulting in a total of nine different crop production scenarios. Three scenarios for input and output prices are considered for each crop production scenario: current average prices, estimated average prices with removal of fertilizer subsidies, and selling produce at peak prices. Two types of integrated crop-livestock production options are also considered: sale of sheep, and milk production with stall feeding in the dry season.

All 109 farms in the study villages were characterized based on a census of family size, herd size and land allocations by crop. Data was collected with the assistance of CMDT field agents. These field agents already collect such information for a subset of farmers and crops, including GPS measurements of some cotton fields, and were thus familiar with both the procedures and the village inhabitants. Additional information regarding farmer priorities, crop and livestock management practices, and off-farm activities was gathered in focus group meetings and informal discussions over a three year period of field research. We followed the CMDT definition of a farm household or "Unité de Production Agricole," a group of people who manage land together. Because Malian farm families are often multi-generational and polygamous, these households range greatly in size, from three to 86 household members in the study villages. The impact of each scenario was calculated not for a set of "representative" farms or farm types, but for each individual farm in the study area. Using representative farms reduces the variability of a set of farms by assuming that outcomes are relatively homogeneous for farm types defined ex-ante. Analysing each individual farm allowed us to explore the effect of farm characteristics without pre-defined ideas of which of these characteristics would have explanatory power, and could therefore provide greater insight into the variability of outcomes.

Crop intensification scenarios were developed using data on yields and input use from two sources. The first was the AfricaRISING Mali Baseline Survey (ARBES), conducted in 2014 for 700 households in eight villages in Bougouni district, including some households in the study villages (Howard et al., 2016). The second was a detailed household characterization survey covering 19 households in Sibirila and Dieba, which we conducted in December 2013. We used median yields from these sources as typical farmer yields for our scenarios, and 90th percentile yields as best farmer yields. Gross margins were calculated using reported costs of production from the ARBES survey, including fertilizers, seed, pesticides, and any other costs, but excluding family labour. Gross margins per capita can thus be considered an economic return to family labour. Median yields were assumed to incur median input costs, while 90th percentile yields were assumed to incur 75th percentile input costs. Because spending on inputs and yield were only loosely correlated, we assumed efficient input use for the best farmer yield scenario. We used data from the researcher-managed trials in the area conducted by the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) to determine values for attainable yields and the associated input costs for groundnut, sorghum, millet, and cowpea. Technical briefs from the Malian Institute d'Economie Rurale (IER) were similarly used for cotton and maize. These trial yields are taken to represent the current best practices from available research.

We used a linear programming model to optimize crop land allocation in order to maximize gross margins at each intensification level subject to certain constraints. First, the household was required to grow enough grain (rice, maize, sorghum, or millet) to achieve at least 80% of its caloric needs. If this could not be attained, the household maximizes food self-sufficiency instead of gross margins. To calculate caloric needs we estimated adult equivalents as a fraction of the total household size based on the detailed characterization survey, then used data from FAO (2001) for calorie needs. The second constraint was based on CMDT policy, which provides subsidized fertilizer on credit sufficient for up to two hectares of maize for each hectare of cotton they cultivate. Maize could be grown without fertilizer, but would face a severe yield penalty, so farmers prefer to grow sorghum if they cannot access fertilizer for maize. We have assumed this practice to be universal to simplify our calculations. The third constraint was to maintain total cropped area constant, except for the land expansion scenarios which are based on a 50% increase over the current land area. Because the areas used for rice are distinct from those used for other crops, rice areas were excluded from optimization and maintained constant even in cropland expansion scenarios.

Market price data was collected monthly for one year (September 2014-September 2015) by IER agents in the study area. We explored effects of three price scenarios, including average prices for crops, a scenario in which the CMDT no longer offers subsidized fertilizer and credit to cotton growers, and a scenario using peak prices. The scenario without fertilizer subsidies used 58% higher fertilizer prices, which reflects the price difference between subsidized fertilizer purchased—usually on credit—through the CMDT and open market fertilizer prices (Africa Fertilizer, 2017). Since the CMDT controls

Table 1. Parameters used in crop scenarios

Crop	**At median yields**				**At best farmer yields**				**At attainable yields**			
	Yield (t/ha)	Gross margin (USD/ha)			Yield (t/ha)	Gross margin (USD/ha)			Yield (t/ha)	Gross margin (USD/ha)		
		Mean price	Peak price	No subsidy		Mean price	Peak price	No subsidy		Mean price	Peak price	No subsidy
Cotton	0.9	265	308	198	1.6	518	593	428	3.0	1089	1089	983
Groundnut	0.5	183	459	183	1.0	368	945	358	2.0	965	2493	934
Maize	1.6	177	352	118	2.5	304	580	224	5.0	722	1268	637
Millet	0.3	77	146	77	0.9	237	452	237	2.0	497	991	470
Rice	0.8	191	303	174	2.4	586	917	546	4.0	1034	1592	995
Sorghum	0.5	103	236	103	1.1	206	484	199	3.0	573	1368	546

both input prices and cotton prices, this scenario could also affect cotton prices. However, in our model we left cotton prices constant due to lack of relevant data, disregarding the fact that the producer price for cotton has been judged as too high. (International Monetary Fund, 2006) Therefore, the cotton price and gross margin are likely to be less favourable than we describe here. Since inter-annual price variability (FAO, 2017) was less than intra-annual variability, we used annual peak prices as recorded in the local market price data to calculate revenue and gross margin in the peak price scenario. Yields and gross margins used in each scenario are listed in Table 1.

Estimates of animal production were based on cattle numbers (divided into draft animals and other cattle) and small ruminant numbers (sheep and goats combined) from the farm census. Current herd composition and offtake rates were estimated from the ARBES and detailed characterization data. For the first livestock scenario, sheep reproduction rates of 1.9 lambs per female per year were taken from a monitoring study by Wilson (1986) in Central Mali. Such high reproduction and offtake rates can be considered a "best farmer practice" option. Input costs were limited to proper veterinary care at US$4 per animal plus US$14 fixed costs for the herd per year. As there are sufficient graze and browse resources around these villages throughout the year, supplemental feeding is not required. The second scenario of milk production was based on models of lifetime productivity of dairy cattle in the nearby district of Koutiala (de Ridder et al., 2015). Stall-fed cows consumed a total of 300 kg of cowpea hay and 240 kg of cottonseed cake during the stable feeding period of March-June, when calving usually occurs and when feed resources are most limited. Following de Ridder et al. (2015), veterinary costs were $5 per cow, while cottonseed cake costs were $45 per cow per year. Gross margins for livestock scenarios were calculated at current herd size and then with a 50% increase in the current number of sheep or cattle, depending on the scenario. In the increased herd size scenarios, farms without animals were assigned a number of sheep or cattle corresponding to the average of the families in the same farm size class, multiplied by 1.5. Size classes were defined by the amount of cultivated land, because herd size is closely correlated with cultivated area, as: 0-5 ha, 5-9 ha, 10-14 ha, 15-19 ha, 20-24 ha, and ≥25 ha.

Market price data for livestock products came from the same monthly market surveys as crop price data. We averaged prices for milk because these prices do not vary much over time. As sheep prices vary strongly throughout the year, we compared gross margins obtained with the average price over the year (US$100 per head) and with the peak price commonly obtained prior to the Muslim festival of Eid al Adha, known in the region as Tabaski (US$130 per head). Prices increase just before Tabaski because it is customary for families to purchase a ram to slaughter for the festival. Because animal production is currently not subsidized, we did not include a subsidy removal scenario here. For cattle supplementation we estimated the fodder requirement in cowpea or groundnut haulms, and assumed these are interchangeable. In the study villages, fodder markets are essentially non-existent, and transportation to towns where such markets do exist is difficult and expensive, so we assigned zero cost to fodder produced on-farm. This presumes some integration between crop and livestock components of the farm, so we considered two combined scenarios of crop and livestock production, for both cattle and small ruminants: optimization at best farmer practice (90th percentile) yields and mean prices, and optimization at best farmer practice with peak prices, both on current land areas. The first scenario assumed most land is devoted to cotton. The most economical option for producing fodder is by growing groundnut, as the grain can still be sold, so an area of cotton was converted to groundnut, in order to produce 300 kg of haulms per cow. At peak prices, land was allocated to groundnut anyhow, so the second scenario of combined production did not require a change in crop production.

We compared gross margins from the agricultural scenarios to the World Bank's absolute poverty line of US$1.90 per person per day at purchasing power parity. We used five-year averages (2010-2015) for both PPP and market exchange rate conversions (from to calculate an annual value of US$250 per person as the absolute poverty line for Mali. We also compared farm earnings with the average income from gold mining (US$1225 per person per year) from a nearby village where mining is common (Ollenburger et al., 2016). Other income sources common in the area include small shops and family businesses, remittances, and sale of firewood and charcoal, whose potential per capita incomes ranged from $600/year in the case of firewood sales to $1800/year in the case of family businesses (Howard et al., 2016).

Results

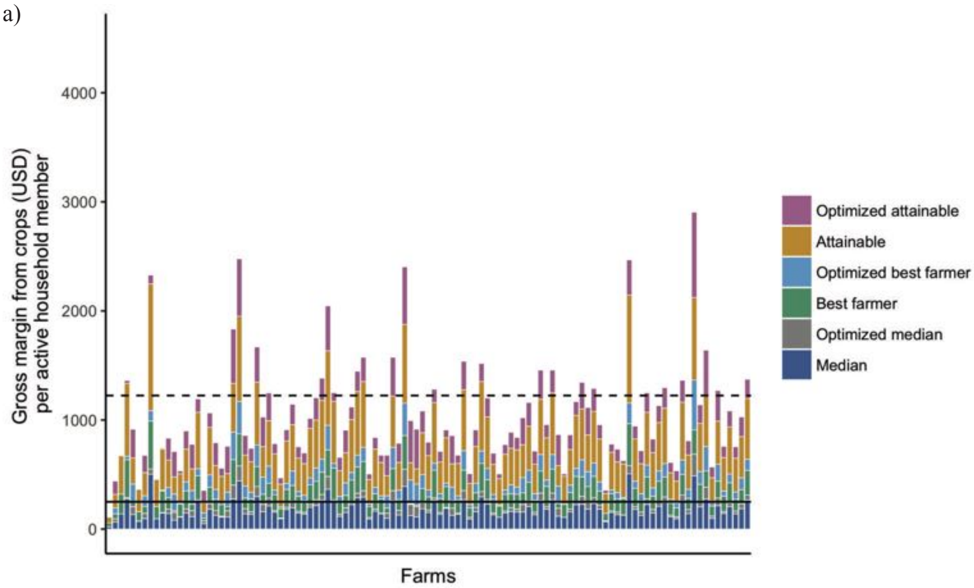
Cropping systems are currently diverse (Figure 1). Cotton, maize and groundnut occupy most of the cultivated area, complemented by other crops including rice, sorghum and millet. In the optimization scenarios crop allocation results in enough maize to meet family food needs, enough cotton to procure the inputs for maize, and the rest of the land allocated to the most profitable crop (Figure 1). This is cotton in all intensification scenarios given average prices, with groundnut becoming more profitable when sold at peak prices, when groundnut prices are double the yearly average. The resulting cropping patterns should not be considered a projection of future land allocation, because farmers use multiple criteria for crop allocation decisions. Rather, it simply represents the crop allocation that maximizes gross margins while attaining food self-sufficiency.

Most households (70%) produce enough grain to be self-sufficient in staple food, even in the median yield scenario (Table 2). Of the 25 farm households which are not food self-sufficient at median yields, seven are large households (35-80 people), with large herds (27-78 TLU) but relatively little land on a per-capita basis. These farm households likely have other resources to ensure they are food secure. The remaining eighteen farms are

Table 2. Village-level food self-sufficiency in crop production scenarios.

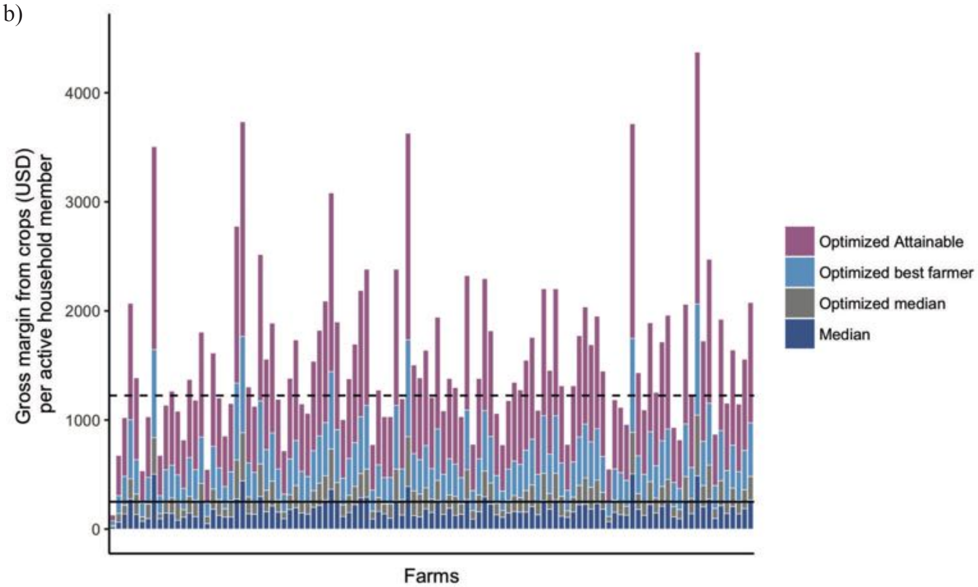
Land scenario	Yield scenario	Above 80% of required calories produced on-farm from **grain**	Above 100% of required calories produced on-farm from **all crops**
Current	Median	70%	79%
	Best farmer	95%	99%
	Attainable	98%	99%
Optimized	Median	96%	88%
	Best farmer	96%	99%
	Attainable	99%	99%
Expansion	Median	99%	98%
	Best farmer	99%	99%
	Attainable	99%	100%

a)



4000
3000
2000
1000
0
Gross margin from crops (USD) per active household member
Farms
Optimized attainable
Attainable
Optimized best farmer
Best farmer
Optimized median
Median

b)



4000
3000
2000
1000
0
Gross margin from crops (USD) per active household member
Farms
Optimized Attainable
Optimized best farmer
Optimized median
Median

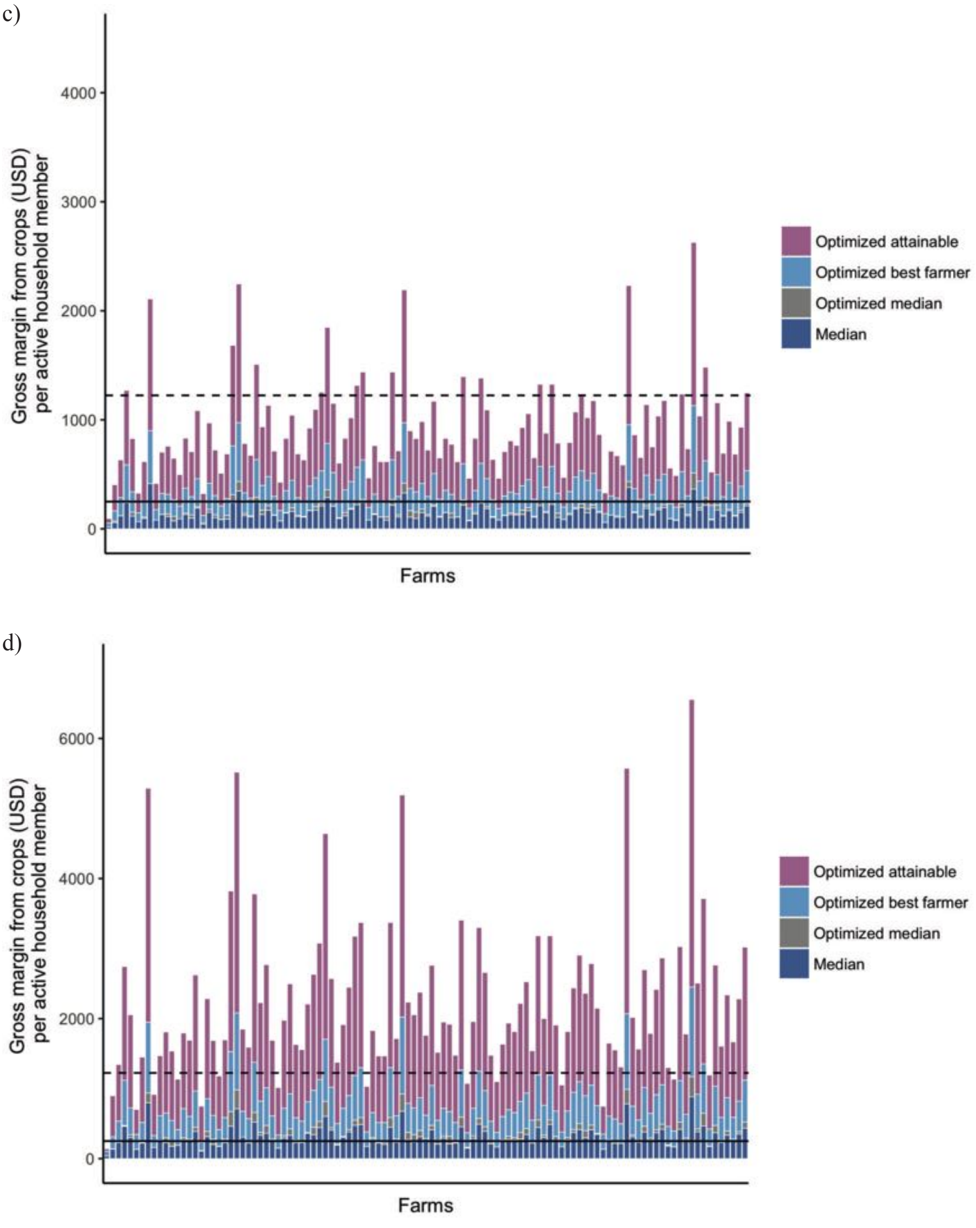


Figure 2. Income from crop production, per active household member. Farms are ordered as in Figure 1, note that income per capita is not correlated with farm size. The solid line represents the World Bank's extreme poverty line of US$1.90 per person per day at purchasing power parity, equivalent to US$ 250 per person per year at market exchange rates. The dashed line is the average income from gold mining (US$1225/person/year), the most profitable off-farm activity reported in the area.
a) Profits with intensification and optimization on current land area.
b) Profits with intensification and optimization of land use on 150% of current cropped area
c) Profits with intensification and optimization on current land area at non-subsidized input prices
d) Profits with intensification and optimization on current land area when crops are sold at peak prices

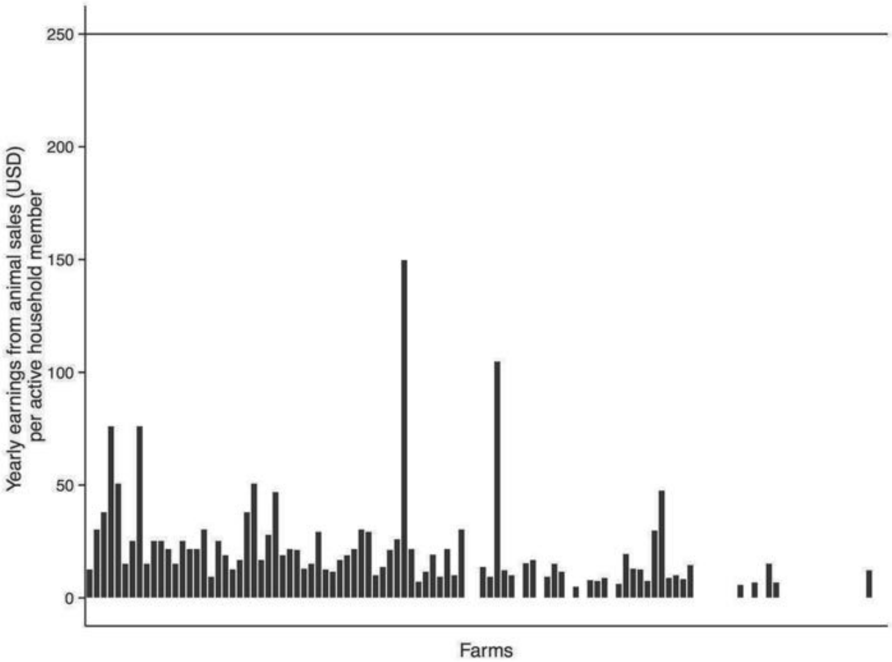


Figure 3. Income from reported sales of livestock, per active household member. Farms are ordered as in Figures 1 and 2. The solid line represents the World Bank's extreme poverty line of US$1.90 per person per day at purchasing power parity, equivalent to US$250 per person per year at market exchange rates.

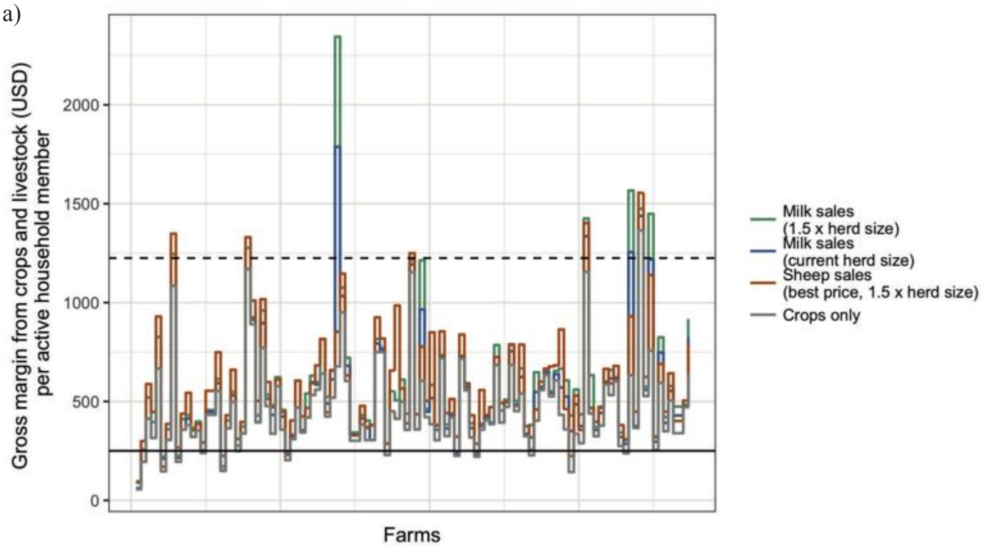
smaller than average households, with smaller than average cultivated area on both a per capita and absolute basis, and few animals. Improving yields to best farmer levels reduces the number of non-self-sufficient households to below 1% (one household in our 109-household sample), while optimizing crop allocation at current yields leaves only 13 farming households non-self-sufficient, 3 large and 10 small households.

By contrast, incomes remain low. Gross margins per capita are not correlated with farm size (Figure 2), in large part because farm size is closely correlated with household size. Thus, while larger households have more total income, this income is divided among a large number of active household members. At median yields, gains from cropland optimization are minimal, indicating that farmers are operating near maximum profits. Gains from optimization increase with larger yields. At mean prices, attaining best farmer yields dramatically reduces the number of farms below the extreme poverty line, but cropland expansion has even greater benefits. Less than one quarter of farms have per capita gross margins higher than the US$1225 level attainable from gold mining until maximum attainable yields (Table 3). The farms that do best are largely the same in all yield, land and price scenarios, although differences in initial crop allocation explain some of the variation in the relative gain from optimizing crop area allocation. In general, households with larger landholdings per capita perform best, but the group of most profitable farm households is still diverse: household sizes range from 2 to 65 people, land sizes from 1.5 ha to 48.5 ha, and herd sizes from zero to 114 TLU. The effect of prices is notable. At median yields 20% of farmers earn enough to exceed the extreme poverty

Table 3. Percentage of households in three study villages meeting poverty thresholds (US$/person/year) in crop scenarios. US$250 per person per year is equivalent, at market exchange rates, to the World Bank's extreme poverty line of US$1.90/ person/day at purchasing power parity.

Land scenario	Yield scenario	Percent above extreme poverty threshold ($250)			Percent above average income from gold mining ($1225)		
		Mean prices	Non-subsidized prices	Peak prices	Mean prices	Non-subsidized prices	Peak prices
Current	Median	20%	6%	60%	0%	0%	0%
	Best farmer	77%	61%	98%	0%	0%	5%
	Attainable	98%	98%	99%	14%	10%	61%
Optimized	Median	33%	12%	74%	0%	0%	0%
	Best farmer	87%	84%	98%	1%	0%	12%
	Attainable	99%	99%	99%	24%	19%	86%
Expansion	Median	72%	42%	94%	0%	0%	6%
	Best farmer	96%	96%	99%	6%	5%	42%
	Attainable	99%	99%	99%	59%	51%	96%

a)



b)

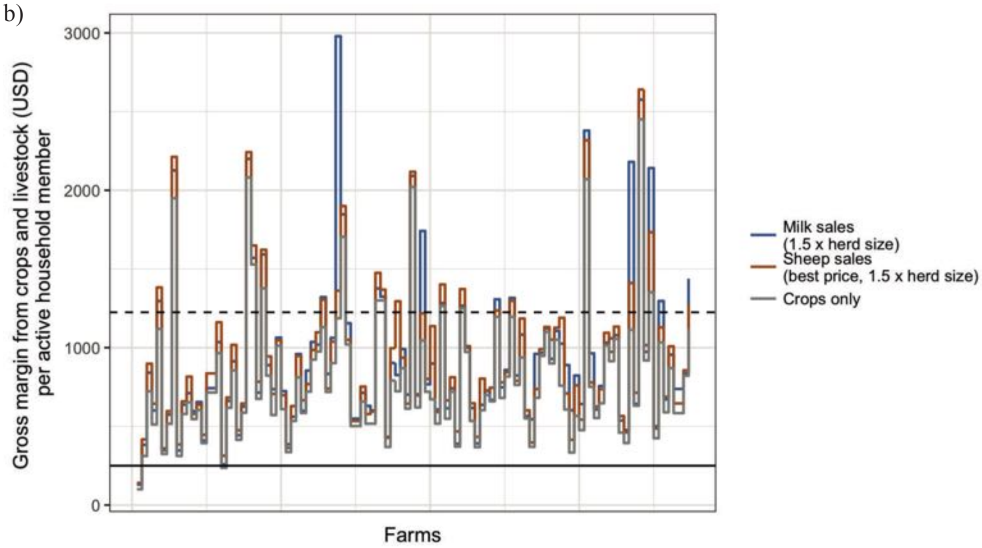


Figure 4. Income from selected livestock scenarios, per active household member. Farms are ordered as in Figures 1 and 2. The solid line represents the World Bank's extreme poverty line of US$1.90 per person per day at purchasing power parity, equivalent to US$ 250 per person per year at market exchange rates. The dashed line is the average income from gold mining (US$1225/person/year), the most profitable off-farm activity reported in the area.
a) Livestock income plus crop income from the scenario with best farmer yields and mean prices. In this scenario some cotton area is converted to groundnut to account for fodder needs for cattle feeding in milk production.
b) Livestock income plus crop income from the scenario with best farmer yields and peak prices. In this crop scenario the majority of land is planted to groundnut, and all households produce sufficient fodder for cattle feeding in milk production.

threshold at mean prices. This drops to only 6% if subsidies are removed. The impact is greater at lower yield levels; median gross margin at median yields drops from $195 per person in the mean price scenario to $149 without subsidies—a 24% drop from an already low baseline. In contrast, at peak prices 60% of farms exceed the extreme poverty threshold even at median yields. At peak prices and attainable yields, groundnut production can be highly profitable: 25% of farms have gross margins above $2600 per person per year.

Current incomes from livestock are extremely small (Figure 3). While other areas in Mali count substantial populations of pastoralists, in the study villages all inhabitants are Bambara agriculturalists, whose animals are primarily for traction as well as investment and savings. Milk production is essentially zero: our survey results and focus group discussion revealed that herders may milk a few animals for their personal consumption, but milk is neither regularly consumed nor sold. Animal sales are rare, and most commonly heads are sold to cover either expected or emergency household expenses (ILRI, 2011). The combined crop-livestock production scenarios can, however, provide important sources of additional income. At current herd sizes and mean prices these contributions are small, except for a few households with large numbers of cattle (Figure 4a). However, because of strong demand around Tabaski, sales of sheep during this peak period can provide significant income. When herd sizes increase, this becomes an even more profitable option. Milk production, for those families with large herd sizes, can also be profitable, although at mean prices re-allocation of cotton to grow groundnut for fodder comes with substantial opportunity cost, reducing overall profits somewhat (Figure 4a). With peak prices land optimization already allocates land to groundnut, so that groundnut haulms can be used for dry season feeding at no additional monetary cost—though this requires labour for collection and proper storage. This scenario produces sufficient groundnut haulms for cattle feeding for all households in the case of current herd size, and all but one in the case of a 50% herd size increase (Figure 4b). The farms with highest profits from milk production tend to be those with large cattle herds, most over 30 animals, and large land areas, most over 10 ha. In comparison, less well-endowed farm households have few cattle beyond draft animals, but are more likely to have small ruminants and thus a wider range of farms can benefit from intensification options based on these relatively inexpensive animals.

Discussion

This simple scenario analysis allows us to define the boundaries of possibilities for intensification, or the "solution space" within which farmers are working. We designed these scenarios to be as simple as possible, and to provide best-case estimates: they do not consider specific labour bottlenecks, risk, or farmers' preferences—for example, for specific crops, or crop diversity. What we describe here is in essence the maximum attainable gross margin in a given scenario, and farmers will, in all probability, continue to grow a variety of crops, resulting in lower profits while also reducing risk. We also do not consider differences in yield potential among farms, because relationships between farm characteristics and factors like labour productivity or fertilizer use efficiency that would affect farm incomes are not straightforward (Falconnier et al., 2015). Despite these simplifications, there is still much to be learned from the results. Given current technology and economic conditions, the potential gains from intensification of dryland agriculture—whether sustainable or not—are not competitive with off-farm options for most farming households. Farmers already obtain near-maximum profits given the options available to them: optimizing crop allocation provides few benefits in terms of income unless yields or prices change dramatically. Moving beyond intensification, many more farmers could move out of extreme poverty if they are able to expand the area they cultivate. Thus, as found by Harris and Orr (2014) for many other places, farmers in Bougouni may be able to move out of extreme poverty by intensifying crop production, but it is difficult for them to move much beyond that through intensification alone. Changes in price structures and/or increases in the amount of land per capita a household is able to cultivate—which in turn would require labour-saving technology such as increased mechanization and use of chemical herbicides—are needed in order to improve farmer incomes beyond the minimal requirements for survival.

In general, the scenarios which can compete with off-farm income options include drastic increases in yield, in cultivated area, in commodity prices, or some combination of these. Achieving high yields would require capital investments in seed, fertilizers, pesticides and herbicides, as well as labour for improved management. Crop land expansion would require increases in labour productivity. The widespread availability of draft animals in the study area is a result of targeted policy including credit and subsidies to farmers: similar efforts could help farmers purchase tractors. However, either case raises questions around environmental trade-offs, from increased use of chemical inputs or from cropland expansion at the expense of natural fallows, and thus will not fit the standard definitions of sustainable intensification.

Where farmers can take advantage of peak off-season prices, they depend on secure storage facilities, transportation infrastructure, and access to markets, as well as the financial capacity to absorb the costs and risks of deferred sales. It is also important to note that should production of market crops like groundnut increase as dramatically as in these scenarios, prices would almost certainly fall, and if supply becomes more constant over the year, the annual variability will no longer exist as an opportunity to exploit. Conversely, current profitability is supported by subsidies to fertilizer and guaranteed prices for cotton, policies which have been criticized as economically unsustainable by international institutions (IMF, 2006).

Integrated crop-livestock scenarios are effective at reducing poverty at best farmer yields. Small ruminant scenarios are feasible given current infrastructure, so the positive results are encouraging, as is the fact that gains are obtained across the entire farm population (Figure 4). Farm size is not a good predictor of the potential impact, and sheep sales can substantially increase farm income for positions at both ends of the x-axis—very small and very large farms. The main constraints identified by farmers for increasing small ruminant production are veterinary care for animals and market access. Animals are currently sold to itinerant traders, who pay well below the market price, although direct sales to neighbours or in local markets do occur around Tabaski. Gains from milk production, in contrast, are concentrated among a few farms, namely those with large herds. Purchasing cattle is a much larger investment than purchasing small ruminants, making milk production a less feasible option for smaller farms. In addition, milk production for the market requires a cold chain from farm to consumer—expensive infrastructure which does not currently exist. The smallholder dairy sector in Mali as a whole is very small, and is constrained by low and fluctuating supply. In addition, local milk faces difficulty competing with imported milk powder, mainly from Europe (Rietveld, 2009).

In Mali, where agricultural extension has centred around cotton since the colonial period, there are systemic barriers to the adoption of alternative cash crops by smallholder farmers. Farmers depend on access to credit and to subsidized inputs for maize, their key food crop. These inputs are contingent on cotton production, so farmers who wish to replace cotton with another cash crop must also find alternative sources of credit and inputs, usually at substantially higher prices if they are available. Extending provision of subsidized fertilizer and credit to crops beyond cotton is unattractive to the Malian state, for whom cotton income provides a key source of revenue. Because cotton sales are controlled by a monopoly purchaser, they are easily measured and taxed, while sales of other crops and livestock often move through informal channels, making them less amenable to state control and taxation (Koenig et al., 1998). The CMDT, which once provided support to crops other than cotton, has withdrawn this support as well as other rural development activities due to financial problems and pressure from international financial institutions. While other rural development organizations once provided support to groundnut and other grain crops, these no longer exist. No other institutions have filled the resulting void (Serra, 2014).

Our results raise important questions for the identified goals of reducing or ending hunger and poverty through improved agricultural production that form the basis for development programs like AGRA and Feed the Future (AGRA, 2015; USAID, 2011). Farmers in the area identify food self-sufficiency as their primary goal for agriculture (Ollenburger et al., 2016), and credit fertilized maize, which has largely replaced sorghum in the study site, for improving their food self-sufficiency (Laris and Foltz, 2014). However, for the majority of farming households who are currently at or near food self-sufficiency, there are few incentives to intensify grain production given current price regimes, particularly without cropland expansion, as is required by most definitions of sustainable intensification (e.g. Godfray et al., 2010; Pretty et al., 2011). This indicates a disconnect between current agricultural research and development priorities and the factors that make grain production profitable. If changes in prices and land expansion have the biggest impact on the profitability of agriculture, investments in storage facilities and mechanization are likely to be more effective in increasing agricultural productivity and in reducing poverty than best management practices for crop production.

What then should be the focus of agricultural research? First, researchers should not limit themselves to a pre-defined pathway or set of technologies such as sustainable intensification, but rather base their research priorities on what best fits existing socio-ecological niches. Second, one clear positive result that can be achieved with agricultural intensification is increased household level food self-sufficiency. This suggests that research on intensification of staple crops might best focus on food insecure households —the same households which are routinely under-represented in many research activities (Haile et al., 2017; Chambers and Ghildyal, 1985; Falconnier et al., 2017). Finally, for farm households which are already food self-sufficient, researchers may be able to suggest a variety of options, not limited to intensification, to meet farmers' other objectives. Crop diversification options that provide additional sources of protein and micronutrients may improve the nutritional status of food self-sufficient farmers. Legumes can provide both high-quality food for farm households and improve soil fertility when grown in rotation (Giller et al., 1997). Given the effect of time of sale, groundnut storage and marketing clearly have the potential for high impact on household incomes. Farmers in these areas are already exploring tree crops like mango and cashew as high value cash crops with relatively low labour demands, and would likely benefit from additional research on these crops and their management. While data on tree crops were insufficient to include them in the current study, cashew production, for example, has been profitable for smallholders in northern Côte d'Ivoire, not far from our study site (Koné, 2010).

Barriers to achieving higher yields are only partly based on non-adoption of already-available options, as evidenced by the large gaps between median and best farmer yields. The large gap between best farmer yields and attainable yields shows that improved technology can have an impact, however in this case the barriers to adoption are structural. Farmers' main barrier to intensifying maize production, for example, is that fertilizer availability is limited by the amount of cotton that they grow and by the CMDT's inconsistently applied and changing policies on the provision of subsidized fertilizer for maize (Laris and Foltz, 2014). If farm households had access to credit and to subsidized fertilizer independent of cotton, some might want to expand land area or intensify production of other crops. But agriculture is only one way to earn income, and for many farmers other options are more attractive—livestock production, migration, work in small businesses or gold mining. The design and promotion of technologies should thus be considered in their socio-ecological niche, where they compete not only with existing farming practices but also with other sources of income. Methods based on iterative cycles of farming system re-design and co-learning among farmers, researchers and other stakeholders can be a basis for a systems agronomy that identifies promising options (Descheemaeker et al., 2016). The concept of a basket of multiple "best-fit" technology options to answer co-defined research questions (Giller et al., 2011) is in contrast to the "best bet" technological solutions promoted by large-scale development projects. It calls for differently organized research and extension processes, which are driven by the priorities identified by farmers, as opposed to the focus on technology transfer and capacity-building of many Green Revolution projects (Moseley, 2017). While farmers have shown considerable flexibility in adapting the products of current research and development projects to meet their goals, this is no substitute for a system actually designed to address their needs and aspirations.

Researchers can also function as a "bridge" between farmers and policy makers. When working with development programs that have fixed goals and objectives, research can identify who would likely benefit from program outputs, and, just as importantly, who is left out (Carr and Onzere, 2017). If researchers take farmers' goals and perceptions seriously, they can transmit those to policymakers, helping to expand the overlap between farmer and state or donor interests: either by changing policy so state goals align more closely with farmer aspirations, or by helping state actors develop incentives that can help make state goals more attractive to farmers. In order to do this effectively, agricultural scientists must move beyond narrowly defined research questions and objectives to consider who is defining them, and even to challenge the framing and priorities of those funding their research. This, in turn, would require a substantial transformation of how the state and donor institutions define, fund and evaluate agronomic research.

Conclusions

Using a relatively limited set of data and simple models, we have been able to delineate a solution space for agricultural intensification in the district of Bougouni. Like rapid prototyping exercises in engineering or feasibility studies in business contexts, this exercise allows us to relatively quickly identify the scope of opportunities and constraints for intensification of rainfed agriculture. The limited benefits from intensification in this high-potential area leads us to question the technocratic narrative promoted by agricultural development programs promoting a Green Revolution for sub-Saharan Africa. Their narrative is based on three intertwining assumptions. First, "The low performance of agriculture in Africa is at the heart of its food insecurity and slow economic growth" (Toenniessen et al., 2008, p. 1). Second, that improved agricultural productivity is a pathway out of poverty; and finally that low productivity is largely a technological problem requiring technical solutions (Toenniessen et al., 2008). We contest all of these assertions. First, while low yields may be a contributing factor to rural poverty, claiming that low productivity is the key component disregards historical factors (Bhattacharyya, 2009) and current political and economic issues including lack of investment in rural infrastructure, health, and education (Crook, 2003; Acemoglu & Robinson, 2010; Hope, 2000)(Acemoglu and Robinson, 2010; Bhattacharyya, 2009; Crook, 2003; Hope, 2000; Ikejiaku, 2009; Jerven, 2010). Secondly, our analysis contributes to a growing body of literature showing that narrowing yield gaps in dryland agriculture alone is rarely a pathway out of poverty (Harris & Orr, 2014; Frelat et al., 2015). Finally, non-adoption of yield-improving technologies may be a rational decision by farmers given their limited impact, or a consequence of their lack of access to key components of those technologies. The existence of yield-increasing technology options in and of itself is not sufficient to improve actual farmer yields, or the gaps between current and attainable yield levels would not be so great. Farmers may see additional investments in crop production beyond those required for their own food self-sufficiency to be less attractive than focusing labour and capital investments on activities with higher profit-generating potential (Sumberg, 2005).

To improve rural livelihoods while also increasing the production of staple foods to feed a growing population, it is vital that researchers, policymakers, development practitioners and other stakeholders find ways in which their goals can intersect with farmers' priorities rather than simply imposing their own goals on rural communities. This may mean implementing agricultural support policies that challenge the neoliberal position for a declining role of government. If the goal is to improve smallholder livelihoods, agricultural interventions directly linked to food production must be accompanied by efforts to address the priorities rural people themselves identify – road infrastructure, health care, and education. If they do not take into account existing social and ecological conditions and respond to farmers' priorities, the intensification practices proposed by many agricultural development institutions may simply be solutions in search of a problem.

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Chapter 5

Exploring village futures: A participatory approach to modeling land use change in Mali's Guinea Savannah

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Ollenburger, M. H., K. Descheemaeker, T. A. Crane, and K. E. Giller. Exploring village futures: A participatory approach to modeling land use change in Southern Mali's Guinea Savannah

Abstract

Sustainable intensification is often seen as the goal of agricultural research for development. Yet technical options for intensification may fit poorly for land-abundant, labor-constrained farming systems. In order to investigate alternative pathways of agricultural development for such areas, we used a three-stage companion modeling process in two villages in the Bougouni district in southern Mali. Scenarios were generated through focus group discussions, explored with local farmers through a land use game, and analyzed using an agent-based model. Scenarios including mechanization through purchase or rental of tractors and increased production of cashew as a perennial cash crop resulted in increased incomes and lowered inequality. Subsidies for tractor purchase have limited additional impact when credit is available, and rental of tractor services distributes benefits beyond those who own tractors. Cashew production had an even larger impact on incomes, which increased up to ten times their initial value. These scenarios do not meet the definition of sustainable intensification, as they include significant expansion of land cultivated with staple crops or perennial trees. Expansion is likely inevitable, but provides an opportunity for greatly improved farmer livelihoods. Our results suggest that tree crops such as cashew can contribute to a farming system that is sustainable not only in environmental terms, but also in the economic and social dimensions.

Keywords: scenario analysis, companion modeling, participatory methods, land use change, farming systems

Introduction

Agricultural research for development in sub-Saharan Africa has coalesced around the idea of sustainable intensification: increasing agricultural production while maintaining or reducing the area of cultivated land and protecting the environment (Pretty et al. 2011). This agenda has in part arisen because research is largely conducted within a context of land scarcity, an increasingly important issue in many parts of the continent (Hengsdijk et al. 2014). The specific technologies and methods promoted may vary widely based on socio-ecological niches, researcher priorities, and donor objectives, but the basic principles of sustainable intensification are, though inconsistently defined, rarely questioned (Struik and Kuyper 2017, Weltin et al. 2018).

However, while land scarcity is a common concern, it is not universal. Also in areas where land is abundantly available, intensification is presented by researchers and development practitioners as a desirable alternative to cropland expansion—a 'cure for land hunger' (de Ridder et al. 2004) or a way to preserve the carbon sequestration potential and other ecosystem services which uncultivated rangeland can provide (Powell et al. 1996). For farmers, these arguments have tended to be unconvincing, as shown by the limited adoption of intensification technologies, particularly in land-abundant areas (Kassie et al. 2015, Glover et al. 2016, Kpadonou et al. 2017). In the absence of systemic changes that would allow for improved market access and higher producer prices, sustainable intensification is not an attractive pathway out of poverty for most smallholders (Harris and Orr 2014, Ollenburger et al. 2018). While this can be seen as an argument for industrialization and urbanization, that too is challenging. In many places the industrial sector has insufficient capacity to absorb a large increase in the workforce, as would result from a significant exodus from rural areas, particularly when combined with predicted rapid population growth.

Southern Mali's Guinea Savannah provides one example of a land-abundant area where most peoples' livelihoods are based in agriculture. This area also forms part of what the World Bank has termed "Africa's Sleeping Giant"—areas of low population density and high agricultural potential that could be key areas for agriculture-led rural development. However, agricultural productivity has been stagnant over the past 20 years (Ollenburger et al. 2016), and sustainable intensification strategies are unlikely to have major impacts on farmers' livelihoods (Ollenburger et al. 2018).

The question then remains: how can rural people make a living where they are, and can they do so sustainably? Farmers themselves have a wealth of knowledge and experience adapting their agricultural practices to a changing technological, cultural, and economic environment, as well as to their local agroecology. In recognition of this, farming systems research uses participatory methodologies to facilitate co-learning processes among farmers and researchers that can identify approaches to agricultural development that fit diverse socio-ecological niches (Descheemaeker et al. 2016). Cycles of co-learning that prioritize farmer participation at all stages, from the design of experiments, through farmer-managed trials, evaluation and analysis have proved to be effective tools for designing improved technologies and farming systems (Falconnier et al. 2017).

Companion modeling is a process to mediate co-learning processes among farmers, researchers, and diverse groups of other stakeholders, particularly for land use and management issues (Etienne et al. 2011). Researchers and farmers develop scenarios and explore them using tools including board game representations and agent-based models.

The principal approach of the companion modeling process is to develop a common conceptual model that is accepted and understood by all stakeholders. Exploration of future scenarios may then be based on a commonly held view of how the current land use system functions (Etienne et al. 2011). Research may be largely qualitative and focused on understanding social dynamics, as seen in a participatory process to design agricultural landscapes in coffee-producing communities in Mexico (Speelman et al. 2014). Agent-based spatial models can incorporate more detailed representation of environmental factors, as in the process used to develop sustainable land use strategies for agropastoral systems in Sahelian Senegal (D'Aquino and Bah 2014). Models may also simulate biophysical and socioeconomic processes in order to provide quantitative evaluation of scenarios. For example, linked socioeconomic and biophysical models were used to estimate the impacts of drought and changes in pasture access on ecosystem services, and the effect of those changes on the livelihoods of Masai herders in Kenya (Boone et al. 2011). The degree of participation by local people varies, from jointly-constructed models (e.g. D'Aquino and Bah 2014) to researcher-designed models with limited local input (e.g. Boone et al. 2011).

This article reports on the application of tools from companion modeling and farming systems research with the aim to identify and development pathways beyond intensification in a land-abundant area of southern Mali. While scenario analysis is a common technique used to explore possible futures, the scenarios used are often defined by researchers (Alcamo 2008, Winkler et al. 2011, Herrero et al. 2014). Instead, as in other participatory scenario planning exercises (e.g. Johnson et al. 2012, Butler et al. 2015), we aimed to elicit key components of future scenarios from farmers themselves so that these would better align with their own priorities and aspirations. We then explored these scenarios using a board game played with farmersand an agent-based model evaluate impacts on social, economic, and environmental sustainability . At the level of the farm household, income and total wealth were used as economic indicators, while food self-sufficiency served as a social indicator. These were identified by farmers as their goals for agricultural production. At village level, inequality in land and wealth, as measured by GINI coefficients, were used as social indicators. Environmental indicators, also evaluated at the village level, were the amount of land cleared and the expansion of cultivation into unsuitable land.

Methods

The process of exploring village futures had three stages. Each of these provided unique insights into the construction of scenarios and the interpretation of scenario outcomes. First, focus group discussions identified possibilities for changes in farming systems, which were used to define future scenarios. Next, a role-playing game was developed that provided a concrete representation of key aspects of those scenarios—accessibility of tractors and the opportunity to plant cashew. Through the process of playing the game, the game's results, and the discussions of the process, farmers and researchers explored strategies and outcomes in a representation of the village territory. Finally, an agent-based model was developed, with decision-making rules and structure informed by the game. Compared to the game, the model incorporated more detail in physical, social and economic processes, and was used to explore a wider range of scenarios and quantify impacts in different dimensions of sustainability. Each of these stages is further elaborated below.

Study Area

Research was conducted in two study villages in the Bougouni district of southern Mali. Sibirila and Dieba both have populations of approximately 1000 people, all of whom are ethnic Bambara farmers. Many households keep some livestock for draft and other purposes, and off-farm income provides important supplemental resources; however, farming provides the main source of income (Ollenburger et al. 2018). Farm households can include large, polygamous extended families, and range in size from four to eighty persons.

Both study villages were founded over 100 years ago, identified as “before the time of Samori,” referring to Samori Touré, who occupied the area in the 1890s. During that time the village of Sibirila relocated to avoid slaving raids, while Dieba was sufficiently remote that residents could avoid the worst raids. Since the early 1900s, village locations have shifted within a 5-10 km radius of the current village sites, but occupation has been largely continuous. The most common farming system, introduced 30-40 years ago, is based on rotations of cotton, maize and groundnut. Use of animal traction began to be widely adopted in the 1980s, when the Malian parastatal cotton company, the Compagnie Malienne pour le Développement du Textile (CMDT) began providing credit for the purchase of draft animals and equipment (Bainville and Dufumier 2007). The introduction of cash cropping and animal traction has led to increases in herd sizes and increased use of fertilizers and, more recently, herbicides (Dufumier and Bainville 2006).

Participatory scenario development

Initial focus group discussions took place in April 2016. A first meeting was held in which the goals of the activity were presented. At this meeting, researchers asked questions about changes that had taken place in the past, especially in the previous 20-25 years, in order to help establish a shared baseline for talking about future changes. During the follow-up discussions on village futures, villagers were separated into four focus groups by age and gender—older and younger, women and men—in order to facilitate participation by a more diverse group. Groups consisted of 10-15 people, and while participation was open to anyone, the majority of those participating were familiar with the researchers as a result of 2-3 years of on-farm experimentation and associated research activities (Umutoni et al. 2016, Ollenburger et al. 2018). Initial questions were quite general, asking participants how they saw their families’ lives changing in the next five, ten or twenty years. From here, discussion centered on changes in agriculture and land use, including creation of a village map in the present and identifying areas that could be used differently in the future—for expansion of fields, for grazing land, or other uses.

Exploring scenarios with a role-playing game

Scenarios were defined based on two key drivers that had been identified in the initial focus group discussions, namely the introduction of tractors and expansion of cashew as a tree crop. A role-playing game was developed based on the defined scenarios. The game board represented the village territory. Proportions of cultivated land, savannah, and land unsuitable for cultivation were based on 2013 Landsat images (Ollenburger et al., in preparation). The game had five players, representing heads of households which differed in land area cultivated, and assets owned (Table 1). Cultivated land was limited by the number of draft animals and tractors each player had. Regression analysis of farm census data (Ollenburger et al., 2016) estimated the average amount of land cultivated per draft team at 9 ha per season. We estimated that a tractor can plow on average 1.5-2 ha/day, including time spent traveling between plots, for a total of 45 ha of draft capacity per year. Draft capacity was represented by tokens, which were placed on the board to denote one hectare of cultivated land per token. These could be allocated each turn by the players and unused draft tokens could be rented to other players, at costs determined by the players themselves. A turn represented one three-year rotation of cotton, maize, and groundnut. Within the game, a turn consisted of three stages. First, players could invest in draft animals. Next, players allocated their tokens to cultivate land. Finally, the income from crop production was calculated and added to existing wealth. Tractors could be purchased for an initial upfront payment plus continuing costs in the following turns, beginning after the first round of play. Land productivity decreased after two turns of continuous cultivation, and again after four turns. Land could be abandoned to fallow as productivity declined, or planted to trees, for which the players had to purchase seed. The game was played for seven turns, representing 21 years. After gameplay was completed, participants discussed the process of playing the game, the final results, and how these might relate to future changes in the village. Players' in-game behavior, and more importantly their reasoning for that behavior, was used in developing the agent-based model and informed the interpretation of the model outputs.

Agent-based modeling

Model structure

The MALI-sene (Multi-agent land use and intensification-socio-ecological niche exploration) model was developed in Python 3.5, using the Mesa agent-based modeling framework (Masad and Kazil 2015). Mesa was chosen because Python is widely used in the larger scientific community, making model code more accessible than would be the case for a language designed specifically for agent-based models. To our knowledge, this is the first application of Mesa to land-use change modeling. The MALI-sene model simulates agricultural and land-use change at the village scale, using four types of agents: Land, CropPlot, TreePlot, and Owner. Land contains location-specific properties and does not move. Each CropPlot agent represents a one hectare field, while TreePlot agents represent one hectare of cashew plantation. Owners represent farm households.

Model parameters and sources

Owner agents' initial properties—household size, cropped area, livestock and draft ownership—were initialized using data from a census of farmers taken in 2013 CropPlots all followed a cotton-maize-groundnut rotation, with the first crop chosen at random. Crop yield and price data were taken from . The model included two management options: a low-input, low-yield option based on median yields in the area; and a high-input, high-yield option based on 90th percentile "best farmer" yields. Cashew yield data was taken from those reported by the African Cashew Initiative for nearby areas (Kankoudry Bila et al. 2010, Koné 2010).

Land properties included land suitability as an inherent quality; and cultivation history. Land suitability was based on Landsat imagery from 2013, SRTM (Shuttle Radar Topographic Mission) digital elevation maps, and typical soil profiles for the area. Land could fall into one of four classes: plateau, elevated, sloping, and lowland. Plateau areas, which are treeless, have shallow soils and are generally unsuitable for crop production, were determined from Landsat imagery. Areas with greater than 3% slope (based on the digital elevation model) were considered sloping, flat land above 380 meters above sea level was elevated, and flat land below 380 meters was lowland. Typically, soils on elevated lands are shallower and poorer, lowland soils are richest, and soils on slopes are intermediate. We assigned suitability values of 0.5 for elevated, 1 for sloping, and 1.5 for lowland soils.

There is considerable debate about the effects of cultivation on soil properties. We used two sources which reported yields from long-term trials in the region: at N'Tarla station in Koutiala district, Mali, as reported in (Ripoche et al. 2015); and a trial of fallowing options (Tian et al. 2005). With low-input management, decline . Under high-input management, yields . When Owner agents expand or move plots, they select the unoccupied plot with the highest potential within a 1 km radius from the centroid of their other plots.

Model Calibration

The model was run for the period 1987-2013 for Sibirila in order to calibrate . We compared results of calibration runs to village population as reported in the 1987 and 2009 census (INSTAT 2009), and the reported rural population growth rate of 2.4% per year. Census estimates of in-migration accounted for one third of the growth rate for the district as a whole. The high growth rates in urban areas suggested that this fraction is smaller in rural areas. For this exercise, we estimated a 0.4% per year in-migration rate, represented by a new Owner agent introduced at every second step. Endogenous population growth is implemented as a probability of adding additional family members within each Owner agent, and was calibrated to increase population by 2% per year. Based on traditional practice in the area, migrants get land without payment, but may not bring animals with them.

Rates of land expansion were calibrated based on remote sensing estimates of cultivated land. In 1986, Bougouni district as a whole was estimated to have 7% of land area cultivated (Laris et al. 2015). We use this estimate as we do not have a 1986 estimate for the village itself. In 2013, our Landsat classification estimate was of 12% cultivated land in Sibirila itself. After calibration, the simulated expansion went from 5% cultivated land in 1986 to 10% in 2013.

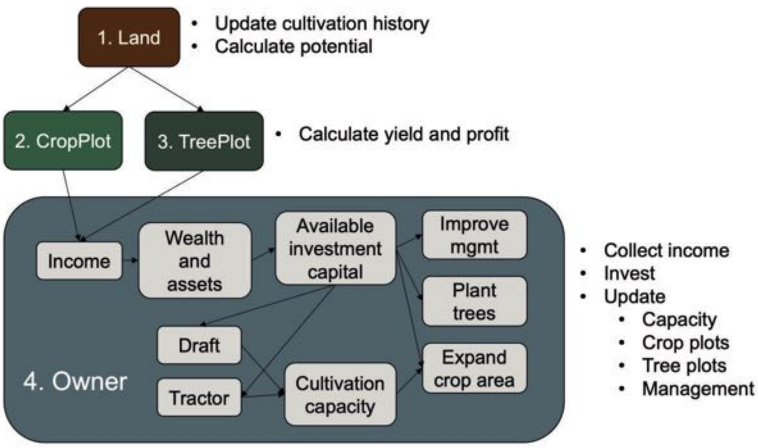

Figure 1. Model schematic showing key processes

Additional information on specific parameters and their sources and full model code are available at GitHub (https://github.com/mollenburger/Mali-sene/), and a schematic is shown in Figure 1.

Model initialization and process

At model initialization, Owners are placed at random on a virtual map (a grid of stationary Land agents), and are assigned TreePlots and CropPlots on Land units within a one-kilometer radius, with the number of plots based on census information, and locations picked to maximize land potential. At each model step, which represents one year, the crop combined with the Owner's choice of high-input or low-input management determine base yields, which are then adjusted based on land potential (suitability and cultivation history). Gross margins for each plot are calculated based on those yields, and the sum of gross margins of all owned plots comprise the Owner's income for the year. After accounting for household expenses, the Owner may use leftover income to expand their land area cultivated, improve management on existing cropland, plant trees, or purchase draft or non-draft livestock. Total cultivated land can be limited either by the Owner's draft capacity (including any rental), or available wealth, which must cover a minimum low-input cost plus hired draft or weeding labor. Household labor is sufficient to maintain 1.5 ha per person, based on both farmer estimates of weeding labor requirements and on analysis of farm size. Above this, weeding labor costs an estimated US$50 per hectare, based on farmer-reported wage rates and weeding labor requirements. New plots are placed on the highest-potential land unit within 1 km of the Owner. They may also invest in livestock, draft animals, or tractors, or in planting trees, which is restricted to already existing CropPlot locations. For the first three years after trees are planted, crop cultivation can continue, as trees are too small to significantly impact field crop growth. After those three years, the trees shade any other crops, so CropPlots must be taken out of cultivation and Owners may decide to clear a new plot for cultivation. Owners try to fallow plots which have been cultivated for over 10 years. The lowest potential plots are fallowed first. Owners may also switch from low-input to high-input management on some plots, incurring higher costs but producing higher yields (Figure 1). Once crop production is secure, Owners can invest in assets: draft animals, non-draft cattle, or in some cases tractors. Leftover wealth is carried over to the following year.

Modeled scenarios

Model scenarios were created by varying tree planting preference and tractor availability. The tree preference factor determined the probability that a given Owner would plant trees if the necessary resources were available. This was set at 0.03, 0.3 and 0.8 (on a 0-1 scale), for low, medium, and high tree preference scenarios, and all Owners were assigned the same preference in each scenario. The low value is set near zero to represent current practice. The medium value produces a scenario in which crop production is still prioritized but tree planting is common, and the high value is an aggressive expansion of tree crops. The specific values are essentially arbitrary, chosen to provide a wide range, while avoiding nonsensical results that result from preferences at 0 and 1. TreePlots are planted on the least productive CropPlotsre required to maintain enough CropPlots to meet their household food requirements in maize.

Tractors were made available for Owners to either purchase or rent. Purchased tractors could be subsidized or unsubsidized. In both cases equipment costs and credit conditions were based on the terms of the 2015 "1000 tractors" program (Mali Tracteurs SA 2015). In the subsidized case the purchaser pays half the cost of equipment, as in the 2015 program, while in the unsubsidized case they cover the full price of the same equipment. A minimum rental fraction determined the fraction of total draft capacity an Owner with a tractor rented out to other owners. This was the same for all tractor owners and was set at 0, 0.3 and 0.5, based on values observed in the games. In a final set of scenarios tractors were available for rent but not purchase. Rental cost per hectare was set at the same values as for the unsubsidized tractor purchase case, and rental capacity was unlimited.

The model was run for 22 years, to match the time period covered by the land use game and the timespan used for calibration, for both villages. The village of Dieba maintains a pasture reserve of approximately 1000 ha, about 15% of the estimated village territory. In addition to modeling scenarios in which that reserve was maintained, we modeled a selection of scenarios where it was opened to crop cultivation, so that by comparing the results we could estimate the effect of this reserve. Unless otherwise noted, results for Dieba described below are from the scenarios in which the pasture reserve is maintained.

Model outputs and analysis

At the household level, model outputs included Owner incomes, accumulated wealth and assets, and food self-sufficiency, as measured by the household's ability to meet its grain needs with its own production. Total assets were calculated by adding the Owner's cash wealth, the value of their livestock, and where applicable the value of their tractors. At the village level land use maps were produced for each model step which were used to calculate land use percentages and identify land "saturation" points at which cultivation expanded into marginal areas. Village-scale inequality in terms of both assets and land cultivated were calculated as GINI coefficients (using the ineq package in R). Data analysis was conducted in R and figures created using the ggplot2 package.

Results

Village futures

The primary objective of the focus group discussions was to develop scenarios for further exploration and the conversations were deliberately open-ended. Participants initially identified needs like improved access to health services, better education, and improved roads, before focusing on agricultural and land use practices. Two key elements emerged here: mechanization and plantations of tree crops.

The first change farmers anticipated was mechanization. This was likely influenced by the tractor subsidy program being planned at the time of our conversations. Despite bureaucratic obstacles that prevented them from participating in that program, farmers saw the purchase of tractors as an excellent opportunity, allowing them to double or triple the amount of land they could cultivate. Farmers thought that the purchase of tractors by a few of the largest families in the village would then allow others to rent plowing services. Despite envisioning greatly expanded cultivation, farmers did not have a sense that land could become scarce. While fallow periods have declined somewhat in recent years, this was attributed not to land scarcity but to the increasing availability of fertilizer, making soil fertility maintenance more attractive than working to clear new land. In-migration continues to be freely permitted, and local residents can expand their field areas as they see fit, without restriction. Only one woman suggested that perhaps they should limit in-migration, because Minianka migrants from Mali's most productive cotton area can often cultivate much more than a typical resident family.

In Sibirila, a few farmers have begun planting cashew as an alternative cash crop. In nearby Côte d'Ivoire, cashew is a major export crop, and production has expanded in southern Mali in recent years (N'Guessan and Bamba 2008). Those who have planted cashew noted several characteristics that make it attractive: it is relatively easy to establish from seed, can be sold easily for good prices, and matures late in the dry season, near the time when funds are most needed to purchase inputs for other crops. Mango trees are also common in the area, but the most productive varieties must be purchased as plants or graft stock, making establishment expensive and challenging. In addition, mango production is seasonal, and the products are highly perishable, making storage, transport, and commercialization of mango more difficult than for a more easily stored crop like cashew. However, the recent construction of a mango processing facility in nearby Yanfolila could make mango production more profitable in the future.

Land use game

The land use game was played twice, once in Sibirila and once in Dieba. In both cases players modified the game as they played. In Sibirila, players continued to cultivate field crops for one turn (3 years) after planting cashew trees on a plot, saying that for the first years the trees are so small they have no adverse impact on crop production. In Dieba, players wanted to purchase dairy cows instead of draft animals, despite the fact that these earned no income in the game framework. Price was set at half that of a draft ox, by general consensus.

In Sibirila, players began planting cashew trees as soon as they fallowed land, and generally considered that to be the obvious thing to do. In Dieba, most players initially preferred to fallow a portion of their land and only planted trees when reminded to by other players. The difference between villages is likely because cashew production already occurs at a small scale in Sibirila, while it is relatively unknown in Dieba. In both villages, the players who could purchase tractors did so as soon as possible, but spent no more than half the draft capacity of the tractor expanding their own land. The other tokens (representing remaining capacity) were rented out by the tractor owner, who could set the rental price. In Sibirila the tractor owner charged only enough to cover his costs, while at Dieba the price charged provided a small profit for the tractor owner. When asked, tractor owners from both villages considered renting services the obvious thing to do, and that it would be selfish to keep all the benefit to themselves. Because less wealthy farmers could now rent tractor time, land became more evenly distributed as the game progressed (Table 1).

Notably, even though cashew production was more profitable than staple crops, players insisted that they would continue producing their own food, rather than selling cashew to buy maize. While the cashew plantations might allow them to reduce the amount of land needed for annual crops, they saw reliance on the market for their staple food as risky because of the difficulty involved in calculating how much grain the family would need, as well as the potential for grain prices to increase. Players in both villages pointed out that if only one person in the village was growing maize, he could charge very high prices and everyone else would have to pay.

In both cases, the final map showed a marked decrease in the amount of uncultivated land. As the game progressed, land that would have been left fallow was now planted to trees and thus unavailable for clearance and annual crop cultivation. In Dieba, most of the remaining free land was in the area designated as pasture under local customary law.

Table 1. Land use change simulated in a board game played by farmers in the villages of Sibirila and Dieba. Initial cultivated area was the same in both cases, but final areas varied based on players' decisions.

	Initial area cultivated (ha)		Final area cultivated (ha)			
			Sibirila		Dieba	
Player	Crops	Trees	Crops	Trees	Crops	Trees
1	27	2	20	82	23	72
2	18	0	21	51	20	53
3	9	0	16	32	16	36
4	9	0	16	27	15	29
5	4	0	8	19	12	18
Total	67	2	81	211	86	208
All cultivated land	69			292		294

Players saw this as evidence for why such a space was important to maintain and said they would continue to exclude cultivation in that area, even if that meant limiting crop cultivation. In Sibirila, uncropped space was distributed more evenly around the village, but players were unconcerned about potential pasture scarcity. Once the trees were established, they said, animals could graze below, and if people needed more space for food crops, they could cut the trees. There was some concern about the difficulty of protecting the trees in the dry season, and in Dieba players mentioned the potential for increased conflict with transhumant herders who travel through the area. In general, players in Sibirila thought that the final game board could represent a realistic future for the village, while in Dieba players thought there would be fewer trees in reality. Instead they considered dairy cattle a good investment, especially if marketing opportunities would improve, perhaps along the paved highway from Bamako, which passes 40 km away.

Model results

Distribution of cropland at model initialization had substantial overlap with current cropped area as seen in Landsat imagery, indicating that our assessment of land suitability was consistent with farmers' own choices for field establishment. In Sibirila, the area west of the village was classified in the model as medium to low suitability, and was thus sparsely occupied, while in reality this area has relatively high rates of cultivationHowever, we chose not to adjust the suitability classes because we were less concerned with matching specific spatial patterns of cropland than in exploring village-wide trends. In Dieba, the overlap of observed and initial modeled cropland was much closer, with only a few discrepancies occurring where fields were planted on or near plateau areas the model avoided. Dieba's reserved pasture area had an average suitability slightly greater than the overall mean for the village (0.92 for pasture compared to an overall average of 0.85), but less than the average suitability of cultivated land. This indicates that while the village has not reserved its best land for pasture, neither is this an area unfit for crop cultivation—a result which confirms impressions from on-the-ground observations.

Tree planting preference:	Income per person (US$, average) 0.03	0.3	0.8
Tractor types:			
None	170	826	1632
Subsidized	169	814	1484
Unsubsidized	170	819	1589
Rental	406	1278	2458

Table 2. Annual income per person, averaged in years 19-21 of modelled scenarios without tractors, with subsidized tractors, unsubsidized tractors, or tractor rental; and with tree planting preferences of 0.03, 0.3 and 0.8 representing the probability that any given farmer will plant trees given the resources available to do so. Initial annual incomes per person average US$190.

All the scenarios explored in the model, except for the base case in which tree planting continued to be rare and tractors were unavailable, increased farmer wealth and income. Tree planting preference had the largest overall impact—indeed, without income from tree crops, no owners were able to purchase tractors. Annual incomes per person increased from an initial value of about US$200/person to a maximum of US$2500/person with high tree preference and unlimited tractor rental (Table 2). Tractor rental alone increased incomes to $400/person, more than double the values without tractors, but trees had a much greater impact: even without tractors, average income in high tree preference scenarios was $1600/person. Subsidization of tractors reduced incomes slightly when compared to the unsubsidized case in the high tree preference scenario. While subsidies allowed more farmers to purchase tractors, this led to increased expansion of less-profitable staple crops and a correspondingly smaller tree crop area. Food self-sufficiency was also highest in the high tree preference scenarios, with 90% meeting their household grain requirements from own production, and lowest in the low tree preference scenario at 68%. Increased income earned from tree crops was invested in increasing staple crop production and thus food self-sufficiency, either by improving management or expanding crop area. In the moderate tree preference scenario, 84-86% of households were food self-sufficient, with the highest percentage found in the case with subsidized tractors. In the high and low tree preference scenarios tractor availability had no impact on food self-sufficiency.

When they could be purchased, tractors generally lead to increases in wealth for those who owned them, but the average impacts at village scale were modest. This was reflected in each scenario's impact on wealth and land inequality, as measured by the GINI coefficient of total assets (Table 3a) and of cultivated land area (Table 3b). In the baseline scenario without trees or tractors, the GINI score for assets increased slightly, from its initial value of 0.61 to 0.67. Final GINI scores decreased with increasing tree planting preference. With medium tree preference, final GINI was 0.59, and with high preference this decreased to 0.5. Tree planting reduced inequality because its limited demands on capital and labor made it accessible to nearly all households. Because establishing tree plantations required a small initial investment, even poorer farmers could plant trees, and because labor demands are low, smaller households with less available labor can expand the area planted to trees more easily than the area under more labor-intensive staple crops. Tractor purchases had mixed effects on inequality. Introducing unsubsidized tractors increased final GINI values when compared to the no tractor scenario. Subsidized tractors lowered final inequality where tree planting preference was high, while having little impact in the medium tree preference scenario. In the medium tree preference scenarios, only a few farmers could afford unsubsidized tractors, increasing inequality, while subsidies allowed more widespread access. In the high tree preference scenario, final tractor ownership was near-universal in the subsidized case, but poorer farmers spent large fractions of their income purchasing tractors, which reduced the area of trees they could cultivate and thus their total income. Compared to scenarios without tractors, rental reduced inequality in all but the high tree preference case, by providing a means for farmers with few or no draft animals to increase their cultivated areas. Inequality in cultivated land followed largely similar patterns (Table 3b). The minimum rental fraction in tractor purchase scenarios had very little effect. Increasing minimum rental fraction tended to increase GINI scores for total assets, while reducing land inequality, in both cases only slightly (results not shown). While more farmers were able to expand their cultivated area by renting tractor time, resulting in a more equal land distribution, the additional profits made by tractor owners from rental offset wider benefits from land expansion, resulting in greater wealth inequality. Because the rental fractions had little effect, we adopt the intermediate value of 30% of tractor capacity rented out in further discussion below.

Opening Dieba's pasture reserve decreased GINI scores for total assets by 9-24%, with the strongest impact in the high tree preference scenario with tractor rental. This is also the scenario with the highest percentage of cultivated land, and the scenario with the highest inequality when the pasture reserve is kept in place. Income per person also increased when the pasture area is opened, by 7%-16%. The largest increase in income came in the scenario with high tree preference and unsubsidized tractors, where incomes increased by $250 per person per year.

a)

	GINI coefficient, total assets		
Tree planting preference:	0.03	0.3	0.8
Tractor types:			
None	0.675	0.587	0.501
Subsidized	0.674	0.582	0.494
Unsubsidized	0.675	0.580	0.495
Rental	0.559	0.569	0.531

b)

	GINI coefficient, land cultivated		
Tree planting preference:	0.03	0.3	0.8
Tractor types:			
None	0.445	0.417	0.391
Subsidized	0.445	0.400	0.348
Unsubsidized	0.445	0.422	0.381
Rental	0.379	0.393	0.385

Table 3. Inequality in distribution of (a) assets and (b) land, in modelled scenarios without tractors, ability to purchase subsidized or unsubsidized tractors, or unlimited tractor rental, and with tree planting preferences of 0.03, 0.3 and 0.8 representing the probability that any given farmer will plant trees given the resources available to do so. The GINI coefficient ranges from zero (perfectly equal resource distribution) to one (maximum concentration of resources). Initial GINI coefficients were 0.614 for assets and 0.411 for land. Results presented for a minimum rental fraction of 0.3.

Length of continuous annual crop cultivation tended to increase from its initial average of 5.6 years (Figures 2 and 3). This was most notable in the case without tree planting, where field age in year 20 reached an average of 21 years, with improved management often used to counteract the decline in land potential with time. In scenarios with higher rates of tree planting, potential income from tree crops planted on fallows provided an additional incentive to remove land from annual crop cultivation, resulting in average field ages of 9-13 years in the medium tree preference scenarios, and 6-8 years in the high tree preference scenarios.

In the 22-year model timespan, cultivated fractions largely remained too low to show significant land scarcity effects, except in scenarios with high tree preference and/or tractor rental (Figure 4). Average suitability of cultivated land (including both crops and trees) tended to decline when cultivated fractions reached about 40% of arable land. The average suitability of land dedicated to annual crops remained higher than that of land planted to trees, because tree planting and land fallowing occurred on the least productive land first. Tree planting occurs on cropped land, but since, unlike fallow, tree plantations then become permanent, new crop fields must be cleared in order to continue staple crop production. As the amount of available land declines, eventually new crop fields are pushed into less-suitable areas, although this effect can only be seen over long time scales or in scenarios with very high expansion rates.

Discussion

The companion modeling process

The three-stage process of scenario development, collaborative game, and agent-based model provided a valuable framework for exploring ideas about the future of farming, while allowing farmers' own goals and priorities to guide the process. The changes that farmers identified are clearly linked to their own constraints. Because land is abundant and labor scarce, they saw more potential in mechanization and tree crops with low labor demands, as opposed to yield-improving technologies requiring investment of labor and capital on existing land. Both during scenario development and the game, researchers needed to incorporate participants' adaptations of the process, wanting to incorporate non-draft livestock into the game. These adaptations contributed to understanding farmers'

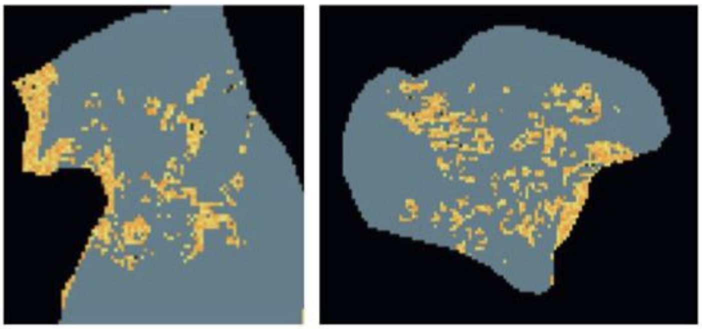

Figure 2. Land use maps in modelled scenarios at initialization for Dieba (left) and Sibirila (right). Orange pixels show crop fields, with shade indicating field age, green show tree plantations, and grey areas are uncultivated. Black areas of the map are outside the village territory and cannot be cleared for cultivation.

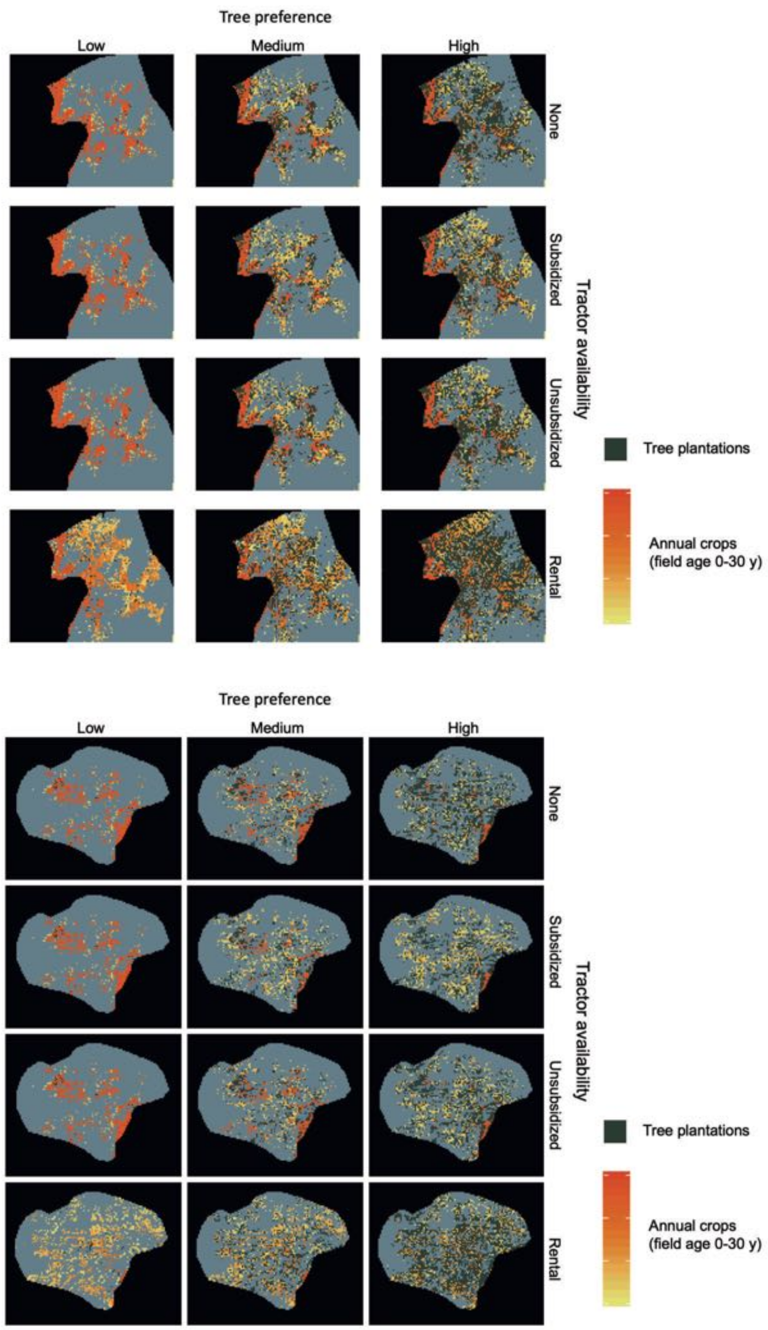

Figure 3. Land use maps in year 20 for Dieba (top) and Sibirila (bottom); in modelled scenarios without tractors, with ability to purchase subsidized or unsubsidized tractors, or with unlimited tractor rental; with low, medium, and high tree planting preferences representing the likelihood that any given farmer will plant trees given the ability to do so. Orange pixels show crop fields, with shade indicating field age, green show tree plantations, and grey areas are uncultivated. Black areas of the map are outside the village territory and cannot be cleared for cultivation.

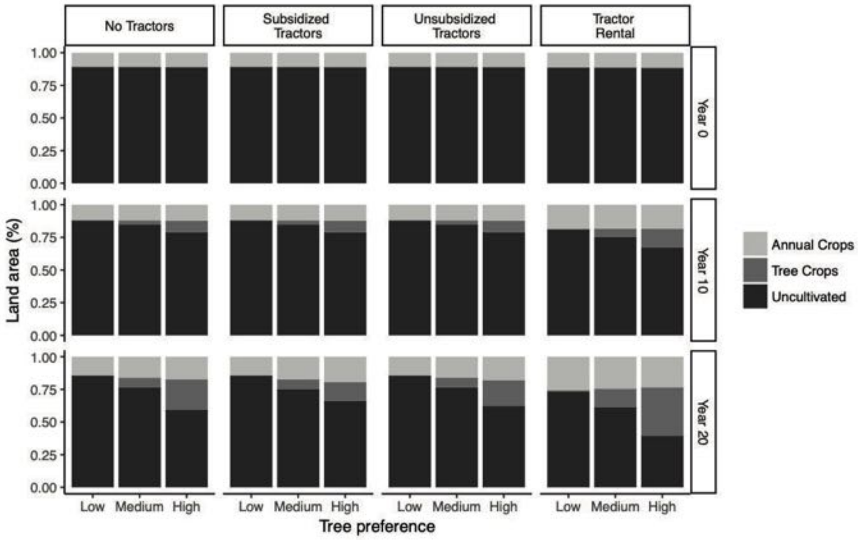

Figure 4. Land use by cultivation type in modelled scenarios without tractors, with the ability to purchase subsidized or unsubsidized tractors, or with unlimited tractor rental; with low, medium, and high tree planting preferences representing the likelihood that any given farmer will plant trees given the ability to do so. In the low tree preference scenarios tractor purchase was rare because of lower incomes. Results are shown for Sibirila; those for Dieba are similar.

practices and decisions. Continuing crop cultivation under young trees was a way to make maximum use of available land and so save labor costs of land clearing, while non-draft livestock were used primarily as a form of savings in the game, as is also seen in practice. These adaptations were then included in the agent-based model.

The MALI-sene model occupies a space between highly participatory, more qualitative models , and researcher-constructed, biophysically detailed models (Boone et al. 2011). In our case, farmer participation was limited to the first two steps of scenario generation and gaming, and the representation of the physical landscape was simplified. The resulting model would not be appropriate for detailed future predictions or evaluating complex processes such as soil carbon dynamics. It does, however provide insight into long-term landscape dynamics and allows us to evaluate scenarios based on key changes which farmers identified themselves.

Interpretation of model results

The model assumed that farmers optimize their use of capital and labor, their most limited resources, rather than land, which remains abundant. Modelled maps reflected what farmers described in initial scenario discussionsIt is in this sense that intensification may have a land sparing effect—farmers are not explicitly preserving land, but labor. In scenarios with tree crops, the results changed. Tree planting provided additional income with lower demands on labor, making expansion more attractive. The availability of more profitable land use options prompted farmers to expand faster, not to save land, because, as they noted in the land use game, they do not consider the expansion of cultivated land to have negative consequences. This aligns with the typical rural development trajectory of expansion before intensification (de Ridder et al. 2004).

In addition, new land can be acquired with little cost. Both communities still have tenure systems based on land use: anyone native to the village is free to clear new land, and fallow land reverts back to common property—thus the only cost associated with expansion is the labor required to clear new land. In more densely populated areas of sub-Saharan Africa, tenure systems have evolved as land became more scarce (Benjaminsen 2002, Ellis and Freeman 2004), and cashew plantation has been explicitly described as a way to maintain control of land area, when fallowing would otherwise be practiced (Dufumier 2005, Ollenburger et al. 2016). Changes in tenure systems were not suggested in any discussions with farmers, but should these occur, they could either encourage or restrain expansion.

Tractor purchase increased incomes among tractor owners, but also for non-owners, who could expand their own cultivation by renting tractor services. However, if these areas are still planted in staple crops with relatively low profitability, the increase in farm size has limited impact on household. Tractor owners did not massively expand their crop areas to capture a greater fraction of available land, but rather rented much of their capacity, reducing inequality in the tractor scenarios, even where rental was not mandated. Once cultivated area exceeded a household's capacity to weed—above 1.5 ha per person—additional paid labor was required to expand further and rental became a more attractive source of income. Reduced labor demands throughout the cropping season, for example through increased use of herbicides, could relax this constraint and change land use dynamics. Social constraints may, however, still limit an individual farmer or household's ability or willingness to expand far beyond typical farm sizes, and rental income is likely to remain important as an immediate and assured source of revenue, unlike uncertain and often delayed farm income.

The widespread benefit of tractor ownership seen here might be considered a reason to support tractor subsidies, but the negligible difference in impact between subsidized and unsubsidized tractor scenarios did not seem to justify the scale of investment that would be required. Simply making tractors available, with appropriate credit systems, was equally effective in improving overall incomes, as the increased initial cost of equipment was easily recouped over less than 10 years. The 2015 program was intended to distribute 1000 tractors, of which 50% of the cost would be covered by the Malian government. For 1000 tractors, this would cost the state the equivalent of nine million dollars (US). Nine million dollars spent improving infrastructure, providing health services, literacy programs, or agricultural extension would likely have larger impacts on farmer livelihoods and well-being. Accusations of corruption within the subsidy program and barriers to access for smallholders further support this conclusion

Expanded cashew production was the most effective strategy to improve incomes. Even without tractors, average income with high tree preference reached US$1600. Because cashew establishment is inexpensive and straightforward, even smaller, poorer households could take advantage of the opportunity to plant this profitable crop. Cashew markets in Mali are currently limited, but linkages to markets in Côte d'Ivoire may be possible. The global market for cashew is growing, and West Africa has begun to develop processing and export capacity, led by Côte d'Ivoire and Nigeria (Dendena and Corsi 2014) . Large-scale expansion of cashew production such as that seen in high preference scenarios would certainly have an impact on market prices, and may therefore not be realistic. However, there may be other tree crops that have similar key characteristics—ease of establishment, low demand for labor, and relatively high price—that would result in similar benefits.

Mixing cashew with other tree crops, such as mango or indigenous fruit tree crops, would also provide income diversification (Kalinganire et al. 2007).

Implications for sustainability

All of the modeled scenarios violate a key principle of sustainable intensification: they expand, rather than maintain or reduce, area cultivated. Clearing woody savannah for crop production has impacts on global carbon cycles and implications for global climate change, as well as more local environmental consequences from changes in the water cycle and loss of biodiversity (Vasconcelos et al. 2015). However, it is clear that intensifying current crops, on current land area, will not significantly improve farming incomes (Harris and Orr 2014, Ollenburger et al. 2018). Farmers in this area are reluctant to take land out of staple crop production in order to plant higher-value crops, because of market uncertainties and the traditional importance to heads of household of providing for the family. Introducing new cash crops, then, does not lead to crop substitution on existing area but incentivizes expansion. This presents a fundamental conflict between the aims of improving farmer incomes and limiting cropland expansion.

Setting limits to land expansion by local people seems unlikely to happen. Although grazing on rangelands provides the bulk of livestock diets , current rangeland productivity far exceeds the demand of local cattle. Since it is unlikely that rainy season fodder scarcity would become a limiting factor for livestock production, there are few obvious costs associated with decreasing rangeland area. Nevertheless, the village of Dieba maintains a pasture reserve despite the opportunity cost in reduced income and increased inequality. However, the larger, wealthier households who tend to hold more decision-making power also own more livestock and benefit most from maintaining pasture. While this dynamic has potentially problematic social implications, it may act in favor of conservation of uncultivated savannah.

If we accept that expansion is inevitable, we can then consider the social and environmental implications of different types of expansion. Where tractor rental services were available but tree crops were not, modeled increases in income resulted from expanding annual crop area—in Sibirila, this increased from 600 ha to 1400 ha. A scenario with unsubsidized tractors and medium tree planting preference left a similar amount of uncultivated savannah, but instead expanded annual crops to only 900 ha and added 400 ha of cashew. This second scenario resulted in more than double the average per capita income compared to the scenario with only tractor rental, and reductions in wealth and land inequality. While cashew plantations do not provide the same ecosystem services as natural savannah, they do reduce soil disturbance and thus provide environmental benefits when compared to annual cropping systems (Vasconcelos et al. 2015, Rogé et al. 2017). Where tree planting preference is high, the increased demand for land can accelerate the process of land saturation, leading to earlier exploitation of more marginal land, with associated land degradation and negative environmental impacts. However, at more moderate levels tree planting can be a promising option for improving farming system sustainability.

Conclusion

Expansion of land area, and the increased earning potential that comes with it, was a key positive outcome of the game scenarios for farmers. Mechanization would allow them to clear more land, while income from tree crops could allow heads of household to pay younger men for their farming work, making off-farm options like gold mining or migration less attractive, and ensuring sufficient labor to meet the demands of a larger land area. Farmers considered the environmental trade-offs of land expansion of minor importance. In part, this stems from the difficulty local people have in imagining the disappearance of woody savannah rangelands, given their current abundance. In addition, the resources they take from rangelands are a minor contributor to household livelihoods, whereas agriculture forms the main source of income, and adult heads of household are unlikely to encounter any serious constraints due to land scarcity within their lifetimes.

The sustainability of future scenarios thus depends substantially on the framework within which those scenarios are viewed. To farmers, expansion of a high-value, low-labor tree crop appears to have no real downside. On the other hand, land conversion of the type described in these scenarios contributes to global climate change, and, if considered on longer timescales, could lead to significant land scarcity at the local level. However, it is unrealistic and unreasonable to expect smallholder farmers to concern themselves with global climate implications of land clearing, much less to forego income generating opportunities that could markedly improve their lives. If, as in Dieba, farmers see potential benefits in reserving land, they may do so: if savannah land is needed for livestock grazing, if legal protected areas are enforced, or if there are other clear benefits to protecting land it may be excluded from cultivation. Improved agricultural technology and market forces are likely to be insufficient In the absence of policies that provide incentives for preserving uncultivated land, cropland expansion will occur. Researchers may be able to influence the magnitude of impact due to land conversion by developing crop production options with lower environmental impact, but eliminating cropland expansion excludes farmers' best options for improving their lives.

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Chapter 6

General Discussion and Conclusions

Introduction

The preceding chapters have addressed specific objectives of this thesis, beginning in Chapter 1 with the overall goal of exploring options that would allow farmers to improve their livelihoods while maintaining the natural resource base on which those livelihoods depend. This chapter presents a summary of key results, followed by a discussion of a theme that appears also in the previous two chapters: What roles should scientists play in agricultural research for development?

In Chapter 2 we characterize farming systems and land use change over two decades, and find that although southern Mali forms part of the so-called Sleeping Giant, agricultural productivity has been largely stagnant since the adoption of the cotton-based system promoted by the CMDT. Chapter 3 characterizes rangelands' important contributions to farming systems and farmer livelihoods, and provides evidence that this ecosystem, while threatened by population growth and cropland expansion, is currently thriving under local management. Chapter 4 identifies a solution space for sustainable intensification, and shows that cropland expansion and changes in market conditions have potentially greater impacts than intensification on existing land. The limited potential impact of intensification highlights the disconnect between development goals of reducing hunger and poverty through sustainable intensification and the limited incentives farmers have to invest in intensifying staple crop production. This chapter also introduces potentially-profitable livestock production options, which have the potential to both increase the value of rangeland, incentivizing its conservation, but also to increase the stress placed on those rangelands. Livestock options also require changes in markets, infrastructure, and institutional support in order to be feasible. Chapter 5 combines knowledge gained from the previous chapters with information from focus group discussions with village farmers to create scenarios based on increased tree crop production and tractor availability. These scenarios were then explored with farmers through a land use game, and further expanded using an agent-based model. Expansion of cultivated land occurs in all of the scenarios we studied; however, the negative impact of expansion may be less for tree crops than for annual field crops, making tree crops the more sustainable option. These farmer-identified options showed greater potential to improve farmer livelihoods than the researcher-proposed strategies evaluated in Chapter 4, once again raising questions about the suitability of sustainable intensification in this area and the role of scientists in agricultural change.

Research *for*, *in*, or *and* Development

In an environment where agricultural research is expected to produce development outcomes, it becomes difficult to delineate the boundary separating "research" from "development." As scientists, is it our job to "do development?" What role should scientists play in development-oriented agricultural research? Perhaps the most common framework for development-oriented agricultural research is "research for development", or R4D. In the R4D framework, researchers' role is to produce new technologies, which they then pass on to others for implementation and upscaling. While research priorities may be influenced by development objectives, information primarily flows in a linear pipeline from researchers to development practitioners to farmers (Leeuwis et al. 2017)

Coe et al. (2014) describe an alternative “research in development” paradigm that views technical options, delivery mechanisms, and appropriate institutional and policy environments as parts of an integrated whole. Innovation in all three areas, integrated across scales and sectors, is needed in order to achieve significant development impacts. Technical innovations should be considered at scales from field to landscape, while institutional policy may range from the village to the national level. Agricultural research processes, rather than being a pipeline from researcher to farmer, become iterative processes in which researchers and farmers work cooperatively to develop, test, and evaluate new options (Coe et al. 2014). Research in development processes create collaborative networks of researchers, development organizations, farmers and other stakeholders and supports those networks in developing their own ‘capacity to innovate’ (Leeuwis et al. 2017). Stakeholder networks with the capacity to innovate identify problems and experiment with potential solutions, be these technical or social, and researchers can then respond to those priorities.

Abstract discussions about research paradigms and semantic distinctions between research in development and research for development may seem esoteric, but in fact the research in development approach shares similarities with commercial research and development. Commercial R&D processes drive innovations in industrial agriculture. Bayer, John Deere, and others develop new hybrids, new inputs, new machines, and sell them to farmers. Agricultural technology development in Africa, on the other hand, is still largely (though not entirely) the purview of publicly funded scientific research institutions. Research institutions, as the name suggests, employ scientists who are evaluated based on metrics like publication records. At the same time, they are being asked to move beyond the R4D pipeline approach, to produce “demand-driven” research, to “disseminate” the results of that research, and are evaluated on the number of farmers using the technologies they develop. (Sumberg and Reece 2004).

In commercial R&D, researchers are among a number of actors involved in technology development. Marketing professionals, user experience experts, industrial designers, project managers, and others bring their own set of knowledge and skills to inform technical research. Even a product as simple as an ice cream scoop required a team of six people (Ulrich and Eppinger 2016). The process is also slow—at Pioneer, developing a new maize hybrid might take six years (Griffin 1997). Specialists may enter and exit the project during different phases: market researchers might be needed initially, while manufacturing specialists would join later.

Interdisciplinary research for development projects sometimes mirror the structure of a commercial R&D team. Social scientists are asked to do market research—either to identify the target market for a new technology or to describe the current user base of an existing one. Agronomists are asked to function as sales representatives for the technologies they develop. The result is a disconnect between what scientists are trained to do, what they are interested in doing, and what they are increasingly being asked to do.

Sumberg and Reece (2004) describe ways in which concepts and theory from new product development could inform agricultural research for development. They argue for clarifying the roles of research and product development within research-focused institutions, and for the importance of the multi-step process of design, starting with a fuller understanding of potential users of a given product. And they suggest that research organizations actually hire product development professionals, even if they do not have PhDs in relevant fields.

I think of this as a shift toward farming systems engineering. My bachelor's degree is in mechanical engineering, and my first experience with development-oriented research was in the context of a course I helped develop, called "Product Design for the Developing World." Helping American engineering students to identify and design solutions for problems like sanitation and crop processing for end users in Guatemala convinced me very quickly of the critical importance of understanding the people you expect will use the thing you build. The same is true for agronomic and farming systems research.

The process of design

Product design and scientific research both start by identifying a need—a gap in existing research or an unsolved problem. The next crucial step is problem definition. How we define the problem shapes the kinds of solutions we can consider. Once we have identified the problem clearly, we identify a set of characteristics a solution should have, known as a design specification. Based on that design specification we can then develop prototypes, followed by a final product (Ulrich 2011). Take as an example a broken bridge. Our problem is that people need to cross the river. We now have several options: we can repair the current structure, we can replace the old bridge with a new one, or maybe we can move the road. All of these options have advantages and disadvantages—and before continuing the process we need to understand those. What will be the cost of shutting down the road? How long will the bridge take to repair or replace? Are there alternative routes? What is the condition of the current structure? We can get information from people living in the area who use the bridge regularly, we can look at similar bridges elsewhere, we can analyze the damage and its causes or monitor traffic patterns through time. When we have collected enough information to be confident in our decision-making, we can create a design specification. Say we have decided to replace the old bridge. Whatever the new bridge might look like, it must have adequate carrying capacity, its cost must be reasonable, and its construction should not shut down traffic for longer than necessary. It is only once we have clearly defined the problem and the design specification that we can choose whether to build a suspension bridge or a truss bridge or a drawbridge.

How could we apply this process to design better farming systems in Southern Mali? We can take the Africa RISING project mission statement as a starting point. "Through action research and development partnerships, Africa RISING will create opportunities for smallholder farm households to move out of hunger and poverty through sustainably intensified farming systems that improve food, nutrition, and income security, particularly for women and children, and conserve or enhance the natural resource base" (Africa RISING 2012). The project's conceptual framework defines a number of "guiding principles" to achieve this goal: focus on the farm household, stepwise progress toward sustainable intensification, Research-for-Development platforms, farm typologies and development domains as methods for "targeting" and "scaling" promising technologies (Africa RISING 2013).

The mission statement includes a design problem: a need to improve household incomes and food security, while protecting the natural environment. The Africa RISING program intends to solve its design problem through "sustainably intensified farming systems." While project documents repeatedly refer to "demand-driven" research, in product design terms, this is a technology-push approach (Ulrich and Eppinger 2016). "Sustainably intensified farming systems" are the product. It is assumed that the design problem can be solved through sustainable intensification, and the project is tasked with

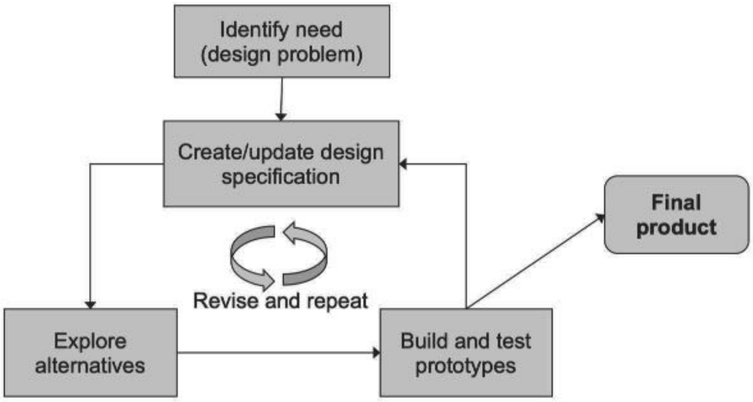

Figure 1. Steps in the product design process

determining how this can be done. Household typologies and development domains are in essence ways of identifying customers who may be interested in using the product. While Africa RISING does acknowledge that the SI product will look different for different types of households and different environments, it is assumed that the concept is broad enough that it can be tailored to fit most, if not all, situations.

Sustainable intensification is certainly a broad concept, and has been defined a number of different ways (Pretty et al. 2011, Garnett et al. 2013, Petersen and Snapp 2015). However, most definitions, including that used by the Africa RISING project, share the principle of increased output per unit of land and minimization of cropland expansion, even if intensity may sometimes be based on returns to inputs or, more rarely, labor. Given the vagueness of the term, it is possible to argue that sustainable intensification (through improved labor efficiency, for example) doesn't preclude cropland expansion, but that stretches the definition of the term to such an extent that what usefulness it has is compromised.

Chapter 4 of this thesis argues that in places where land is abundant, like Bougouni district, sustainable intensification is not a viable product for most farmers regardless of how carefully it is tailored to their socio-ecological niche. To return to the earlier bridge-building analogy: suspension bridges are lovely, but if we're building a railroad bridge across a creek we can do so with less disruption and at much lower cost by using a pre-fabricated truss structure. In the same way, high-yielding systems based around staple grain production may produce marketable surpluses that can improve food security at larger scales, but their income-generating potential for smallholder farmers is limited. The costs in capital and labor do not justify the benefits on a household scale, making sustainable intensification of the farming system an ineffective pathway out of poverty. Farmers are aware of the limited profit potential of current agricultural systems, and are therefore reluctant to invest in optimizing a system designed to ensure a family's food supply.

If sustainable intensification is not a suitable product for southern Mali, how might we design something better? Let us retrace the design process, beginning by re-evaluating the problem definition (Figure 1). It is clear from conversations with farmers, survey work, and published literature that farm households in southern Mali want to improve their incomes, and they want to continue producing enough staple grains to feed themselves from their own production (Bingen 1998, Koenig et al. 1998). At a policy level, the Malian Government's National Policy on Food and Nutrition Security (Politique Nationale de Sécurité Alimentaire et Nutritionnelle) has as its first strategic focus an effort to improve national-level food security by increasing smallholder production and sales of staple grains (Presidence de la Republique du Mali 2017). And there are many reasons to be concerned for protecting the natural environment, from local water quality to global carbon cycles. So we retain the three objectives of the Africa RISING problem statement: improved livelihoods, food security, and protection of the natural environment. Returning to the example of the bridge, we agree that the river needs to be crossed. But if we then declare that sustainable intensification of existing farming systems is the solution, we bypass the other steps in the design process, resulting in a product that does not adequately meet our objectives.

If we instead continue, we should start with a general, yet critical question: is designing improved farming systems an effective strategy for solving our problem? Do we need a bridge at all? Perhaps rather than building a new bridge here, we should divert traffic to the city, where there are already bridges. In the agricultural context, perhaps we should encourage people to get out of farming entirely. Migration, or a shift from farming to other livelihood strategies, is likely the best option for some households (Dorward 2009). Not everyone needs to cross the river here. But city traffic is already bad enough, and in any case, we're bridge builders, and bridges are useful. As are improved farming systems. So let us assume that, while other strategies are also worthwhile, we can focus here on agricultural innovations. We have decided to build a bridge.

Now we move on to the next step in the process, the design specification. We can look to a variety of sources for inspiration: what was successful in the past, what customers (farmers) are exploring on their own, what has worked elsewhere. And we can extrapolate from those to design technologies that do not yet exist.

A farming systems design specification

If we look at the recent history of agricultural innovation in sub-humid Southern Mali, it is clear that the most significant change has been the introduction of the CMDT-promoted package of cotton, maize, fertilizer, and animal traction. In our study villages, maize has essentially replaced sorghum as the staple food grain, the majority of farmers grow cotton, and nearly all farmers either own or rent draft oxen for field preparation (Ollenburger et al. 2016). If we want to replicate that widespread adoption, we should learn from it. What characteristics of this technology package have made it so widely adopted? What impact has it had, particularly as concerns the problem we have defined?

It is important to note that the CMDT package has been supported by policy interventions—credit for traction animals and equipment initially, and continuing subsidies and credit for fertilizer. The CMDT is a guaranteed buyer for whatever quantity of cotton a village produces, and they are responsible for the transportation of product from the village. The technologies themselves had a number of desirable characteristics as well. Animal traction improved labor productivity. Because land was abundant, this allowed households to cultivate larger areas. Cotton itself has characteristics that make it attractive, notably that it can be stored for long periods without expensive facilities.

Has adoption of this farming system contributed toward the goals of increased income, improved food security at local and national scales, and protection of the natural environment? This is debated (Benjaminsen et al. 2010). Cotton production has tended to increase incomes, and maize has helped increase food self-sufficiency for many farmers, but the increased cost and debt burden has increased inequality and sometimes lead to increased levels of social conflict (Moseley 2005). The environmental impact of cotton is mixed: pesticide use is high, and the introduction of animal traction has tended to increase the rate of cropland expansion. However, fertilizers made available through the production of cotton have had a generally positive impact on soil fertility (Ripoche et al. 2015). Because cotton is more labor-intensive than most cereal crops, it may also reduce the amount of land a household cultivates, as compared to a farming system without cotton (Baudron et al. 2009).

How does this help us create a design specification? If we look at the cotton-based system in the abstract, it has a set of characteristics that seem to have contributed to its success: it includes a cash crop, with a stable market, that stores well. It gives farmers access to a system of credit that allows them to produce a desirable food crop. In addition, cotton is grown in rotation with food crops and does not require major changes to the existing farming system. The cotton-based system draws on the financial and technical support of the CMDT, an organization that was already well-established when it began operating in the Guinea Savannah zone. In general, its impact on the first two components of the problem definition (income and food security) has been largely positive, while its environmental impact is mixed, but not dramatically different from grain-based farming systems.

For an example of a design based on suggestions from end users, we see in Chapter 5 that cashew is a potential cash crop that is of interest to farmers. We can repeat the process used for the historical example of cotton. What makes cashew attractive? What impact might cashew production have on our problem? Cashew lacks the institutional support of the CMDT. However, it provides income during the period when fertilizer must be purchased for grain crops, reducing growers' reliance on the CMDT for credit. There is a limited market for cashew in Mali at the moment, but traders active in nearby Côte d'Ivoire could expand into Mali if production increases (N'Guessan and Bamba 2008). Cashew, like cotton, can be stored relatively easily, because the outer husk contains compounds that make it unpalatable to animals and insects. The startup cost is low, because the trees can be started from seed. Labor requirements are also low, and cashew harvest, when labor demand is highest, occurs during the late dry season when there are fewer competing demands for family labor. Per-hectare environmental impact is low, as few to no inputs are used and soil is protected by the year-round vegetative cover (Akadie et al. 2008). However, the ease of establishment makes expansion into uncultivated area more likely, and along with it loss of biodiversity (Vasconcelos et al. 2015).

We can also consider options used elsewhere, or suggested by research. In Chapter 3, we explore livestock-based options which have their own characteristics, including low labor demand and environmental impact, but are limited by a lack of institutional support and poor market access. Others have investigated the potential of high-value vegetable crops, which are challenging because of their perishability, but have transformed farming systems in peri-urban and nearby rural areas (Keita and Zhang 2010). Both livestock and

Table 1. Existing agricultural production options and their implied design specifications. Effects are relative to a “baseline” system that includes only staple cereals (maize, sorghum, groundnut).

Example system	Increases farmer income?	Improves food security?*		Protects the natural resource base?		Design specification
		Household	National	Impact per hectare**	Land demand	
Cereals only	0	0	0	0	0	
Cotton-Maize with animal traction	+ Cotton earnings are secure cash source	++ Access to fertilizer increases maize production	++	++ High fertilizer and pesticide use	+ Animal traction allows more land clearance	Mechanized agriculture: mixed food and cash crops, improved labor productivity, land expansion
Cashew	++ Assuming access to markets	0	0	- - Permanent soil cover, no tillage, low/no input use	++ Low labor demand allows widespread expansion	Tree crops: low-labor, high-value perennials which are easily established and whose products can be stored, plantations expand into rangelands
Sheep production	++ If animals can be sold at peak times and fodder is produced on-farm	+ Increased household meat consumption	0	- - - Managed grazing of rangelands at reasonable stocking densities has few negative impacts	- Increases value of uncropped rangeland, incentivizing conservation	Small animals for meat: low cost per animal, rapid reproduction, high market demand, reduces demand for land
Milk production	+ Some farmers benefit but markets do not exist for larger-scale production	+ Increased consumption of dairy products	0	- - - Managed grazing of rangelands at reasonable stocking densities has few negative impacts	- Increases value of uncropped rangeland, incentivizing conservation	Dairy: High initial investment required in infrastructure and by individual farmers. Coordination is needed to benefit from economies of scale. Difficult to implement given current conditions.
Vegetable production	+/++ Depends on market availability, storage, processing	+ Increased vegetable consumption	0	+/- Impact depends on production system	- High labor requirements reduce land demand	Intensive horticulture: High-value crops with high labor requirements, with either a clear value chain for fresh product or a method for local processing and storage; high labor requirements reduce land demand

**direct effect, not including the beneficial effects of increased income on household food security; national food security considered in terms of staple crops as described in policy documents*
***note that increased impact is undesirable*

vegetable options have limited impact on household or national food self-sufficiency, but they are potentially profitable for farmers, and can be managed so as to reduce environmental impact.

These examples can be used to infer several design specifications for farming system improvement options (Table 1). These specifications focus on the farm-level view of each system, because smallholder farmers largely base their decisions on impacts at this level. However, farm-level impacts are often the result of larger scale institutional and policy decisions, so the design of new systems requires us to expand our point of view. No single one of the above options meets all of our objectives: they all have potential to improve income, and if food markets are functioning, that alone will improve family food security. Environmental impacts, however, are varied, and few options are available for increasing the production of staple grains as needed to improve national level food security.

Design and objectives

The implied design specifications in Table 1 can guide us in identifying key characteristics of agricultural systems that can meet all three of our objectives. Tree crops have lower environmental impact and higher potential profit per hectare than cotton or grain crops. Their low labor demand, however, facilitates the expansion of plantations and the associated disappearance of natural vegetation. High-value crops like vegetables have essentially the inverse profile—because labor requirements are high, they are likely to be concentrated in small areas. However, most high-value crops are perishable, requiring good market coordination or capacity for local processing and storage. Livestock production, especially the production of small ruminants for meat, is perhaps the option which best protects the natural environment, but would require additional support in the form of veterinary care and marketing.

The cotton-maize system has been somewhat effective at improving food security and generating income for farmers, but less effective in terms of protecting the natural resource base. Can we design a mechanized agriculture that improves performance in all three areas? We have identified market support as a key component of the existing cotton-maize system. The CMDT facilitates both the purchase of inputs needed for cotton, and the sale of the final product. Similar support for staple grains could encourage farmers to increase their production of these crops, improving national food security. Indeed, in recent years, CMDT support has been extended to include the provision of fertilizer specifically for maize (Ollenburger et al. 2016). Facilitating the development of stable markets for grains like maize and sorghum would provide an incentive for farmers to increase their production of these grains. Without specific subsidies or other incentives, however, staple grain production is simply not profitable on small scales. This is true for commodity agriculture in North America just as it is in Mali (Gloy 2018, Ollenburger et al. 2018). In areas like Bougouni, where labor constraints limit household production, improved mechanization and herbicides would allow households to cultivate larger areas, increasing their own earnings and producing additional grain surpluses. Sustainable production practices, if they are adopted, can reduce the environmental impact of grain crops, but increasing crop areas will unavoidably have negative consequences for environmental sustainability.

Environmental protection, and particularly the minimization of cropland expansion, is a difficult goal to meet through changes at the farm level. Is this surprising? While it is appealing to think that technology and markets can, with minimal outside intervention, allow us to meet any challenge, this is unrealistic. Agricultural intensification does not necessarily have land-sparing effects (de Ridder et al. 2004, Baudron et al. 2012, Byerlee et al. 2014). We see in chapter 4 that increased fertilizer availability further concentrates cultivated land, as soil fertility can be maintained more easily and fallow periods shorten, but is unlikely to change the total amount of land a household cultivates. Therefore, if we want to preserve uncultivated area it is not new technology or improved market efficiency but explicit conservation policy that will be necessary. Policy can of course be mediated by markets, as with payments for ecosystem services, carbon trading and the REDD+ program (Center for Climate and Energy Solutions 2015). Conservation policy can also be made on a local level, as with the reserved pasture area seen in Dieba (Chapter 5, this thesis). But absent policy restrictions, increased agricultural yields and profitability tend to expand the agricultural frontier, not reduce it (Byerlee et al. 2014). Innovations in farming systems, on their own, are not effective tools for enacting policy.

Next steps and the importance of process

The next step in the design process would be the further refinement of specifications, development of testable prototypes, and a continuing process of adaptation resulting, ideally, in a set of options that meet the design objectives and are easily marketable to farmers. Participatory research methods provide a framework for this process, and iterative co-learning cycles among diverse groups of farmers and researchers are effective ways of testing and improving designs for improved farming systems and their component parts (Falconnier et al. 2017).

Flexibility, collaboration, and communication are key to the process of product design. Product design teams work best when they are assembled based on what skills are needed for a given project, and the best product design teams flatten hierarchies as much as possible. Product design is a process with a high failure rate—ideas are developed, tested, and improved or discarded, in a long-term process (Ulrich and Eppinger 2016). None of these things are easily adapted to academia or to research institutions like the CGIAR, or to project-based research funding as it is currently conceived. Project proposals expect a clear set of target outcomes and a schedule of activities to meet them, meaning that the important work of problem identification and developing design specifications is often overlooked. Instead, institutions and individuals propose activities based on their areas of interest—for example, a CGIAR center's mandate crops. Even broadly conceived projects like Africa RISING begin with a pre-defined problem and a constrained set of solutions. The pressure to show immediate progress precludes in-depth efforts to clearly understand problems as well as wide-ranging experimentation with high rates of failure. Finally, a product design process requires researchers to play very different roles than many are accustomed to. As in participatory action research, in the product design process scientists, farmers, NGOs, government officials, and others all have valuable insights to share, and scientific knowledge is not elevated above farmers' knowledge. For scientists who have built their identity on their superior understanding of their specialty, this can be jarring.

The framework and process of product design presented here is one of many possible ways to approach agricultural research. Beyond agriculture, the challenges of rural poverty and food insecurity demand many approaches, and I have neglected most of them to focus on agricultural innovation. In the realm of agricultural innovation, treating farming systems design as an engineering problem can facilitate the process of research and development by encouraging collaboration, creativity and flexibility. It also provides an alternative perspective on the roles of scientists. There are a variety of approaches to new product design. In addition to the demand-driven example I have focused on here, there are examples where the technology comes first, and is then marketed. There is a long list of products which originated as specialized equipment for space travel: memory foam, certain types of home insulation, and the miniaturized cameras used in phones, for example (https://www.jpl.nasa.gov/infographics/infographic.view.php?id=11358). Without research into basic physics over the last century, we would not have consumer electronics. Prioritizing impact should not mean neglecting research that does not have an immediate application. At the same time, just as product design and development is a discipline in its own right, farming system design requires its own set of skills. These skills are not often taught in academic research settings. If research institutions are to effectively develop technical innovations, they will have to create a research in development system with high capacity to innovate. They cannot expect scientists to transition seamlessly into design roles. Institutional structures will need to adapt to encourage interdisciplinary collaboration, and stakeholder groups must have real influence on research priorities. Design processes themselves should be organized and managed in ways that allow teams to identify design problems and pursue them, calling on specialists to provide expertise as required based on the problems being addressed.

Finally, if we identify farmers as our customers, as the end users of our work, rather than as 'beneficiaries,' we become accountable to them; they are ultimately the ones who decide whether we succeed or fail. To truly make researchers accountable to farmers would require systemic changes in both research and funding institutions, a subject well beyond the scope of this thesis and of my own expertise. But a shift in perspective that focuses more attention on people and their needs, goals, and aspirations is sorely needed.

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Summary

For more than a decade, sub-Saharan Africa has been the focus of calls for a new Green Revolution. Like its predecessor, the African Green Revolution aims to increase the productivity of smallholder farmers, improving their own food security and income as well as that of the continent as a whole. This is to be done with minimum environmental damage, through "sustainable intensification." While sustainable intensification has shown potential in places where high population density precludes cropland expansion, evidence of its effectiveness in land-abundant, labor-limited areas is limited.

The World Bank identified the Guinea Savannah regions of Africa as a "Sleeping Giant" because of its high agricultural potential and low population density. They argue that agricultural development in these regions could drive economic growth both locally and at the national level. Bougouni district, in southern Mali, is a part of this zone, which we use as a case study to explore potential futures for smallholder agriculture in the area.

We explored the history of the area's agriculture using a panel data set for three villages, as well as remote sensing analysis, census and weather data (Chapter 2). Over the period of the panel data (1994-2012), agricultural change was minor. Cultivated area per household was highly correlated with household size and the number of draft animals a household owned. This relationship remained constant over the full period, suggesting little change in labor productivity. Yields of major crops remained stagnant, even as fertilizer input increased. Cropland expansion occurred in parallel with population growth, but up to the present, over half the arable land in the study villages was not cultivated.

Because uncultivated rangeland made up such a large percentage of the land, we characterized the productivity, management and use of these rangelands (Chapter 3). In two villages, we assessed biomass quantity and species composition at 2-month intervals, tracked a sample of village herds, and used remote sensing combined with regression analysis to map the productivity of herbaceous biomass in a woody savannah landscape. We found that rangelands produced 2-2.5 t/ha of herbaceous biomass at their peak productivity, from a diverse mix of annual and perennial species, notably Andropogon gayanus and A. pseudapricus. Because of the dense tree cover in the area, it was not possible to estimate herbaceous biomass directly using remote sensing imagery. Instead, a regression analysis based on the relationship of tree cover density to herbaceous biomass was used to calculate grass biomass for the area.

Rangelands are a key forage source for cattle. Four herds were tracked in each of two villages in October 2015, near the end of the rainy season; January 2016, the cool dry season; and April 2016, the hot dry season. Herds covered distances of 10-18 km each day, and the locations of grazing areas were dependent on the season. During most of the year, the forage supply far exceeded the demands of grazing herds, but in the late dry season forage becomes scarce and herders supplement grazing with cut tree fodders, or send herds on transhumance to the south. Village traditional leaders are largely responsible for regulating the use of rangelands, but as these are considered communal property, there are few restrictions on non-timber uses.

Proponents of the African Green Revolution see low agricultural productivity as a technological problem at the root of rural poverty, and propose technology options for intensification of agriculture to reduce poverty and improve food security. However, investments of labor and capital to increase yields of staple crops must compete with

alternatives both on and off the farm. An analysis of farm census data for three villages in the district of Bougouni explored the solution space of possible gains from intensification (Chapter 4). With yields equivalent to the best farmers yields in the area, households can achieve food self-sufficiency, and most can raise income levels above the threshold for extreme poverty. Yields equal to those obtained in on-station trials improved the picture further. However, other options were considerably more profitable. The average annual income for a gold miner in the area was US$1225. At constant prices and land areas, only 25% of households in the study villages could achieve per capita incomes above this level. If we consider options that do not meet criteria for sustainable intensification, we find that expanding land area and timing crop sales to correspond to peak price points result in more dramatic increases in profit. Dairy production has potential to provide high income to a few households with large herds, but would require large investments in infrastructure and improved market access. Production of small ruminants for meat, particularly rams sold at peak holiday prices, could raise incomes for a larger number of households, because initial costs are modest. While small ruminant production does not require the complex infrastructure of dairy marketing, current production potential is limited by a lack of veterinary services and limited market access.

In land-abundant, labor-constrained farming systems like those found in southern Mali, agricultural development should not be restricted to sustainable intensification. Using a companion modeling process, we worked with local farmers in two villages to develop scenarios, explore them using a land use board game, then analyzed further impacts with an agent-based model. Farmers identified tractor availability and increased cashew production as key drivers for agricultural change, so scenarios were defined based on these drivers. The game was developed with the board representing the village territory. Five players, representing heads of household, had varying draft capacity and initial assets. They could choose to plant trees on fallow land, and the wealthiest farmer could purchase a tractor, which could be rented to other players to allow them to expand their fields. Tractor owners rented out approximately half of their draft capacity to other players, at prices slightly above cost. When players fallowed land, they planted trees on that land, increasing their income. Players considered it too risky to rely on markets for the household's food supply, however, so cashew plantations expanded land area rather than replacing staple crops.

The agent-based model Mali-sene (Multi-agent land-use and intensification socio-ecological niche exploration) simulated behavior seen in the land use game, and was used to explore a range of scenarios with different rates of tree planting as well as access to tractor rental and purchase. Scenarios with extensive tree planting resulted in high rates of land conversion, with the majority of cultivated land in tree plantations. Scenarios where tractor rental was available but tree planting was minimal resulted in somewhat lower rates of land conversion, but converted land was planted to annual staple crops. Introducing only tractor rental more than doubled average per capita annual income to $400, while cashew planting alone resulted in incomes of up to $1600 per capita. High rates of tree planting resulted in lower levels of inequality in both land ownership and wealth, as the low initial cost and high profit potential allowed a broad range of households to benefit from planting cashew.

It seems clear that cropland expansion is highly likely to occur in this area, and preventing expansion comes at a real cost to local farmers. Tractor availability and cashew planting both led to land conversion, but the environmental impacts of cashew, as a perennial tree crop, are likely to be lower than the impacts of staples. A holistic evaluation of sustainability that considers farmer livelihoods might therefore conclude that expansion is as sustainable as intensification.

The process of developing agricultural technology innovations in sub-Saharan Africa is generally led by scientists, but has many commonalities with engineering and product design methodologies (Chapter 6). Increased attention to the steps in this process, from problem definition to developing design specifications to testing possible solutions, could help research for development projects develop more relevant technical solutions for farmers.

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About the author

Mary Ollenburger was born on March 16, 1983 in Princeton, NJ, USA and grew up in Elkhart, IN, USA. She received a BSc in Mechanical Engineering from the California Institute of Technology in 2006, but after a few months of working as an engineer she joined the US Peace Corps' Sustainable Agriculture Program. Placed in the Ecuadorian Andes, she spent two years working on irrigation and school garden projects, extending her stay to a third year of working with the Peace Corps Ecuador country office in volunteer training and program monitoring and evaluation. On her return, Mary began an MSc program in Crop and Soil Science at Michigan State University. Her thesis work with Dr. Sieglinde Snapp involved modeling maize-pigeonpea rotational and intercropping systems in northern Malawi. She began PhD work in the Plant Production Systems Group at Wageningen University in 2012, in connection with the McKnight project 'Pathways to Agro-ecological Intensification of Sorghum and Millet Cropping Systems of Southern Mali.' She then moved to Mali in 2013, where she was eventually a visiting researcher at the International Crop Research Institute for the Semi-Arid Tropics (ICRISAT), and conducted fieldwork in Bougouni district as part of the Africa Research in Sustainable Intensification for the Next Generation (Africa RISING) project of USAID. She returned to Wageningen and then the US in 2016. Mary is currently employed as a researcher with the University of Maryland Center for Environmental Science and the Joint Global Change Research Institute, near Washington DC, where she works on improving representations of agricultural intensification in multi-sector, multi-scale models.

Peer-reviewed journal publications

Ollenburger, M.H., Descheemaeker, K., & Giller, K. E. Forest, pasture, fallow: Using and conserving rangelands in Mali's Guinea Savannah. Agriculture, Ecosystems and Environment, submitted.

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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 of literature (4.5 ECTS)

Waking the sleeping giant

Writing of project proposal (4.5 ECTS)

Evolving contributions of common use lands to farming system productivity in Southern Mali

Post-graduate courses (10.5 ECTS)
- Sampling in space and time for monitoring of natural resources; PE&RC (2013)
- Farming systems; PE&RC (2013)
- GIS and remote sensing training; ICRISAT Niamey (2013)
- Companion modelling; PE&RC (2016)

Invited review of (unpublished) journal manuscript (2 ECTS)
- Food Security: farm typology in India (2015-2016)
- Agronomy for Sustainable Development: farm heterogeneity and livelihoods in Burkina Faso (2016)

Deficiency, refresh, brush-up courses (3 ECTS)
- Systems, simulation, and systems management; PPS (2012)

Competence strengthening / skills courses (1.6 ECTS)
- Monitoring and evaluation workshop; IFPRI/Africa RISING (2015)
- Career assessment; WGS (2016)
- Making an impact; WGS (2016)

PE&RC Annual meetings, seminars and the PE&RC weekend (1 ECTS)
- PE&RC Weekend (2012)
- PE&RC Biodiversity symposium (2012)

Discussion groups / local seminars / other scientific meetings (4.5 ECTS)
- Sustainable agricultural intensification discussion group (2013-2016)
- Project meetings: McKnight and Africa RISING country meetings and regional planning meetings (2013-2016)

International symposia, workshops and conferences (3.6 ECTS)
- Farming systems design conference; Montpellier, France (2015)
- Contested agronomy conference; Brighton, UK (2016)

Supervision of MSc students
- Farm typology, contributions of organic cotton to farm livelihoods
- Grazing itineraries, biomass budgets

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