Integrated crop management strategies in Sahelian land use systems to improve agricultural productivity and sustainability: A case study in Mali

Odiaba Samaké

Promotor: Prof. dr. M.J. Kropff
Hoogleraar in de Gewas- en Onkruidecologie
Prof. dr. ir. E.M.A. Smaling
Hoogleraar in de Bodemkunde

Co-promotor: Dr. ir. T.J. Stomph
Universitair docent bij de leerstoelgroep Gewas- en Onkruidecologie

Samenstelling promotiecommissie:
Prof. dr. ir. O. Oenema (Wageningen Universiteit)
Prof. dr. K.E. Giller (Wageningen Universiteit)
Dr. ir. B.H. Janssen (Wageningen Universiteit)
Prof. dr. R. Merckx (Katholieke Universiteit Leuven, België)

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Abstract

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Sustainability of food production in the Sahel of West Africa requires Integrated Crop Management (ICM) strategies including different technologies that take into account constraints of stakeholders at different scale levels. To achieve this objective, combined effects of growing cowpea after different fallow durations followed by millet sole crop or intercropped with cowpea, and application of P-fertilizers were quantitatively evaluated. Prior to implementation of the experiments, a multi-scale characterization was adapted to determine major opportunities and constraints to millet production. The method used so far has been mainly used at higher integration levels. The approach used in this study involved less spatial scale analysis than earlier multi-scale characterizations and was conducted at the lower scale levels (i.e., region, district and village levels). The results showed that the main constraints to millet production were the low state budgets for investment at the regional and district levels that lead to high prices of inputs and low prices of outputs at the village level. Low soil fertility and high *Striga* infestation reduce millet production at the village level resulting in a problem of self-sufficiency at the district and regional levels. Surveys conducted at the village level showed that homefields were more fertile than bushfields, because of application of organic manures and animal penning around the village. Only fallows restore the fertility in bushfields representing 99% of the village territory. Millet grain yields and *Striga* infestation were consistent with these fertility gradients. The results of a 4-years experiment in bushfields indicated that cowpea grown in 1998, had a positive effect on subsequent millet grain yields, soil organic C and N and reduced *Striga* infestation. The increase in yield due to millet-cowpea rotation was 37% in 1999 compared to 3−5 years continuous millet cropping. Including millet/cowpea intercrop in alternative-row configuration after cowpea did not result in significant increase in millet grain yield compared to millet-cowpea rotation in the first and second year, but increased millet grain yields by the third growing season with 22%, the total yields all years and minimized risks of food security in low rainfall years. The effect of intercropping on *Striga* lasted longer than rotation. The effects of two years fallow on millet grain yield, soil organic C and N and *Striga* were comparable to those of 5−7 years fallows. P fertilizers enhanced the effects on yield and organic C of both millet sole crop and intercrop with cowpea after a 1-year cowpea crop without significant effect on N and *Striga*. The model QUEFTS gave a reasonable estimate of nutrient-limited millet yields that can be calculated on the basis of only soil N, P-Bray-I, and exchangeable K. But, validation with input parameters from other millet cropping environments are needed to improve its predictive value for a wide range of environments.

Key words: Millet, cowpea, rotation, intercropping, fallow, soil fertility, nutrient uptake, modelling, Sahel.

Preface

This thesis has partly been written in the framework of the Desert Margin Programme (DMP), project officially designated ‘Optimization of Resource Use’ (ORU) in the semi-arid regions of West Africa, a joint activity of the NARS (National Agricultural Services), ICRISAT Sahelian Center of Niamey and Wageningen Agricultural University. The project was conducted in Burkina Faso, Mali and Niger and was financed by the Ecoregional fund to support methodological initiatives, administered by ISNAR, The Hague, The Netherlands.

The aim of the project was to provide analytical tools through multidisciplinary geo-referred databases targeted at different scale levels, that guide in development and evaluation of technology and/or policy changes in resource management, decision makers (including farmers) by district or village level, agricultural researchers and development agencies (NGOs and government agencies) in the Desert Margins of West Africa. Other important objective of the project was to increase skills of scientists of national agricultural research services in systems analysis. The project ended early in December 1999. However, ISNAR continued to support this thesis work through Wageningen University. My thanks to Professor Eric Smaling for getting extra funds to achieve this work.

The thesis work started in 1998 under a ‘Sandwich programme’ which involved Wageningen University, ICRISAT Sahelian Center of Niamey (Niger) and the ‘Institut d’Economie Rurale’ (IER) which is the national agricultural research Institute of Mali. The completion of this exciting experience would have not been possible without the support and cooperation of many individuals and institutions. I acknowledge all of them.

I am thankful to Dr. Niek Van Duivenbooden who motivated me to undertake this PhD study and enable me to come to Wageningen University. Throughout this period, I received constructive criticism and guidance from him.

I am particularly grateful to Professor Martin J. Kropff and Professor Johan Bouma accepting to promote my study. Professor Eric Smaling took over the work from Professor Johan Bouma and during the last three years Dr TjeerdJan Stomph joined as co-promotor replacing Dr Lammert Bastiaans. Their comments and suggestions on the structure and contents of the thesis have considerably improved its quality and readability. I learned a lot from all of them and particularly TjeerdJan Stomph for his availability ‘as usual’ and I really benefited from his knowledge and experiences in multi-scale characterization and problems related to agricultural production in Africa. TjeerdJan, thanks to you and your family for your friendship. Many thanks to Dr.

Lammert Bastiaans, who supported me from 1998 to 2000. He contributed a lot in improving the research proposal. I am very grateful to Professor Bert H. Janssen for teaching me how to parameterize and use the model QUEFTS in this study.

Many thanks are due to Maja Slingerland and students of the Crop and Weed Ecology discussion group of C.T. de Wit Graduate School for their constructive comments on draft version of some chapters.

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Experiments were conducted in the village Lagassagou in northern Mali under the supervision of Dr. Kabirou N'Diaye to whom I address my gratitude. Thanks to the staff of the 'Equipe System de Productions et Gestion des Ressources Naturelles' (ESPGRN) of Mopti (Mali), and particularly Karim Diarra and Aly Konta all research technicians for their help in data collection. I am also grateful to Dr Amadou Kodio, Dr. Ousmane Diallo for their technical helps in the field and Mohamed Sidi Mohamed Touré for data analyses. I would like to acknowledge Dr. Bino Témé, General Director of IER, Dr. Moussa Kané, former Director of the Agronomic Research Center of Mopti and Dr. Mamadou D. Doumbia chief of the national soil, water and plant laboratory of Sotuba for providing facilities and other assistance for this research. Many thanks to all farmers of the village Lagassagou for their co-operation.

Finally, I owe all respect to my wife Kadiatou Coulibaly who, during my stays in Wageningen took care of our family. Her good understanding, endurance and moral support were valuable to fulfil this work. I thank my children Mamadou, Assétou, Ousmane, Mariam and Saran for their patience, their courage and their feeling to be abandoned during my stay abroad.

Wageningen, April 2003

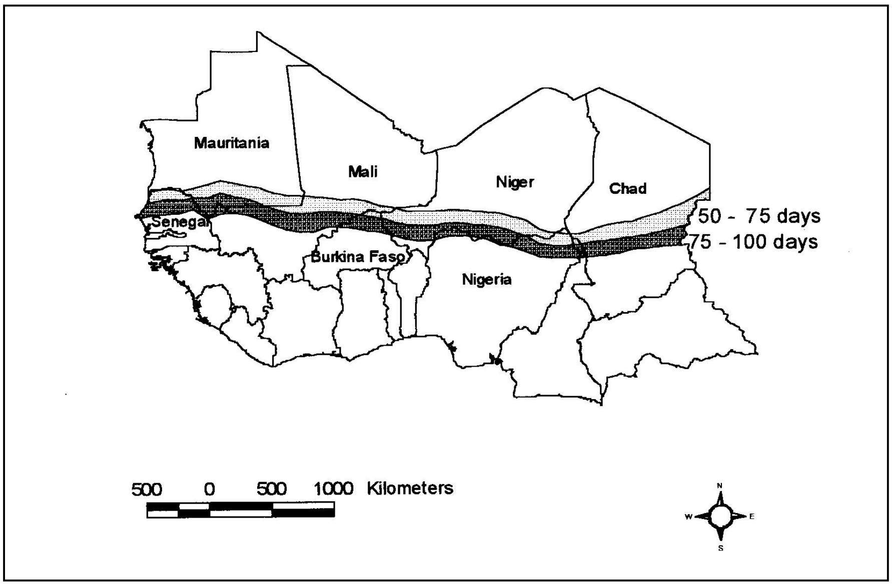
Contents

CHAPTER 1

General introduction

Environmental setting

The Sahel is the agro-ecological zone in West Africa between the latitudes 12°30' and 16°36' North, and between the longitudes 18°30' to 24°40' East. This zone is the transition between the Sahara desert and the sub-humid Sudanian Savanna region. It extends from Senegal in the West to Chad in the East, and further includes parts of Mauritania, Mali, Burkina Faso, Niger, and Nigeria (Map 1). Average annual rainfall ranges from 100 mm in the North to 600 mm in the South (Le Houerou, 1989) with a high spatial and temporal variability. The zone is characterized by a short rainy season between May and October and a dry period from November to April. Rains are caused by the monsoon, a wind coming from the Gulf of Guinea and by the northern movement of the Intertropical Convergence Zone (Le Houerou, 1989). Deviations from the long-term average tend to persist for extended periods of time. Topography of the landscape is in general flat, or slightly sloping. The predominant soils used for crop growth in this zone are classified as alfisols and ultisols containing more than 80% sand and less than 15% clay (Hartmann and Gandah, 1982). Natural vegetation consists of trees and shrubs, with an uneven spatial distribution. Biophysical and socio-economical conditions vary both in space and in time, resulting in a variety of land use systems with variation in productivity across and within agro-ecological zones.



Map 1. Map of the Sahel in West Africa (Source: Samaké and van Duivenbooden, 1999).

The agricultural sector is by far the most important economical activity in the Sahelian countries. More than 80% of the population lives in rural areas and depends on agriculture (Kieft *et al.*, 1994). This sector is predominantly based on arable cropping systems ranging from shifting cultivation to permanent cultivation, and these arable systems are often associated with sedentary and nomadic animal husbandry. Irrigation is only of local importance around the major rivers and lakes. Cropping systems are mainly based on rainfed cereal crops (sorghum and millet) sole cropped or intercropped with other crops with limited or no external inputs. Fertilizer use increased only in East Africa and Coastal West Africa (Table 1). The use of inorganic fertilizers is constrained by the unreliable benefits of using recommended packages of (hybrid) seeds and fertilizers (Ruthenberg, 1980; Anderson, 1992) and lack of access to capital (Hoekstra and Corbett, 1995; Témé *et al*., 1995) while organic inputs such as manure are limited by their availability. In most countries per hectare yields have changed little over the 15 years between 1988 and 2002. At the same time the potential for yield improvement seems to exist. Yamoah *et al.* (2002) reported that millet plots treated with a combination of crop residues and fertilizer yielded as much as 2160 kg ha^{-1} whereas their unfertilized plots produced 210 kg ha^{-1}. Food shortage occurs in many areas due to the low increase in agricultural production compared to the increase in food needs as a result of the fast growing population. For the semi-arid zone in West Africa, Cleaver and Donovan (1995) and the Club de Sahel (1991) estimated the annual increase in output of production systems at 1.3% compared to an increase in food demand of 2.8%. While at least part of this output increase is caused by an increase in area under arable cropping. Millet yields in Burkina Faso increased in the past decades. However, in most countries, including Mali, millet yields did not increase (Table 2). Grain production becomes insufficient for survival in some areas. So, young and strong family members try their luck elsewhere, resulting in labour shortage during the growing season (Veeneklaas *et al.,* 1990).

Table 1. Fertilizer use per hectare and fertilizer use per region in Africa (Source: van Reuler and Prins, 1993).

Region	Fertilizer use in 1990 ($kg\ ha^{-1}$)	Fertilizer use in Africa between 1975–1990 ($\times 10^3$ t)			
		1975	1980	1985	1990
Sudano-Sahel	5.3	158.1	128.1	173.1	167.5
Coastal West Africa	10.4	129.9	251.0	397.3	460.0
Central Africa	1.1	27.6	45.6	73.7	19.1
East Africa	8.0	108.5	142.3	216.7	229.8
Southern Africa	14.6	268.5	391.4	359.6	353.6

Table 2. Average millet grain yields (kg ha^{-1}) in the Sahelian countries in West Africa in three five year periods between 1988 and 2002 (FAO, 1988–2002), the overall average is a weighted average based on acreage per country.

Countries	1988–1992	1993–1997	1998–2002
Burkina Faso	588	665	738
Gambia	1026	1015	1068
Chad	443	410	432
Mali	726	649	771
Mauritania	362	280	307
Niger	407	349	425
Senegal	609	629	623
*Average**	*507*	*568*	*532*

* Average is a weighted average based on acreage in each country.

Problems related to current agricultural systems

Biophysical constraints

The major biophysical constraints to agricultural production in the Sahelian zone in West Africa are the uncertain, variable and low rainfall and unfavourable physical and chemical properties of soils. From his study on the environmental risks based on long-term daily rainfall data, Sivakumar (1989) reported that the risks of drought are higher during crop establishment and the grain-filling phase than during intermediate crop phases. Hengsdijk and van Keulen (2002) analysed the role of water limitation to millet production by relating total annual rainfall and simulated water-limited millet yield using 31 years of weather data and two soil types. They showed that below 500 mm rainfall, rainfed crop production in West Africa was extremely low and complete crop failure occurred in many years. Between 500 and 800 mm rainfall, yields tended to increase with increasing total rainfall and above 800 mm rainfall no further increase was observed. Above 500 mm rainfall yields between years were very variable and production was often limited by water shortage due to unfavourable distribution of rainfall.

Despite the role of limited rainfall in attainable production, fertility generally limits actual yields in all rainfall zones. The work done by Seligman *et al.* (1992), Breman (1995b) and Piéri (1985; 1986) showed that the availability of nitrogen (N) and phosphorus (P) in semi-arid regions in the Sahel limits growth more than moisture availability. Throughout the Sahel soils have a low nutrient content, and are especially poor in nitrogen and phosphorus (Breman, 1995a; Brouwer and Powell, 1993; van der

Pol, 1992; Stoorvogel and Smaling, 1990a, b; Penning de Vries and Djitèye, 1982). Differences are quite marked from the Equatorial Forest in the South to Sudan Savanna in the North (Table 3).

Soil fertility declines in the region according to several authors. Stoorvogel and Smaling (1990a) estimated an annual depletion in soil nutrients for the years 1982–84 to 12 kg ha^{-1} for potassium (K_2O), 14 kg ha^{-1} for nitrogen (N) and 4 kg ha^{-1} for phosphorus (P_2O_5). In another study, Buerkert and Hiernaux (1998) estimated average nutrient outputs from fields in the Sahelian zone of West African at 15 kg N ha^{-1}, 2 kg P ha^{-1} and 15 kg K ha^{-1} based on information of the removal of the harvested components including straw for housing and animal feed. Bationo *et al.* (1994) reported that continuous cultivation of cereals in the Sahelian zone has led to a drastic reduction in organic matter levels and a subsequent soil acidification in the Sahelian zones. In northern Nigeria, Jones (1971) found that during 18 years of continuous cropping, soil organic matter declined at the rate of 3–5% per annum. Continuous cereal cropping systems increases crop pest, weed (*Striga*) and disease incidences, and decreases soil chemical and physical characteristics (Juo and Lal, 1977; Dembélé *et al.*, 1994; Piéri, 1989). On the basis of long-term experiments, Piéri (1991) estimated an average annual yield loss of 3 to 5% directly related to the decline in the level of soil fertility in the sub-Saharan Africa. The FAO statistics, though, do not show a decline in yield in most Sahelian countries (Table 2, Figure 1).

In addition to the loss of natural vegetation to arable systems, the over use of woody and herbaceous natural vegetation for human needs (selling woody and non-woody products and medicine) and animal feed has uncovered soils and contributed to land degradation and the decline of the nutrient content of the soils. Sivakumar and Wills (1995) reported that 65% of the African agricultural land, 31% of permanent pasture land, and 19% of forest and woodland has already been degraded. In combination with the high temperature in the early rainy season this causes high seedling mortality, poor crop establishment and yield losses. Scherr (1999) provided reviews of land

Table 3. Soil chemical characteristics of 0–20 cm layer of upland soils on acid parent materials in different agro-ecological zones in West Africa (Windmeijer and Andriesse, 1993).

Agro-ecological zones	pH-H_2O	Organic C (g kg^{-1})	Total N (g kg^{-1})	Total P (mg kg^{-1})
Equatorial Forest	5.3	24.5	1.60	628
Guinea Savanna	5.7	11.7	1.39	392
Sudan Savanna	6.8	3.3	0.49	287

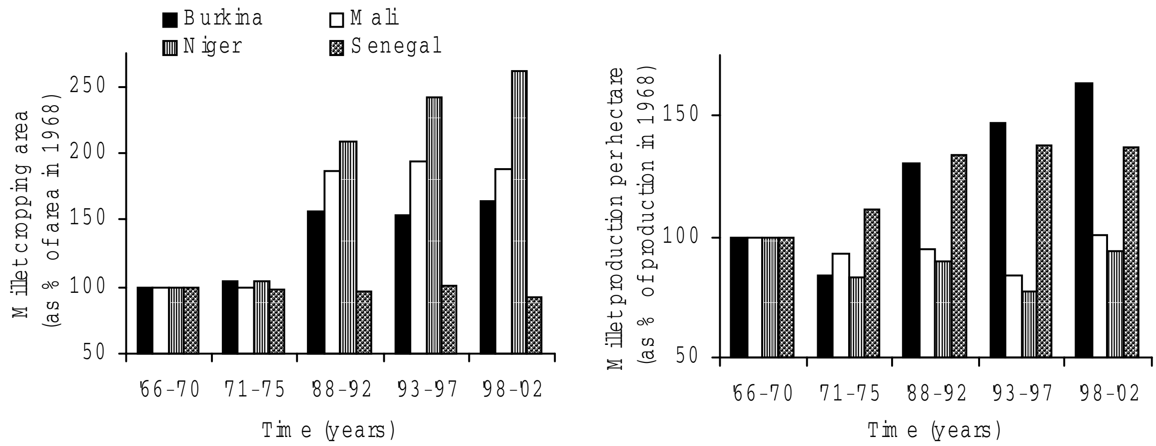


Figure 1. Changes over the last three decades in millet-cropping area and per hectare millet grain production relative to area and production around 1968 in four Sahelian countries in West Africa (FAO, 1966–2002).

productivity in Africa and estimated crop production losses due to land degradation at more than 20% during the last forty years. Kieft *et al.* (1994) reported that the bare soil in Mali increased from 4% in 1952 to 26% in 1975. However, Mazzucato and Niemeijer (2001) did not find any evidence of land degradation in their study near Fada N'Gourma in Burkina Faso. They reported that cultivated soils were in some respect more fertile than uncultivated soils and stated that soil organic matter and the soil content in major nutrients (nitrogen, phosphorus and potassium) did not seem to have declined since the late 1960s. In other words, there is an apparent contradiction between nutrient budget studies and yield statistics, this will need further exploration.

Biotic constraints

Major biotic constraints to millet production include pests, weeds (*Striga*), diseases (*Heliochelius albipunctuella*), low yielding potential of local varieties, and grain eating birds (Spencer and Sivakumar, 1987). The importance of these constraints relative to the importance of fertility and erratic rainfall is low, possibly with the exception of *Striga*. M'Boob (1989) reported that *Striga* (i.e., witchweed) threatens the livelihood of 300 million people and causes annual yield losses estimated at $7 billion. More than 17 countries in West, Central Africa and Southern Africa are highly infested and complete crop losses are common in these areas (Lagoke *et al.*, 1991). In Mali, Konaté (1986) reported that *Striga* threatens the major food crops (millet, sorghum, maize and cowpea) with field infestation, varying from 1 to 80% and yield losses varying between 25 to 100%. *Striga hermonthica* is a hemi-parasitic weed of millet and sorghum. The weed is an obligate parasite, implying that it will only germinate if triggered by the presence of host roots (or other sources that produce the chemical stimulants that stimulate germination) and it only completes its cycle and produce seed if attached to a host.

Options to increase production

To increase food production, small-scale farmers traditionally rely on options to shift from a cultivated area to an uncultivated one when crop yields decline leaving the field fallow to replenish soil fertility under natural regrowth and to reduce the *Striga* seedbank. Already 30 years ago, the increasing population pressure resulted in the reduction of the length of fallow periods (Swinkels *et al.,* 1977), this has since continued to the point that the fallow system is losing its effectiveness in natural restoration of soil fertility. Nutrient recovery from the currently most often observed short fallow cycle is not sufficient to cover the demand of crops during the years when plots are cultivated (van der Pol, 1992). In some areas, fallow systems have been replaced by continuous cereal cropping systems.

In addition to fallow use, the application of manure, household waste and mulch are traditional ways to improve soil fertility and productivity. The principal constraint to this practice is the finite supply of organic fertilizers. Cattle grazing on fallow, pasture and harvested fields do not produce enough manure to support crop production on all fields. The availability of manure can be increased by penning animals to facilitate manure collection. However, not all families posses enough large animals to keep all their fields well fertilized with manure, and the area needed for animal feed far exceeds currently available acreage (de Ridder and van Keulen, 1990). Mulching is little used in the Sahel because of the demand for crop residues for human needs (fuel and construction materials) and animal feed. Camara (1996) reported that less than 10% of crop residues are buried to return nutrients removed from the soil profile in Koutiala zone in the Southern Mali. Piéri (1985) concluded that even 3 to 5 ton ha^{-1} of crop residues are not sufficient by themselves to appreciably increase soil fertility and water retention capacity. Although farmers are aware of detrimental effects of these traditional production systems, they fail to invest in long-term soil fertility for reasons such as low investment capacity and the economic risks related to erratic rainfall (Dugué, 1993a).

Another method used by farmers is intercropping cereals with legumes (Reddy *et al.*, 1990). Traditionally, seeds of millet and cowpea are mixed and sown in the same seed hole with lower density of the cowpea intercrop than of the main crop millet (Shetty *et al.*, 1987). Studies have shown land equivalent ratios larger than one and so a yield advantage of intercropping over sole cropping in the tropics (Fukai, 1993;

Shetty *et al.*, 1987). Reddy *et al.* (1992) found 29% increase in soil organic matter under millet/cowpea intercrop, compared to millet monocrop. In depth analyses of the benefits of intercropping systems in different environments are still insufficient.

The need for integrated crop management strategies for sustainable agricultural production in the Sahel

The Sahelian agricultural sector, which is mainly subsistence-oriented and facing soil poverty and *Striga* problems, does not provide enough cereals to meet the food demand of the increasing population. For some time increase in the area under cultivation has provided an appreciable increase in total production, but in many countries the cultivated area stagnates as land becomes scarce (Figure 1). The World Bank (1984) and the Club of Sahel (1991) showed that the increase in agricultural outputs from 1960s to 1980s in the Sahel was mainly due to expansion of cultivated areas to marginal and fragile environments. They indicated that the impact of research and extension on intensification of crop production system had been negligible.

While yields have not been declining so far, the question remains how intensification can be supported and what intensification is possible given current practices and resource base at farming systems level. In the past, most improved technologies for long-term crop production were developed on a basis of a specific scientific discipline, i.e., a single component technology (soil fertility, variety improvement, crop protection etc.). In addition, the developed technologies were proposed to mitigate problems that were not perceived in the same way by farmers, or did not fit in the local farming systems (Kessler and Moolhuijzen, 1994; Marcussen, 1994; FAO, 1995; INSAH, 1997).

The contradicting reports and the major constraints to agricultural production found in this Chapter indicate the need for in depth exploration of agricultural systems and the development of technologies that improve productivity in a sustainable way for low-input farming systems in the Sahel of West Africa. The hypothesis underlying the work reported in this thesis is that an integrated approach to soil fertility and *Striga* management will be needed to facilitate yield increase of cereals in the Sahelian zone.

Aim and outline of the study

The aim of the study reported in this thesis is to increase our understanding of millet-based cropping systems in the Sahelian zone of Mali by identifying constraints and by searching for intervention points to make millet-cropping systems more productive and sustainable. The main focus of this study was to increase productivity at low cost for subsistence farming systems in Sahelian West Africa and to provide analytical tools to evaluate soil fertility-millet yield relationships at the field level that can be used for evaluation at higher scales as well. Although alternative cropping systems have been evaluated before, it was never done in the new context of drastically reduced fallow periods. The specific objectives are:

- To describe the agro-ecosystems at the region, district and village levels on the basis of biophysical, socio-economic and to identify constraints to millet-cropping systems;
- To explain main-induced spatial variation of soil fertility, *Striga* infestation and millet yields and to describe fallow characteristics;
- To evaluate the individual effects of fallow–legume–millet rotation and millet/cowpea intercropping after fallow–legume rotation on productivity and *Striga* infestation in field that do currently not receive other inputs;
- To evaluate the effect of phosphorous fertilizer use in fields that receive no other inputs in interaction with length of the fallow period and use of cowpea in rotation and/or intercropping with millet;
- To develop an analytical tool to evaluate the relation between soil fertility, nutrient uptake and millet yield.

Figure 2 gives an overview of the contents of the different chapters. To achieve these objectives, explorative studies were conducted in the Fifth Region of Mali to describe agricultural production systems and to identify constraints in millet-based cropping systems at the regional, district and village levels. These results are discussed in Chapter 2. Chapter 3 presents the results of field surveys at key sites in the district of Bankass to explain spatial variation of fallow characteristics, soil fertility, *Striga* infestation and millet grain yields. Chapters 4 and 5 describe the results of field experiments that were carried out in a village territory to determine the effects of (1) millet-cowpea rotation and millet/cowpea intercropping systems in combination with different length of the fallow period and (2) inorganic P-fertilizers on soil fertility, millet grain yield and *Striga* infestation. Data from field surveys and a set of fertilizer experiments were combined in Chapter 6 using the model QUEFTS (Quantitative Evaluation of Fertilizer Systems) developed by Janssen *et al.* (1990) to analyse the relations between soil fertility, nutrient uptake, millet yield and *Striga* infestation. In Chapter 7, the results of the different studies are discussed in the context of sustainable development of agricultural systems in the Sahelian zone in West Africa.

The research was carried out as a collaborative research programme between Wageningen University, ICRISAT and the Institut d'Economie Rurale (IER) in Mali, West Africa. Financial support for the study was provided by the Eco-regional trust funds of ISNAR in the Netherlands to support methodological research.

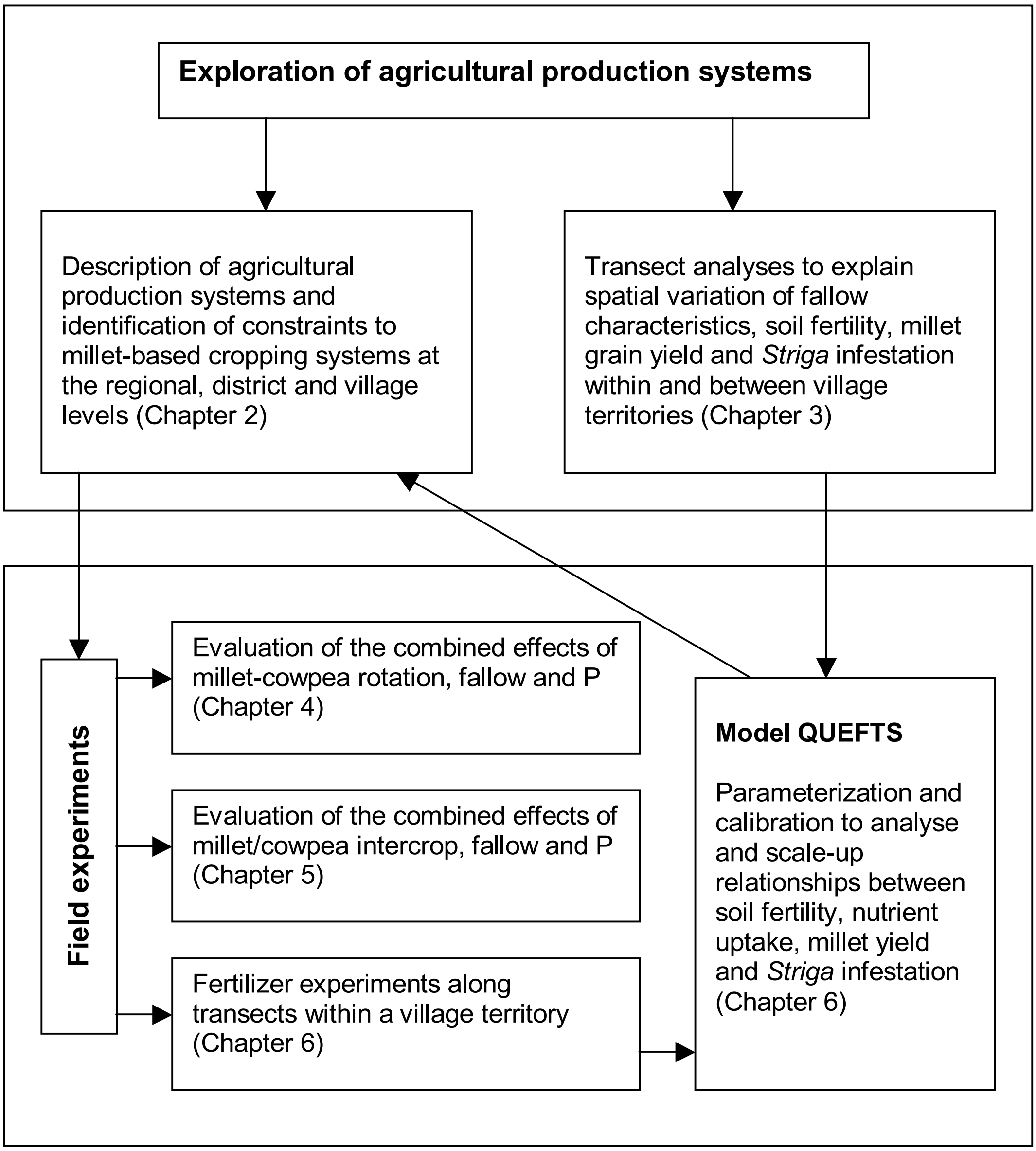


Figure 2. Structure of the thesis.

CHAPTER 2

Analysis of constraints to agricultural production in the Sahel: A case study of millet cropping systems in Mali

Abstract
A multi-scale characterization approach was adapted to identify the major constraints to millet production systems in the Fifth Region of Mali. The characterization was conducted at the regional, district and village level. For the first two levels mainly secondary data were used, while at the village level additional data were collected. The results show variation in biophysical and socio-economic conditions at the three scale levels. Constraints to millet production systems were analysed, with attention to the level at which they can be addressed. Special attention is given to the socio-economic stratification in the village. This analysis shows that development of technologies and interventions to increase millet productivity should consider constraints at all three scales. Results were also used to set research priorities for improvements in the sustainability of millet production systems in the Fifth Region and similar zones of the Sahel of West Africa.

Key words: Multi-scale characterization approach, pearl millet production, constraints, Fifth Region, Mali.

Introduction

In the arid and semi-arid tropics of West Africa, pearl millet (*Pennisetum glaucum* (L.) R. Br.) is a major staple food crop. This cereal is the most drought tolerant of those grown in the West African Savannah region (Konaté, 1986) and is particularly adapted to major abiotic constraints to plant production, such as high air and soil temperature, nutrient-poor soils and low and erratic rainfall conditions (Stoorvogel and Smaling, 1990a, b; Seligman *et al.*, 1992; Piéri, 1989; Penning de Vries and Djitèye, 1982). Biotic constraints include the low genetic yield potential of local landraces, diseases, the parasitic weed *Striga hermonthica* and grain eating birds (Spencer and Sivakumar, 1987). Farmers usually have a low purchasing capacity under these conditions and use little or no external inputs. As a consequence, crop yield per hectare is low and highly variable between years and fields. Over the last decade crop yield has not changed much in the Sahel (Table 1) with the exception of Burkina Faso, where a steadier yield increase was observed. Increase in total millet production in the Sahel has been realized through an increase in the area under cultivation (Table 1). In order to improve livelihood of rural areas in the drier parts of the Sahel, there is a need to develop strategies to increase millet production for this zone in a more sustainable way.

Table 1. Average area under millet cultivation (×1000 ha) and millet grain yields (kg ha^{-1}) in seven Sahelian countries in West Africa in three periods between 1988 and 2002 (FAO, 1998–2002), and the change between 1988–1992 and 1998–2002 of acreage (%) and yield (kg ha^{-1}) in the first period.

	Period 1 1988–1992		Period 2 1993–1997		Period 3 1998–2002		Change between periods 1 and 3 (%)	
Countries	Area	Yield	Area	Yield	Area	Yield	Area	Yield
Burkina Faso	1,204	588	1,171	665	1,258	738	+ *4.5*	+ *25.4*
Chad	545	443	617	410	808	432	+ *48.3*	– *2.5*
Gambia	49	1026	57	1015	84	1068	+ *71.6*	+ *4.1*
Mali	1,112	727	1,164	649	1,122	771	+ *0.9*	+ *6.1*
Mauritania	13	362	21	280	17	307	+ *25.4*	– *15.4*
Niger	4,214	407	4,870	349	5,267	425	+ *25.0*	+ *4.4*
Senegal	873	609	919	629	844	623	– *3.3*	+ *2.2*
Total area	*8010*	-	*8819*	-	*9400*	-	+ *17.3*	-
*Average yield**	-	*507*	-	*568*	-	*532*		+ *4.9*

* Average is a weighted average based on acreage in each country.

Since decades, improved technologies for millet production have been developed in several West African countries and also in India on the basis of one or a few disciplines. This has led to single component technologies such as soil fertility management, genetic improvement, crop protection etc. (van Duivenbooden and Cissé, 1993; Niangado *et al*., 1992; ICRISAT, 1984–1990; Maiti and Bidinger, 1981). These technologies were proposed to mitigate problems that were not always perceived in the same way by farmers, or did not match socio-economic conditions of the target group. As a consequence their adoption by the end user has been below expectation (Kessler and Moolhuijzen, 1994; Marcussen, 1994; FAO, 1995; INSAH, 1997; Bationo *et al*., 1998). Examples of potentially interesting and profitable technologies include application of fertilizer for improved production and reduced infestation with the hemi-parasitic weed *Striga hermonthica*. Millet grain yield can increase by up to 100% after fertilizer use (Yamoah *et al.,* 2002) and *Striga* infestation has been found to be reduced by 55–82% in sorghum after urea was applied (Hess and Ejeta, 1987). Despite their potential, farmers rarely apply these technologies and it has been found that this is mainly due to poor investment capacity (Dugué, 1993a). Another reason for poor adoption of proposed technologies is the poor and uncertain access of farmers to inputs. The poor and uncertain access and low investment capacity are not only an issue related to the farming system itself but also to the environment determined by decisions and factors at the district, regional or national level. Roads, banks and markets are all needed to enable adoption of capital requiring technologies like for instance fertilizer use.

Multi-scale characterization has been proposed as a method to analyse constraints to development of a farming system at different hierarchical levels (Andriesse *et al*., 1995). This method is presented in the literature as a tool to assess the variability in the biophysical and socio-economic environments in which farmers work, to improve analysis of constraints and thus to allow the identification of focussed interventions in the appropriate systems and at the right scale (Andriesse *et al*., 1995; Stomph *et al.,* 1994). Several studies on multi-scale characterization have been carried out on agro-ecosystems in countries in West and Central Africa. The first attempts have been undertaken by ILRI, Wageningen, in collaboration with IITA within the framework of the Wetland Utilization Research Project-WURP (Hekstra *et al*., 1983). This work was followed by that of Windmeijer and Andriesse (1993), Andriesse *et al*. (1994), van Duivenbooden and Windmeijer (1995) and Thenkabail and Nolte (1995) on quantifying variation in inland valley agro-ecosystems in West and Central Africa. The element of multi-scale agro-ecological characterization adds to methods like rapid rural appraisal in that an attempt is made to determine what constraints to production systems are playing a role for larger groups of people, villages or districts. To give some examples: poor and erratic rainfall is not the problem of a field, a farm or a village but an attribute of a much wider zone. Lack of cattle to produce manure is in some cases linked to an individual farm household, in some cases to a village or a zone. By analysing the largest entity that has the same problem, one can determine to what extent an individual household can expect to solve the problem and to what extent the problem surpasses the individual household. The analysis can also help to determine to what extent different households are comparable so that when a solution to a constraint is found in a study, the conditions under which the solution works is analysed simultaneously and possibilities for transfer to other households, villages, districts or regions can be analysed.

In this study, previously obtained results have been supplemented with additional data in an attempt to use the strengths of the multi-scale characterisation and the rapid rural appraisal methods for the analysis of major constraints to millet-based cropping systems on deep sandy soils in the Fifth Region of Mali. The analysis has been carried out at the village, district and regional level. On the basis of this analysis research priorities were determined to arrive at improved integrated management of millet production.

Materials and methods

The study was conducted in the framework of the Desert Margin Programme (DMP) in

Burkina Faso, Mali and Niger. In Mali, the investigations focused on millet-based cropping systems on deep sandy soils in the Fifth Region, as millet is the major staple crop in the agro-ecological zones bordering the desert. Three hierarchical levels have been selected: the village (Lagassagou), the district (Bankass) and the region (Map 1). The Bankass district is one of the two districts in the Fifth region where deep sandy soils are found and where millet-based cropping systems prevail. The choice between Bankass district and Koro district was made in favour of Bankass district because it has slightly more favourable growing conditions, a higher population pressure, a slightly better infrastructure. Together these characteristics make the district more representative to conditions where changes may be expected. Furthermore a larger amount of secondary data is available to support the analysis.

Through a rapid rural appraisal in 1997, villages in the Bankass district have been analysed and the village Lagassagou (3°62' W, 13°83' N) was chosen for a more detailed analysis. Criteria for the choice of the village were:

- The village has deep sandy soils;
- The village is inhabited by the largest ethnic group in the district (the Dogon), and considers millet-based cropping systems as their main activity;
- The distance to markets was representative;
- The full variation in millet-based cropping systems encountered in the district was also observed within the village (DRSPR, 1992);
- The presence of data from earlier village studies.

The characterization of the village Lagassagou was carried out in October and November 1997 by a multidisciplinary farming systems research team of IER (Institut d'Economie Rurale), the national research institute. The rapid rural appraisal method was used. This method characterizes an agro-ecological zone on the basis of a selected site and extrapolates the results to a regional level (Legoupil and Lidon, 1993). Interviews were held with the village, lineage and households chiefs to determine the number of persons per household and to identify their farming strategies (cropping techniques, crop types, fallow systems, manure and fertilizer use etc.), available resources (land tenure, labour, livestock, equipment), production objectives and constraints to agricultural production. Next to interviews other available sources of information were used. For population composition also the official booklets with family information ('Carnet de famille') were consulted. The current short-term dynamics in land use was observed by monitoring actual land use in the village territory with the help of a GPS in 1999, 2000 and 2001. Rainfall data between 1992 and 2001 were used to relate to farmers' assessment of drought problems. As amounts of organic fertilizers applied to fields were given in cartloads, five samples of such cartloads were weighed and the average of 240 kg per cartload was used to translate information to SI units.

Information from this diagnostic survey and the interviews was analysed to make a typology of the production units. In the context of this study, a production unit (PU) is defined as a household or a group of households in which members work on the same fields and eat together. The typology of production units was aimed at defining groups with a specific combination of land use system and resource endowment as these are expected to react differently to proposed technologies. Criteria for distinction between households were:

- Number of people per household;
- Total available land per household;
- Number of carts and ploughs per household;
- Number of cattle per household (excluding small ruminants).

The characterization of the Bankass district is mainly based on secondary data from earlier studies (PIRT, 1983, 1989; DNEF, 1990). These were supplemented by a field survey of land use in 2000 and 2001. Land use of a selection of in total 18 sites was observed in 2000–2001 and compared with land use at these sites as determined from earlier aerial photographs (PIRT, 1983). The 18 sites were 500 by 500 m each and placed in the three agro-ecological zones that were distinguished in the district (Map 3). The land use surveys were made with a Trimble GPS after a differential correction using a base station at the 'Centre Régional de Recherche Agronomique de Mopti' at about 130 km distance. The method allows determination of positioning of areas under different land use with 10-meter accuracy. Average rainfall for the three different agro-ecological zones within the district were calculated on the basis of 32 years data between 1970 and 2001. Descriptions of major soil types were taken from Cissé and Gosseye (1990).

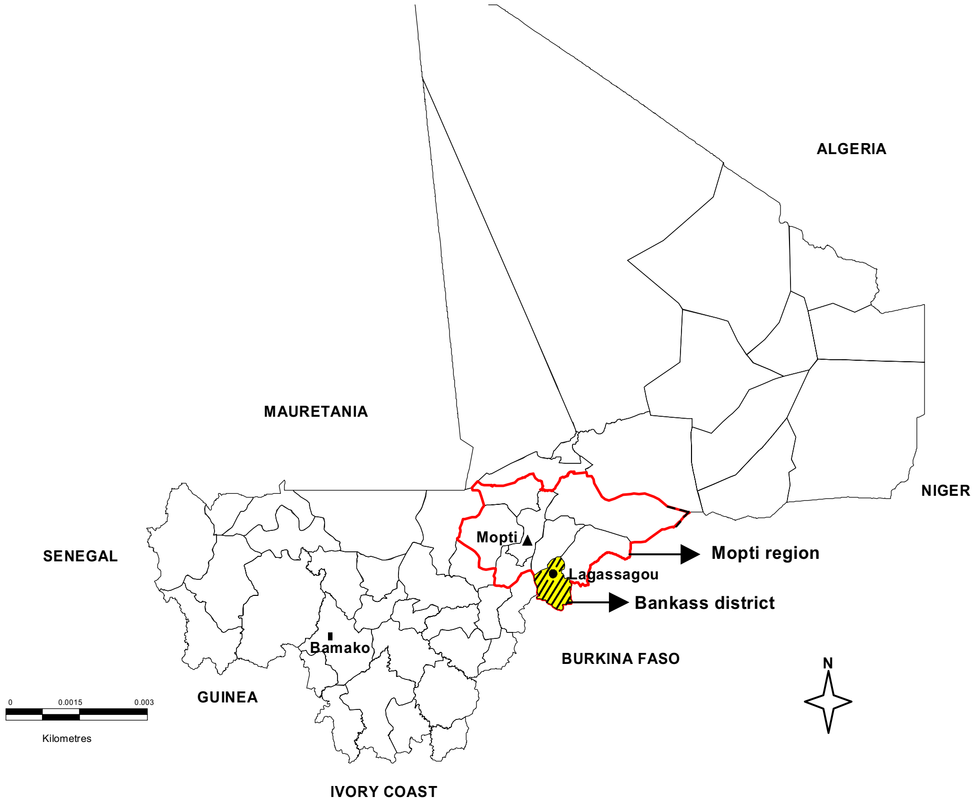
The characterization of the Fifth region was fully based on secondary data collected in previous studies (Cissé and Gosseye, 1990; DRSPR, 1992; van Duivenbooden and Veeneklaas, 1993; Veeneklaas *et al.*, 1990). Data on major soil types, vegetation, infrastructure (roads, markets), average annual rainfall, human population density, major production systems, objectives of and constraints to agricultural productions were analysed.

Results and discussion

Characterization at the Fifth Region level

Landscapes

The Fifth Region of Mali covers 67,736 km^2. It includes eight districts: Bandiagara,



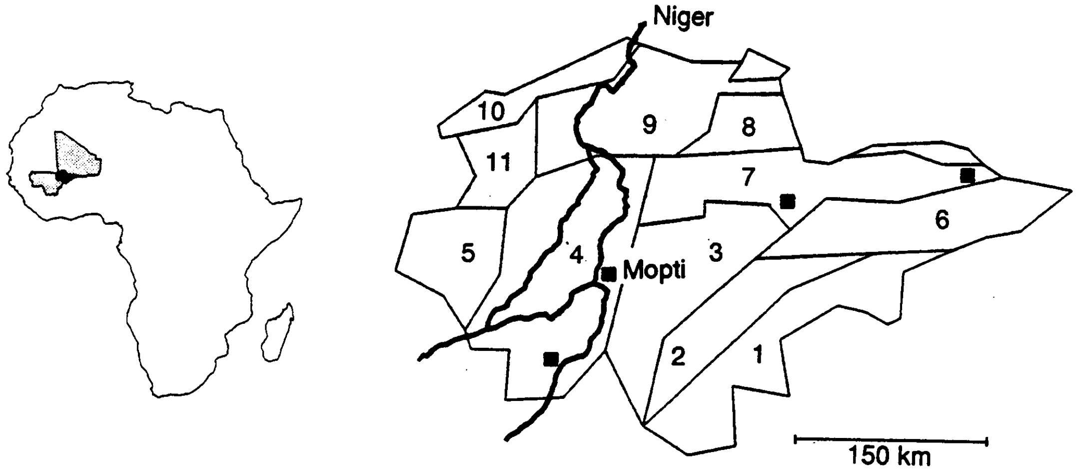
Map 1. Location of the Fifth Region, the Bankass district and the Lagassagou village in Mali.

Bankass, Djenné, Douentza, Koro, Mopti, Tennenkou and Youwarou. The region is dominated by the Central Delta of the river Niger with an area of 16,000 km^2 that is flooded annually in most years. The inland valleys and the upland zones of the region offer opportunities for development of arable farming (42%), animal husbandry (56%) and fisheries (Cissé and Gosseye, 1990). Seven agro-ecological zones (Map 2) and seven major soil types (Table 2) are distinguished in the region (Cissé and Gosseye, 1990; PIRT, 1983):

- **The Plateau zone** (i.e., Dogon plateau or Bandiagara plateau) is rocky (80% of the zone) and has an average altitude of 700 m above sea level. Soils are moderately deep to shallow and sandy to sandy at the surface with very low to moderate water holding capacity (Table 3) and low to medium fertility (van Duivenbooden and Veeneklaas, 1993). The Plateau represents 16% of the total area of the region and includes the district of Bandiagara and part of the district of Douentza. This zone is suitable for herding, forestry and horticulture (onion). Only 20% of the zone is suitable for cereal production (millet, sorghum).

- The Séno zones comprise the **Séno-Bankass** zone (i.e., Séno-Gondo) with 6,527 km^2 and the **Séno-Mango** zone with 9,300 km^2. Together, they represent about 23% of the total area of the region. The zone includes the districts of Bankass and Koro and part of the district of Douentza. Parent materials are mainly formed by eolian sand deposits originating from weathering of the sandstone of the Plateau. Most soils are deep and loamy-sand to sandy-loam at the surface, with a low water holding capacity and a low fertility (van Duivenbooden and Veeneklaas, 1993). Gravely clay represents 28% if the total area of the Séno-Mango and is used for pasture. This zone is suitable for cereal cropping and herding. Millet is the main cereal in this zone. Sorghum is grown only in depressions, i.e., low parts in the area where soil fertility and moisture contents are relatively high.
- The **Central Delta**, the **Méma-Dioura** and the **Sourou** zones are alluvial plains. The Central Delta and the Méma-Dioura constitute together the 'interior Delta' along the river Niger with 16,079 and 5,403 km^2, respectively, and include the districts of Djenné, Mopti, Tennenkou and Youwarou. The Sourou zone with an area of 9,320 km^2 is situated along the river Sourou in the south of the Fifth Region bordering with the Burkina Faso and includes the southern part of the Bankass district. Soils are deep in all alluvial plains but differ in texture. In the **Méma-Dioura** soils are mostly loamy-sand to sandy-loam at the surface with moderate to very low water holding capacity. In the **Central** Delta soils are clay-loam to silt-loam. In the **Sourou** zone most soils are sandy-loam, silty-loam to silty-clay with medium to high fertility (van Duivenbooden and Veeneklaas, 1993), next to these also gravely clay is found (29% of the area) which is used for pasture. These plains represent 46% of the regional area and are subject to seasonal inundation with poor and imperfect drainage. This zone is suitable for arable cereal cropping (rice and sorghum), herding, fishing and forestry. Rice is the major crop in the Central Delta and the Méma while sorghum is the major crop in the Sourou zone.
- The **Gourma** is a zone in the north of the Central Delta and north-east of the Plateau with altitudes varying between 250 and 400 m. This zone includes the district of Douentza and represents 15% of the total area of the region. Soils are moderately deep to shallow and sandy-loam at the surface with low to very low water holding capacity and low in fertility. Gravely loam soils are also found (34% of the area) and these are used for pasture.

Millet is produced only on Soil type A and B (see Tables 2 and 3), which means that the millet production areas are mainly found in the Séno zones and on the Plateau. Based on soil characteristics, about 35% of the region is suitable for millet production.



Map 2. The different agro-ecological zones of the Fifth Region of Mali (Source: van Duivenbooden and Veeneklaas, 1993); agro-ecological zones 8–11 are not considered.

Table 2. Areas (km^2) of the major soil types by agro-ecological zones in the Fifth Region of Mali, numbers correspond to areas in Map 2 (Source: Veeneklaas *et al.*, 1990), data on soil types are given in Table 3.

Soil type	Sourou (1)	Séno-Bankass (2)	Plateau (3)	Central Delta (4)	Méma-Dioura (5)	Séno-Mango (6)	Gourma (7)	Total
A	-*	2,477	-	64	391	4,430	-	7,362
B	2,327	3,866	5,162	375	2,319	884	2,323	17,256
C	2,521	-	102	41	1,334	366	2,271	6,635
D	147	-	108	10,176	927	511	809	12,678
E	4,325	184	2,174	3,427	432	2,749	3,671	16,962
F	-	-	-	1,112	-	-	109	1,221
X**	-	-	3,344	64	-	360	1,034	4,802
Y	-	-	-	820	-	0	-	820
Total	9,320	6,527	10,890	16,079	5,403	9,300	10,217	67,736

* Non-existent. ** X = Rock; Y = Permanent water.

Table 3. Characteristics of the different soil types in the Fifth Region as indicated in Table 2 (Source: Veeneklaas *et al*., 1990).

Soil type	Texture (%)			Water content (mm/m)		Available water (mm/m)
	Sand	Silt	Clay	pF 2.5	pF 4.2	
A	77.5	10.0	12.5	98	56	42
B	60.0	30.0	10.0	160	46	112
C	62.5	10.0	27.5	151	115	36
D	10.0	47.5	42.5	335	173	162
E	32.5	35.0	32.5	256	134	122
F	38.5	44.0	17.5	235	76	159
X	Rock	-	-	-	-	-
Y	Permanent water bodies	-	-	-	-	-

Rainfall

The region belongs to the north Sahel-Soudanian bio-climatic zone characterized by a short erratic rainy season from June to September and a long dry season from October to May. Three rainfall zones can be distinguished in the region (Table 4). The 30-year averages (1958–1988) show considerable differences in precipitation between rainfall zones and between years. The length of the growing period is shorter in the North (zone III) than in the South (zone I) mainly caused by an earlier end of the rainy season.

Natural vegetation

The natural vegetation consists of woody and herbaceous species. Most natural vegetation serves human needs in the region. It plays a minor role in restoration of soil fertility, and products are used for selling of wood, firewood, construction materials, agricultural tools, pharmaceutical purposes and animal feed (Table 5). The 'Club du Sahel' cited by Bocoum (1990) reported wood productivity of 0.13 m^3 ha^{-1} yr^{-1} for non-agricultural lands (forest and fallow) receiving annual rainfall between 400 and 600 mm. The stock of woody vegetation varies between agro-ecological zones. The highest total wood stock of the region is found in the Séno (24.2%) and Sourou (22.5%) zones because of strong natural regeneration of trees on fallow lands in the Séno zone and the classified forests of the Sourou zone. The difficult access to both zones is another major reason for the larger wood reserves. The lesser wood reserves in the Central Delta are a consequence of the annual flooding.

Table 4. The different rainfall zones and average annual precipitation (mm) of the Fifth Region from 1958 to 1988. The 20% lowest values (6 years) were assumed to represent a dry year and the 60% intermediate values (18 years) a normal year, in which average rainfall ranges from 257 mm in the north to 545 mm in the south. The 20% highest values (6 years) represent a wet year (Cissé and Gosseye, 1990).

Rainfall zones (meteorological stations)	Agro-ecological zones	Annual rainfall (mm)		
		Average year	Dry year	Humid year
Zone I *				
Bankass, Koro	Sourou Séno-Bankass	544	368	689
Zone II				
Djenné, Mopti (airport), Douentza	Central Delta Plateau	461	306	663
Zone III Douentza, Hombori	Méma-Dioura Gourma Séno-Mango	379	237	512

* Rainfall zones and reference stations.

Table 5. Total wood stock and consumption in 1990 for the Fifth Region of Mali (Bocoum, 1990; Cissé and Gosseye, 1990).

Agro–ecological zone	Area ($ha \times 10^3$)	Total stock ($m^3 \times 10^3$)	Stock ($m^3\ ha^{-1}$)	Consumption ($m^3\ yr^{-1} \times 10^3$)	Sales* ($m^3\ yr^{-1}$)
Sourou	932	5,880	6.30	230	-**
Séno-Bankass	653	2,470	3.78	406	-
Plateau	1,089	4,760	4.36	581	12,300
Central Delta	1,608	1,440	0.89	230	-
Méma-Dioura	540	3,390	6.28	53	9,240
Séno-Mango	930	3,840	4.12	33	-
Gourma	1,022	4,290	4.20	187	37,400
Region	6,774	26,070	4.28	1,720	-

* Wood exported to Mopti city only.

** No export of wood.

Infrastructure

There are three tarmac roads in or passing through the Fifth Region: Bamako–Mopti–Gao (1250 km); Mopti–Djenné (135 km) and Mopti–Bandiagara (65 km), the latter road is prolonged by a well-maintained dirt road: Bandiagara–Bankass–Koro–Burkina Faso (200 km). The river Niger also serves as major infrastructure for transport of people and goods in the direction of the Bamako–Gao road.

The only agro-industry in the region is concentrated in the regional capital Mopti and consists of a milk-processing plant, which serves the local market in Mopti, a fish-smoking facility which serves both the national and international markets (Ghana, Burkina Faso, Ivory Coast) and a rice mill of mainly regional importance. The milk processed in Mopti comes from villages within a range of 15 km.

The market in Mopti is the major link between the regional economic activities and the national and international markets. The other markets of some importance in the region are the cattle markets in Fatoma and Douentza at 10 km and 175 km distance from Mopti, respectively. Banks and other services are all concentrated in Mopti.

Regional and national tax-generating activities are very limited. Only export products such as fish (smoked and fresh), cattle, artisanal products (tissues, pottery) that are formally traded generate income that can again be invested in the economy, next to paying for salaries etc. The state budget for the region is very low to cover the different costs of investment (agro-industries, road, fertilizer subsidy).

Population

The rural population size of the Fifth Region of Mali was estimated towards the end of the 1980s at 1,072,000 persons (Table 6) with an average of 15.5 persons km^{-2}. The growth rate was then estimated to be 0.67% per year (Cissé and Gosseye, 1990). In addition, Mopti city hosted a population of 73,979 people who were not directly involved in agricultural activities. The population density differs between the agro-ecological zones (Table 6). The highest density was observed in the Séno-Bankass zone. The reason is the larger availability of arable land in this zone compared to the Central Delta and the Méma-Dioura that are seasonally flooded. The original ethnic groups are Peul, Dogon, Kel Tamacheq, Sonrhai, Bozo, Somono, Bamanan, Dafing, Samogo and Bobo.

Land rights

At the level of the region, decisions related to land use are governed by the Local Development Council regrouping technical services (agricultural sectors, health, and education), political and administrative institutions. National and international development projects, NGOs, and organization of farmers also participate in decision making. At the level of the region, land belongs to the state (Riddell, 1986). When and where there is no need for the state to use the land, state laws recognize the customary land rights. Areas subject to legal rules for which the real estate is recognized and that is protected by state laws are not important and represent less than 10% of the cultivated area in Mali (Sissoko, 1999) and probably much less in this region. The pastoral code, which rules access to common pastures, is not well known and is neither applied by the autochthonous population, nor by the transhumance herders. For the use of crop residues, animals in transhumance are not allowed to graze on fields recently harvested without authorization of the owner (Riddell, 1986).

Land use systems

In all agro-ecological zones of the Fifth Region, land use consists of arable cropping often associated with animal husbandry, forestry and fisheries. Cropping systems are mainly based on rainfed cereal cropping (millet, sorghum) in uplands and rice in the inland valleys. Millet is the major crop in the region (van Duivenbooden, 1993). Fishing is practiced along the rivers Niger and Sourou. Animals (cattle, goats, sheep etc.) are raised in all zones using sedentary or ‘transhumance’ systems. Milk production varies between 0.5 litre per cow per day in the dry season and 1 litre per cow per day in the rainy season. The first calving of cows is at the age of 3–5 years as it is for the Sahel zone in Mali as a whole (Breman and de Ridder, 1991). Liveweight gains during the rainy season are only 200–350 g per day in the area, and for cows it takes up to 4 years to reach the marketable weight of 150 to 200 kg (PNVA, 1997). The low animal productivity is associated to the poor nutritional quality of pastures, the lack of genetic improvement, and poor animal health care and management.

Table 6. Area (km^2) and population size of the Fifth Region of Mali in 1987 (Source: Cissé and Gosseye, 1990).

Agro-ecological zone	Area (km^2)	Number of heads (in thousands)	Density (heads km^{-2})
Sourou	9,320	130	13.9
Séno-Bankass	6,527	209	32.0
Plateau	10,890	296	27.2
Central Delta	16,079	291	18.1
Méma-Dioura	5,403	30	5.6
Séno-Mango	9,300	21	2.3
Gourma	10,217	95	9.3
Region	67,736	1,072	15.5

The major constraints to agricultural production at the level of the region are natural resource degradation, low budget for investment, lack of an agro-industry and poor infrastructure.

Characterization at the district level

Landscapes

The Bankass district covers 6,613 km^2 and is found between longitude 3°15' to 4°05' W and between latitude 13°10' to 14°15' N. Three agro-ecological zones can be distinguished in the district based on physiographic differences: the Dogon plateau or Bandiagara plateau, the Séno zone and the Sourou zone (Map 3). Of the total area of the district, 13.1% are permanent water bodies (mainly in the Sourou zone), roads and housing areas (DNEF, 1990). The remaining land is divided as follows:

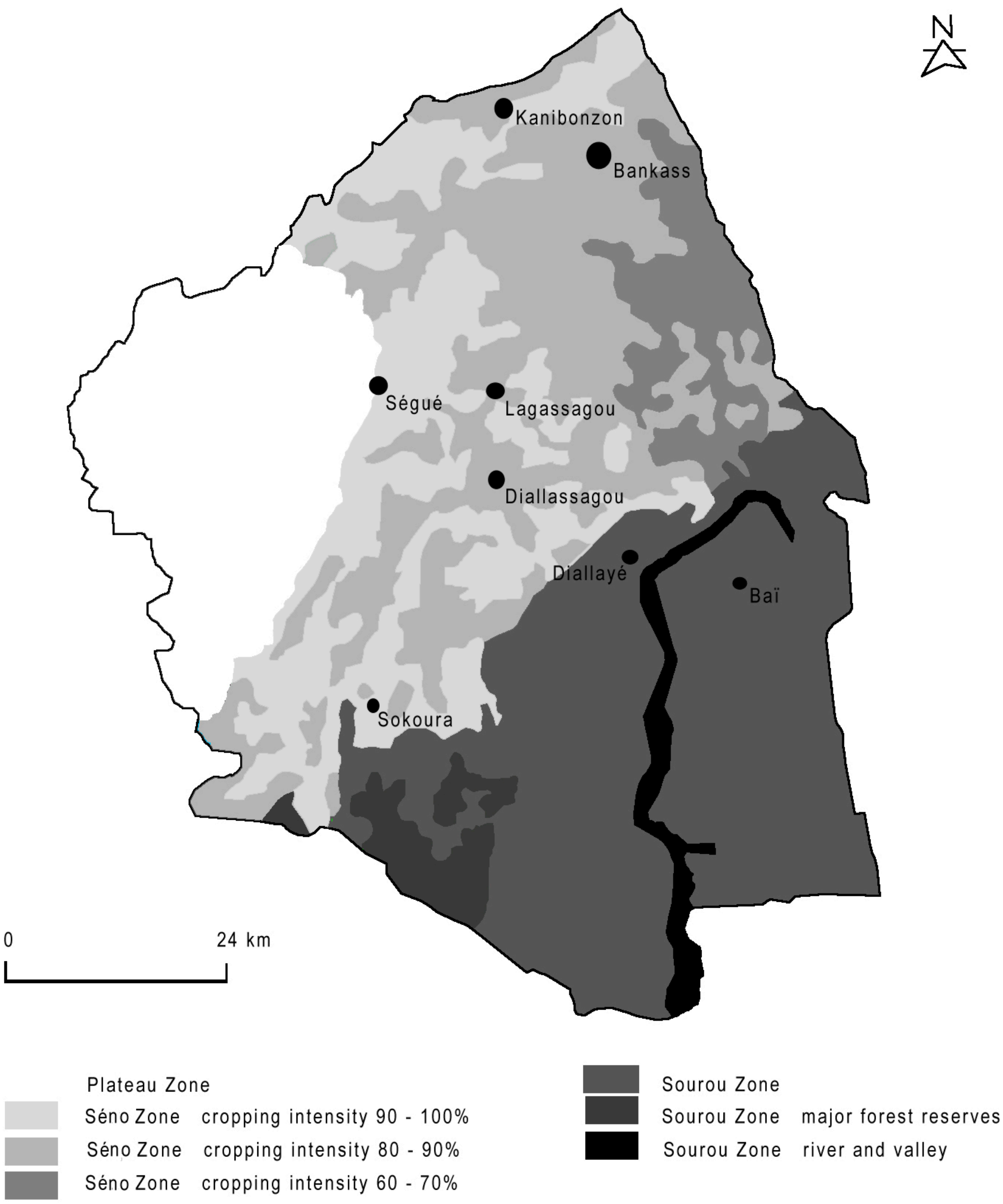
- The Plateau zone represents 17.3% of the Bankass district. The relief is rocky with only 10% arable land (PIRT, 1983). Agricultural activities are based on small-scale horticulture and cereal cropping (millet and sorghum), fruit trees and animal herding.
- The Séno-Bankass zone is a sandy plain called the Séno (i.e., sandy zone in Peul). It covers about 45% of the district of which 85% is arable land (PIRT, 1983). Along a north to south transect going from the Plateau towards the Sourou, the landscape changes from undulating to flat. The major production system is a combination of millet-based arable farming and animal husbandry.
- The Sourou zone (also called Samori zone) covers 24.5% of the district of which 70% is arable land (DNEF, 1990; PIRT, 1983). This zone is suitable for arable cereal cropping (sorghum, rice, and millet), animal herding, fisheries and forestry.

Natural vegetation

Natural vegetation in the Plateau zone comprises herbaceous species (e.g., *Andropogon* spp., *Eragrostis tremula* and *Aristida* sp.), tree species (e.g., *Vitellaria paradoxa, Lannea microcarpa, Acacia albida*) and shrubs (*Combretum glutinosum*, *Boscia* spp., *Guiera senegalensis*).

In the Séno-Bankass zone, the main woody species are: *Acacia albida, Balanites aegyptiaca, Tamarindus indica, Prosopis africana, Guiera senegalensis*, and some *Combretaceae* and the herbaceous species: *Cassia mimosoides, Aristida funiculata, Zornia glochidiata, Eragrostis tremula, Cenchrus biflorus* and *Andropogon gayanus*.

In the Sourou zone, the natural vegetation is composed of arboreal savanna with as main woody species: *Anogeissus leocarpus, Acacia seyal, Pterocarpus lucens, Ziziphus mauritiana*, *Prosopis africana, Guiera senegalensis, Acacia albida, Balanites aegyptiaca*, and *Mitragyna inermis*. The herbaceous stratum comprises *Vetiveria nigritana* and *Panicum* spp.



Map 3. Representation of the different agro-ecological zones of the Bankass district in the Fifth Region of Mali. The land use intensity as observed in 2001–2002 in the Séno-Bankass zone is indicated as well as the major woodland reserves.

Infrastructure

Only the well-maintained dirt road Mopti–Burkina Faso passes through the district. In addition, there are dirt tracks that link villages within the district. There are village markets of importance at district level, including the market in the district capital Bankass. There are eight village markets in the Séno zone, the maximum distance from any village to a village market is around 15 km.

Population

The population of the Bankass district has been steadily increasing from 147,000 people in 1976 through 168,000 people in 1996 to an estimated 195,500 people in 2000 (DNSI, 2001). The observed increase in population corresponds to an annual growth rate of less than 1% before 1996 and of about 4% between 1996 and 2000. The annual growth rate of 2.5% as reported in 1996 (Anonymous, 1996) cannot explain the observed trend over the full period. Only a steadily increasing growth rate can explain this increase in population. In 2000, 49.7% of the population was female and the 195,500 people made up 34,710 households (DNSI, 2001). The population is not evenly distributed over the district (Table 7). Population density is higher in the Séno zone than in the Sourou and Plateau zones resulting in land pressure as observed at the district level.

Three ethnic groups constitute 95% of the population: the Dogon, the Peul and the Dafing. The Dogon people, who are generally arable farmers or agro-pastors, represent 70% of the total population. They live in the Séno and the Plateau zones. The Peul represent 15% of the total population and mainly practice sedentary and nomadic herding. They live in all three zones. The Dafing people live in the Sourou zone and the bordering areas of the other zones. As the Dogon, they are arable farmers or agro-pastors and represent 10% of the total population. The Samogo, the Marka, the Mossi and the Bobo are minor ethnic groups and represent only 5% of the total population. They live in the Sourou zone and the southern part of the Séno zone. In general, villages are inhabited by a single ethnic group.

Land resources

The total arable land area of the Bankass district is estimated at 297,800 ha of which, in 1990, 70% was cultivated and 30% was under fallow and forest (DNEF, 1990). In 1983,

Table 7. Average population density (DNSI, 1990; Anonymous, 1996) and available land resource for three distinguished agro-ecological zones in the Bankass district. Population densities are estimated from a representative 'arrondissement'* in each zone, names are given between brackets.

Agro-ecological zone	Population density (heads km^{-2})	Arable land (%)	Head km^{-2} arable land
Plateau zone (Ségué)	13	10	130
Séno zone (Dialassagou)	46	85	54
Sourou zone (Baye)	12	70	17

* The 'arrondissement' was an administrative entity before 1999 when the decentralization and the creation of 'communes' changed administrative entities.

Table 8. Land use intensity in the Bankass district in 1987 (PIRT, 1989) and 2000 (own observations).

Sampling areas	Number of observed sites	Cultivated areas (%)	
		1987–1989	2000–2001
Area 1	8	>70	90–100
Area 2	4	40–70	60–70
Area 3	6	10–40	80–90

cultivated areas represented 65% of total arable land (PIRT, 1983), so a 7% increase in land use ratio was observed between 1983 and 1990. These results are consistent with those obtained from the 1987 SPOT image interpretation field surveys from 1987 to 1989 (PIRT, 1989) in the same zone. A further increase was observed between 1987–1989 and 2000 as indicated by the survey on land use intensity in selected samples of areas also observed in 1987 (Table 8).

Land use systems

In all agro-ecological zones of the Bankass district, farming systems always combine cropping and livestock systems. On the Plateau and the Séno zones, millet is the major crop covering 75% of the cultivated areas (grown as mono- or mixed crop). In the valley of the river Sourou, millet is of minor importance (20%) while sorghum (55%) and rice (15%) are more important crops (Tessougué *et al*., 1998). The remaining acreage in all zones is cultivated with fonio, cowpea, groundnut, sorrels, sesame and bambara groundnut as sole crop or in intercropping with millet or sorghum.

Livestock density data were available from one source only (PNVA, 1997) which gives total numbers for the district in one single year, so no trends with time or variation in space could be analysed. The source mentioned 406,110 cattle, 312,310 sheep, 437,300 goats, 12,710 horses and 26,350 donkeys in the mid-1990s.

Fishing is only of importance in the river Sourou and is carried out by specialized fishermen from the Bozo tribe, also living in the Delta zone along the river Niger. The main species are *Tilapia, Clarias* and *Protopterus annectens*. They sell their products locally.

There are two forests. A major one occurs in the Sourou zone, and a smaller one in the Plateau zone. These forests are used for wood collection. Furthermore, tree resources on cropland, pastures and fallow areas are also used for firewood, construction materials, feed, food and medical purposes, depending on the species.

The major constraints at the district level are reduction of fallow and pasture area and increase in cropped area, the lack of credit for agricultural activities and the lack of well-organized co-operatives for input and output sales and low and erratic rainfall. The increase in cultivated area and reduction in fallow and pasture area causes conflicts between farmers and herders (DRSPR, 1992).

Characterization at the village level

Soils

The village Lagassagou is found on soil type A as indicated in Tables 2 and 3. Like in the other areas in the Séno-Bankass zone, soils are deep and sandy (Table 3) at the surface with low to moderate water holding capacity and low fertility (van Duivenbooden and Veeneklaas, 1993). According to farmers, soils close to the village are relatively fertile because of the application of organic manure whereas bushfields are unfertile.

Rainfall

The rainfall recorded in the village between 1992 and 2002 showed an average of about 570 mm in 42 events per year. Year to year variation is considerable (Figure 1) as is representative of Sahelian conditions (Sivakumar *et al*., 1993; Sivakumar and Hatfield, 1990). Farmers mentioned 1993 and 2000 as years with rainfall deficits and bad distribution leading to sand blasting at the start of the rainy season and yield reduction. Data confirm that these years had a relatively low rainfall and bad rain distribution. Rainfall in 2001 was also low, but well distributed in time and space, allowing planting in the first decade of June, leaving the impression on farmers of a reasonably normal rainy season. Spatial variability of rainfall was evoked to be one of the major reasons of cropping fields scattered over the village territory. According to farmers, in the same village a farmer can achieve a good harvest on one field, and see the crop fail on another field.

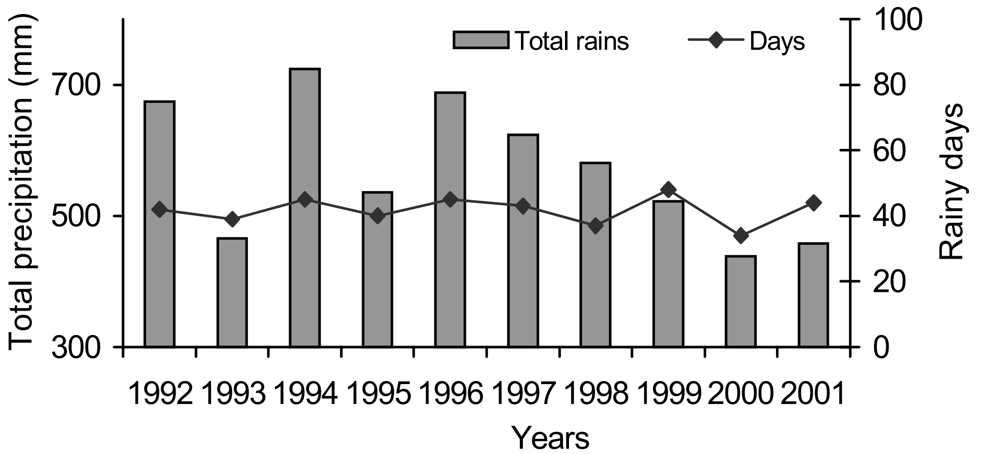


Figure 1. Annual rainfall in the village Lagassagou between 1992 and 2001.

Table 9. Average population size of a household in Lagassagou in 2001.

Population size	Men	Women	Boys	Girls	Total
Total number of persons	6	7	8	4	25
Active persons (9–55 years)	5	6	3	2	16

Infrastructure

Lagassagou village has no market. The closest markets are in Soula (10 km) and Dialassagou (15 km). The village is connected to the district capital (Bankass) and the surrounding villages by dirt tracks only. Bankass, is linked to Mopti City, the capital of the Fifth Region, by a well-maintained road.

Population, labour and social organization

Lagassagou counted 830 heads in 2001 of which 407 women. The labour force (64% of all people) consists of 278 male and 258 female active persons.

The inactive population is composed of boys and girls of 1 to 9 years old representing 28% of the total population and persons older than 60 years representing only 8% (Table 9). In 1971, the number of persons living in the village was 365, so between 1971 and 2001 the increase was 127%. The population can be divided over 33 productions units (PU) organized in either extended families (49%) or in core families (51%).

The village chief and his counsellors, who represent formal and traditional power, lead the village. Beside this, there is the lineage that is an important structural organization that rules customary land tenure. A production unit is headed by a chief called *Gua-tigi* (*Gua* means kitchen in the Bambara language and *tigi* stands for responsible). The *Gua-tigi* is the elder man of the household(s) who takes all decisions related to social and economic affairs concerning the households of the production unit, after consulting the other members. Youth and women organizations exist in Lagassagou for certain collective economic and social affairs (construction of infrastructures, common fields, ceremonies, self-help etc.). Income from the common fields is used for collective purposes.

Typology of production units

The results of a village survey conducted in 1997 were used to distinguish three types of production units (PU) (Table 10). Major criteria for the distinction between production units were the available land resources, labour, livestock and agricultural equipment. The following differences were observed between the production units.

PU-A has 0.5 active persons ha^{-1} available, whereas type B and C have only 0.23 and

0.12 active persons per ha, respectively. In rural areas, the available labour is also important in increasing off-farm revenues. Farmers indicated that it is easier for households with a large labour force to send people to a town for off-farm employment. The effect of sending one person in the household for off-farm employment on the agricultural workload for the remaining people in the household can be calculated as the percentage increase in the land that every remaining person has to cultivate. In this way it was found that the cultivated area per active person will increase by 4, 10 and 33% if one person would be taken from the labour force of PU-A, PU-B or PU-C, respectively.

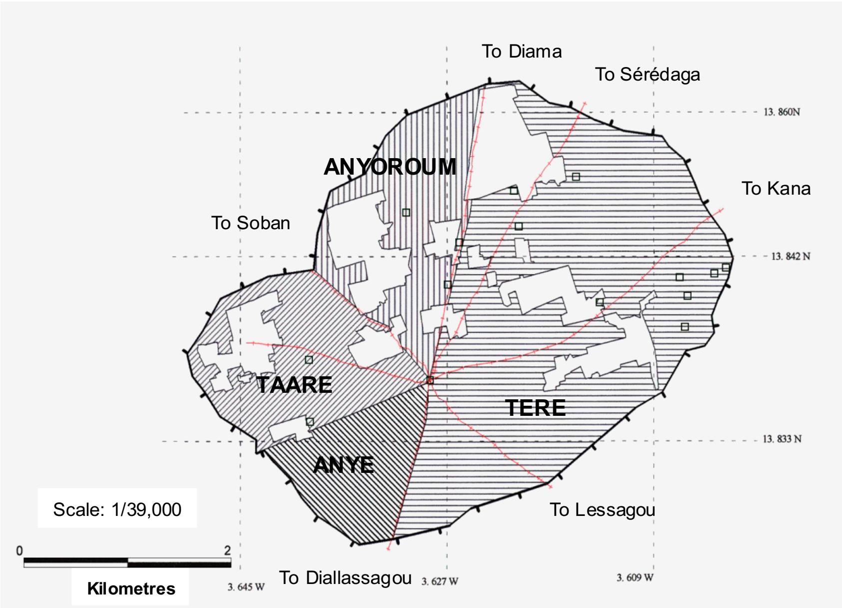
In addition, PU-A has more livestock per unit of arable land (0.21 TLU -tropical livestock unit- ha^{-1}) and, therefore, more manure available per unit area cultivated land than PU-B (0.11 TLU ha^{-1}) or PU-C (0.06 TLU ha^{-1}).

Table 10. Characteristics of the three types of production unit (PU) distinguished in Lagassagou in 1999.

Characteristics	PU-A	PU-B	PU-C
Average available labour			
Total population (persons PU^{-1})	47	16	6
Active population (persons PU^{-1})	27	11	4
Distribution (% of the village total)	45	36	19
Average land resource per production unit			
Total arable land (ha)	51.5	47.8	29.7
Cultivated area (%)	78	71	59
Fallow (%)	22	29	41
Equipment			
Ploughs (number PU^{-1})	1.1	1.1	0.3
Carts (number PU^{-1})	1.3	1.3	0.3
Livestock (numbers of animals PU^{-1})			
Cattle	7.2	2.5	0.9
Sheep	7.4	4.7	1.0
Goats	10.5	6.8	0.9
Donkeys**	1.3	0.9	0.3
Livestock density (TLU ha^{-1}*)	8.6	3.9	1.1

* Cattle = 0.8; sheep and goat = 0.1 (FAO, 1974). The number of the species is multiplied by the corresponding factor to obtain the number of tropical livestock units (TLU).

** Because of lack of data, donkeys are estimated as equivalent to cattle.



Map 4. Available land per lineage in the Lagassagou village. Fallow is indicated by white area, squares are test plots.

The available land increases with the size of the production unit, but not in proportion. This leads to a higher ratio of cultivated over total land for the larger production units. As none-cropped land is available for pasture to all other villagers the lower ratio will lead to a higher loss in soil fertility to other production units. The number of ploughs, carts and animals for traction (e.g., oxen and donkeys) determine agricultural mechanization, the higher availability for PU-A and PU-B imply they can cultivate more area per unit of labour in a shorter time than PU-C, which is especially relevant during weeding. Although not mentioned by farmers during the survey, it can be deduced that differences in income exist between production units. The availability of higher number of cattle gives PU-A and PU-B a potential access to cash for investment in inputs, PU-C does not have this possibility.

Land resources and land ownership

The customary land right stipulates that only families who founded the village own the land and can decide on access to land. These decisions related to land (e.g., access to land and solutions to conflicts) are co-ordinated by the village chief, his counsellors and the lineage chiefs (Maiga *et al.*, 1994). The administrative authority interferes only in case of disagreement. Land resources in the Lagassagou village belong to four lineages: *Tèrè, Anyoroum, Taaré* and *Anyè*. The lineage *Tèrè* holds land resources in the eastern part of the village representing 56.9% of the total 1430 ha of village territory (Map 4). The three other lineages share the second part of the area at different proportions (i.e., 17.63, 14.58, and 10.85% for *Anyoroum*, *Taaré* and *Anyè*, respectively). Land is not sold but can be allocated for cultivation to external people (other households and migrants), who are not allowed to plant trees or to carry out other long-term management practices (e.g., construction of houses and stone-lines for soil and water conservation) without prior authorization from the landowners.

The area under fallow and the average age of fallow dramatically declined from 1952 to 2001 (Table 11 and Map 4). In 1999 and 2001, respectively 70% and 82% of the village territory in Lagassagou was cultivated. In contrast, Karambé (1998) reported that aerial photographs taken in 1952 showed that fallow periods longer than ten years represented 52.6% of the total village territory in Lagassagou, while shorter fallow periods (< 10 years) covered another 16.5%, leaving no more than 31% as cultivated land.

Field types

A distinction is made between fields near the village, called *soforo* or homefields (*so* means house and *foro* stands for field), and fields away from the village, called *kungoforo* or bushfields (*kungo* means bush). Fields close to the village (the homefields) represent only 1% of the village territory, while bushfields represent 99%. There are marked differences in the level of fertility of soils between the village and the bushfields, as all available organic fertilizers (animal manure and household waste) are applied close to the village, a phenomenon well known in West Africa. Sédogo (1993) reported soil N content values ranging from 0.9 to 1.8 g kg^{-1} in homefields compared to

Table 11. Changes in of land use intensity in Lagassagou village between 1952 and 2001 (1952 data from Karambé, 1998).

Land use systems	Total area (ha)			
	1952	1997	1999	2001
Total arable land	1428	1428	1428	1428
Cultivated area	442	846	1009	1177
Fallow land				
1–3 years fallow	-*	-	257	201
4–5 years fallow	-	-	146	44
6–7 years fallow	-	-	15	6
7–10 years fallow	75	-	0	0
> 10 years	675	-	0	0
Total fallow land	750	582	418	251
Forest	236	0	0	0

* No data.

0.2 to 0.5 g kg^{-1} in bushfields in the Sudan-Savannah zone in Burkina Faso. These differences are caused by the fertility management strategy of the farmers; they apply all manure and household waste in a small ring directly surrounding the village. Also cattle are mostly corralled overnight in this same ring extending no further than 200 m from the village edge.

According to the type of usage of produce, there are common fields called *foroba* (*foro* means field and *ba* is big) and individual fields called *jonforo* (*jon* stands for slave). Cultivation of the common fields is carried out by all members of the production unit and is generally organized by the chief of the PU (i.e., *Gua-tigi*). Men and women can have individual fields, which are always bushfields, poor in organic matter and nutrients. Common fields are more or less fertile and include those located close to the village and bushfields recently brought under cultivation. Income from the products of common fields is shared by all members of the PU while that of individual fields is individually used, except in case of a food crisis when all members will have access.

Fallow use

Shifting cultivation using fallow is common practice in Lagassagou. The results of the survey showed that 71.8% of the selected farmers periodically leave fields fallow to restore fertility when yield declines. Some farmers (15.6%) fallow because of yield decline and also because of labour shortage. In general, farmers who mentioned labour shortage as a reason of fallowing had few active persons at the beginning of the growing season (mainly PU-C). The remaining 12.6% of the farmers mentioned several other reasons, including weed infestation by *Striga hermonthica* and need for grazing area. All farmers mentioned that they use fallow only in bushfields.

Fields are left fallow for 1 to 7 years, with 3–4 years as most common duration (68.7%) while periods of 1–2 years (15.6%), 5–6 years (9.4%) and 7 years (6.3%) are found in small proportions. More than 7-year-old fallow fields were not found in Lagassagou. These results were consistent with findings of Swinkels *et al*. (1997) in western Kenya.

Farmers mentioned that fallow vegetation is used as fodder for small ruminants during the growing season and for all animals during the dry season. Branches of trees on fallow land are removed for fuel, construction materials and agricultural tools (hoes, knives, and hatchets) while the leaves of woody and herbaceous vegetation are grazed by animals and removed for medicine. Only 12.5% of the farmers plant trees, especially baobab, in their fields. Farmers reported that fallow vegetation is not burned in Lagassagou. During clearing for cultivation, only smaller trees and shrubs are cut down at the onset of the rainy season and burned. Some species are intentionally left on the cleared fields.

Cropping systems

Though a large part of the agricultural production is for domestic consumption, crop products are also sold at the local market. Millet is the most important crop grown on about 75% of the total cultivated areas. Eighty percent of the millet-cultivated area is under millet sole crop. Bambara groundnut, groundnut, cowpea, fonio (*Digitaria exilis*), and ‘sorrel’ (*Hibiscus sabdarifa*) are other crops grown in Lagassagou. Cowpea, sorrel and bambara groundnut are grown either as sole crop or as an intercrop in millet. Average grain yields for the different crops were determined from a sample of 10 fields (Table 12). In general, millet grain yields in bushfields are lower than in fields close to the village.

In the group interviews farmers indicated that crop rotation including fallow periods was only applied in bushfields. The most important types of rotation in Lagassagou village are bambara groundnut–millet, fonio–fallow–millet, groundnut–millet, and fallow–millet. The millet–cowpea rotation system is only practiced since 2000 in Lagassagou. The potential for millet–legume rotation may be promising under Sahelian conditions because of the residual effects of N from biological fixation (Klaij *et al.*, 1994).

Intercropping is mainly practised in fields far away from the village. They include millet/cowpea, millet/sorrel, groundnut/sorrel, millet/sorrel and bambara groundnut/sorrel. In the millet/cowpea intercropping system, millet is planted together with cowpea in the same seeding holes, but cowpea is only planted in one out of five to six seeding holes.

All grains are kept in local granaries. No improved grain conservation technology is available in the village. Millet losses due to storage insects are low, but cowpea grains are severely attacked by Bruchids.

In the village, small amounts of the inorganic fertilizer NPK (15:15:15) are used at millet planting. When applied, the inorganic fertilizer is generally applied in fields close

Table 12. Average grain yields of crops in Lagassagou from 1998 to 2000.

Field type	Crop type	Average yield (kg ha^{-1})
Bushfields	Millet	450
	Groundnut	1100
	Cowpea*	80
	Fonio	800
	Sorrel	-**
Fields close to the compounds	Millet	1050

* In intercropping with millet; ** Sorrel production was not estimated.

to the village in the seeding holes at rates between 30 to 40 kg ha^{-1}, while organic manure is applied at rates between 500 and 2000 kg ha^{-1}. Results of the interviews held with farmers showed that 60% of the available organic fertilizers were applied between 0 and 100 m from the village and the remaining 40%, between 100 and 200 m. The main reasons farmers mentioned for the low external input supply in the fields at larger distance from the village, are the lack of sufficient income to buy inorganic fertilizers and lack of agricultural equipment to transport the manure to these more remote fields.

Animal penning also contributes to fertility restoration of fields. According to farmers, animals are penned in small areas of the fields between 100 and 200 m from the village. The amount and distribution of organic and inorganic fertilizers depend on the availability of agricultural equipment and the amount of livestock. Investigations showed that crop residues are not incorporated directly to restore soil fertility. They are used for domestic purposes (hangars, enclosures, tools, heating, and litters for organic manure production) and animal feed.

Animal husbandry

In Lagassagou, livestock activities are practiced in a very extensive way. They contribute to food security, animal traction and manure production. In the rainy season, cattle moved in transhumance by herders to the Sourou and the Plateau zones because of the scarcity of pasture. After the millet harvest, these animals come back to the village and feed on crop residues, tree products such as pods of *Acacia albida* and whatever pasture remains. Small ruminants, donkeys and draught oxen are managed as sedentary livestock. Poultry is also raised in the village but their number is not estimated.

The unfavourable climatic conditions lead to the reproduction and the dissemination of parasites in particular ticks and worms. According to farmers, livestock vaccination and treatment against internal and external parasites are not practiced in the village because of their costs.

Agro-forestry activities

There is no forest in Lagassagou except a small woody area of about 0.25 ha called ‘sacred wood’. All trees and shrubs come from natural growth and regeneration of woody vegetation in fields and fallow fields. The results of the survey show that the density of trees and shrubs was 230 ha^{-1} in the cultivated area and 643 and 748 trees per hectare were observed in 3- and 7-years-old fallow, respectively. Among the trees, *Acacia* sp. was most abundant. According to farmers, successive dry years in the last decades in addition to human use and animal grazing have caused the reduction in the density of the woody vegetation and the lack of firewood. But no observed data on temporal dynamics of woody vegetation are available.

In summary major constraints at the village level are low soil fertility and high *Striga* infestation level in bushfields. Low amounts of animal manure to improve soil fertility in cropped fields. Lack of pasture for animal feeding, lack of firewood and lack of low cost improved cowpea grain conservation technology. Land tenure rules for immigrant households give these uncertain access to land. Poor access to markets because of distance, poor roads and lack of transport means.

Constraint analysis

Constraints to millet-based cropping systems can be defined at all three levels of analysis (Table 13). At the regional and district level the main constraint is the low state budget for investment (e.g., fertilizer subsidy, agro-industries and roads). Farm gate prices of fertilizers are therefore higher and millet price is lower compared to the regional market price. For example, in July 2000, the price of fertilizer NPK (15:15:15) in Mopti City was 270 FCFA kg^{-1} compared to 350 FCFA kg^{-1} on the village market of Dialassagou located at 15 km away from Lagassagou. Millet prices in the same period were 125 FCFA kg^{-1} in Mopti City versus 85 FCFA kg^{-1} in the Dialassagou market. Of the total millet production in the Bankass district in 2000, (237,910 tons), only 0.4% was sold within the district and 2.3% within the region (DRAMER, 2001; ORM, 2001). Better farm gate prices may well increase this proportion, but no data are available to support this statement.

The major constraints to millet production identified at the village level are the low soil fertility in terms of N and P and the high *Striga* incidence. Large fertility differences can be observed within the village territory, but fertility of the majority of the fields is very low. The observed differences in fertility and in *Striga* incidence between fields are related to differences in crop management.

The high population density per unit area has reduced land resource per head to the point that the fallow system, commonly used to restore soil fertility and to control *Striga* infestation, is losing its effectiveness. With a land use intensity of 80% on average and bushfields left fallow on average for three years, the cultivation period has to be 9 years. Currently, farmers claim they cultivate fields for no longer than 3 to 5 years. So either they will have to increase the duration of the cropped period or they will gradually have to reduce fallow duration. The possibilities to improve soil fertility by using animal manure more intensively seems to be limited as more cattle would be needed requiring again extra animal feed. Currently, animals are already fed partly on external feed sources during the transhumance period.

With investment by regional and district authorities in infrastructure the ration in farm gate prices of inputs and outputs could be improved. In this way farmers would have more opportunities for income generation.

Table 13. Constraints related to millet-based production systems in the Fifth Region of Mali at regional, district and village level.

Identifiers	Region	District	Village
Biophysical	• Reduction of forest areas	• Reduction of already limited forest cover • Erratic and low rainfall in millet production areas	• Low soil fertility, crop pest (*Striga*) infestation, sand blasting at the start of the rainy season • Scarcity of pasture and lack of firewood • Erratic and low rainfall
Infra-structural	• Lack of agro-industry • Insufficient good quality roads connecting district to the regional capital and the national road system • Concentration of support services in the regional capital Mopti	• Low quality of the road system communicating villages and markets	• Distance to village markets, and poor roads to connect villages to the district centre and the national road system • Insufficient means of transportation • Lack of organization (such as co-operatives) for inputs supply and output sales
Population	• Rural exodus leading to influx of jobless people in the regional capital	• Increasing rate of population growth and related migration to major forest reserves • Increased tension between farmers and herdsman over pasture use	• Uncertain land tenure for immigrants • High and increasing land pressure, so insufficient land for pasture, cultivation and fallow • Labour shortage in smaller production units
Production system	• Lack of major income generating activities, so low investment budget • Withdrawal of the state as support to agricultural activities	• Low budget for investments by the district authorities • Lack of co-operatives for organization of input supplies and output sales • Lack of credit for agricultural activities	• Price ratio of inputs to outputs unfavourable • Lack of credit facilities or income to buy fertilizer • Lack of transportation, means to carry organic manure to bushfields • Lack of appropriate grain conservation technologies

Given the land pressure in the village either fallow will be completely abandoned or households will move to areas currently under natural vegetation in other parts of the district. When district authorities want to avoid such movements and the conflict around pasture use and destruction of wood reserves that are the consequence of this, they will have to facilitate improvements in the productivity of current millet-based cropping systems at village level.

Conclusion and research priority setting

Some 35% of the land resources in the Fifth Region of Mali is suitable for millet production (the main staple crop), whereas half of this is on the deep sandy soils in the south of the region. However, there are constraints that prevent development and intensification of this cropping system. These constraints should be addressed at different scale levels, in accordance with the actors involved. The major constraint identified at the regional level is the distance to major markets and the lack of an agro-industry related to products from millet-based production systems. This distance in kilometres is amplified in terms of distance in travel time, as road infrastructure is poor. The budget for investment in roads and agro-industry is too limited to support agricultural development at the village level. Such investments are needed to create a market for cash crops that could be grown on areas currently under millet-based production systems.

At the village level, soil poverty and *Striga* infestation are the major limiting factors for improved millet productivity. Diversification into cash crops is not an issue as long as markets and processing facilities are not available at the district or regional level. Currently even non-negligible storage losses occur mainly in cowpea. The scarcity of land resources and the low price ratio between agricultural outputs and inputs limit applicability of available strategies to improve the level of soil fertility and reduce *Striga* infestation. An extra complication is that land, labour and animal resources are not evenly distributed over households and production units in the villages. A distinction can be made between resource-rich and resource-poor production units. Resource-rich production units have:

- Ample labour with regards to available land, so that youngsters can do off-farm work in Mopti or cities at greater distance;
- More cattle in absolute terms and per hectare cropped land;
- Access to agricultural equipment, including transportation means.

Resource-poor production units do not have one or several of these attributes.

While macro-economic measures are needed to lift constraints at the regional and district level, farmers cannot wait for these solutions. Therefore, improved low-cost low external input options are needed to improve agricultural productivity. These constraints identified at the village and household level, where crop management takes place, can be the starting points for an integrated research to improve millet productivity in the Séno zone of the Fifth Region and similar areas in West Africa. Since farmers cannot expect any help from the higher scale level over the coming time in terms of improved infrastructure and thereby improved cost/benefit ratios, research should be focussed on integrated packages at low cost that link fallow management and other fertility and *Striga* management options in a sustainable way.

CHAPTER 3

Man-induced spatial variation of soil fertility and millet yields in the Sahel of Mali

Abstract
A quantitative analysis is given of temporal variation in fallow characteristics, and spatial variation in fallow distribution, millet yield and soil fertility in three villages in the Bankass area in Sahelian Mali. Plots of 5 m × 5 m were installed at 10, 50, 100, 200, 500, 1000 and 2000 m along four transects laid out from the edge of the village compounds to the outer boundary of the village territory. It was found that fallow is currently only practiced in bushfields. Significant increases in the amount of organic C and soil nutrients (N, P and K) were found with increasing fallow duration. This was due to gradual accumulation of organic matter from fallow vegetation and the presence of leguminous species. The amounts of soil nutrients and organic C followed fertility gradients in the village territory with the higher levels observed in homefields and the lower levels in bushfields. Also millet grain yield levels followed this gradient with around 1060 kg ha^{-1} observed in fields close to the village gradually decreasing to an average of 520 kg ha^{-1} in bushfields. Yields in bushfields ranged from 450 kg ha^{-1} on fields cultivated since several years to 640 kg ha^{-1} after 4–7 years of fallow. Regression analysis showed that millet yields were negatively correlated with *Striga* infestation. Future research needs to focus on the relationship between *Striga* infestation and soil factors.

Key words: Pearl millet yield, fallow, soil fertility, *Striga*, Mali.

Introduction

Over the last decades, sub-Saharan Africa's population growth rate has exceeded the growth of agricultural production (Club de Sahel, 1991; Cleaver and Donovan, 1995). One reason is the lack of success in raising production per unit production factor (e.g., land, labour, capital). Poverty and labour constraints, particularly during the peak season, add to the lack in advances and adoption of higher-yielding or drought-prone millet varieties and the use of fertilizing materials to raise the productive power of the generally poor soils. As a consequence, production increases have mainly been realized by opening up new land, thereby reducing the area under fallow. Currently, fallow periods have, in general, decreased to below five years.

About 250 million people produce their food through shifting cultivation systems, i.e., alternating cultivation with periods of restorative fallow (Robinson and McKean, 1992). Several factors affect the natural regeneration capacity of fallows, such as soil compaction, density of trees, incidence of bushfires and methods of land clearing. Decaying litter and roots from herbaceous and woody vegetation contribute to the recovery of soil organic matter (Young, 1989; Roose *et al*., 1979). The rates of decay of vegetation residues vary according to climate, fallow management and vegetation types. In the northern region of Ivory Coast, César and Coulibaly (1991) showed that *Andropogon gayanus* was able to add 5 tons of organic matter ha^{-1} yr^{-1} through the rooting system. In the drier zone of Senegal, Charreau (1972) estimated total organic matter production in fallow, based on herbaceous species, at 1 t ha^{-1} yr^{-1}.

Meanwhile, lack of mineral and organic fertilizers has caused poor soils to become even poorer. A continental study on soil fertility dynamics concluded that soil fertility in sub-Saharan Africa is declining (Stoorvogel *et al*., 1993). When taking a closer look, however, differences are observed. Some countries have depletion rates of up to 40 kg N ha^{-1} yr^{-1}, whereas others have no net depletion. Within countries, there are also major differences in both soil fertility status and its rate of change. In southern Mali, van der Pol (1992) calculated net nutrient deficits of 25 kg N ha^{-1} yr^{-1} and 20 kg K ha^{-1} yr^{-1} for the entire region, but at village level, Kanté (2001) showed that attractive cotton prices provide strong incentives for farmers to manage soil fertility more intensively. In the latter case, a cash crop can apparently act as an engine to the entire farming system.

In the Sudan-savanna and Sahelian zones of West Africa, farmers mainly grow millet and sorghum, yielding on average 200 kg and 800 kg ha^{-1} $year^{-1}$, respectively (Dugué, 1993b). In the sandy soils of the Sahel, Penning de Vries and Djitèye (1982) reported nitrogen contents as low as 0.2 g kg^{-1}. Shetty *et al.* (1998) found soil N contents between 0.1 and 0.4 g kg^{-1} and P between 1 and 3 mg P kg^{-1} in samples from the research stations of Sadoré (Niger) and Cinzana (Mali).

Interactions between soil chemical properties and soil moisture, micro-topography, trees, and shrubs can cause variation in crop productivity within fields (Brouwer and Bouma, 1997; Stein *et al.,* 1997). Animal penning is also an important cause of micro-variability of soil fertility and crop yields. Gandah (1999), working in Niger, showed that dry season animal penning added 2 to 30 kg P ha^{-1} and 18 to 257 kg N ha^{-1} on those spots in the field where animals were penned. Other factors including rain, wind-born dust and weed infestation may contribute to variation in crop growth and yield patterns among fields. In south-west Niger, Herrmann (1996) estimated annual inputs of 16–33 kg C ha^{-1}, 1.0–4.0 kg N ha^{-1}, 0.4–1.0 kg P ha^{-1} and 13.8 kg K ha^{-1} from 620–1860 kg ha^{-1} of solids deposition on surface soil from the atmosphere. Spatial variability among fields is also induced by farmers themselves, as part of their soil fertility management strategies. They distribute the scarce fertilizer resources in an uneven way. Farmers in Uganda maintain fertility in banana gardens at the expense of other fields (Wortmann and Kaizzi, 1998).

To feed a growing number of inhabitants, Sahelian farmers tend to cultivate increasing amounts of land with only modest organic inputs, thereby reducing fallow duration and soil fertility, and, in addition, facing massive infestation of the parasitic weed *Striga hermonthica*. M'Boob (1989) reported that *Striga* causes annual crop yield losses up to $\$7\times10^9$ in Africa. Adetimirin *et al.* (2000) showed that pre-flowering stress of maize due to *Striga* infestation resulted in a 44% reduction in the number of cobs per maize plant.

In view of the above, spatial variation was analysed in village territories of the Bankass area, Fifth Region, Mali. Fallow characteristics, soil fertility, yield and *Striga* infestation were quantified in order to get a clear picture of the current variability of these farming systems. More specifically, the objectives of this study were:

- To show the fallow dynamics of the area, and find out how it relates to soil fertility;
- To determine how soil fertility is spatially managed once the land is cultivated;
- To determine the relation between soil fertility, millet yield and the occurrence of *Striga hermonthica.*

Materials and methods

Study area

The study area comprises three villages (Lagassagou, Déna and Dimbal) in the Bankass area, which is located between longitude 3°15' to 4°05' W and latitude 13°10' to 14°15' N. This area belongs to the north Sahelo-Soudanian bio-climatic zone characterized by a short, monomodal rainy season from June to September. The 30-year average annual rainfall (1971–2000) is 540 mm in 30 rainy days. The landform is mainly flat to gently undulating, and soils are deep and sandy.

Fallow characterization and effects on soil fertility and yields

In June 1998, nine fields with fallow periods of 0–7 years were selected in each village. Vegetation dynamics and the above-ground biomass production of herbaceous species were recorded. Floristic composition was quantified according to the 'Points Quadrats' method described by Daget and Poissonet (1971) and Poissonet and César (1972). In each fallow, ten lines were laid out *at random*. Along these lines, observations on the presence of species were made at 4 cm intervals for plants shorter than 20 cm, and at 20 cm intervals for taller plants. On a total of 100 points, a stick was vertically placed in the vegetation. The species of any plant touching the stick was recorded as present, at any point more than one species could thus be recorded present. From these data, the 'specific contribution' was calculated as the ratio between the number of times a species was observed and the total number of times any species was observed (Daget and Poissonet, 1971).

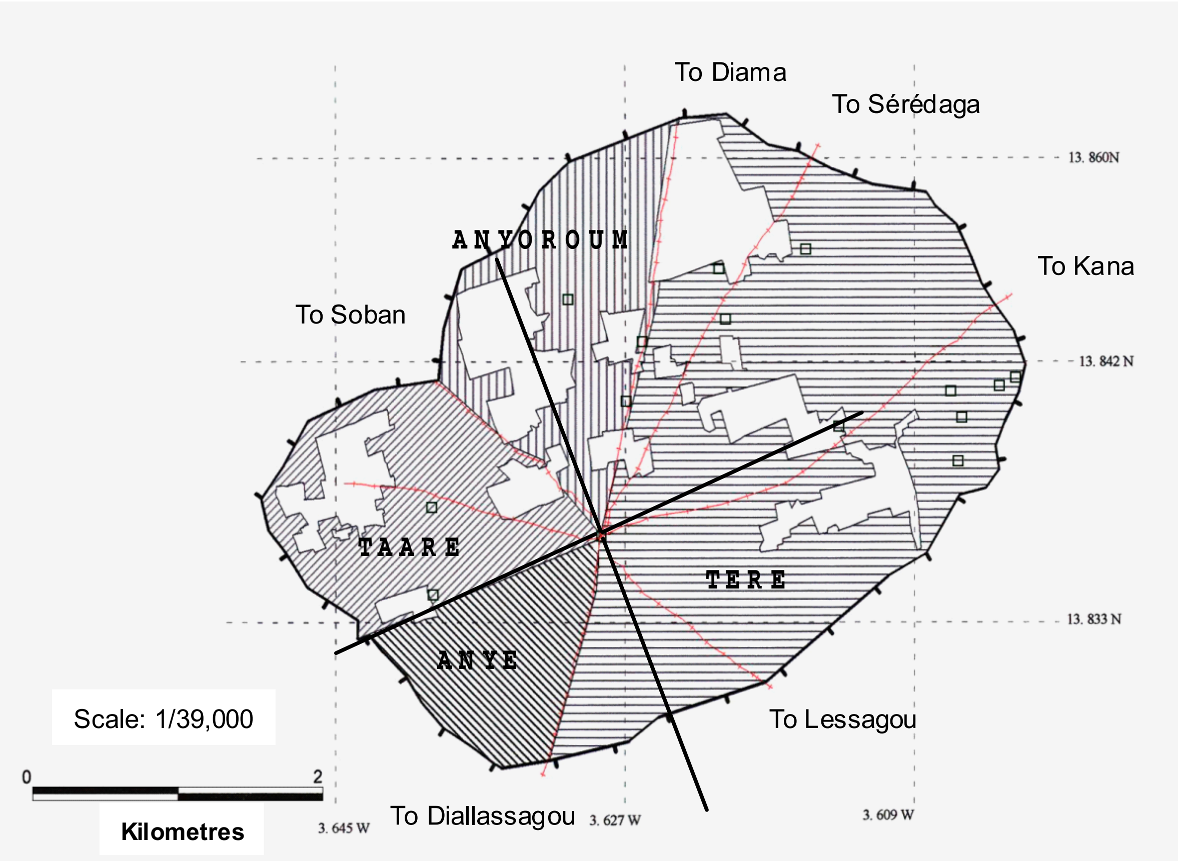
For quantitative analysis of the dry weight production and nutrient concentration in the vegetation, the above-ground herbaceous biomass was mowed from ten squares of 5 m × 5 m in each sampling area, air dried for two weeks, weighed and dried in a forced-draft oven at 60 °C for 72 hours and weighed. Sub-samples were taken to determine N, P, and K in the above-ground biomass. The number of trees and shrubs was counted on a 100 m × 100 m in the same areas. Biomass production from trees and shrubs was not estimated in this study.

A local variety of pearl millet (*Pennisetum glaucum* (L.) R. Br.) was grown in 1998 in each village using the above-mentioned fields with the 0–7 years fallow histories. The 0 year fallow was a field cultivated in at least two preceding seasons. Continuous cultivation only occurs on the fields close to the village, whereas further away farmers said the average cultivation period of a plot was 3–5 years. Thus, a plot with a recorded fallow duration of 0 year is a plot cultivated at least during the previous 3–5 years. Plot size was 100 m^2. Several seeds were used per seed hole at seeding, and thinned to three plants per hill, 20 days after emergence. Treatments received no further external inputs. Weeding was done manually using traditional hoeing. At maturity, millet was harvested and heads were sun-dried two weeks before threshing and weighing of grain yield. Bulk samples of soils were taken (only in Lagassagou) at 0–15 cm depth from each plot at plot clearing to determine the amounts of organic C, total N and available P and K contents. One-way analysis of variance (ANOVA) and Duncan's multiple range test were used to assess the difference between treatment means.

Spatial variation of soil fertility, Striga*, and millet yields*

Transect studies were conducted in the same villages from 1998 to 2000 to determine spatial variation of crop productivity between fields. The same study was conducted again in Lagassagou in 2001 to relate yield, *Striga* infestation and soil factors. Plots of 5 m × 5 m were installed at 10, 50, 100, 200, 500, 1000 and 2000 m along four transects laid out from the edge of the village compounds to the outer boundary of the village territory (for Lagassagou see Map 1). Information was collected from each plot on land cover (trees, shrubs, herbaceous vegetation), cropping systems (sole cropping, crop rotation, intercropping, weeding intensities, fallow system, fertilizer use and animal husbandry), planting patterns (crop species, crop densities), and use of crop residues.

The number of *Striga* stalks was counted each year, a week before millet harvest. Heads of harvested millet were sun-dried two weeks before threshing and weighing of grain yield. Samples of the above-ground biomass were taken from each plot and analysed for total N, P and K. In Lagassagou before planting, composite soil samples were collected from the surface 0–15 cm, and analysed for C, N, P and K. Regression



Map 1. Available land per lineage in the Lagassagou village. Solid lines are the transects as described in the text.

analyses were used to assess correlation between yield, soil nutrients and *Striga* infestation.

In addition, interviews were held with farmers of the sampled plots to collect information related to each individual plot about the amount of applied inorganic fertilizer, the number of cartloads of organic manure per field, animal penning, fallow duration and cropping periods and erosion control if any. To translate manure application rates to SI units, the average weight of a cartload was estimated at 240 kg fresh weight on the basis of five samples. The quantity of manure produced from field penning of cattle was estimated only in the village of Lagassagou in 1999. Quantitative evaluation of solid dejection of the 117 cattle of the village was done twice a week from December to May by collecting the dropped faeces in a single observation square of 50 m × 50 m, where animals were penned (Quilfen and Milleville, 1982).

Survey of land use changes between 1987 and 2001

To determine changes between 1987 and 2001 in the percentage of land under cultivation and under natural or fallow vegetation, three areas were selected in the district of Bankass. These areas had been used in 1989 to obtain the same information. Cultivated and fallow areas were measured from *random* samples of 500 m × 500 m in 2001 with a Trimble GPS after a differential correction using a base station at the 'Centre Régional de Recherche Agronomique de Mopti' at about 130 km away. Data obtained from this survey were compared to those from the previous study (PIRT, 1989). Accuracy of the used equipment is within 10 m. Table 1 shows a summary of the activities reported in this chapter.

Results and discussion

Fallow characterization and effects on soil fertility and yield

The area under fallow decreased from about 50% of the total arable land (297,800 ha; DNEF, 1990) in 1987–1989 to 18% in 2000–2001 in the Bankass district (Table 2). This decrease in fallow land was primarily due to the expansion of cultivated areas that results in reduction of pasture and forest and leads to conflicts between farmers and herders and among farmers (ESPGRN, 1999).

Table 1. Summary of activities carried out to evaluate spatial variation in millet production areas in the Bankass district in Mali between 1998 and 2001.

Activities	Location	Periods
Village assembly for discussion of survey of fallow areas	Lagassagou, Déna, Dimbal	20–21 May 1998
Fallow characterization	Lagassagou, Déna, Dimbal	
• Selection of fields and designation of sub-plots for millet cultivation and for continuation of fallow		1–10 June 1998
• Evaluation of millet productivity and *Striga* infestation on cultivated sub-plots		June–Nov. 1998
• Estimation of floristic composition of herbaceous biomass production on fallow sub-plots		September 1998
Transect study	Lagassagou, Déna, Dimbal	1998–2001
Observation of land use in 18 geo-referenced plots of 500 m × 500 m for comparison with an aerial photograph survey in 1987 (PIRT, 1989)	Bankass district	December 2000–January 2001

Table 2. Land use intensity in the Bankass district in 1987 (PIRT, 1989) and 2000 (own observations).

Sampling areas	Number of observed sites	Cultivated areas (%)	
		1987–1989	2000–2001
Area 1	8	>70	90–100
Area 2	4	40–70	60–70
Area 3	6	10–40	80–90

Table 3. Number of woody and herbaceous species and number of individual trees and shrubs observed per hectare, specific contribution of herbaceous vegetation in land cover, and total above-ground dry weight and nutrient content of the herbaceous vegetation in fallows of different length.

Parameters	Fallow duration (years)						
	1	2	3	4	5	6	7
Woody vegetation							
Number of species ha^{-1}	18	20	20	20	20	20	19
Density (plant ha^{-1})							
Trees (>8 m)	142	194	211	232	241	241	246
Trees (2–8 m)	201	211	212	248	189	195	201
Shrubs (<2 m)	217	217	240	291	308	311	301
Total	560	622	643	681	711	744	748
Herbaceous vegetation							
Number of species ha^{-1}	22	19	14	12	11	11	13
Specific contribution (%)							
Graminaceous species	45.8	59.2	61.3	65.6	66.3	58.4	45.5
Leguminous species	24.6	16.8	14.5	11.3	10.9	14.9	22.8
Total	70.4	76.0	75.8	76.9	77.2	73.3	68.3
Above-ground herbaceous biomass (kg DM ha^{-1})	2610	3080	3284	3560	3500	3450	2900
Std error (kg DM ha^{-1})	126	219	261	162	94	98	90
Nutrient contents (%)							
N	1.40	1.44	1.47	1.48	1.50	1.54	1.61
P_2O_5	0.15	0.16	0.17	0.19	0.19	0.20	0.21
K_2O	1.19	1.25	1.27	1.30	1.35	1.39	1.44

Increasing fallow lengths had no strong effect on the number of tree and shrub species (Table 3). However, their densities increased gradually from 560 to 777 plants ha^{-1} in fallow periods of 1 to 7 years as trees regenerated from stumps and roots left by farmers during land clearing and some new shrubs appeared. Some species (*Combretum glutinosum, Piliostigma reticulata, Calotropis procera* and *Guiera senegalensis*) cleared during cultivation, rapidly regenerated, and dominated during the first few years. *Balanites aegyptiaca, Acacia albida, Acacia nilotica, Sclerocarya birrea* and *Prosopis africana* were the dominant tree species in the zone regardless the length of the fallow period. *Piliostigma reticulata* and *Guiera senegalensis* were the dominant shrub species.

The number of herbaceous species decreased until year 5, but recovered in longer fallow (Table 3). This was due to pioneer species such as *Pennisetum pedicelatum* and *Alysicarpus ovalifolius* that grow well during and shortly after cultivating periods but disappear progressively with increasing fallow duration (Figure 1). Species such as *Andropogon gayanus*, however, succeeded pioneer species and became more important with increasing fallow periods. Table 3 also shows that graminaceous species dominate in the early years, but are gradually taken over by leguminous species. The most important leguminous species were *Cassia mimosoides, Zornia glochidiata,* and *Alysicarpus ovalifolius*, whereas the predominant graminaceous species included *Pennisetum pedicelatum, Andropogon gayanus,* and *Eragrostis tremula* (Figure 1).

The total above-ground herbaceous biomass production of the various fallows showed peak production in fallows of 4–6 years (Table 3). The decrease in herbaceous

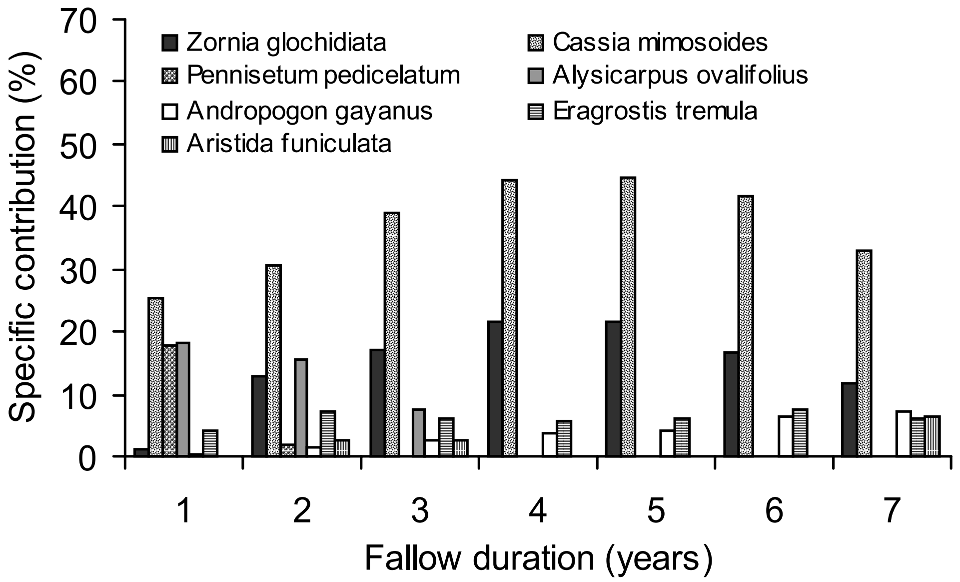


Figure 1. Specific contribution of the main herbaceous species in 1998.

biomass with increasing fallow length beyond four years may be attributed to the increase in density of woody species that progressively intercept more resources in the fallow system, as was also found by Yossi (1998).

The total N, P and K contents in the above-ground herbaceous biomass significantly increased with increasing fallow lengths ($P<0.05$). The highest amounts of nutrient uptake by herbaceous species on a per hectare basis were obtained in fallows that lasted 4–6 years (Table 3). The increase in N concentration in plant tissue in the later fallow stages may be due to the greater abundance of leguminous species later in the succession.

Soil organic C increased significantly ($P<0.05$) as fallow duration increased (Table 4). This can be explained by the progressive accumulation and decaying of the above-ground and root biomass. Increasing levels of soil organic C paralleled increases in the amounts of total N and available P, but not available K. Longer fallow duration also resulted in significantly higher millet yields (Figure 2). The increase in millet grain yield with increasing fallow duration was consistent with the increases in the amounts of organic matter and nutrient contents in soil.

Spatial variation of yield patterns, soil fertility and Striga

Interviews with farmers revealed that spatial variation of millet yields, soil nutrient content and *Striga* infestation between fields were induced by crop management strategies such as animal penning, manure application and crop–fallow rotation. The total amount of manure provided in 1998 in Lagassagou, through six months dry season cattle penning and household refuse, was estimated at 22,800 kg, distributed up to 200 m from the village compounds, on roughly 19 ha. Reasons for this type of

Table 4. Effects of fallow duration (years) on nutrient status in the upper 0–15 cm soil layer. All fields are unfertilized bushfields at 500 to 2000 m distances from the village boundaries.

Nutrients		Fallow duration (years)						
	CM*	1	2	3	4	5	6	7
Organic C (g kg^{-1})	1.50 f	1.90 e	2.57 d	2.60 d	2.85 c	3.02 b	3.12 b	3.40 a
Total N (g kg^{-1})	0.14 b	0.17 ab	0.19 ab	0.20 ab	0.22 a	0.22 a	0.23 a	0.25 a
P-Bray (mg kg^{-1})	2.26	2.32	2.46	2.47	2.50	2.52	2.57	2.65
Avail. K (mg kg^{-1})	5.70	5.54	5.84	5.80	5.77	5.98	5.59	5.54

* CM = millet cultivated during at least 3–5 preceding growing seasons. Means within rows followed by the same letter are not significantly different ($P<0.05$). No significant differences were observed in soil P and K levels.

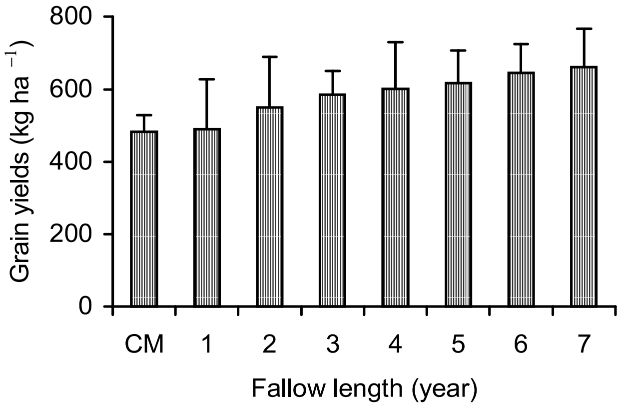


Figure 2. Influence of fallow duration on average millet grain yield in Lagassagou, Déna and Dimbal in 1998; CM indicates millet grown without fallow in 3–5 consecutive years. Error bars indicate standard error of the means.

localized application were the low amount of manure produced and the lack of transport to apply organic fertilizers further away. Crop residues from 1998 remaining in the field for the 1999 planting season was estimated at 490 kg ha^{-1} in the fields close to the village and 560 kg ha^{-1} in bushfields. Nutrient inputs from similarly low amounts of residues (315 kg ha^{-1}) were estimated at only 0.15 kg N ha^{-1} and 0.01 kg P ha^{-1} in Sahelian agro-ecosystems (Hiernaux *et al*., 1997).

Cropping intensity (i.e., the ratio of cultivated land and total land) decreased at greater distance from the village. Close to the villages, 100% of the total arable land was cultivated while in bushfields 87% of the area was cropped, the remaining land was under fallow for less than 8 years. Within 200 m from the villages, 97% of the cultivated area was under millet monoculture from 1998 to 2000, whereas 3% was under millet/cowpea intercrop. In bushfields, the average frequency of millet sole crop was lower (61%) and that of intercropping higher (11%). The main intercropping systems observed in bushfields in the three villages included millet/cowpea, millet/sorrel (*Hibiscus sabdarifa)*, groundnut/sorrel, and bambara groundnut/sorrel. No differences in cropping intensity were found between villages.

Planting densities of millet significantly decreased with increasing distances from the village compounds. Figure 3 shows that the average number of hills decreased from 10,000 ha^{-1} in the homefields at 10–50 m from the village boundary, to 5,000 ha^{-1} in bushfields beyond 500 m from the village boundary. No significant differences were observed between villages in the number of hills ha^{-1} and per type of field. Weeding frequencies were also variable between fields and tended to be higher in fields closer to the village. According to farmers, homefields were weeded 3–4 times during a growing season while bushfields were weeded only twice. This was explained by the higher infestation with annual grasses caused by the application of organic manure and household wastes on the homefields.

In three consecutive years (1998–2000), millet yields significantly decreased with increasing distance from the village (Figure 4). Average highest yields were obtained at 10–200 m (880−1240 kg ha^{-1}) and the lowest at 1000–2000 m from the village (450–580 kg ha^{-1}). Among villages, averaged grain production in Lagassagou (940 kg ha^{-1}) was higher than in Déna (760 kg ha^{-1}) and Dimbal (680 kg ha^{-1}). Between years, averaged yields obtained in 1998 (800 kg ha^{-1}) and 1999 (870 kg ha^{-1}) were higher than those obtained in 2000 (700 kg ha^{-1}). This was probably because of late planting and partial replanting in 2000, due to the late and erratic onset of the rainy season.

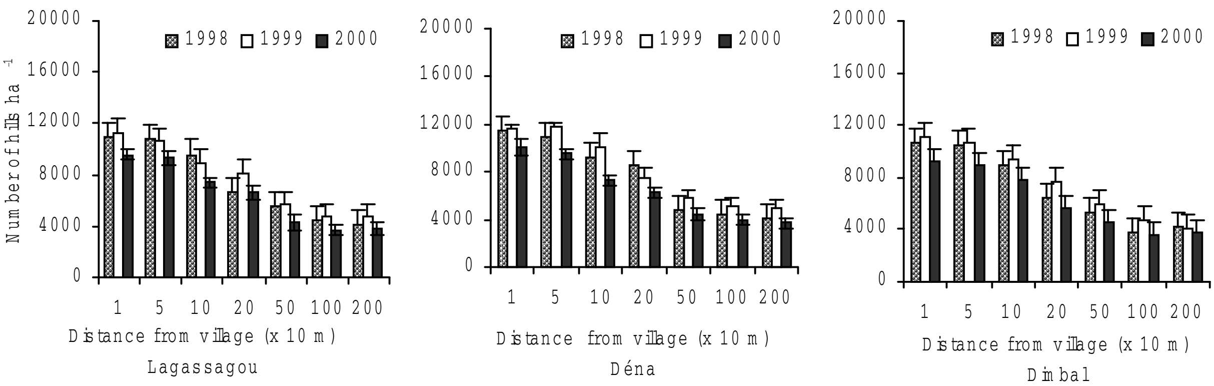


Figure 3. Cropping density (no hills ha^{-1}) as related to distance of the plots from the village in Lagassagou, Déna and Dimbal. Error bars indicate standard error of the means.

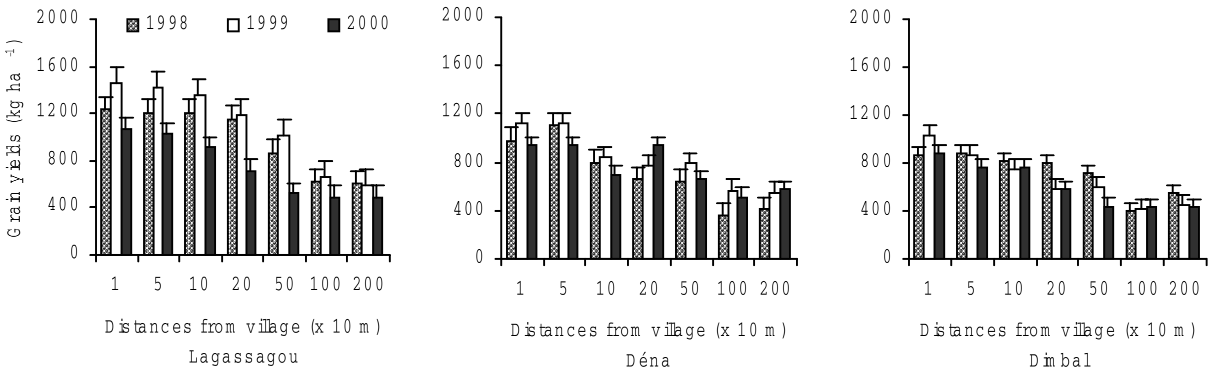


Figure 4. Grain yield (kg ha^{-1}) of millet in response to distances of the plots from the villages of Lagassagou, Déna and Dimbal. Error bars indicate standard error of the means.

Soil chemical properties followed fertility gradients running from the village compounds to the boundary of the village territory (Table 5). Differences in soil fertility parameters and pH between fields are most probably because of unknown quantities of applications of household waste and organic manure around the village. These results confirmed results obtained by Sédogo (1993) at Saria, Burkina Faso, who found pH values ranging from 6.7 to 8.3 in homefields, and 5.7 to 6.2 in bushfields, and organic carbon contents ranging from 11–20 g kg^{-1} in homefields to 2–5 g kg^{-1} in bushfields. Meanwhile, it should be borne in mind that soil fertility and millet yields within the 200 m range (i.e., 10% of the 2000 m radius of the village territory) represent a mere 1% of the entire village territory.

Striga infestation significantly increased with increasing distance from the village (Figure 5). Bushfields at 500–2000 m had the highest numbers of emerged *Striga* plants with on average 11,800 plants ha^{-1}.

Table 5. Average soil chemical characteristics of plots scattered at different distances from the village before planting in 1998 in Lagassagou.

Soil nutrients	Distance (m)						
	10	50	100	200	500	1000	2000
Organic C (g kg^{-1})	5.4 a*	5.5 a	3.6 b	2.4 c	1.2 d	1.5 d	1.0 d
Total N (g kg^{-1})	0.25 a	0.23 a	0.19 a	0.14 ab	0.11 b	0.10 c	0.12 c
Available P (mg kg^{-1})	8.4 a	8.2 a	4.5 b	3.6 b	2.5 c	2.5 c	2.5 c
Available K (mg kg^{-1})	28.7 a	25.5 b	22.4 c	16.1 d	9.2 e	5.5 f	5.5 f
pH (water)	8.5 a	8.1 a	7.2 b	7.0 b	6.0 c	5.2 d	5.2 d

* Column means values with the same letter are not significantly different at 5% probability level.

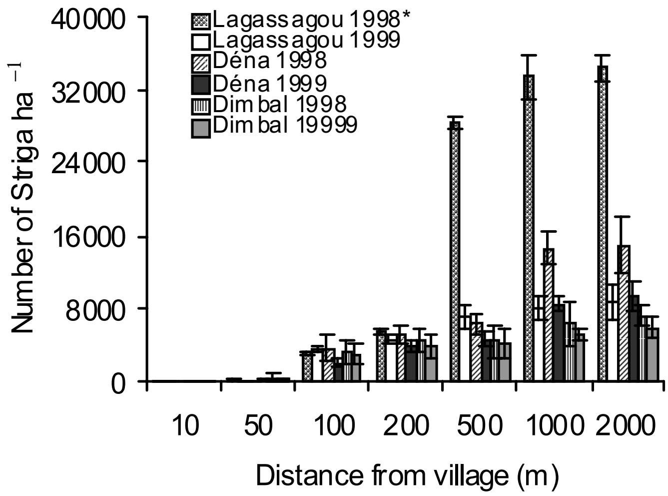


Figure 5. Density of *Striga* (plants ha^{-1}) at different distances from the villages. Error bars indicate standard error of the means.

Between villages, *Striga* infestation in 1998 was higher in Lagassagou than in Déna and Dimbal. Among years, averaged densities of *Striga* were higher in 1998 (8,400 plants ha^{-1}) than in 1999 (4,000 plants ha^{-1}). In 2000, the authors observed hardly any *Striga* in the region, and no *Striga* plants were observed in any of the three villages. Major differences in *Striga* infestation between villages and between years might be due to sowing periods. In 1998, millet was sown from 20–30 May in Lagassagou and from 10–20 June in Déna and Dimbal. In the three villages, millet was planted from 1 to 10 July in 1999 and from 20 July to 10 August in 2000. These results are in agreement with those of Hess and Williams (1994) who concluded that late planting of pearl millet reduces *Striga* infestation and minimizes yield reduction. Late sowing can, however, not be recommended as a control measure in the Sahel, where rainfall is limited and unpredictable.

Multiple linear regression analyses determining correlation between yield, soil fertility parameters and the degree of *Striga* infestation for 1998 and 2001 are given in Table 6. Although yield was significantly correlated with each soil fertility parameter, the correlation of yield with *Striga* was found to give the highest percentage variation explained in both years. Addition of any of the fertility parameters did not improve the regression model.

For 1999 and 2000, no soil fertility data were available. Nevertheless these years can provide interesting extra information as in 1999 *Striga* infestation levels were relatively low (about 9,000 plants ha^{-1}) compared to 1998 and 2001 (32,000 and 27,000 *Striga* plants ha^{-1}, respectively), and no *Striga* was observed in 2000. Regression of soil fertility data in 2001 on soil fertility data of the same plots in 1998 learns that very

Table 6. Correlation coefficients for simple linear regression of millet grain yield on the indicated explaining variables. The coefficients in bold are selected as explaining variables in a stepwise regression analysis. The last row indicates the range of averaged observed *Striga* infestation levels at 1000–2000 m distance from the village compounds.

Explaining variable	1998	1999	2000	2001
N	0.426	0.689	0.465	0.313
P	0.423	0.612	0.594	0.437
K	0.719	**0.867**	**0.687**	0.650
C	0.490	0.707	0.651	0.520
Striga	**0.806**	0.558	not relevant	**0.690**
Striga infestation at 1000–2000 m (stalks ha^{-1})	33,000	9,000	0	27,500

little differences exist between fertility in the plots in both years. Regression coefficients were not significantly different from 1 and correlation coefficients were 0.91 or above at 26 degrees of freedom. This makes it possible to estimate the relative effect of *Striga* and fertility on yields also in 1999 and 2000 with the use of the averaged fertility levels in each plot from the 1998 and 2001 chemical analyses. The results (Table 6) show that at low *Striga* infestation levels, *Striga* explains less of the variation in yield levels between plots along the transects, while fertility accounts for slightly more of the variance than when *Striga* is present. At lower *Striga* infestation (1999 and 2000), potassium seems to be the single most important soil fertility indicator and a stepwise regression only includes potassium in both years. When *Striga* is not regarded in 1998 and 2001 also potassium is selected in a stepwise regression. Therefore, *Striga* and fertility seem to interact, and in different years their relative importance changes in explaining variability in millet yields between fields in the village territory.

The relationship between soil fertility parameters and *Striga* is not fully understood. It is generally believed that the application of nutrients reduces infestation by *Striga*. Mansfield (1982) reported that up to 150 kg N ha^{-1} might be needed to reduce *Striga* infestation effectively. In contrast, Boukar *et al.* (1996) found that *Striga* density was higher with an application of 60 kg N ha^{-1} than without N application.

Conclusions

Traditional management of soil fertility in millet cropping systems in the Bankass area is based on the use of organic fertilizers in fields close to the village (i.e., 1% of the total territory), and short fallow in bushfields. Increasing fallow length gradually increased the densities of trees and shrubs without significant effects on the number of species. However, the number of herbaceous species decreased between 1 and 5 year fallow duration and increased again after 7-years fallow. This was due to succession starting with pioneer species such as *Pennisetum pedicelatum* and *Alysicarpus ovalifolius* that grow well during and shortly after cultivation, and disappear progressively with increasing fallow duration and the perennial species that take some time to establish in fallow vegetation.

The amounts of organic C, N and P in the topsoil (0–15 cm depth) significantly increased with increasing fallow duration because of the gradual accumulation of organic matter from herbaceous and woody vegetation and the presence of leguminous species that potentially contributed to N supply by symbiotic N-fixation. Results also show that spatial variation in soil fertility between fields within village territories followed fertility gradients with the highest amounts of nutrients close to the village and the lowest in bushfields. Differences in nutrient contents were due to application of all household waste and available manure directly around the villages.

Despite the increase in fertility with increasing fallow duration the fertility of the oldest fallow plots was lower than that of plots around the village that receive organic fertilizer on an annual basis. The amount of organic C was 5.5 g kg^{-1} in fields at 10–50 m from the compounds versus 3.2 g kg^{-1} in 5–8 year old fallow. Available P was 8.3 mg kg^{-1} in fields at 10–50 m from the compounds and 2.6 mg kg^{-1} in 5–8 year old fallow. Millet grain yields followed the same gradients, ranging from 1060 kg ha^{-1} in homefields to 620 kg ha^{-1} in bushfields the first year after a fallow period of at least 4 years and decreasing further to 450 kg ha^{-1} in bushfields after 3–5 subsequent years of millet cultivation. Millet yields in bushfields averaged 520 kg ha^{-1} when combining all plots with different fallow duration prior to millet production and different periods of continuous millet cultivation.

Multiple regression analyses between yields, soil fertility parameters and the degree of *Striga* infestation showed that yields were significantly correlated with organic C, N, P and K individually. But all these parameters also showed strong positive correlation among themselves. Correlation of yield on *Striga* was found to give the highest percentage of variation explained. Addition of any of the fertility parameters did not improve the regression model. Also, *Striga* infestation and soil fertility were negatively correlated. The relationships between yield, *Striga* density and soil factors are not fully understood. To design improved integrated management strategies of fertility and *Striga* future research needs to focus more on the interactions between these factors.

CHAPTER 4

Integrated crop management strategies to enhance agricultural productivity in the semi-arid tropics of West Africa: Effects of cropping systems and fallow duration on millet productivity and *Striga* infestation

Abstract

A four-years study was conducted from 1998 to 2001 to evaluate different integrated crop management systems for millet-based cropping systems in West Africa. The experiment was conducted on a sandy soil in the village Lagassagou in northern Mali using a factorial split-plot design with as main plot treatments four fallow periods (0, 2, 5, and 7 years). Sub-plot treatments were three cropping systems: (1) continuous cultivation of millet from 1998 to 2001, (2) cowpea in 1998 followed by three years of a millet crop and (3) cowpea in 1998 followed by three years of a millet/cowpea intercrop. No fertilizers or pesticides were applied. The 1998-cowpea crop had a positive effect on subsequent millet yield and on soil nitrogen levels in 1999 and 2001. In 2000, no differences were observed but yields were extremely low after a late replanting. Soil C levels were enhanced in 2000 in the intercrop and in 2001 both in the intercrop and the monoculture millet crop after growing cowpea in 1998. Soil N was significantly higher in 2000 both in the intercrop and in the monoculture after cowpea. An increased fallow length had a positive effect on millet grain yield varying on average from 300 kg ha^{-1} with continuous millet to 450–470 kg ha^{-1} with 2–7 years fallow. Growing a cowpea crop in 1998 reduced infestation of millet with the parasitic weed *Striga hermonthica* in 1999 but this effect could not be detected anymore in 2001 in millet monoculture. In 2000, no *Striga* infestation was observed in all fields as a result of late planting. In the mixed cropping system a reduction in *Striga hermonthica* was observed in 2001. A longer fallow period reduced the infestation of the fields with *S. hermonthica* more both in 1999 and 2001.

Key words: Fallow, rotation, intercropping, grain yields, soil fertility, *Striga*.

Introduction

The increasing population density in the West-African Sahel necessitates an increase in food production. The production increase during the past decades has been obtained mainly through an increase in land area under cultivation (World Bank, 1984; Club du Sahel, 1991) and was possible only through decreasing fallow periods and replacement of traditional shifting cultivation systems by continuous cereal cropping. In the near future, possibilities for a further increase in land area under cultivation are limited. Therefore, productivity per hectare will have to increase. The needed increase will be difficult to attain as soils are strongly weathered, fragile and generally have a low inherent fertility. Most arable fields currently have a negative nutrient balance because of the small amount of fertilizers used to replace the nutrients that have been removed from the soil system (Bationo *et al.*, 1998; Buerkert and Hiernaux, 1998; van der Pol, 1992; Stoorvogel and Smaling, 1990b).

The change from shifting cultivation to short fallow rotations and finally to continuous cropping systems aggravates soil problems on these soils. Bationo *et al.* (1994) reported that continuous cultivation of cereals in the Sahel zone has led to a drastic reduction in organic matter levels and a subsequent soil acidification. In northern Nigeria, Jones (1971) found that after 18 years of continuous cropping, soil organic matter declined at a rate of 3–5% per annum. Continuous cereal cropping systems also negatively influence soil physical characteristics (Juo and Lal, 1977; Dembélé *et al.*, 1994; Piéri, 1989) and increase incidence of pests, diseases and weeds. Specially the incidence of the semi-parasitic weed *Striga hermonthica* has been found to be linked with too narrow crop-fallow rotations and continuous cropping at low input levels. In addition to the reduction of the length of fallow periods, the fallow vegetation and crop residues are used as pasture and fodder. The dung produced by the cattle is applied on land under continuous cultivation. In Burkina Faso, Dugué (1993b) estimated that only 10% of crop residues are left in the field after a growing season. Therefore, nutrient accumulation during the short-fallow period might not be sufficient to satisfy crop nutrient requirements in the long run at a sufficient production level for farmers to maintain a living.

A future agricultural production growth in the Sahel must depend on sustainable soil productivity, and therefore on improved technologies rather than on expansion of area under cultivation. Mineral fertilizers may appear to be the best means of restoring soil fertility and increasing crop yields (Bationo *et al.,* 1998; Piéri, 1989; van Reuler and Janssen, 1989), but inorganic and organic fertilizers are not always available and their use is not always economical (Ruthenberg, 1980; Anderson, 1992) and is limited by the lack of access to capital (Hoekstra and Corbett, 1995; Témé *et al.*, 1995). Therefore, non-fertilizer-based technologies that improve soil fertility and bring *Striga* infestation back to tolerable levels, require special attention. Studies have shown that cereal–legume rotations and cereal/legume intercrops can help to improve soil chemical characteristics (Bagayoko *et al.*, 1992; Tarawali *et al.*, 1992; Gakale and Clegg, 1987; Reddy *et al.*, 1990, 1992) and reduce *Striga* infestation. However, Bationo and Ntare (2000) found that fallow–millet rotations supplied more mineral N than legume−millet rotations. Quantitative information on cereal production, *Striga* infestation and soil chemical characteristics in fallow−millet, fallow−legume−millet and fallow–legume–millet/legume intercrop rotations under Sahelian agro-climatic conditions is lacking. The objective of this study was to compare in three subsequent years the effects on total productivity of these three rotation management systems at four lengths of the fallow period currently encountered in the Sahel (Chapter 3).

Materials and methods

A four-year on-farm study was conducted between 1998 and 2001 in Lagassagou, a village in the Sahelian zone of Mali. Soils were homogeneously sandy with a low organic matter and nutrient content (Table 1). At the onset of the rainy season in 1998, fields that had been fallow for different periods were cleared manually. All woody and herbaceous residues were burned in the field to imitate farmers' practices at the end of a fallow period. In contrast to these practices, ashes were homogeneously spread over the field to reduce heterogeneity.

The basic experimental set-up in 1998 (Table 2) was a split-plot design with three lengths of the fallow period (2, 5, and 7 years) and a control (3–5 subsequent years of continuous millet cropping) as main plot treatments (MPT). For each fallow period, there were four replicates in the bushfields of the village territory, so a total of 16 fields were used. Two, five and seven years of fallow covers well the range of lengths of fallow periods encountered in the village (Chapter 3). All fields had been infested by *Striga hermonthica* in earlier years, either the last few years or the years before they had been put to fallow, however, no quantitative information on the extent of the infestation in the different fields could be given by the farmers. The three sub-plot treatments (SPT) were different rotations: pearl millet (*Pennicetum glaucum* (L.)) in 1998 followed by three years of pearl millet monocrop (MM), cowpea (*Vigna unguiculata* L.) in 1998 followed by three years of pearl millet monocrop (LM) and cowpea in 1998 followed by three years with a pearl millet/cowpea intercrop (LM/C). The main plots were 300 m^2 and sub-plots 100 m^2.

Prior to sowing in 1998, soil samples were taken from the first 15 cm of the soil profile in a 2 by 2 meter grid and bulked per replication of each fallow treatment. A sub-sample was analysed for soil organic C and N content. Monocultures of well-adapted local varieties of pearl millet (var. Toroniou) and cowpea (var. IT89DK-245) were sown on ridges to avoid seedling mortality by sand blasting. The crops were sown after the first major rainfall event. Millet was sown at 1.0 m between and within rows and thinned to three plants per hill 15 days after emergence. Cowpea was sown at 0.5 m × 0.25 m spacing with four to six beans per hill and reduced to two plants per hill at 20 days after sowing. At harvest crop residues were removed for feeding to animals, as would be the case under standard farming practice, though, animals were not allowed to graze on the plots.

The same variety of millet was homogeneously planted in all plots following the spatial design of the experiment in 1998. Plots were planted at the first major rainfall event in all years, i.e. between 1 and 10 July in 1999, between 11 and 14 June and again between 20 July and 10 August in 2000 (after the first sowing failed), and between 1 and 10 June in 2001. Millet was sown at 10–15 seeds per hill, and these hills were thinned to three plants 15 days after emergence. In the intercropped millet, cowpea (var. IT89DK-245) was sown in addition to the millet at 1.0 m between cowpea rows and 0.25 m between plants within rows and 0.5 m distance between millet and cowpea rows. Hills were sown 15 days after millet emergence at 3–6 grains and thinned to 2 plants at 20 days after sowing. Because farmers in this zone use shifting

Table 1. General characteristics of the topsoil (0–15 cm) of the fallow treatments at the beginning of the 1998-growing season.

Nutrients	CM*	F2	F5	F7
Organic C (g kg^{-1})	1.64	2.57	2.78	2.92
Total N (g kg^{-1})	0.14	0.20	0.21	0.24
Available P (mg kg^{-1})	2.26	2.46	2.52	2.65
Available K (mg kg^{-1})	5.70	5.84	5.98	5.54

* CM = land cultivated with millet in 3–5 preceding years; F2, F5 and F7 = fallow periods of 2, 5 and 7 years, respectively.

Table 2. Schedule of cropping sequence in the tested crop rotations.

Cropping systems	History of fallow	1998	1999	2000	2001
CM-MM*	1995-1997 Millet	Millet	Millet	Millet	Millet
CM-LM	1995-1997 Millet	Cowpea	Millet	Millet	Millet
CM-LM/C	1995-1997 Millet	Cowpea	M/C	M/C	M/C
F2-MM	1995 millet then 1996-1997: Fallow	Millet	Millet	Millet	Millet
F2-LM	1995 millet then 1996-1997: Fallow	Cowpea	Millet	Millet	Millet
F2-LM/C	1995 millet then 1996-1997: Fallow	Cowpea	M/C	M/C	M/C
F5-MM	1992 millet then 1993-1997: Fallow	Millet	Millet	Millet	Millet
F5-LM	1992 millet then 1993-1997: Fallow	Cowpea	Millet	Millet	Millet
F5-LM/C	1992 millet then 1993-1997: Fallow	Cowpea	M/C	M/C	M/C
F7-MM	1990 millet then 1991-1997: Fallow	Millet	Millet	Millet	Millet
F7-LM	1990 millet then 1991-1997: Fallow	Cowpea	Millet	Millet	Millet
F7-LM/C	1990 millet then 1991-1997: Fallow	Cowpea	M/C	M/C	M/C

* CM = 3–5 subsequent years millet cropping preceding experimental years 1998–2001; F2, F5 and F7 = 2, 5 or 7 years fallow, respectively; MM = millet after millet; LM = millet after cowpea; LM/C = millet/cowpea intercrop after cowpea; M/C = millet/cowpea intercrop.

cultivation with no external inputs in bushfields (Chapters 2 and 3, Samaké *et al.*, in prep.), no fertilizers or pesticides were applied. All plots were kept weed-free by manual hoeing until 35 days after emergence of millet and before the apparition of *Striga hermonthica.*

Before planting soil samples were taken from each plot at 0–15 cm depth in a 2 × 2 m grid, and bulked per plot. A sub-sample was analysed for soil organic C and N content. At maturity, heads of millet were harvested from each plot, sun dried for two weeks, threshed and weighed to determine grain yield. Also the number of *Striga hermonthica* shoots was counted in all plots. Random samples of total above-ground dry matter were collected to determine nitrogen concentration in the millet tissue. Chemical analyses were carried out at the national soil and plant laboratory of Sotuba in Bamako, Mali. Organic C was determined using the Walkley-Black method (Nelson and Sommers, 1982) and total N was determined as described by Nelson and Sommers (1980). Analysis of variance and Duncan's multiple range tests were used to assess differences between treatment means.

Results and discussion

Rainfall distribution

Seasonal rainfall in 1998 was 581 mm, which is close to the ten-year average rainfall of 570 mm in Lagassagou. In 1999, 2000 and 2001, precipitation was lower than the ten-year average with 522, 438 mm and 460 mm, respectively. Most rainfall was observed in July and August in all years (Figure 1). Rainfall distribution was favourable for crop growth in 1998, 1999 and 2001. In 2000, a long period of drought

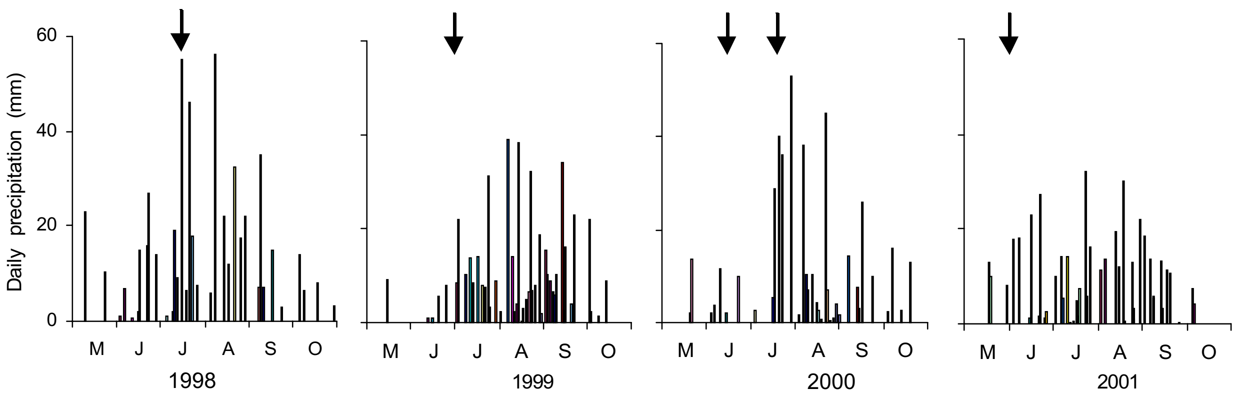


Figure 1. Daily rainfall (May-October) in Lagassagou village in 1998–2001, the arrows indicate the date of sowing, in 2000 the millet had to be sown a second time after the early season drought.

occurred between mid June and mid July causing seedling mortality. Therefore the crop had to be replanted, drastically shortening the crop cycle.

Effects on millet yield

The 1998-cowpea crop increased millet yield in 1999 and 2001 significantly ($P<0.05$) with 37 and 34%, respectively, compared to millet grown after the 1998 millet crop independent of the fallow treatment (Figure 2). Similar results were obtained by Bagayoko *et al*. (1992) who showed that yields of grain sorghum in the first and second year following soybean were, respectively, 44 and 6% higher than yield of continuous grain sorghum. Overall yields obtained in 2000 were much lower than in 1999 and 2001 and no significant differences ($P<0.05$) were observed between the different cropping systems. Also variability was higher in this low rainfall year. These effects are related to the late replanting after the early season drought. Also planting time between fields differed more in this year because of labour shortage in the village.

In the millet/cowpea intercrop sown after the 1998 cowpea crop (LM/C) millet yield was comparable to the millet monocrop sown after cowpea in 1999 and 2000 (Figure 2). In the third growing season, millet yield was 25% higher in the millet/cowpea intercrop than in the millet sole crop after cowpea in 1998 and 69% higher than the MM treatment. Total grain production in the millet/cowpea intercrop was higher than yields in the other treatments in all years. Millet yield in the intercrop was similar to millet yield in the monoculture after the 1998 cowpea crop. That indicates that

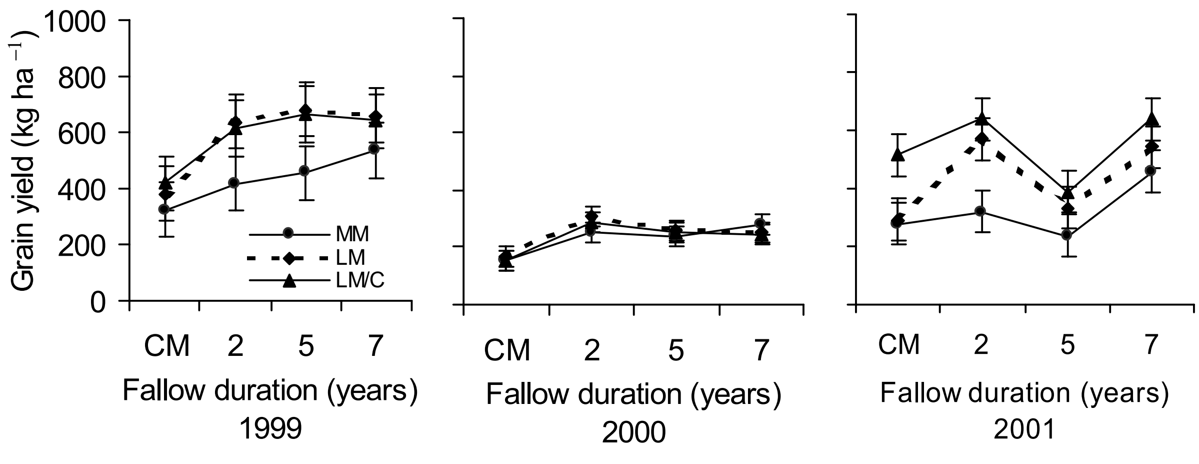


Figure 2. Effects of cropping systems and length of the fallow period on millet grain yield (kg ha^{-1}) in Lagassagou, in the northern Mali. Error bars show standard error of the difference between means. Cropping systems are millet in 1998–2001 (MM), cowpea in 1998 and millet in 1999–2001 (LM) and cowpea in 1998 and millet/cowpea intercrop in 1999–2001 (LM/C).

Table 3. Effects of fallow duration on cowpea grain yield (kg ha^{-1}) in 1999 and 2000 in Lagassagou, northern Mali. CM = 3–5 years of subsequent millet cropping.

Fallow duration	1999	2000
CM	210	330
F2 (fallow 2 years)	180	350
F5 (fallow 5 years)	190	310
F7 (fallow 7 years)	210	330
SED*	40	37
P > F**	0.953	0.876

* Standard error of the difference.

** Probability of treatment effects (level of significance).

growing the cowpea as an intercrop enhances total yield with cowpea production and in the long term also millet yield as a result of improved soil fertility. As cowpea production was higher in 2000 than in 1999, despite the poor rainfall in 2000 it can be concluded that risk of poor millet yield in a bad rainfall year can be compensated by an intercrop, improving food security and overall systems productivity.

Fallow duration significantly affected millet grain yield in all three years (Figure 2). No interactions were observed between length of the fallow period and the rotation and intercrop treatments. In all years, millet yields were lower in the millet grown after continuous millet (CM) than in the millet crops grown after fallow, regardless the length of the fallow period. The only exception was the yield of millet in 2001 in the plots cropped after a five-year fallow period. This was observed in all treatments and all replicates and we found no explanation for this. From 1999–2001, millet grain yields following 3–5 years of millet (CM) averaged 300 kg ha^{-1}, while millet grain yields after 2–7 years fallow averaged 460 kg ha^{-1}. No significant differences in millet or cowpea yields were observed between fallow treatments (Figure 2, Table 3).

Nitrogen uptake

Nitrogen uptake in millet above-ground dry matter was higher in 1999 and 2001 when millet followed the 1998 cowpea crop than when it followed the 1998 millet crop (Table 4). No significant differences between N uptake from the different cropping systems were observed in 2000. Fallow systems also affected N uptake. A significant increase in N uptake was observed with a 2-years fallow period compared to 3–5 years continuous millet. Increasing fallow duration to 7 years did not significantly increase millet N uptake in all years. No significant interaction was found between the length of the fallow period and cropping systems. The increased N uptake did not result in a linear increase in yield. Nitrogen content significantly increased in the treatments with an increased N uptake.

Soil organic C and N

Cropping systems and fallow systems significantly affected soil organic C and N (Table 5). The general trend from 1998 to 2001 is a reduction in both soil quality parameters in the continuous millet cropping system. This is most probably caused by the small amounts of annual crop residues left in the fields as residues were used for animal feeding and domestic uses (Chapters 2 and 3). The reduction with time, though, differs between treatments as does the starting content (Table 1). The 1998 cowpea crop seemed to restore the soil organic carbon at the starting level (similar to the level after a 2-years fallow period) and improved the soil nitrogen content. As nitrogen content varies during the season the comparison between years is difficult because of

Table 4. Effects of fallow-cowpea-millet rotation systems on millet nitrogen uptake (kg ha^{-1}) in the village Lagassagou in northern Mali. MM = millet after millet; LM = millet after one year cowpea; LM/C = millet/cowpea intercrop after one year cowpea. CM = 3–5 subsequent years millet cropping. For abbreviations see also Table 2.

Cropping systems	1999	2000	2001
Cropping system (CS)			
MM	22.1 a[†]	13.1	13.2 a
LM	30.9 b	15.0	21.0 b
LM/C	27.0 c	12.9	23.7 b
SED[*]	0.98	0.97	1.82 b
P > F[**]	<0.001	0.251	0.001
Fallow duration (F)			
CM	21.0 a	9.6 a	12.4 a
F2	27.5 b	15.4 b	19.2 b
F5	28.8 b	15.2 b	22.4 b
F7	29.4 b	14.4 b	23.2 b
SED	1.14	1.12	2.10
P > F	<0.001	0.002	0.003
Interactions CS × F	0.242	>0.999	0.999

[*] Standard error of the difference.

[**] Probability of treatment effects (level of significance).

[†] Means within a column followed by the same letter are not significantly different.

different timing of sampling. The significant difference in soil N content after the cowpea and millet crop in 1998 is indicative of the positive role of the cowpea crop in enhancing soil N content. Sowing an intercrop in 1999 further maintained the soil N content at a higher level in 2000. In 2001, however, the increase in the intercrop was not significant. The positive effect of the 1998 cowpea crop on soil N content was measured until 2000. The effect of the cowpea intercrop on soil organic C was also positive in 1999, when significantly more soil organic C was observed compared to the millet sole crops following the 1998 cowpea crop and following the 1998 millet crop. In 2001, the difference with the millet monocrop following millet in 1998 was maintained but the difference with the millet monocrop after the 1998 cowpea crop was no longer significant.

Table 5. Effects of fallow-cowpea-millet rotation systems on organic carbon and total nitrogen content (g kg^{-1}) in soil. MM = millet after millet; LM = millet after one year cowpea; LM/C = millet/cowpea intercrop after one year cowpea. CM = 3−5 subsequent years millet cropping. See also Table 2.

	Soil organic C				Soil N			
Treatments	1998	1999	2000	2001	1998	1999	2000	2001
Cropping system (CS)								
MM	2.48[1]	2.14 b	1.89 b	1.54 b	0.20[1]	0.19 b	0.17 c	0.16
LM	2.48[1]	2.52 a[1]	2.11 b	2.01 a	0.20[1]	0.25 a[1]	0.20 b	0.16
LM/C	2.48[1]	2.52 a[1]	2.46 a	2.22 a	0.20[1]	0.25 a[1]	0.24 a	0.18
SED*	-	0.11	0.08	0.08	-	0.02	0.01	0.02
P > F**	-	0.03	<0.001	<0.001	-	0.05	<0.001	0.49
Fallow duration (F)								
CM	1.64 b	1.92 b†	1.61 c	1.31 b	0.14 b	0.19	0.17 c	0.12 b
F2	2.57 a	2.25 ab	2.17 b	2.20 a	0.20 a	0.21	0.19 b	0.14 b
F5	2.78 a	2.64 a	2.59 a	2.17 a	0.21 a	0.23	0.21 ab	0.18 ab
F7	2.92 a	2.51 a	2.23 b	2.03 a	0.24 a	0.23	0.23 a	0.20 a
SED	0.15	0.16	0.10	0.08	0.01	0.02	0.01	0.02
P > F	0.001	0.02	<0.001	<0.001	0.013	0.52	0.009	0.006
Interactions CS × F	-	0.56	0.59	0.15	-	0.51	0.998	0.42

* Standard error of the difference.

** Probability of treatment effects (level of significance).

† Means within a column followed by the same letter are not significantly different.

1 Data are from a bulked sample over the marked treatments within a column.

The difference in soil organic C in the plots continuously cropped under millet since at least 1995 compared to the plots where a fallow period preceded the millet crops lasted until 2001. Differences in soil N content were not significant after the 1998 cowpea crop at the start of the 1999 rainy season, but were significant at the start of the 2000 and 2001 cropping seasons. As no fertilizer N was supplied to the soil under study in 1998, the difference of soil N between the different treatments is an indication of symbiotic N_2-fixation by the cowpea crop either as sole or as intercrop or an increased soil microbial activity caused by soil changes in the cropping sequence (Turco *et al.,* 1990).

Effects on Striga

No significant differences were observed in *Striga* infestation in the different cropping systems. A trend of lower infestation when cowpea was grown in rotation or in intercrop with millet (LM and LM/C) was in accordance with expectations, but the overall variability was too high to distinguish between treatment means (CV was 32% and 58% in 1999 and 2001, respectively).

Fallow duration significantly affected *Striga hermonthica* infestation (Figure 3). In 1999 as well as in 2001, the infestation was higher in 3−5 subsequent years millet cropping systems (MM) than in a 2-years fallow system. Van Ast *et al.* (2003, in prep.) indicated that the longevity of *Striga* in South Sudanian and North Guinean zone of

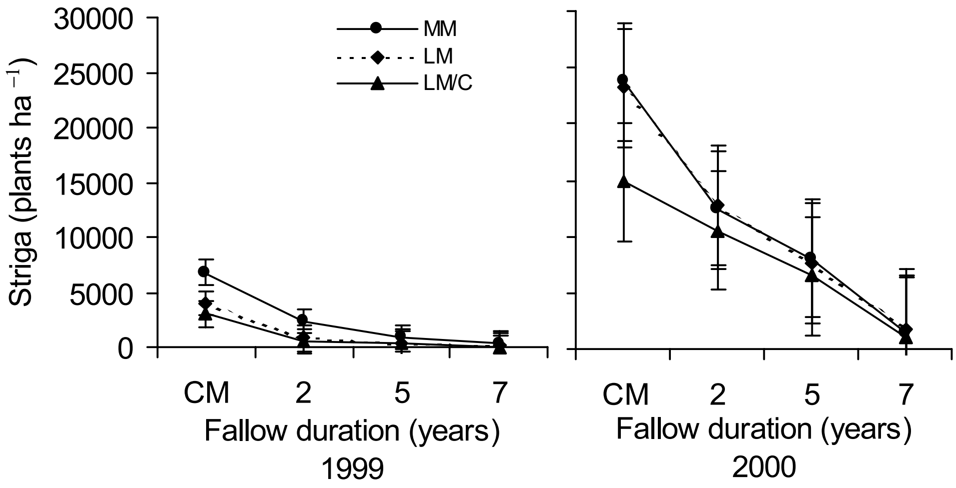


Figure 3. Influence of cropping system and fallow duration on *Striga* infestation (plants ha^{-1}) in three millet cropping systems: millet in 1998–2001 (MM), cowpea in 1998 and millet in 1999–2001 (LM) and cowpea in 1998 and millet/cowpea in 1999–2001 (LM/C). Note that the levels of *Striga* infestation differ between years.

Mali is much shorter than commonly reported and showed that the decline in viability seeds buried at 5 and 10 cm depths followed an exponential pattern, resulting in a mortality of 70–95% at the end of the first year experiment. Increasing fallow periods from 2 to 7 years did not result in any significant additional reduction in the number of *Striga* in 1999, when infestation levels were very moderate. Infestation was significantly lower after a 7-years fallow period than after a 2-years fallow period, while infestation after 5 years fallow differed neither from 2 years fallow, nor from 7 years fallow. Also the rather high variability made discrimination between treatments difficult (CV is 37% and 58% in 1999 and 2001, respectively). No *Striga* emerged in 2000 probably due to the late replanting from 20 July to 10 August in 2000, interestingly farmers claim that late sowing always is accompanied by low infestation or absence of *Striga*. No significant interaction was observed between cropping systems and increasing fallow duration.

Conclusions

In this study, cowpea grown in rotation with millet improved millet yield in the first growing season after the cowpea crop, but not in the two following seasons in which millet production was monitored. It maintained enhanced soil organic C at higher levels over the three years in the study and enhanced soil N content in the first year after the cowpea crop, but not thereafter. Including a cowpea intercrop in alternate-row configuration with millet in a fallow–cowpea–millet or millet–cowpea–millet rotation after the cowpea crop did not significantly affect millet grain yield compared to a millet monocrop in the first and the second year after the cowpea crop. By the third growing season, millet yield in the intercrop increased with 22% over that in the sole crop. Including an intercrop into the millet improved the total grain yield as cowpea grain production was significant and did not come at the expense of millet grain production. The intercrop minimized food security risk in the year 1999 with poor rainfall. Neither including cowpea in the rotation nor cowpea intercrop had a significant effect on *Striga* infestation, although there was a trend for lower *Striga* infestation after the millet/cowpea intercrop. The low discriminative power in this experiment seems to be partly due to the high variability in *Striga* infestation levels, which in turn are probably due to highly variable initial infestation levels. When fallow is possible the effect of two years fallow on millet grain yield is comparable to that of 5–7 years fallow. Extending the fallow period to 7 years further reduced *Striga* infestation especially when overall infestation levels were higher. The residual effect of fallow over time has not been established beyond three years. As land is becoming so limited that farmers have to increase cropping intensity in order to produce enough to feed their families, including cowpea after short fallow periods in rotation with millet/cowpea intercrop in bushfields seems an interesting option for resource poor farmers in the Sahelian zone in West Africa. Even in poor rainfall years, adding cowpea in an intercrop with millet does not seem to reduce millet yields while overall system productivity increases. Including one year of pure cowpea crop in a rotation with millet does not seem to be as effective as 2 to 7 years fallow in maintaining millet yields, nor in reducing *Striga* infestation levels. As farmers will be forced to reduce fallow duration under growing land pressure other solutions will have to be found building further one a system including cowpea sole crop and millet/cowpea intercrop as replacement of millet pure crop and fallow.

CHAPTER 5

Integrated pearl millet management strategies for the semi-arid tropics of West Africa: Effects of P-fertilizer application on millet productivity and *Striga* infestation

Abstract

A four-years study was conducted between 1998 and 2001 to determine the effects of P-fertilizer application on millet yield and soil characteristics in millet-based cropping systems differing in fallow duration and the use of cowpea as a rotation crop or intercrop. The experiment was conducted on a sandy soil in a Sahelian village in Mali using a factorial strip-split plot design with four fallow periods (0, 2, 5, and 7 years) as main treatments, four rates of P fertilizer as sub-plot treatments and three cropping systems as sub-sub-plot treatments. The cropping systems were: four years of millet monoculture, a cowpea crop followed by three years of millet monoculture and cowpea followed by three years of a millet/cowpea intercrop. The grain legume cowpea, grown in 1998, had a positive effect on subsequent millet yield and on soil N levels in the first year after the cowpea crop but not in subsequent years. The addition of P fertilizer enhanced yields strongly in all treatments. This effect was independent of the use of cowpea in rotation or as an intercrop and of the duration of the fallow period. Only in 2001 an interaction between fallow duration and P fertilizer was observed. An annual application of 100 kg ha^{-1} TSP resulted in comparable yields as in the treatment with a one time application of TRP followed by an annual application of 100 kg ha^{-1}. Both these treatments resulted in higher yields than a one-time application of 300 kg ha^{-1} TRP. Application of P resulted in an increased soil organic C content. Soil N content and Striga infestation were not affected by P-fertilizer application.

The results showed that P fertilizer in a continuous monoculture of millet has a similar effect on yield as introducing a fallow period in a non-fertilized plot and a stronger effect than the inclusion of cowpea in rotation or as an intercrop without fertilizer. The combination of P fertilizer and fallow and cowpea in the cropping system could even boost yield from 250 kg ha^{-1} to a level of 1200 kg ha^{-1} in bushfields in 2001. These are comparable to the yields in manured homefields.

Key words: Millet–cowpea rotation, millet/cowpea intercrop, P fertilizer, fallow, grain yields, soil fertility, *Striga*.

Introduction

Low inherent soil fertility characterizes subsistence agriculture in the Sahel of West Africa, together with uncertain and low rainfall. Based on simulation studies, Hengsdijk and van Keulen (2002) showed that below 500 mm rainfall, rainfed millet production in West Africa is very low with a high chance for complete crop failure. Above 500 mm rainfall, yields increase with increasing rainfall but even above 800 mm rainfall production can be limited by water shortage due to unfavourable distribution patterns. Not only water explains poor productivity in these conditions. Soils have a low nutrient content, especially nitrogen and phosphorus (Breman, 1995a; Brouwer and Powell, 1993; van der Pol, 1992). The work done by Seligman *et al.* (1992), Breman (1995b) and Piéri (1985, 1986) showed that the availability of nitrogen (N) and phosphorus (P) in semi-arid regions limits growth more than moisture availability. Several authors claim the nutrient situation is further degrading under current cropping practices. In their continent wide study Stoorvogel and Smaling (1990a) reported annual depletion in soil nutrients for the years 82–84 of 12 kg ha^{-1} for potassium (K_2O), 14 kg ha^{-1} for nitrogen (N) and 4 kg ha^{-1} for phosphorus (P_2O_5) for Mali. The removal of harvested components, including the straw used for housing and animal feeding, result in nutrient outputs from fields in the Sahelian zone of West Africa of 15 kg N ha^{-1}, 2 kg P ha^{-1} and 15 kg K ha^{-1} according to Buerkert and Hiernaux (1998). On the basis of long-term experiments, Piéri (1991) estimated an average annual yield loss of 3 to 5% directly related to the decline in the level of soil fertility in the sub-Saharan Africa. However, the long-term FAO statistics do not show such a decline at the level of the individual countries. This might be explained by the fact that the depletion is not homogeneously distributed. The depletion takes place in bushfields. Nutrients are removed from these fields and partly added to homefields through manure application (cf Chapter 3). Nutrient levels in bushfields are restored during fallow periods. However, these fallow periods decline strongly as a result of population pressure. A decline in soil fertility in these fields is therefore to be expected.

In addition to fertility management problems, farmers in the Sahel of West Africa face weed problems and related labour shortage during certain phases of crop production. A major weed problem is posed by *Striga hermonthica*, a hemi-parasitic weed attacking major staple crops such as sorghum, maize and pearl millet. M'Boob (1989) estimated that *Striga* causes annual crop yield losses in Africa of around $7 billion. In the early 1990s, the total crop area affected by this hemi-parasitic weed was estimated at about 5 million ha in six West-African countries together (Sauerborn, 1991). In the Gambia, a two-year study has shown crop losses due to *Striga* of 20 to 35% implying an annual loss of about 10,000 tonnes of cereal grains for the country valued at over US$ 900,000 (Carson, 1986). In Nigeria, Parkinson (1985) reported losses of 10–91% in sorghum and maize yields attributed to *Striga hermonthica* (L.) and costs were estimated at about US$ 250 million annually (Lagoke, 1986). In Mali, *Striga* threatens the major food crops such as millet and sorghum (*S. hermonthica*), maize and rice (*S. hermonthica* and *S. asiatica)* and cowpea (*S. asiatica)* with field infestations varying from 1 to 80% and yield losses ranging from 25 to 100% (Konaté, 1986).

The problem of *Striga* and of fertility seem to be linked and therefore an integrated approach to the solution of both problems seems most appropriate. Yamoah *et al.*

(2002) reported that millet yield doubled in response to fertilizer application. Buerkert *et al.* (2001) showed that NPK fertilizer placement at 0.4 g P per hill raised average cereal yield between 26 and 220%. Hess and Ejeta (1987) found a reduction in numbers and weight of *Striga hermonthica* on sorghum in Niger of 55–82% after application of 47 kg N ha^{-1} in the form of urea. However, Doggett (1988) and Ogborn (1987) found that application of nitrogenous fertilizers frequently increased *Striga* emergence on infertile and highly infested soils.

A fallow period may reduce the incidence of diseases and pests (Trenbath, 1993) and may increase soil fertility and yield (Chapter 4; Gathumbi *et al*., 2002; Juo and Lal, 1977). Also the use of a legume in an intercrop, or the inclusion of a legume cover crop in a rotation with cereal crops can help to improve fertility (Bagayoko *et al*., 1992; Tarawali *et al*., 1992; Gakale and Clegg, 1987; Stern, 1993; Reddy *et al*., 1992; Oxfori and Stern, 1987; Dakora and Keya, 1997; Bationo *et al*., 1996; Chapter 4). The fertility enhancing effect of a fallow period or legume intercrops or rotation crops does not last for a long time. Legume crops are essentially relevant for improving nitrogen levels, but do not address the phosphorous problem. To our knowledge, the combined effects of cropping systems, short-term fallow and fertilizer application as a means to maintain crop productivity and limit *Striga* infestation have not been reported. Work initiated in Burkina Faso on the effects of fertilizer application on a sorghum/cowpea intercrop and the development of *Striga hermonthica* were not completed (Traoré and Ouédraogo, 1996). The objective of this study was to determine the effect of applying P fertilizer to millet-based cropping systems differing in fallow periods and the use of cowpea as a rotation crop or in an intercrop with millet (cropping systems introduced in Chapter 4).

Materials and methods

A four-years field experiment was conducted during the 1998 to 2001 rainy seasons in Lagassagou (3°62' W, 13°83' N), a village in the Sahelian zone of Mali. Experimental details were described in Chapter 4. In all treatments (see Table 2 in Chapter 4) plots were split in four treatments: P0 (no fertilizers, results are reported in Chapter 4); P1 (300 kg TRP ha^{-1} (Tilemsi rock phosphate with 27% P_2O_5) in 1998 and no fertilizer in subsequent years); P2 (300 kg TRP ha^{-1} in 1998 and 100 kg TRP ha^{-1} added in each subsequent year) and P3 (no fertilizer in 1998 and 100 kg triple super phosphate (TSP) ha^{-1} in subsequent years).

Tilemsi rock phosphate was uniformly broadcast before sowing on the soil surface of the respective fertility treatments between 10–20 June 1998. In 1999, 2000 and 2001, the fields were used to evaluate single and combined effects of millet/cowpea intercrop and P fertilizers for the different preceding fallow, rotation and fertilizer treatments on millet (*Pennisetum glaucum* (L.) R. Br.) grain yield, *Striga* infestation and soil fertility indicators. All P fertilizers were broadcast at ploughing prior to sowing. For further details see Chapter 4.

Table 1. Effects of P-fertilizer application and fallow–cowpea–millet rotation systems on millet and cowpea grain yields (kg ha^{-1}) in Lagassagou village in northern Mali. For abbreviations see text and Table 2 in Chapter 4.

Cropping systems	1999		2000		2001
	Millet	Cowpea	Millet	Cowpea	Millet
Cropping system (CS)					
MM	710 b[†]	-	330	-	520 b
LM	860 a	-	360	-	580 b
LM/C	850 a	250	350	420	710 a
SED[*]	30	20	10	10	30
P > F[**]	<0.001		0.338		<0.001
Fallow duration (F)					
CM	650 b	230	250 b	400	400 c
F2	820 a	240	400 a	420	600 b
F5	840 a	240	360 a	420	700 a
F7	900 a	260	380 a	430	720 a
SED	30	30	10	20	30
P > F	<0.001	0.660	<0.001	0.578	<0.001
P-fertilizer (P)					
P0	540 c	200	240 c	330 c	430 c
P1	850 b	280	360 b	410 b	570 b
P2	870 ab	260	380 ab	450 ab	640 ab
P3	950 a	290	410 a	480 a	780 a
SED	30	30	10	20	30
P > F	<0.001	0.072	<0.001	<0.001	<0.001
Interaction					
CS × F	0.977	-	0.568	-	0.590
CS × P	0.996	-	>0.999	-	0.739
F × P	0.999	>0.999	0.996	0.986	<0.001
CS × F × P	>0.999	-	>0.999	-	0.995

[*] Standard error of the difference.

[**] Probability of treatment effects (level of significance).

[†] Means within a column followed by the same letter are not significantly different.

Results and discussion

Effects on millet yield

The main effects of cropping system and fallow duration on yield, soil fertility parameters and *Striga* infestation without P fertilizer have been discussed in Chapter 4. This chapter reports the main effects of P fertilizer and the interaction effects of P fertilizer with cropping system and fallow duration whenever observed. P-fertilizer treatments significantly increased millet grain yield in all years (Table 1). In 1999 and 2000, the fertilizer effect was independent of the duration of the preceding fallow treatment and independent of the inclusion of cowpea as pure crop in the rotation or as intercrop (Figure 1, Table 1). Only in 2001 a significant interaction was observed as the millet in the zero fertility treatment in the plots with five years fallow preceding three years of millet yielded significantly poorer than the millet in the zero fertility treatment in plots with three and seven years fallow (Figure 1). This same yield dip was not observed in the other fertility treatments. No explanation for this result was found. This effect was observed in all four replications of the fallow main plot treatment. Otherwise the general picture in 2001 was identical to that discussed for 1999 and 2000.

All three fertilizer applications resulted in a yield increase in millet grain yield in all years. The application of an annual dose of 100 kg TSP per hectare (P3) consistently gave better yields than application of a single dose of 300 kg TRP per hectare in 1998. Application of additional TRP (annually 100 kg ha^{-1}) yielded intermediate between a single TRP and an annual TSP dose, neither significantly different from one or the other. No interactions were observed between P-fertilizer application regimes and cropping system (Table 1, Figure 1).

Millet yield in the intercrop was similar (2000 and 2001) or higher (2001) than in millet monoculture (Table 1). Cowpea grain yield was not affected by the fertilizer applications in 1999, while in 2000 cowpea grain yield was positively affected. For 2001, cowpea grain yield data are not available as farmers harvested the cowpea prematurely to cope with food shortage in the village. These results show that in the millet cowpea intercrop competition did not lead to any reduction in millet yield also when fertilizer was applied. In the longer run, millet yield in the intercrop even increased compared to millet in a three years monoculture (Figure 1). This might have been due to the N fixation by the legume intercrop in the previous years.

The results in Figure 1 show that P fertilizer in a continuous monoculture of millet has a similar effect on yield as introducing a fallow period in a non-fertilized plot and a stronger effect than the inclusion of cowpea in rotation or as an intercrop without fertilizer. The combination of P fertilizer and fallow and cowpea in the cropping

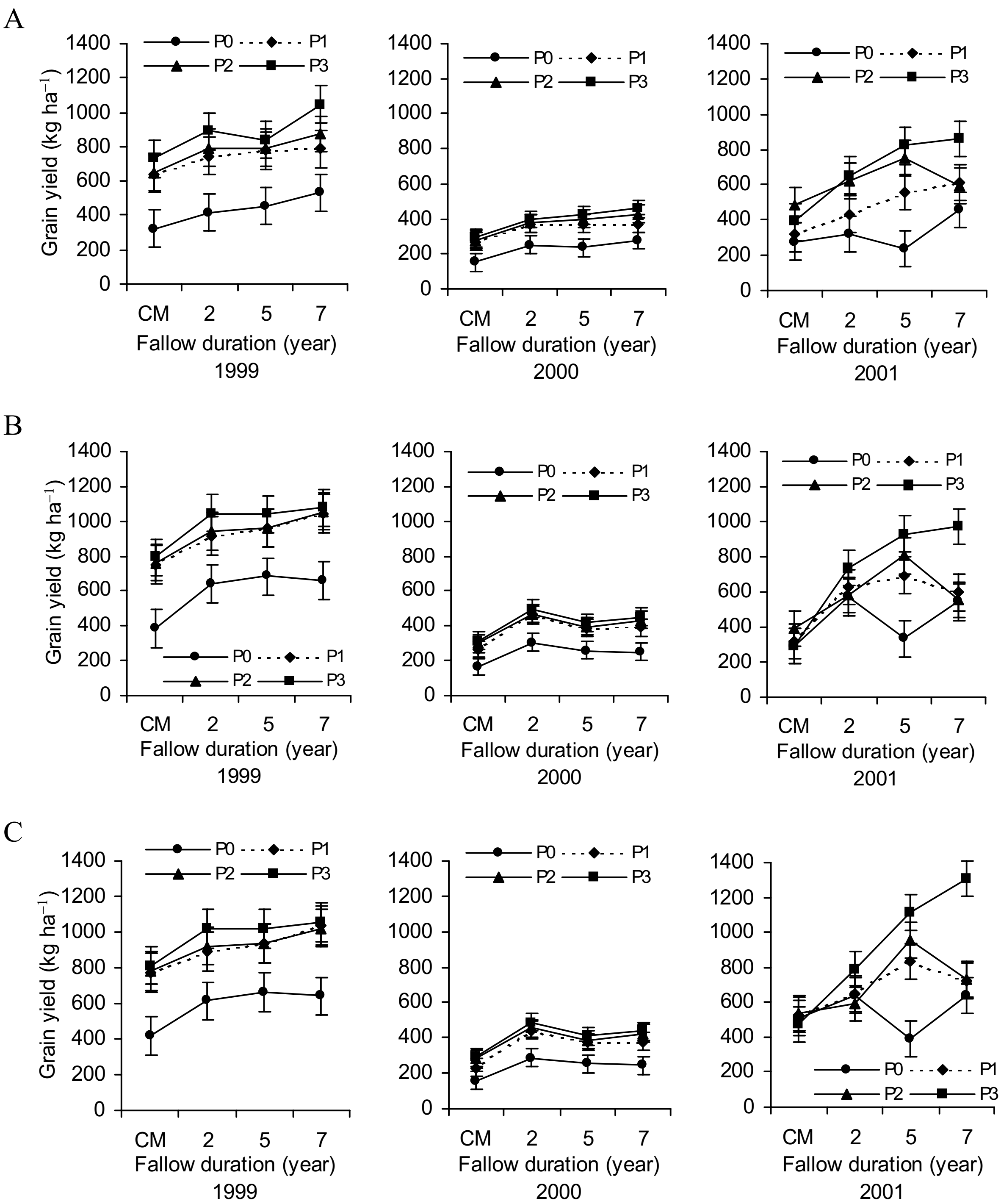


Figure 1. Effects of P-fertilizer application, fallow period prior to millet cultivation and on millet grain yield in 1999, 2000 and 2001 grown in Lagassagou, northern Mali. CM is 3–5 consecutive years of millet cropping prior to 1998. (a) Results for millet monocrop in 1999–2001 following a millet monocrop in 1998, (b) results for a millet monocrop in 1999–2001 following a cowpea monocrop in 1998 and (c) results for a millet/cowpea intercrop in 1999–2001 following a cowpea monocrop in 1998. For P treatments (P0–P3) see text.

system could even boost yield from 250 kg ha^{-1} to a level of 1200 kg ha^{-1} in bush-fields in 2001. These are comparable to the yields in manured homefields (Chapter 3).

The observed effects of P-fertilizer application are in accordance with the literature. Thibout *et al.* (1980) suggested that application of 80 kg P_2O_5 ha^{-1} as TRP in the first cropping year should be followed by annual applications of 20–40 kg P_2O_5 ha^{-1} in dependence of crop type in order to give a sustained yield increase. Roesch and Pichot (1985) reported similar results in Niger suggesting an application of 50 kg P_2O_5 ha^{-1} as Tahoua rock phosphate (Niger) in the first year followed by 15–20 kg P_2O_5 ha^{-1} annually. The report by Bationo *et al.* (1990) that one initial application of a large dose of Tahoua rock phosphate as P source on millet in Niger was found to be more effective in the first three years than three small annual applications also seems to be in line. Although we did not test the use of only annual doses of TRP, the single dose of TRP still had statistically comparable results to the single TRP dose supplemented with annual TRP doses.

Nitrogen uptake

In all three years, P application increased N-concentration in millet significantly. In 2001 the increase was even 45% after TSP application compared to non-fertilized millet. In general, millet N concentrations in 2000 were lower than in 1999 and 2001 (data not shown). As the crop was re-sown in 2000 it could be expected that the natural N-flush occurring at the start of the rainy season had passed (Ganry, 1977). The crop, therefore, had limited access to nitrogen compared to the other years leading to relatively lower N-content in the above-ground dry matter. The lower yield in the year 2000 with poor rainfall and the need for re-sowing can, therefore, not only be attributed to the lack of moisture, but also to the lack of nutrients. No interactions were observed with the effects of fallow duration or cropping system.

Both total above-ground dry matter and N concentrations in the biomass were higher after P-fertilizer application resulting in a higher N uptake in all three years especially with P3 and P2 (Table 2). This suggests that the effect of P fertilizer was partly through improved N uptake, probably at the start of the rainy season when P tends to be poorly available while nitrogen is released through mineralization of organic matter that is present in the soil. No significant interaction was observed for N uptake between P-fertilizer application and the fallow duration or cropping system treatments.

Table 2. Effects of P-fertilizer application on N uptake (kg ha^{-1}) in total above-ground millet biomass at harvest. The significance levels for interactions with fallow duration and cropping system as reported in Chapter 4 are also given.

	1999	2000	2001
P-fertilizer			
P0: No fertilizer	25.3 c[†]	13.0 c	19.5 c
P1: 300 TRP kg ha^{-1} in 1998	34.9 b	22.7 b	27.5 b
P2: P1 + 100 kg TRP ha^{-1} annually	35.2 b	23.6 b	34.1 b
P3: 100 kg TSP ha^{-1} annually	38.2 a	26.6 c	36.4 a
SED[*]	0.70	0.91	1.88
P > F[**]	<0.001	<0.001	<0.001
Interaction			
Cropping system (CS) × P fertilizer (P)	0.14	0.92	0.84
Fallow duration (F) × P	0.93	0.25	0.96
CS × F × P	>0.99	>0.99	>0.99

[*] Standard error of the difference.

[**] Probability of treatment effects (level of significance).

[†] Means within a column followed by the same letter are not significantly different.

Soil organic C and N

Fallow and cropping system strongly affected soil N levels without P fertilizer (see Chapter 4). Addition of P fertilizer did not have an effect on observed soil nitrogen at the start of the 1999, 2000 or 2001 rainy season (data not shown). Neither was there any interaction with reported effects of cropping system or fallow duration. P-fertilizer application, though, did affect the soil carbon content at the start of the rainy season in all years. At the start of the 1999 growing season, P-fertilizer application on millet after a one-year cowpea following 2–7 years fallow resulted in an average amount of organic C (2.87 g kg^{-1}) comparable to values found in plots at 200 m from to the village (2.4 g kg^{-1}) that receive organic manure (Chapter 3). Interactions with cropping system and fallow duration were also significant (Figure 2). At the start of the 1999 rainy season more organic carbon remained in the soil in plots which received 300 kg TRP ha^{-1} in 1998 (P1 and P2) than in plots which did not receive any fertilizer in 1998 (P<0.01) (P0 and P3). Interactions between P-fertilizer application and cropping system (P>0.80) or fallow duration (P>0.14) were not significant. In 2000 and 2001, the effects of P-fertilizer application on soil organic carbon at the start of the cropping season showed an interaction with fallow duration and cropping system. The three-way interaction was not significant. The interaction between P fertilizer and fallow

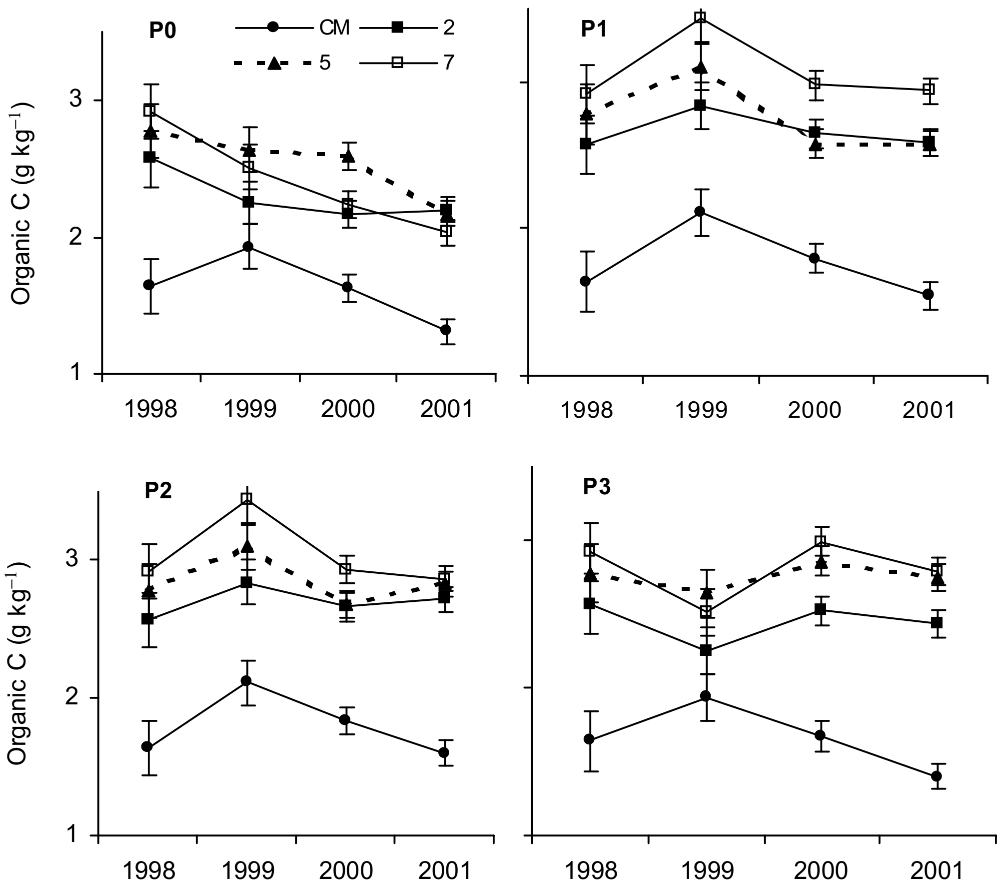


Figure 2. Organic carbon in the soil (g C per kg soil) at the start of the rainy season (1998–2001) for the four P-fertilizer treatments (P0–P3, see text) and within each treatment for the four fallow duration treatments (CM is continuous millet, and 2, 5, and 7 years of fallow prior to 1998). Indicated error bars are standard errors of the difference between means.

duration (P<0.01 in 2000 and 2001) is caused by the much larger effect of P fertilizer, especially TSP on organic carbon level in the plots with a longer fallow duration. The addition of P fertilizer results in a maintenance of the soil organic carbon levels at higher levels throughout the experiment, and this effect is stronger when applied after longer fallow (Figure 3). In the non-fertilized plots a continuous decline in soil organic C was observed. The interaction between P fertilizer application and cropping system is caused by the effect of the cowpea intercrop in maintaining soil organic carbon and the enhancing effect the P fertilizer has on this effect of cowpea intercrop. When millet is grown without use of cowpea as rotation crop or intercrop, organic carbon levels decrease faster and also the positive effect of P fertilizer on organic carbon become less large. The two fertility-improving treatments seem to mutually support each other in maintaining soil organic carbon.

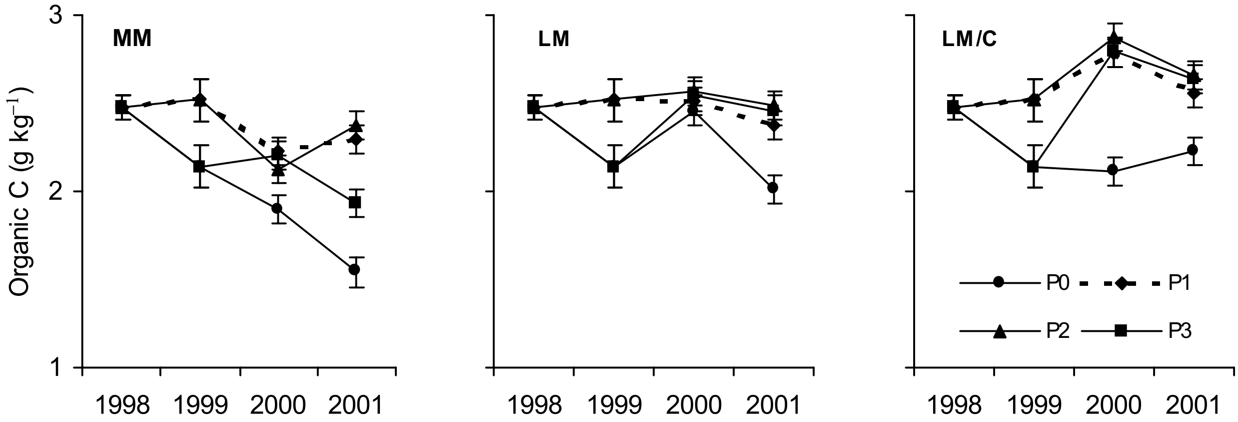


Figure 3. Effects of P-fertilizer application (P0–P3, see text) on the total organic C content in soil (measured at the beginning of the rainy seasons 1998–2001) at different millet–cowpea cropping systems, averages over the four preceding periods (CM, F2, F5 and F7, see Table 2 in Chapter 4). MM = millet after millet; LM = millet after cowpea; LM/C = millet/cowpea intercrop after cowpea.

Effects on Striga

P fertilizer did not affect the *Striga* infestation level (Table 3). The additional replications provided by the three levels of phosphorus treatments to the interaction between cropping systems and fallow duration made this interaction significant where it was not significant in the analysis of only the non-fertilized treatments (Chapter 4). The significant interaction observed now was only significant in 1999 and not in 2001. It implies that sowing of a cowpea crop in 1998 after 3–5 years of millet reduced the *Striga* infestation levels significantly compared to sowing a millet crop. While sowing a cowpea crop after 2, 5 or 7 years of grassy fallow did not further reduce the *Striga* infestation levels. This effect of including cowpea in the rotation with continuous millet did not last until 2001. And the additional internal replication did not change significance of other effects. The fact that additional replication is needed to show the interaction effect should not be regarded as an indication of the low applicability of the result in farm management strategies. It should be kept in mind that infestation levels were not monitored, were certainly not identical between plots and were not a factor that was imposed. The large variability is rather an indication of seedbank density differences. When a field is known to be infested, rotation with pure cowpea seems an interesting option replacing roughly two years of fallow, but the effect did not last so further tests are needed to understand conditions for which this option is valid.

Table 3. Influence of previous crop, fallow duration and P application on *Striga* infestation (number of *Striga* shoots per ha). For abbreviations see Table 2 in Chapter 4.

Cropping systems	1999	2001
Cropping system (CS)		
MM	2990 a[†]	10960
LM	1163 b	10800
LM/C	730 c	7940
SED[*]	290	1320
P > F[**]	<0.001	0.193
Fallow duration (F)		
CM	4640 a	20100 a
F2	1450 b	12030 b
F5	360 c	6780 c
F7	60 c	690 d
SED	330	1520
P > F	<0.001	<0.001
P-fertilizer (P)		
P0	1630	10340
P1	1667	9940
P2	1620	9650
P3	1590	9680
SED	330	1520
P > F	0.999	0.988
Interaction		
CS × F	<0.001	0.814
CS × P	0.941	>0.999
F × P	>0.999	>0.999
CS × F × P	0.995	>0.999

[*] Standard error of the difference.

[**] Probability of treatment effects (level of significance).

[†] Means within a column followed by the same letter are not significantly different.

Conclusions

This study showed that P-fertilizer application increases average millet grain yield in all cropping systems. The increases in yield were 57, 43 and 35% in fertilized MM, LM and LM/C treatments, respectively, compared to the non-fertilized treatments. A yearly application of 100 kg TSP ha^{-1} increased yield more in three years compared to a one time application of 300 kg TRP ha^{-1}. Differences between the effects of the one time application of TRP followed by yearly applications of 100 kg TRP ha^{-1} and TSP were small. Together increased total biomass and higher N concentration in this biomass implied a larger N recovery from the soil. As nitrogen that is not used during a season has little chance of staying in the system, the extra uptake implies more effective use of available resources, without further degradation. Also P-fertilizers lead to maintenance of organic C content in soil at higher levels, without any effect on soil N and *Striga* infestation. The overall effect of fertilizer use is a consistent positive effect in bushfields. The choice in favour of fertilizer application at farming systems level, though, will depend strongly on price differences between these fertilizers and differences in labour inputs needed for their transport and application.

The only effect of P fertilizer on *Striga* that can be expected is a long-term effect on build up of the seedbank. It can be assumed that population increase remains limited as soil carbon levels seem to be maintained longer when P-fertilizer is applied. As soil carbon levels at which a positive effect on *Striga* suppression can be expected have not been reported, though, this possible effect in the longer run would need additional study.

In the search for an optimal crop rotation, the beneficial effects of cowpea on soil N and *Striga* at least compare to that of a two-years fallow period especially with P application. As land is becoming so limited that farmers have to increase cropping intensity in order to produce enough to feed their families, cowpea seems an interesting option in rotation for resource poor farmers in the Western Sahelian zone in West Africa. This study cannot assess the longer-term effects of such a rotation system. Further studies will also be required to explore what is the relative contribution of soil fertility changes and reduced *Striga* infestation to the effect of crop rotation and fallow duration on millet yield and labour use for millet production. It seems clear that fertilizer use in bushfields will further improve productivity. In fact the higher total biomass will also imply more animal feed so more manure for the more productive homefields. This study, though, is not able to indicate what the relative advantage is of applying the same amount of P fertilizer on bush or on homefields.

CHAPTER 6

Modelling nutrient-limited millet production on the basis of chemical soil fertility indices and fertilizer recovery

Abstract

The model QUEFTS (Quantitative Evaluation of the Fertility of Tropical Soils) was calibrated for millet using the native fertility of soils and data from fertilizer trials in Lagassagou village in the Sahel zone of Mali. QUEFTS describes the relationship between soil parameters and yield in four steps: (1*)* assessment of the potential supply of N, P and K on the basis of chemical soil data; (2) calculation of the actual uptakes of N, P and K, as functions of the potential supplies determined in Step 1; (3) designation of yield ranges as functions of the actual uptakes of N, P and K determined in Step 2; (4) calculation of the ultimate yield estimate by combining the three yield ranges established in Step 3. The potential supplies of N, P and K were plotted against all available combinations of soil test values (Step 1) leading to relatively simple equations made up of only one explaining variable. Yield ranges were obtained from the relationship between N, P and K contents in the above-ground plant components and millet grain yield (Step 3). Nitrogen (N) and phosphorus (P) recovery fractions from fertilizers were 73% and 17%, respectively. Average measured and calculated millet yields for non *Striga*-infested homefields corresponded very well, but when comparing individual data points, correlation was poor. Comparison of measured and calculated yields in *Striga*-infested bushfields showed a yield gap of 39%.

Key words: QUEFTS, soil fertility, fertilizer, nutrient uptake, millet grain yield.

Introduction

Pearl millet (*Pennisetum glaucum* (L.) R. Br.) is typically cultivated on soil of low fertility (Jones and Wild, 1975; Manu *et al*., 1991) and low water-holding capacity (Payne *et al.,* 1991). In sub-Saharan Africa, millet cropping is mainly subsistence-oriented, and linked to poor soils (Breman, 1995a; Brouwer and Powell, 1993) and *Striga* infestation (Sauerborn, 1991; M'Boob, 1989; Lagoke, 1986). It is a major food crop grown on about 10 millions ha in West Africa (Kumar, 1989), and is the most important rainfed crop in the Sahel (Purseglove, 1975). It is grown for its grain, but the residues are also valuable as forage, mulch, fuel and construction material (Lamers and Feil, 1995). To meet food demands, farmers expanded areas under millet during the past fifteen decades, without being able to raise production per unit area, with the exception of Burkina Faso (see Table 1 in Chapter 2). Average millet yields per country differ much, i.e., roughly between 400 and 1,000 kg ha^{-1}.

Use of inorganic and organic fertilizers in millet cropping is limited by the lack of access to capital (Hoekstra and Corbett, 1995; Témé *et al*., 1995) and low availability.

Farmers currently tend to concentrate soil fertility around farms and hamlets and on plots where animals are penned. It is part of the 'niche' management that is seen in many parts of low-input agricultural Africa these days (e.g., Smaling, 1998; Smaling and Toulmin, 2000). In the case of Lagassagou, manure and household waste are concentrated in rings around villages (Samaké *et al.,* in prep.). Experiments elsewhere have shown that fertilizer application can nevertheless considerably raise millet production. Yamoah *et al.* (2002) reported that millet plots treated with a combination of crop residues retained on the field after harvest and fertilizer application of 30 kg N ha^{-1} + 13 kg P ha^{-1} yielded as much as 2,160 kg ha^{-1} whereas the non-fertilized plots produced only 210 kg ha^{-1}. In an experimental trial at the Agronomic Research Center of Cinzana (Mali), Bacci et al. (1999) found yield increases from approximately 1,000 kg ha^{-1} in non-fertilized treatments to 1,580 and 1,800 kg ha^{-1} with application of 40 and 80 kg N ha^{-1}, respectively. However, experimentation is expensive and results are location-specific, making it difficult to extrapolate to wider, similar environments. Therefore, it seems useful to try and model the relationships between soil fertility and fertilizer use on the one hand, and nutrient uptake and millet yields on the other hand. The model chosen is known as QUEFTS (Quantitative Evaluation of the Fertility of Tropical Soils), and was initially developed for maize (Janssen *et al.*, 1990, Smaling and Janssen, 1993). The dataset used to calibrate QUEFTS for millet comes from the village Lagassagou, in the Bankass area of Sahelian Mali (Samaké *et al.,* in prep.).

Materials and methods

Theoretical background of QUEFTS

The original version of QUEFTS (Janssen *et al*., 1990) calculates the yield of maize on tropical soils as a function of the availability of soil and fertilizer N, P and K, using a value of the potential grain yield. For maize, this was set at 10,000 kg ha^{-1}. Below this level, maize production must be limited by the supply of N, P and K only. In other words, water supply during the growing season, and extraneous factors such as waterlogging, deficiency of other nutrients or pests, diseases and weed infestation, should not adversely affect crop development. For millet, the same boundary conditions are accepted, but potential grain yield is set at 5,000 kg ha^{-1}.

The calculation procedure in QUEFTS consists of four steps. The essential equations for each step are presented in Table 1.

Step 1. The potential supply of soil nitrogen (SN), phosphorus (SP) and potassium (SK), i.e., the maximum quantity of these nutrients that can be taken up by the crop if no other nutrients or other growth factors are limiting, is derived from empirical

Table 1. Relationship between soil parameters, potential supplies, actual nutrient uptakes and millet grain yields for the original QUEFTS (Janssen *et al.*, 1990). S1 and S2 are the potential supplies of nutrients 1 and 2. U1(2) stands for the actual uptake of nutrient 1 as depending on the potential supply of nutrient 2. The symbols *a, d* and *r* refer to the constants in the equation. Their values are indicated in the equations in Step 3.

Step 1

SN = 17 × (pH – 3) × org. N, or
1.7 × (pH – 3) × org. C

SP = $0.014 \times (1 - 0.5 \times (pH - 6)^2) \times$ total P + 0.5 × P-Olsen, or
$0.35 \times (1 - 0.5 \times (pH - 6)^2) \times$ org. C + 0.5 × P-Olsen

SK = 250 × (3.4 – 0.4 × pH) × exch. K / (2 + 0.9 × org. C)

Step 2

Situation	Condition
A	$S1 < r1 + (S2 - r2)(a2/d1)$
C	$S1 > r1 + (S2 - r2)(2 \times d2/a1 - a2/d1)$
B	S1 in between

	Equation for U1(2)
A	$U1(2) = S1$
C	$U1(2) = r1 + (S2 - r2)(d2/a1)$
B	$U1(2) = S1 - \dfrac{0.25\,[S1 - r1 - (S2 - r2)(a2/d1)]^2}{(S2 - r2)(d2/a1 - a2/d1)}$

Values of constants:

Nutrient	*a*	*d*	*r*
N	30	70	5
P	200	600	0.4
K	30	120	2

Step 3

YNA = 30 × (UN – 5)	YND = 70 × (UN – 5)
YPA = 200 × (UP – 0.4)	YPD = 600 × (UP – 0.4)
YKA = 30 × (UK – 2)	YKD = 120 × (UK – 2)

Step 4

YE = (YNP + YNK + YPN + YPK + YKN + YKP) / 6 equations with soil chemical properties of the 0–15 cm soil layer as independent determinants.

Step 2. If the supply is enhanced, it positively influences the uptake of the other nutrients. In QUEFTS, these interactions are reflected in the way actual uptake of each nutrient (UN, UP and UK) is calculated, namely as a function of the potential supply of that nutrient, taking into account the potential supply of the two other nutrients. It is a theoretical relation, assuming a linear decrease of dU/dS from 1 to 0. Integration of this differential equation results in a parabolic curve (Situation *B*), bounded by a linear relationship between potential supply and actual uptake when the supply of the particular nutrient is low compared to the two other nutrients (Situation *A*), and a plateau value at a relatively high potential supply of the nutrient, implying that increased supply does not lead to any further uptake of that nutrient (Situation *C*).

Step 3. When the potential supply of a nutrient is low compared to the two other nutrients, the particular nutrient is growth-limiting, and its internal concentration in the plant is low, eventually reaching a stage of *maximum dilution*. Nutrient use efficiency (NUE), i.e., the economic yield produced per unit of nutrient in the above-ground dry matter, is then maximum. Values of maximum NUE for maize are 70, 600 and 120 kg grain per kg N, P and K, respectively. When the supply of a nutrient is large and growth is not limited by uptake of that nutrient, the crop takes up more than required until *maximum accumulation* is reached, coinciding with NUE values of 30, 200 and 30 kg grain per kg N, P and K. Moreover, there has to be a minimum uptake (5 kg N, 0.4 kg P and 2 kg K ha^{-1}) before any grainfilling can take place. At this point, three yield (Y) ranges can be calculated, represented by maximum dilution (D) and accumulation (A) of N, P and K in the plant tissue: YND–YNA, YPD–YPA and YKD–YKA.

Step 4. The final yield estimate (YE) is found by comparing the three ranges. The yield range that follows from N uptake is narrowed to the overlap with the range YPD–YPA, leading to a combined estimate YNP, and to the overlap with the range YKD–YKA, with a combined estimate YNK. The same procedure is followed for P and K, and provides six estimates: YNP, YNK, YPN, YPK, YKN, and YKP. The final yield estimate is the average value of these six combined estimates, and lies in the common overlap of the three yield ranges.

Beside the concept of potential supply, QUEFTS uses the concept of *maximum recovery* of fertilizer. Nitrogen recovery, for example, is calculated as the difference in N uptake between an experimental unit receiving NPK and a unit receiving PK, divided by the amount of applied N. If there are no available field data of maximum recovery fractions, QUEFTS uses standard values of 0.5 for N and K and 0.1 for P.

Model calibration

The calibration of QUEFTS for millet was based on experiments carried out in 1998 and 2001 in the village of Lagassagou in Sahelian Mali. Soils were homogeneously sandy (about 90% sand), rainfall was unimodally distributed between June and September (Figure 1), averaging 570 mm in 42 days. Total rainfall in 1998 and 2001 was 581 and 458 mm, respectively.

Farmers apply the earlier described, typically West African ring management system. Therefore in 1998, zero-fertilizer experimental fields were laid out along four transects, i.e., from the edge of the compounds to the boundary of the village territory. Distances were 10, 50, 100, 200 m (the so-called homefields), and at 500, 1000 and 2000 m (the bushfields). In 2001, two series of experiments were conducted in the same village in both homefields and bushfields. Four rates of fertilizer were applied: 0-0-0, 0-10-0, 0-20-0 and 38-20-0 (i.e., 38 kg N ha^{-1}, 20 kg P ha^{-1}, and 0 kg K ha^{-1}). Urea and triple super phosphate (TSP) were the major fertilizers applied. Treatments were arranged in a randomized complete block design with four replicates. Phosphorus was applied at sowing, nitrogen at tillering. A local variety of millet (*Pennicetum glaucum*), well adapted for the zone was sown at 1 × 1 m spacing. Several seeds were used at sowing to allow thinning to three plants per hill, two weeks after emergence. No pesticide was applied. Weeding was done manually using traditional hoeing.

At maturity, heads of millet were harvested from each plot, air-dried, threshed and weighed for grain yield. A week before harvest, the number of *Striga* stalks was counted. The above-ground biomass was collected per plot, air-dried for two weeks

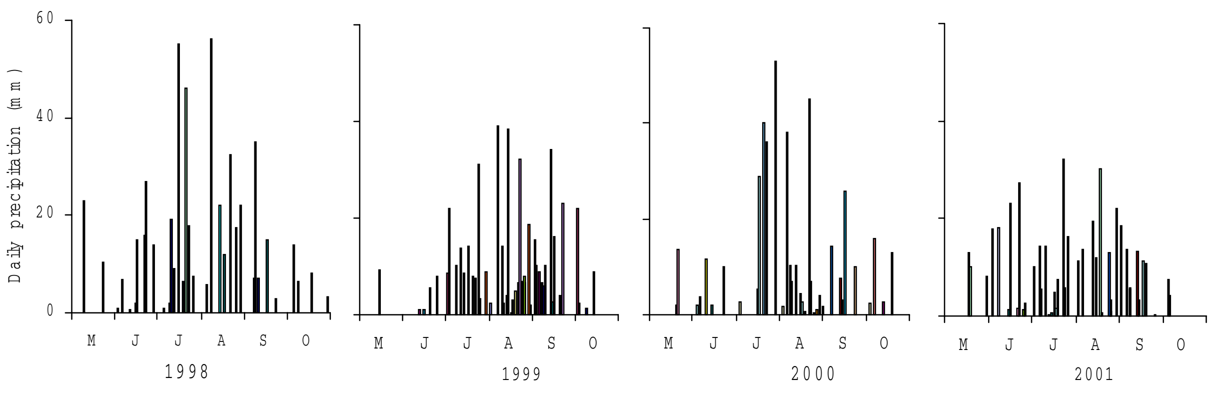


Figure 1. Daily rainfall (May–October) recordings in the village of Lagassagou in 1998–2001.

and weighed. Sub-samples were taken for analysis of N, P, and K concentrations in plant tissues. Composite topsoil (0–15 cm) samples were taken at ploughing, and analysed for organic C, total N, P-Bray I, exchangeable K and pH (Nelson and Sommers, 1982; Olsen and Sommers, 1982; Thomas, 1982).

A full-fledged calibration, as in the case of maize (Smaling and Janssen, 1993), was not possible, as the experiment was not initially meant for a calibration of QUEFTS. Hence, the following limitations apply:

- Data have been taken from only one village;
- Rainfall in 2001 was below average, implying that yields may be partly water-limited rather than nutrient-limited;
- Zero-P fertilizer plots are absent (apart from controls), not allowing SP to reach its probable maximum value;
- The datasets used in 1998 (transect) and 2001 (transect and some separate N fertilizer experiments) were not exactly the same;
- Crop samples were (carefully prepared) composite samples rather than separate samples of different plant parts;
- *r* values in Step 2 (Table 1) were set at zero, due to absence of sound estimates;
- Recovery of N and P were not determined along the same lines, i.e., based on the difference between NPK-fertilzer applications of 38-20-0 and 0-20-0, and between 0-20-0 and 0-0-0, respectively;
- Bushfields had to be excluded from the calibration because of high infestation of *Striga hermonthica.* By using homefields for calibration, and calculating yields for bushfields upon this calibration, one can calculate the difference between expected nutrient-limited yield and observed *Striga*-depressed yield. This yield gap indicates *Striga* effects.

Steps 2 and 4 are based on theoretical knowledge of system properties, and will be used as in Janssen *et al*. (1990). Hence, the empirical components of the model, i.e., Steps 1 and 3, and fertilizer recovery, were determined anew. For Step 1, new equations were developed, based on field data. For Step 3, new values for the maximum accumulation and dilution of N, P and K in the crop were determined. Lastly, maximum fertilizer recovery was determined from the field trials.

Results and discussion

Soil chemical characteristics

The levels of pH, C, N, P, and K of the topsoil (0–15 cm) at ploughing are indicated in Table 2, and very clearly show differences between soil test values in homefields (< 200 m) and bushfields (> 200 m). These differences were due to the low availability of manure, and the lack of means to carry manure further away (Samaké *et al.*, in prep.).

Millet production and Striga *infestation*

Table 3 summarizes part of the experimental results for the different treatments, in homefields and bushfields. The table shows that *Striga* infestation was very high in

Table 2. Soil native nutrient levels according to fertility gradient in Lagassagou village in 2001.

Distances of the fields from the compounds (m)	Organic carbon ($g\ kg^{-1}$)	Total nitrogen ($g\ kg^{-1}$)	P-Bray-I ($mg\ kg^{-1}$)	Exchangeable K ($mmol\ kg^{-1}$)
10	5.4	0.32	7.2	0.67
50	5.5	0.33	7.3	0.67
100	3.8	0.26	5.9	0.36
200	3.1	0.23	5.1	0.19
500	2.0	0.15	2.7	0.15
1000	1.8	0.14	2.6	0.14
2000	1.6	0.12	2.3	0.14

Table 3. Millet yields, harvest indices and nutrient uptake ($kg\ ha^{-1}$) from fertilizer treatments in homefields (10–200 m) and bushfields (500–2000 m) in 2001 in Lagassagou village. NPK: 0-10-0, 0-20-0 and 38-20-0 ($kg\ ha^{-1}$).

Treatments ($kg\ ha^{-1}$)	*Striga* ($plant\ ha^{-1}$)	Biomass ($kg\ ha^{-1}$)	Grain yield ($kg\ ha^{-1}$)	Harvest indices	*n*	Nutrient uptake		
						N	P	K
Homefields								
0-0-0	2500	3520	1130	0.32	16	23.7	5.3	55.3
0-10-0	2800	3740	1000	0.27	20	46.3	7.0	56.1
0-20-0	3700	4290	1160	0.27	20	55.8	8.7	66.0
38-20-0	3100	6080	1730	0.28	4	83.7	12.1	97.2
Bushfields								
0-0-0	16300	2970	480	0.16	12	13.9	3.6	50.3
0-10-0	16700	2460	420	0.17	12	17.0	3.7	30.2
0-20-0	17400	3450	660	0.19	16	26.7	5.9	47.2
38-20-0	15000	3210	1020	0.32	4	32.1	5.8	46.6
Average								
Homefields	3020	4020	1140	0.28	60	52.4	8.3	68.6
Bushfields	16350	3030	580	0.19	44	22.4	4.8	43.6

bushfields, and led initially to the decision not to only include these experiments for the model calibration, as they would not reflect nutrient-limited, but *Striga*-limited yield. However, as the table also shows substantial differences in harvest index between homefields and bushfields, it was necessary to find specific yield/uptake relationships for the two spatial units. Therefore, Step 3, i.e. the 'plant part', was calibrated for both homefields and bushfields.

Nutrient-uptake values, in Table 3, clearly show how application of one nutrient in fertilizer can increase the uptake from the soil of other nutrients. Average N:P:K ratio in millet was 6:1:8. This ratio shows relatively higher K and lower N taken up by millet compared to that of maize, which was estimated at 8:1:6 (Janssen *et al.*, 1990).

N- and P-fertilizer recovery was calculated from Table 3. N recovery was 73% when comparing treatments 0-20-0 and 38-20-0. P recovery was 17% when comparing treatments 0-0-0 and 0-20-0. These values are both higher than the default values used by QUEFTS (50 and 10%, respectively), showing that crops are both N- and P-hungry. P recovery may even be underestimated, as it should ideally have been determined as the difference between N+P and N-only treatments. When it comes to yield increases due to fertilizer, the P-only treatments perform poorly, i.e., they produce more stover but not more grain than the control treatments. The combination of N and P, however, shows grain yield increases of 600 and 540 kg ha^{-1} for homefields and bushfields, respectively. Hence, P and N+P fertilizer both lead to higher N, P and K uptake, but only N+P fertilizer gives markedly higher yields.

Model calibration

Potential N supply was obtained from treatments 0-10-0 and 0-20-0, potential P supply from the control treatments, and potential K supply from treatments 0-10-0, 0-20-0 and 38-20-0. In these cases, SN, SP and SK are supposed to more or less equal UN, UP, UK (Table 1, Step 2, Situation *A*). Potential supplies were plotted against all available (combinations of) soil test values, and eventually led to the regression equations and correlation coefficients given in Table 4. The equations are relatively simple, with only

Table 4. Potential N, P and K supply (kg ha^{-1}), expressed in soil chemical properties (Step 1).

Description	Equations	R^2	*n*
Potential N supply	SN = 132 × total N + 10	0.48^{**}	36
Potential P supply	SP = 0.56 × P-Bray + 3	0.63^{**}	38
Potential K supply	SK = 41.5 × exch. K + 38	0.48^{**}	30

** $P<0.01$

one explaining variable. Adding other soil test values, however, did not increase explanation of potential supply. As mentioned earlier, SN and SK may really reflect potential supply, whereas SP may be underestimated as there were no treatments that had N+K fertilizer, inducing soil-P uptake to be close to its maximum value.

Yield ranges were obtained from the relationship between the N, P and K contents in the above-ground plant components and millet grain yields. The ranges in Figure 2 represent the extremes where the nutrient is maximally accumulated (lower line) and maximally diluted (upper line). The calibrated values for *a* and *d* (Table 1, Figure 2) differ substantially from those obtained for maize (Smaling and Janssen, 1993). However, a continent-wide review by Stoorvogel *et al.* (1993) on crop nutrient uptake revealed that millet is a luxury consumer among the cereals, leading to low Y/UD values. Where maize takes up approximately 25 kg N, 5 kg P, and 25 kg K ton^{-1} harvested product, millet reaches values of 40 kg N, 10 kg P and 60 kg K ton^{-1} harvested product, while at least 80% of the K uptake is found in the stover. Van Duivenbooden (1992), however, reported Y/UD values of 325 kg kg^{-1} for P, and 100 kg kg^{-1} for K, which are substantially higher than those derived from Figure 2.

Table 5. Measured and calculated grain millet yields (kg ha^{-1}) for four different levels of added fertility in home- and bushfields, and absolute differences and classification of differences (0 = +/–100, 1 = 100–300, 2 = 300–500 kg ha^{-1} deviation). The averages are weighted averages of all homefields and all bushfields.

	Millet grain yield (kg ha^{-1})		Differences between measured and calculated yield	
	Measured	Calculated	Difference (kg ha^{-1})	Classification
Homefields				
Average	1137	1124	13	0
No fertilizer	1132	990	142	1
0 N - 23 P_2O_5	1160	1173	–13	0
0 N - 46 P_2O_5	1001	1136	–135	–1
38 N - 46 P_2O_5	1730	1349	381	2
Bushfields				
Average	473	638	–165	–1
No fertilizer	485	611	–126	–1
0 N - 23 P_2O_5	664	849	–185	–1
0 N - 46 P_2O_5	416	785	–369	-2
38 N - 46 P_2O_5	1020	1026	–6	0

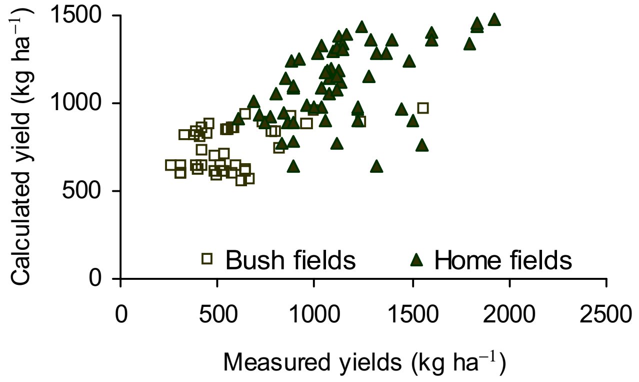


Figure 3. Relationship between measured and calculated yields. Only homefields have been used for calibration.

Based on the equations for SN, SP and SK, the accumulated and diluted yield-uptake ranges, and the calculated fertilizer recoveries, millet grain yields were calculated. Table 5 shows how they relate to measured yields. For homefields, the average calculated and measured yields correspond very well (difference –13 kg ha^{-1}), but Figure 3 shows that when individual data points are compared, correlation in homefields is poor. Yields in the control and, notably, the 38-20-0 treatment were underestimated. Yields obtained in the 0-10-0 treatments was slightly overestimated by the model.

In bushfields, calculated yields were considerably higher than measured yields. The gap can be attributed to *Striga* infestation and is 39%. The 38-20-0 treatment gave higher yields than QUEFTS could calculate, even for the bushfields, which may imply that N application offers additional advantages to the crop, not covered by the chemical soil test values included in this study. Perhaps the rooting volume is increased upon N-fertilizer application, allowing higher uptake of secondary and micronutrients.

Further scrutiny in other millet-growing environments is needed, but in case of lack of alternatives, the model gives a reasonable estimate of nutrient-limited millet yields, and can be calculated on the basis of just three soil test values (total N, P-Bray I, and exchangeable K).

CHAPTER 7

General discussion

The agricultural sector in West Africa is mainly based on subsistence rainfed cereal (sorghum and millet) cropping often associated with sedentary and nomadic animal husbandry. In areas bordering the Sahara desert, pearl millet (*Pennisetum glaucum* (L.) R. Br.) is the most important rainfed staple crop generally cultivated under uncertain rainfall conditions, on soils of low fertility and with high levels of *Striga* infestation, and without or with very low use of external inputs. Application of inorganic fertilizers is constrained by lack of access to capital while the use of organic inputs is limited by their low availability. Millet yields show a remarkable range from about 300 kg ha^{-1} in Mauritania to 1000 kg ha^{-1} in Gambia (Table 2, Chapter 1). In the Southern Region of Mali, Kanté (2001) reported that attractive cotton prices provide strong incentives for farmers to manage soil fertility more intensively, by applying mineral fertilizers and reusing crop residues. Contrary to this region, there is no real cash crop in the Fifth Region. Over the last decades, production increase in this region seems to have been mainly realized through expansion of cultivated areas, at the expense of fallow land (Table 6, Chapter 2). Meanwhile, grain production per unit area has stagnated (Figure 1, Chapter 1).

Evidence of system poverty and deterioration

A major research hypothesis is based on the assumption that the inherent agricultural productivity is low and declining. Studying nutrient stocks and flows provides the necessary insight, but was not a key component of the thesis. Yet, the data collected allow taking a closer look at the flows IN1–IN4 and OUT1–OUT5 of Figure 1. For nutrient mining to be judged properly, one needs to know the status of the nutrient stocks as well to find out what percentage of total stocks is lost each year. It is clear from the data in this thesis that these stocks are very low. Chapters 3 and 6, for example, show that soil nitrogen levels (0–15 cm) are, on average, 0.24 g kg^{-1} for homefields and 0.12 g kg^{-1} for bushfields. Converted to kg ha^{-1}, and at a (sandy soil) bulk density of 1.5 kg dm^{-3}, the N stocks are 585 and 315 kg N ha^{-1} for homefields and bushfields, respectively, whereby it should be borne in mind that the homefields take up a mere 1–2% of the total surface area. Nutrient uptake under zero fertilizer application in the 2001 experiments was 24 and 14 kg N ha^{-1} for the home- and bushfields, respectively. In other words, if nutrient removal in crop products including harvested products (OUT1) and residues (OUT2) would be complete, and no other

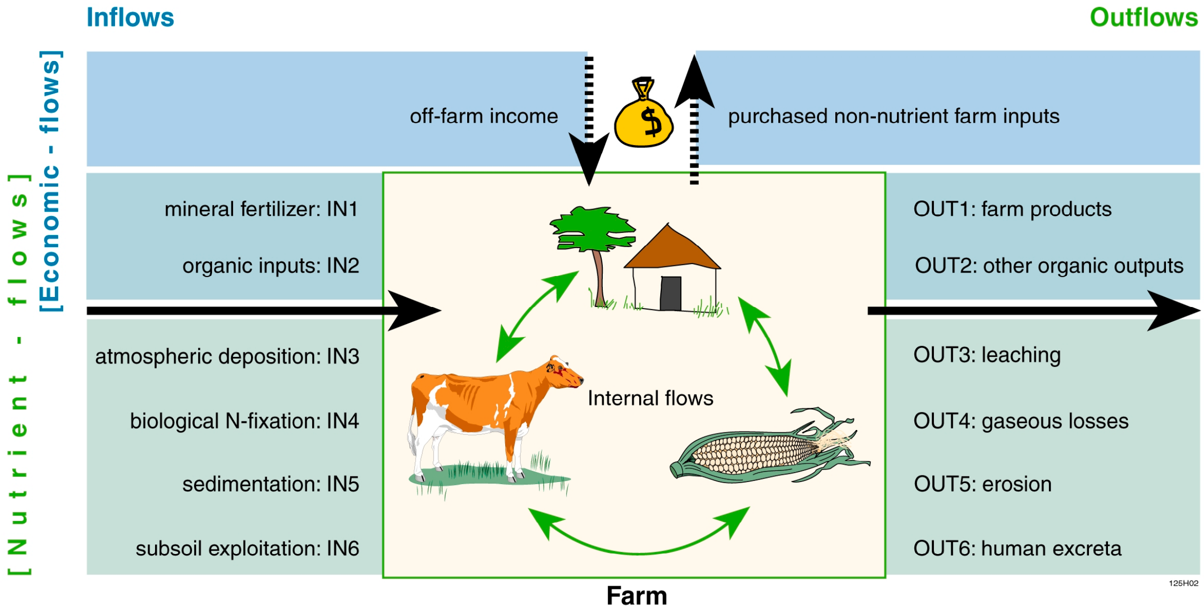


Figure 1. Nutrient flows and economic flows influencing the nutrient balance and household budget (Source: de Jager *et al*., 1998).

flows would play a role, 4.1 and 4.4% of soil nitrogen would be mined on an annual basis in homefields and in bushfields, respectively. Leaching, gaseous losses and erosion are other flows that remove nutrients from the soil (Figure 1). As rains come in heavy thunderstorms (Figure 1, Chapter 4), losses of soil and fertilizer nutrients through leaching (OUT3) may be substantial, particularly in the early stages of the growing season. Gaseous losses (OUT4), however, are most likely not playing a major role in the study area because anaerobic conditions do not commonly occur. Erosion (OUT5) is also rated as low, because of the flat land and the permeable soils.

On the input side, mineral fertilizers (IN1) are hardly used by farmers, but were tested and evaluated as a means of system improvement in Chapters 5 and 6. If phosphorus was applied in fertilizer (0-20-0, NPK in kg ha^{-1}, respectively), nitrogen uptake increased strongly to 56 kg N ha^{-1} in homefields and 27 kg N ha^{-1} in bushfields indicating that application of fertilizer not only increases uptake of the applied nutrient, but also that of nutrients that are not included in the fertilizer. Therefore, application of triple super phosphate or rock phosphate, for example, as done in Chapter 5, may lead to increased mining of N, K and other nutrients. It may, thus, be unwise to apply single-nutrient mineral fertilizers alone. Organic inputs (IN2) have not been quantified but are restricted to the homefields and to scattered patches of bushfield land, where animals are temporarily penned. Assuming that animals rely entirely on what the land has to offer, it is the nutrients in crop residues (OUT2) and fallow vegetation that keeps them going. Assuming that the animals excrete 80% of their nutrient intake, IN2 could be estimated as being 80% of OUT2, again assuming that all residues are used as animal feed. The feedbacks between IN2 and OUT2 are very important, and were looked into in more details by Kanté (2001). The input of nutrients by wet and dry atmospheric deposition (IN3), taken from a recent review by Lesschen *et al*. (2003) shows N inputs of 3–4 kg ha^{-1} yr^{-1}. Herrmann (1996) found that, in south-west Niger, 62 to 186 g m^{-2} of solids was annually deposited on the soil surface from the atmosphere, equivalent to an average nutrient deposition of 1.0–4.0 kg N ha^{-1}, 0.4–1.0 kg P ha^{-1} and 13.8 kg K ha^{-1}. On biological nitrogen fixation (IN4), Giller and Wilson (1991) reported estimates of nitrogen fixation between 23 and 250 kg N ha^{-1} for annual legumes with growth periods of 100–150 days. Using labelled N in Kenya, Ssali and Keya (1986) reported that *Phaseolus* bean fixed 74–91 kg N ha^{-1}, coinciding with 43–52% of total uptake. Eaglesham *et al.* (1981) found that in Nigeria cowpea fixed 80 kg N ha^{-1}, which was 55–60% of total uptake, both when sole-cropped and intercropped.

Hence, based on the above, bushfield N outputs (OUT1) of 14 kg ha^{-1} yr^{-1} meet inputs of 3–4 kg ha^{-1} yr^{-1} (IN3), whereas the IN2–OUT2 feedback provides a negative value of 0.2×OUT2. Lastly, IN1+IN4 will generally be lower than OUT3+OUT4+OUT5 as farmers hardly make use of fertilizers and leguminous species, whereas heavy downpour in the early rainy season may translocate and remove nutrients that have just become available to plants. Fallow land is dwindling at a high rate and may in future no longer be available. The last note on the ‘positive’ side is that OUT1 may not be fully ‘lost’ as long as villagers defecate inside their fields rather than in pit latrines. If they do so, it is always close to the village compounds though, on the land that is already most fertile.

Based on the above, it seems that the current situation in the bushfields is indeed one of low and decreasing fertility. The homefield system may be more sustainable, but occupies only a small portion of land. Increasing grain production in these low-input farming systems must be based on improved soil and crop management technologies that impact on the nutrient stocks and flows, on natural nutrient accumulation in short-term fallows, and on ways to reduce the yield-limiting effect of the parasitic weed *Striga hermonthica*. In this study, the research pathway on sustainable soil and crop management has two tracks: one is to understand the current system, and the other is on-farm experimentation with a selected number of possible improvements. Important at this point is the natural and socio-economic setting of the area, and the degree to which farmers manage their land. This can only be properly understood if more than one spatial scale is taken into consideration. Therefore, the millet-growing ‘system’ is looked upon from a macro/region, a meso/zone and a micro/village scale. Only when the system and its history are properly understood will research choices for sustainable crop and soil management make sense. The dynamics and diversity of the system as depicted in the first part of the research has, therefore, been instrumental in deciding on the choice of experimentation in the second part.

System knowledge

The focus of this thesis has been on millet-based cropping systems. In order to understand constraints and opportunities, an analysis has been made at the level of a village, of the agro-ecological zone in a district where the village is located and at the sub-national level (Fifth Region), and a multi-scale characterization method was followed (Andriesse *et al.*, 1994). The analysis in Chapter 2 showed that, at village level, biological (*Striga* infestation) and soil fertility constraints are the most limiting. Improvement requires investments, and hence, well-functioning input and output markets. The constraints at local level are thus overridden by socio-economic constraints at the higher levels. In a study of changing land use systems in Ecuador, de Koning (1999) also found different drivers of land use change to prevail at different scales, adding to the non-linear concepts in hierarchy theory. In the current study, however, (particularly spatial) data were limited, and the constraint assessment did not surpass the qualitative stage.

In the system analysis described in Chapter 3, the most detailed level is the millet-based cropping system as observed in three Dogon villages. Two such systems exist, i.e., continuous monocropped millet in homefields with application of sufficient manure, and fallow-millet monocrop in bushfields. The homefield system is highly productive within the limits set by rainfall and fertility, but is restricted to 1–2% of the village territory, whereas it is 'subsidized' through lateral nutrient transfers by the other 98–99% of the territory (crops, residues, moving animals). In terms of production units, it was found that the larger ones (in terms of individuals) tend to have more cattle than smaller ones. Larger units have a larger share of the manure produced at village level and leave less land under fallow. As the cattle grazes on the remaining fallow land of the village (< 20%), a gradual transfer of fertility resources from the production units poor in cattle to the production units rich in cattle takes place.

The major non-biophysical constraint to the homefield system seems to be labour availability, although no hard data were gathered to substantiate this claim. A further constraint for expansion of the area under this system is availability of manure, itself limited by the productivity of the bushfields and fallow area. Given the current rather high productivity of the homefield system and its very restricted area, the major improvement in millet production will have to come from improving bushfield system productivity. The most important constraints here are low soil fertility and *Striga* infestation. Changes in this system are technically feasible through a combination of fertilizer applications and cowpea/millet intercropping (Chapters 4, 5, 6). For the poorer production units introduction of this improved management system can only be advocated once the labour inputs have been assessed. For the richer production units the additional cowpea straw could in fact be improving also their cattle production system and, thus, lead to an extra option for cash income.

The question whether production units can and will invest in millet/cowpea intercrop and fertilizer can only be addressed by also considering the next higher levels, the zone and the region. Investment in fertilizer requires opportunities to sell part of the surplus millet and/or cowpea. This is only possible if the millet or cowpea markets of villages become linked to the regional and national grain market. For the richer production units the cattle market could be added as an option for improving their interests in intensifying the system. Millet and cowpea will at regional level have to compete with the world market of rice and wheat. Studies to analyse the possibilities and constraints related to such commercializing of the millet-based cropping system have not been part of this thesis but are needed to fully assess the viability of the suggested systems. At the district level, it was observed that villages of different ethnic composition exist, i.e., sedentary Dogon and semi-nomadic Peul, that have different attitudes to animal and crop production. Further analyses of these differences and the constraints and opportunities as to the described intensification options at the district level are needed.

At the regional and district level the options for facilitating market access of villages are limited as investment capital is limited. Studies at macro-economic level may be needed to assess what return to investments may be expected here in order to attract possible foreign or national investment capital. In other words, comparison of scale-specific constraints to millet production (Table 13, Chapter 2), and elaborated further here on the basis of the information from Chapters 3–6 is to be supplemented by appropriate data to make a more final judgment. For the available options at cropping system level to work, the constraints at higher levels that are related will have to be analysed and addressed simultaneously.

To alleviate the constraint to investment at production unit level, farm gate input and output prices should be more attractive requiring policy intervention at the higher level of organization. Also, the socio-economic and policy environment should enable farmers to stimulate the private sector to invest in input and output market development (Sissoko, 1999). To illustrate the above, a simple economic evaluation of a fertilizer experiment (Samaké, unpublished) conducted in Lagassagou village in 2001 was done, showing that only application of a combination of urea and di-ammonium phosphate (38 kg N ha^{-1} and 20 kg P ha^{-1}) is profitable to farmers, and

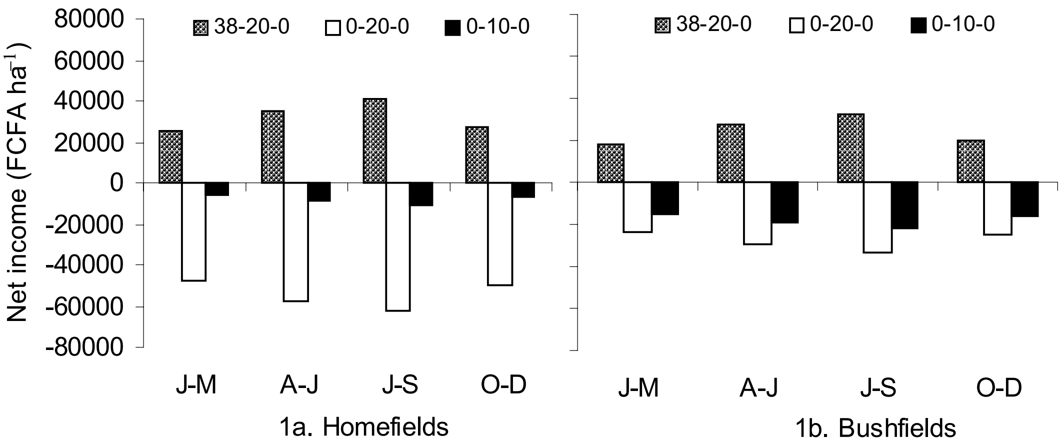


Figure 2. Economic evaluation of inorganic fertilizer use (NPK in kg ha^{-1}) in home- and bushfields on farmers' incomes in Lagassagou, Northern Mali. The price of labour is evaluated at 1000 FCFA per day. Labour cost does not include provision of food during days people are engaged. Millet seeds were obtained in April 2001 at 125 FCFA kg^{-1} in Lagassagou (1 Euro = 655.95 FCFA). Millet prices are average prices of market surveys from 1998 to 2001 in the surrounding village markets. Along the x-axis are the periods of the year when millet would be sold.

most profitable at market prices of millet between April and September (Figure 2). To cash in on these opportunities, farmers should be able to buy these fertilizers in time, and to store and market grain surpluses at the right time. Currently, however, the regional and district authorities have no means to provide farmers with the necessary physical and institutional infrastructure.

Improved management

In the past, the productivity of subsistence agricultural production systems in West Africa relied on extended fallow periods. Increasing population pressure has reduced fallow periods and increased demands on maintenance and improvement of soil fertility. Cereal–legume rotations and intercropping systems have become attractive means to achieve these objectives (Bationo and Ntare, 2000; Cook, 1984). Chapters 4 and 5 showed that the cowpea grown in 1998 had a positive effect on subsequent millet yields and millet N uptake. Yield increase due to millet after cowpea (LM) was 37% in 1999 compared to millet after millet in 1998 (MM). Much higher millet grain yield increases were reported by Bationo and Ntare (2000) who showed that with no application of N fertilizer, millet grain yield after cowpea increased by 57% in Sadore and 87% in Tara (both in Niger). Alvey *et al.* (2001) reported five times higher cereal-shoot dry matter in a pot experiment with soil from fields under cereal–legume rotation compared with soil from fields with four years continuous cereals. An important issue in the acceptance of rotations lies in the role of cowpea in the diet or in providing cash income. An alternative, therefore, may be to sow legume/cereal intercrops rather than rotations. Including millet/cowpea intercrop in alternative-row configuration after cowpea (LM/C), however, did not significantly increase millet grain yield compared to pure millet after cowpea (LM) in the first and the second year, but LM/C increased yields by the third growing season with 22% over LM and 27% over continuous pure millet (MM). In all years, intercropping improved the total grain yield as cowpea grain production was significant and did not come at the expense of millet grain yield. Surprisingly, millet in the intercrop always had equal or higher yields than in millet monocrop. Hence, millet-planting density was possibly not optimal or cowpea may have explored additional resources effectively. Cowpea in the rotation and intercropping systems can also be important to improve the quality of animal feeds, but this has not been analysed in the present study. Fallow also had a significant, positive effect on millet yield. Average grain yields varied from 300 kg ha^{-1} with continuous millet to 450–470 kg ha^{-1} with 2–7 years fallow prior to millet cropping (Chapter 4). Inclusion of fallow in a rotation implies a zero cereal yield, while land tenure also implies that the field is not necessarily available for cropping to the same person who cropped the field prior to the fallow. In summary, it may be concluded that there are good reasons to prefer inclusion of cowpea or other leguminous species over the maintenance of fallow, but the full analysis including the use of labour, land tenure rules for cropping after the investment in the cowpea crop and the value of the cowpea products will be needed to assess the viability of the rotational system.

Application of P-fertilizer increased millet grain yields all years regardless cropping systems and fallow treatments (Chapter 5). An annual application of 100 kg triple super phosphate (TSP) ha^{-1} out yielded the one time application of 300 kg Tilemsi rock phosphate (TRP) ha^{-1} and gave comparable results to those obtained after application of 300 kg TRP ha^{-1} in a first year followed by an annual application of 100 kg TRP ha^{-1}. Meanwhile, the experiment briefly discussed above shows that in order to make millet production profitable, N application in combination with P is imperative. The study shows that biological N fixation in a cowpea–millet multiple cropping system may be able to replace (part of) the necessary N fertilizer, which in case of persistently poor infrastructural services may be the preferred strategy.

As for weed control, neither rotation nor intercropping had a significant effect on *Striga* infestation, although there was a trend of decreasing *Striga* numbers per unit area the first year after a cowpea pure stand and in the cowpea – millet/cowpea rotation intercrop system. The low discriminative power in this experiment seemed to be partly due to the high variability in *Striga* infestation levels (CV is 37 and 58% in 1999 and 2001, respectively). When fallow is possible, the effect of two-years fallow on millet grain yield does not differ from that obtained after 5–7 years fallow. Extending fallow period to seven years further reduced *Striga* infestation only when overall infestation levels were high. Application of P-fertilizers did not result in any significant effect on the number of *Striga*.

This study does not allow assessment of the longer-term effects of millet sole crop versus millet/cowpea rotations and intercropping on soil and crop productivity, nor on *Striga* population dynamics. Further studies, preferably involving modelling components, will be required to explore what is the relative contribution of soil fertility changes and reduced *Striga* infestation to the effect of crop rotation and fallow duration on millet yield. Yet, a modelling study was done in an attempt to relate millet yields to soil fertility indices and nutrient uptake patterns. The model QUEFTS (Quantitative Evaluation of the Fertility of Tropical Soils), originally developed for maize was calibrated for millet using the native fertility of soils and data from fertilizer trials in Lagassagou village (Chapter 6). The calibrated equations for potential supply of N, P and K (Table 5, Chapter 6) were relatively simple, i.e., made up of only one explaining variable. Adding other soil test values did not increase the percentage explanation of potential supply. The modified model gives reasonable nutrient-limited yield estimates, but a number of limitations have been listed which justifies a concerted effort to check and improve the model for other millet-growing environments. Also, QUEFTS has theoretical and empirical components, but it is not a dynamic simulation model. Given the low harvest indices of the millet varieties used, and the poor translocation of nutrients to the grains, a process-based comparison between maize and millet, and subsequent improvement of model components may be necessary. Lastly, QUEFTS assumes no influence on production of other yield-limiting or yield-reducing factors such as rainfall and pests and diseases. Hence, QUEFTS predicts nutrient-limited yield and the additional yield that can be obtained when using fertilizing materials. QUEFTS was also use to assess the yield gap between nutrient-limited and *Striga*-limited yield. In summary, the study has shown that using relatively simple, static models can shed considerable light on the relationship between soil fertility, nutrient uptake and yields. The calibrated model can be used for wider, similar environments and hence, lives up to one of the original points of departure of the thesis, i.e., the desire to scale up village-level findings to larger units of analysis such as districts and regions.

Main conclusions

- Village systems in the Bankass area are made up of homefields and bushfields. The homefields are relatively fertile and seem to allow sustainable agricultural production. However, they occupy a mere 1–2% of the village territory. The remainder (bushfields) has low and declining soil fertility and high rates of *Striga* infestation. Low availability of labour, cash and organic manure make it difficult to improve these systems, while fallow rates are declining rapidly.
- Improved productivity and soil fertility of millet-based cropping systems in bushfields on deep sandy soils in the Fifth Region in Mali can be reached at low investment costs through introduction of cowpea in rotation and as intercrop. When investment capacity allows, fertilizer-P application can be added to this system, making it more productive and further improving soil quality. Although a slight effect of cowpea on *Striga* was observed this system is still not satisfactorily reducing *Striga*-infestation levels, and additional adjustments will have to be found.
- Introduction of this recommendation will need a further analysis of the way to alleviate constraints posed by the current infrastructure and investment capacity at district and regional level. In case of strong improvement, fertilizer-N and -P application becomes profitable, particularly if farmers can sell surpluses when shortages are most imminent.
- To extend the recommendations to other millet-based production systems elaboration of the draft QUEFTS model and thorough calibration and validation over a wider range of systems is needed. The model is considered an essential tool for such extending of results.

References

Adetimirin, V.O., M.E. Aken'Ova and S.K. Kim, 2000. Effects of *Striga hermonthica* on yield components in maize. J. Agric. Sci. 135: 185-191.

Akanvou, R.K., 2001. Quantitative understanding of the performance of upland rice-cover legume cropping systems in West Africa. PhD Thesis, Wageningen University, The Netherlands, 149 pp.

Alvey, S., M. Bagayoko, G. Neumann and A. Buerkert, 2001. Cereal/legume rotation affect chemical properties and biological activities in two West African soils. Plant and Soil 231: 45-54.

Anderson, J.R., 1992. Difficulties in Africa agricultural systems enhancement: Ten hypotheses. Agricultural Systems 38: 387-409.

Andriesse, W. and L.O. Fresco, 1991. A characterization of rice-growing environments in West Africa. Agric. Ecosys. and Environ. 33: 377-395.

Andriesse, W., L.O. Fresco, N. van Duivenbooden and P.N. Windmeijer, 1994. Multi-scale characterization of inland valley agro-ecosystems in West Africa. Neth. J. Agric. Science 42: 159-179.

Andriesse, W., T.J. Stomph and P.N. Windmeijer, 1995. Agro-ecological characterization: A tool for research priority setting and technology transfer. In: Characterization of inland valley agro-ecosystems: A tool for their sustainable use. Proceedings of the 1st Scientific Workshop of the Inland Valley Consortium WARDA, Bouaké, 6-10 Nov. 1995, pp. 31-46.

Anonymous, 1996. Récensement administratif 1996 du cercle de Bankass. Mopti, Mali.

Anonymous, 2002. Subsidize fertilizers for pearl millet production in the Sahel? Working paper, CRRA/Mopti, Mali, 12 pp.

Bacci, L., C. Cantini, F. Pierini, G. Maracchi and F.N. Reyniers, 1999. Effects of sowing date and nitrogen fertilization on growth, development and yield of a short day cultivar of millet (*Pennisetum glaucum* L.) in Mali. Eur. J. of Agron. 10: 9-21.

Bagayoko, M., S.C. Mason and R.J. Sabata, 1992. Effects of previous cropping systems on soil nitrogen and grain sorghum yield. Agron. J. 84: 862-868.

Bationo, A. and A.U. Mokwunye, 1991. Role of manure and crop residues in alleviating soil fertility constraints to crop production with special reference to the Sahelian zones of West Africa. Fert. Res. 29: 177-125.

Bationo, A. and B.R. Ntare, 2000. Rotation and nitrogen fertilizer effects on pearl millet, cowpea amd groundnut yield and soil chemical properties in a sandy soil in the semi-arid tropics. West Africa J. Agric. Science 134: 277-284.

Bationo, A., S.H. Chien, J. Henao, C.B. Christianson and A.U. Mokwunye, 1990.

Agronomic evaluation of two acidulated and partially acidulated phosphate rocks indigenous to Niger. Soil Sci. Soc. Am. J. 54: 1772-1777.

Bationo, A., A. Buerkert, M.P. Sedogo, B.C. Christianson and A.U. Mokwunye, 1994. A critical review of crop residue use as soil amendment in the West African Semi-Arid Tropics. In: J.M. Powell, S. Fernandez-Rivers, T.O. Williams and C. Renard (Eds), Livestock and sustainable nutrient cycling in mixed farming systems of sub-Saharan Africa. Vol. I, Conf. Summary, Proc. Int. Conf. held on 22-26 November, 1993 in Addis Ababa, Ethiopia.

Bationo, A., F. Lompo and S. Koala, 1998. Research on nutrient flows and balances in West Africa: State-of-art. Agric. Ecosys. and Environm. 71: 19-35.

Bocoum, I., 1990. Capitaux ligneux et activités de productions sylvicoles dans la zone ESPR. ESPR, Mopti, Mali.

Boserup, E., 1965. The conditions of agricultural growth: The economics of agrarian change under population pressure. Aldine Publishing Company, Chicago, USA.

Boukar, I., D.E. Hess and W.A. Payne, 1996. Dynamics of moisture, nitrogen, and *Striga* infestation of pearl millet transpiration and growth. Agron. J. 88: 545-549.

Breman, H., 1995a. Sustainable agriculture in the Sahel? (integrated farming, perennials and fertilizers). In: J. Bouma et al. (Eds), Eco-regional approaches for land use and food production. Kluwer Academic Publishers, The Netherlands, pp. 213-235.

Breman, H., 1995b. Opportunities and constraints for sustainable development in semi-arid Africa. UNU/ INTECH Working paper No 18.

Breman, H. and N. de Ridder, 1991. Manuel sur les pâturages des pays sahéliens, Editions Karthala, ACCT, CABO-DLO, and CTA, Paris, Wageningen, 485 pp.

Brouwer, J. and J.M. Powell, 1993. Soil aspects of nutrients cycling in a manure application experiment in Niger. Paper presented at the International Workshop on the role of livestock in nutrient cycling in mixed farming system in sub-sahelian Africa. ILCA, Addis Ababa, 22-26 Nov. 1993.

Brouwer, J. and J. Bouma, 1997. Soil and crop growth variability in the Sahel: Highlights of research (1990-1995) at ICRISAT Sahelian Center. Information Bulletin No 49. ICRISAT, Patancheru 502 324, Andhra Pradesh, India, 42 pp.

Buerkert, A. and P. Hiernaux, 1998. Nutrient in the West African Sudano-Sahelian zone: Losses, transfer and role of external inputs. Z. Pflanzenernahrung und Bodenk. 161: 365-383.

Buerkert, A., A. Bationo and H.P. Piepho, 2001. Efficient phosphorus application strategies for increased crop production in sub-Saharan West Africa. Field Crops Research 72: 1-15.

Camara, O.S., 1996. Utilisation des résidus de récolte et du fumier dans le cercle de

Koutiala: Bilan des éléments nutritifs et analyse économiques. Rapport PSS No 18. Wageningen, AB-DLO, 120 pp.

Carson, A.G., 1986. Research and development strategies for the control of *Striga hermonthica* in The Gambia. In: Proceedings of the FAO/OAU All African Government Consultation on *Striga* Control, 20-24 Oct. 1986, Maroua, Cameroon, pp. 100-117.

César, J. and C. Coulibaly, 1991. Conséquence de l'accroissement démographique sur la qualité de la jachère dans le nord de la Cote d'Ivoire. In: C. Floret and A. Serpantié (Eds), La jachère en Afrique de l'Ouest. Collection Colloques et Séminaires. ORSTOM, Paris, pp. 415-434.

Charreau, C., 1972. Problèmes posés par l'utilisation des sols tropicaux par des cultures annuelles. Agron. Trop. 27: 905-929.

Cissé, S. and P.A. Gosseye (Eds), 1990. Compétition pour des ressources limitées: Le cas de la cinquième région du Mali. Rapport 1. Ressources Naturelles et Population. CABO/ESPR. Wageningen, Pays-Bas.

Cleaver, K.M. and W.G. Donovan, 1995. Agriculture, poverty, and policy reform in sub-Saharan Africa. World Bank Discussion Papers/Africa Technical Department Series No 280, Washington DC.

Club du Sahel, 1991. Synthèse des travaux 1990 du secrétariat du Club du Sahel. Bilan de la décennie 1980-1990 et réflexions pour l'avenir du Sahel. Rapport SAH/D/91/381. Club du Sahel, CILSS, OCDE, Paris, 186 pp.

Cook, R.J., 1984. Root health: Importance and relationship to farming practices. In: D.F. Bezdicek, J.F. Power, D.R. Keeney, M.J. Wright (Eds), Organic Farming: Current technology and its role in a sustainable agriculture. Spec. Publ. 46, ASA, CSSA, SSSA, Madison, WI, pp. 111-127.

Daget, P. and J. Poissonet, 1971. Une méthode d'analyse phytologique des prairies. Critère d'application. Ann. Agron. 22: 5-41.

Dakora, F.D. and S.O. Keya, 1997. Contribution of legume nitrogen fixation to sustainable agriculture in sub-saharan Africa. Soil Biology and Biochemistry 29: 809-917.

de Jager, A., S.M. Nandwa and P.F. Okoth, 1998. Monitoring nutrient flows and economic performance in African farming systems (NUTMON). I. Concepts and methods. In: E.M.A. Smaling (Ed.), Nutrient flows and balances as indicators of productivity and sustainability in sub-Saharan African agro-ecosystems. Agric. Ecosys. Environ. 71: 37-48

de Koning, F., 1999. Spatially explicit analysis of land use change: A case study for Ecuador. PhD Thesis. Wageningen Agricultural University, The Netherlands, 173 pp.

Dembélé, B., A.R. Roques, G. Sallé and C. Tuquet, 1994. Plantes parasites des cultures et des essences forestières au Sahel. Institut du Sahel, Bamako, Mali.

de Ridder, N. and H. van Keulen, 1990. Some aspects of the role of organic matter in sustainable intensified arable farming systems in the West African semi-arid tropics (SAT). Fertilizer Research 26: 299-310.

DNEF, 1990. Notice de Cercle: Cercle de Bankass, Région de Mopti, PIRL, Direction Nationale des Eaux et Forêts, Bamako, Mali.

DNSI, 1980. Recensement Général de la population 1976. Résultats définitifs. Volume III, Répertoire de village. Direction Nationale de la Statistique et de l'Informatique Bamako, Mali.

DNSI, 1990. Recensement Général de la population 1986. Résultats définitifs. Volume 0, Tome 2. Répertoire de village. Direction Nationale de la Statistique et de l'Informatique, Bamako, Mali.

DNSI, 1991. Enquête budget consommation 1988-1989 au Mali. Analyse préliminaire. Direction Nationale de la Statistique et de l'Informatique, Bamako, 54 pp.

DNSI, 2001. Recensement Général de la population et de l'habitat, 1998. Résultats définitifs. Tome 4. Répertoire de village. Direction Nationale de la Statistique et de l'Informatique, Bamako, Mali.

Dogget, H., 1988. Witchweed (*Striga*). In: Sorghum. 2nd edition, Longman Scientific and Technical, Harlow, Essex, UK, pp. 368-404.

DRAMER (Direction Régionale de l'Appui au Monde Rurale), 2001. Bilan annuel de campagne agricole 2000/2001. DRAMER, Mopti, Mali.

DRSPR, 1992. Eléments de reconnaissance générale dans le Séno et dans le delta en cinquième région. Département de Recherche sur les Systèmes de Production Rurale, Mopti, Mali, 163 pp.

Dugué, P., 1993a. Préparation du sol en zone sahelo-soudanienne, atouts et contraintes. In: FSU-SAFGRAD, Technologies Appropriées pour les Paysans des Zones Semi-arides d'Afrique Occidentales, Ouagadougou, Burkina Faso, 2-5 Avril, 1993, 25 pp.

Dugué, P., 1993b. La gestion de la fertilité et l'utilisation des ressources naturelles dans les systèmes agro-pastoraux soudano-sahéliens. Quelques éléments de réflexion à partir des situations du Yatenga (Burkina Faso) et du Sine Saloum (Sénégal). Communication présentée à la journée AGR (Gestion de la fertilité) du 20 Janvier 1993. CIRAD-SAR No 26/93, 15 pp.

Eaglesham, A.R.J., A. Ayanaba, V.R. Rao and D.L. Eskew, 1981. Improving the nitrogen nutrition of maize by intercropping with cowpea. Soil Biol. Biochem. 13: 169-171.

Ejeta, G. and L.G. Butler, 1993. Host-parasite interactions throughout the *Striga* life cycle, and their contributions to *Stiga* resistance. African Crop Sci. J. 1: 75-80.

ESPGRN, 1999. Problématique foncière et institutionnelle de l'utilisation des ressources naturelles en 5ème région du Mali. Equipe Système de Production et Gestion des Ressources Naturelles de Mopti. Rapport final de recherche, Doc. No 4, Mopti, Mali.

FAO/WHO, 1973. Energy and protein requirements. Technical Report Serie No 522. Geneva, Switserland.

FAO, 1974. Production yearbook. Vol. 27, FAO, Rome, Italy, 447 pp.

FAO, 1992. Production yearbook. FAO, Rome, Italy.

FAO, 1995. Akosombo principales. Proc. FAO Workshop Adoption of sustainable land management technologies challenges and opportunities. Ghana, 6-10 February 1995. FAO, Rome, Italy.

FAO, 1966-2002. FAO yearbook 1966-2002, FAO, Rome, Italy.

FAO, 1988-2002. FAO yearbook 1988-2002, FAO, Rome, Italy.

Fukai, S., 1993. Intercropping – base of productivity. Field Crop Research 34: 239-245.

Gakale, L.P. and M.D. Clegg, 1987. Nitrogen from soybean for dryland sorghum. Agron. J. 79: 1057-1067.

Gandah, M., 1999. Spatial variability and farmer resource allocation in millet production in Niger. PhD Thesis, Wageningen Agricultural University, The Netherlands, 115 pp.

Ganry, F., 1977. Etude en microlysimetries de la decomposition de plusieurs types de residues de recolte dans un sol tropical sableux. Agronomie Tropicale 27: 51-65.

Gathumbi, S.M., J.K. Ndufa, K.E. Giller and G. Cadisch, 2002. Do species mixtures increase above- and belowground resource capture in woody and herbaceous tropical legumes? Agron. J. 94: 518-526.

Giller, K.E. and K.J. Wilson, 1991. Nitrogen fixation in tropical cropping systems. CAB International, Wallingford, UK, 171 pp.

Hartmann, R. and M. Gandah, 1982. Hydrodynamic characterization of a sand dune soil in Niger. Med. Fac. Landbouww. Rijksuniv. Gent, pp. 1195-1204.

Hekstra, P., W. Andriesse, C.A. de Vries and G. Bus, 1983. Wet land utilization Research Project, West Africa. Phase I. The inventory: Vol. I; Main report; Vol. II; The physical aspects; Vol. III; the Agronomic, Economic and sociological Aspects: Vol. IV. International Institute for Land Reclamation and Improvement, Wageningen, Wageningen, The Netherlands.

Hengsdijk, H. and H. van Keulen, 2002. The effect of temporal variation on inputs and outputs of future-oriented land use systems in West Africa. Agriculture, Ecosystems and Environment 91: 245-259.

Herrmann, L., 1996. Staubdeposition auf böden West-Afrika. Eigenschaften und Herkunftsgebiete der stäube und ihr einfluss auf boden und standortseigenschaften. Hohenheim Bodenkundliche Hefte 36. Universität Hohenheim, Stuttgart, Germany, 239 pp.

Hess, D.E. and G. Ejeta, 1987. Effect of cultural treatments on infestation of *Striga hermonthica* (Del.) benth. (Scrophulariaceae). In: H.C. Weber and W. Forstreuter (Eds), Proceedings of the 4th International Symposium on Parasitic Flowering Plants, Marburg, Germany, 1987. Philipps-Universitat, Marburg, Germany, pp. 367-375.

Hess, D.E. and J.H. Williams, 1994. Influence of planting date on *Striga* infestation and yield of pearl millet. Phytopathology 84: 1104.

Hiernaux, P., S. Fernadez-Rivera, E. Schlecht, M.D. Turner and T.O. Williams, 1997. Livestock-mediated nutrient transfers in Sahelian agro-ecosystems. ILRI Report, Niamey, Niger, 9 pp.

Hoekstra, D. and J. Corbett, 1995. Sustainable agricultural growth for the highlands of East and central Africa: Prospects to 2020. Paper prepared for the International Food Policy Research Institute (IFPRI). EcoRegions for the developing world: A lens for assessing food, agriculture and the environment to the year 2020.

Holling, C.S., 1992. Cross-scale morphology, geometry, and dynamic of ecosystems. Ecological Monographs 62: 447-502.

ICRISAT, 1984-1990. West African programmes. Annual reports. ICRISAT Sahelian Center, BP 12404, Niamey, Niger.

INSAH (Institut du Sahel), 1997. Gestion des resources naturelles au Sahel. Pratiques vulgarisées. Institut du Sahel, Bamako.

Janssen, B.H. and D. van der Eijk, 1990. Phosphorus supply to plants predicted from chemical soil properties. Transactions 14th Internat. Congress of Soil Science, Kyoto, Japan, pp. II-325-326.

Janssen, B.H., F.C.T. Guiking, D. van der Eijk, E.M.A. Smaling, J. Wolf and H. van Reuler, 1990. A system for quantitative evaluation of the fertility of tropical soils (QUEFTS). Geoderma 46: 299-318.

Jones, M.J., 1971. The maintenance of organic matter under continuous cultivation at Samaru, Nigeria. J. Agric. Sci. Camb. 77: 473-482.

Jones, M.J. and A. Wild, 1975. Soil of the West African savanna. Techn. Commun. Commonw. Bur. of Soils, CAB, Farnham Royal, UK, 55 pp.

Juo, A.S.R. and R. Lal, 1977. The effect of fallow and continuous cultivation on the chemical and physical properties of an alfisol in western Nigeria. Plant and Soil 47: 567-548.

Kanté, S., 2001. Gestion de la fertilité des sols par classe d'exploitation au Mali-Sud.

Documents sur la Gestion des Resources Tropicales 38, Wageningen, The Netherlands, 237 pp.

Karambé, M., 1998. Evolution de l'occupation et de l'utilisation actuelle des terres en zone soudanienne nord au Mali. Cas du terroir villageois de Lagassagou, Cercle de Bankass. In: Rapport de recherche de la campagne 1997 présenté à la 4ème session du Comité de Programme, Sotuba 4-10 Oct., Programme Ress. Forestières, Bamako, Mali, pp. 1-24.

Kessavalou, A., J.W. Doran, W.L. Powers, T.A. Kettler and J.H. Qian, 1996. Bromide and nitrogen-15 tracers of nitrate leaching under irrigated corn in Central Nebraska, USA. Environ. Qual. 25: 1008-1014.

Kessler, J.J. and M. Moolhuijzen, 1994. Low external input sustainable agriculture: Expectation and realities. Neth. J. of Agric. Science 42: 181-194.

Kieft, H., N. Keita and J. van der Heide, 1994. Engrais fertiles? Vers une fertilité durable des terres agricoles au Mali. ETC, Leusden, The Netherlands, 99 pp.

Klaij, M.C., C. Renard and K.C. Reddy, 1994. Low input technology options for millet based cropping systems in the Sahel. Experimental Agriculture 30: 77-82.

Konaté, A., 1986. *Striga* in Mali. In: Proceedings of the FAO/OAU All African Government Consultation on *Striga* Control, 20-24 Oct. 1986, Maroua, Cameroon, pp. 58-61.

Kumar, A.K., 1989. Pearl millet: Current status and future potential. Outlook Agric. 18: 46-53.

Lagoke, S.T.O., 1986. *Striga* in Nigeria. In: Proceedings of the FAO/OAU All African Government Consultation on *Striga* Control, 20-24 Oct. 1986, Maroua, Cameroon, pp. 68-75.

Lamers, J.P.A. and P.R. Feil, 1995. Farmers' knowledge and management of spatial soil and crop growth variability. Neth. J. Agric. Science 43: 375-389.

Lagoke, S.T.O., V. Parkinson and R.M. Agunbiade, 1991. Parasitic weeds and control methods in Africa. In: S.K. Kim (Ed.), Combating *Striga* in Africa. Proceedings, Workshop organized by IITA, ICRISAT and IDRC, 22-24 August 1988, IITA, Ibadan, Nigeria, pp. 151.

Le Houerou, H.N., 1989. The grazing land ecosystems of West African Sahel. Ecological Studies, Vol 75. Springer-Verlag, Berlin, Germany.

Legoupil, J.C. and B. Lidon, 1993. Quelle maitrise de l'eau pour quelle intensification agricole des zones de bas-fonds en Afrique de l'Ouest? Les lecons des expériences passées. Les perspectives pour une nouvelles approche. In: J.Y. Jamin, W. Andriesse, L. Thiombiano and P.N. Windmeijer (Eds), Les recherches sur le bas-fonds en Afrique sub-Saharienne. Priorités pour un consortium régional. Actes du 1er atelier annuel du Consortium bas-fonds, ADRAO, Bouaké, 8-10 Juin 1993.

Bouaké, Cote d'Ivoire, IVC/CBF, pp. 45-60.

Lesschen, J.P., J. Asiamah, P.T. Gicheru, S. Kanté, J.J. Stoorvogel and E.M.A. Smaling, 2003. Scaling soil nutrient balances. FAO-AGLL, Rome (in print).

Maïga, S.A., B. Témé, B. Coulibaly, L. Diarra, A. Kergna, K. Tigana and J. Winpenny, 1994. Ajustement structurel et développement durable. Cas du Mali. IER/Overseas Development Institute (ODI), Bamako, Mali, 92 pp.

Maiti, R.K. and F.R. Bidinger, 1981. Growth and development of the pearl millet plant. Research Bulletin No 6. ICRISAT, Patancheru, India.

Mansfield, R.A., 1982. *Striga* research at the Institute for Agricultural Research 1979–1982. Agronomy Department, ABU, Zaria, Nigeria. Mimeo, 38 pp.

Manu, A., A. Bationo and S.C. Geiger, 1991. Fertility status of selected millet producing soils of West Africa with emphasis on phosphorus. Soil Sci. 152: 315-320.

Marcussen, H.M., 1994. The need for a new perspective on the Sahelian state, an introduction. In: H.M. Marcussen (Ed.), Improved natural resource management, the role of state versus that of the local community. Occasional Paper 12, International Development Studies, Roskilde University, pp. 11-36.

Mazzucato, V. and D. Niemeijer, 2001. Le Sahel: Une dégradation des terres exagérée, un potentiel paysan sous-estimé. IIED, Progr. Zones Arides. Dossier No 1, 27 pp.

M'Boob, S.S., 1989. A regional programme for *Striga* control in west and central Africa. In: T.O. Robson and H.R. Broad (Eds), *Striga*-improved management in Africa. FAO, Rome, Italy, pp. 190-194.

Nelson, D.W. and L.E. Sommers, 1980. Total nitrogen analysis for soil and plant tissues. Journal of the Association of Official Analytical Chemistry 63: 770-778.

Nelson, D.W. and L.E. Sommers, 1982. Total carbon, organic carbon, and organic matter. In: A.L. Page, R.H. Miller and D.R. Keeney (Eds), Methods of soil analysis. Part 2, Second edition. American Society of Agronomy, pp. 539-579.

Niangado, O., K. Touré, S. Traoré, M. Bagayoko, O. Katilé, A. Konaté, O. Coulibaly and M. N'Diaye. 1992. Comité de programme des cultures céréalières et légumineuses. Programme mil. Bamako, 13-17 Avril 1992, Mali.

Odum, H.T., 1994. Ecological and general systems, an introduction to systems ecology. Revised Edition, University Press of Colorado, USA, 644 pp.

Ogborn, J.E.A., 1987. *Striga* control under peasant farming conditions. In: L.J. Musselman (Ed.), Parasitic weeds in agriculture. Vol. 1. Striga. CRC Press, Boca Raton, FL, pp. 145-158.

Ogungbile, A.O., R. Tabo, N. van Duivenbooden and S.K. Debrah, 1998. Analysis of Constraints to agricultural production in the Sudan Savanna zone of Nigeria using multi-scale characterization. Neth. J. of Agric. Science 46: 27-38.

ORM (Office Riz Mopti), 2001. Bilan annuel de campagne agricole 2000/2001. ORM, Mopti, Mali.

Oxfori, F. and W.R. Stern, 1987. Cereal-legume intercropping systems. Adv. Agron. 41: 41-90.

Parkinson, V., 1985. *Striga*, serious threat to maize production in Africa and research being conducted at IITA. In: Proceedings of the OAU/FAO Workshop on *Striga,* 23-27 Sept. 1985, Yaoundé, Cameroon, pp. 47-57.

Parkan, J., 1986. Développement des ressources forestières, Burkina Faso: Bilan et évolution des disponibilités en bois, alternatives des productions forestières et actions sur la consommation, 1986-1995. Rapport de synthèse, Food and Agriculture Organization (FAO) of the United Nations, Rome.

Penning de Vries, F.W.T. and M.A. Djitèye (Eds), 1982. La production des pâturages sahéliens. Une étude des sols, des végétations et de l'exploitation de cette ressource naturelle. Agric. Res. Reports 918, Pudoc, Wageningen, The Netherlands, 525 pp.

Pesch, C.J. and A.H. Pieterse, 1982. Inhibition of germination in *Striga* by means of urea. Experimentia 38: 559-560.

Piéri, C., 1991. Les bases agronomiques de l'amélioration et du maintien de la fertilité des terres de Savanes au sud du Sahara. In: Savane d'Afrique terres fertiles? Actes des Rencontres Internationales, Montpellier, France, 10-14 décembre 1990. Ministère de la Cooperation Internationale en Recherche Agronomique pour le Dévelopment (CIRAD), France, pp. 43-73.

Piéri, C., 1985. Fertilisation des cultures vivrières et fertilité des sols en agriculture paysanne sub-saharienne: l'expérience de l'IRAT. In: H.W. Ohm and J.G. Naggy (Eds), Technologie appropriée pour les paysans des zones semi-arides de l'Afrique de l'Ouest. Purdue University, West Lafayette, Indiana, USA, pp. 254-278.

Piéri, C., 1986. Fertilisation des cultures vivrières et fertilité des sols en agriculture paysanne sub-saharienne. Agron. Trop. 41: 1-20.

Piéri, C., 1989. Fertilité des terre de savane. Bilan de trente ans de recherche et de développement agricoles au Sud du Sahara. Ministère de la Coopération/CIRAD, Paris, 444 pp.

Piéri, C., 1991. Les bases agronomiques de l'amélioration et du maintien de la fertilité des terres de Savanes au sud du Sahara. In: Savane d'Afrique terres fertiles? Actes des Rencontres Internationales, Montpellier, France, 10-14 décembre 1990. Ministère de la Cooperation Internationale en Recherche Agronomique pour le Dévelopment (CIRAD), France, pp 43-73.

PIRT (Projet Inventaire des Ressources Terrestres au Mali), 1983. Vol 1 Atlas. TAMS, for USAID and Government of Republic of Mali, Bamako, Mali.

PIRT (Projet Inventaire des Ressources Terrestres au Mali), 1989. Etude et cartographie actualisées des ressources terrestres et de l'utilisation actuelle des terres en zone ESPR. Sévaré, Mali, 92 pp.

PNVA (Programme National de Vulgarisation Agricole), 1997. Bilan de la campagne agricole 1996-1997 de la Coordination Régional de Mopti, Mali, 138 pp.

Poissonet, J. and J. César, 1972. Structure spécifique de la strate herbacée dans la savane à palmier ronier de Lamto, Cote d'Ivoire. Ann. Univers. d'Abidjan, Serie E 5: 577-601.

Prudencio, C.Y., 1993. Ring management of soils and crops in the West Africa semi-arid tropics: The case of the Mossi farming system in Burkina Faso. Agricultural, Ecosystems and Environment 47: 237-264.

Purseglove, J.W., 1975. Tropical crops: Monocotyledons. Second edition, Longman Group limited, London, 607 pp.

Quilfen, J.P. and P. Milleville, 1982. Résidus de culture et fumure animale: Un aspect des relations agriculture-élevage dans le Nord de la Haute-Volta. Agronomie Tropicale 39: 206-212.

Reddy, K.C., J. van der Ploeg and I. Maga, 1990. Genotype effects in millet/cowpea intercropping in semi-arid tropics of Niger. Exp. Agric. 26: 387-396.

Reddy, K.C., P. Visser and P. Buckner, 1992. Pear millet and cowpea yields in sole and intercrop systems, and their after-effects on soil and crop productivity. Field Crops Res. 28: 315-326.

Reenberg, A. and H.S. Marcussen (Eds), 1995. The Sahel, ethnobotany, agricultural and pastoralist strategies, Development aid strategies. Proc. of the 7th Danish Sahel Workshop, 4-6 January 1995. SEREIN Occasional Paper No 1, Univ. of Copenhagen, Denmark, 180 pp.

Riddell, J., 1986. Land tenure issues in West African livestock and range development projects. LTC Research paper, Land Tenure Center, University of Wisconsin, Madison, USA, 77 pp.

Robinson, D.M. and S.J. McKean, 1992. Shifting cultivation and alternatives: An annotated bibliography, 1972-1989. CAB International, Wallingord, 282 pp.

Roesch, M. and J. Pichot, 1985. Utilisation du phosphate naturel de Tahoua en fumure de fond et en fumure d'entretien dans les sols sableux du Niger. Agronomie Tropicale 40: 89-97.

Roose, E., J. Arrivets and J.F. Poulain, 1979. Dynamique actuelle des deux sols ferrugineux tropicaux indurés issus de granite sous sorgho et savane Soudano-Sahélienne, Saria 1971−1974, Burkina Faso, ORSTOM, Paris, 123 pp.

Ruthenberg, H., 1980. Farming systems in the tropics. Third edition, Clarendon Press, Oxford, UK, 424 pp.

Samaké, O. and N. van Duivenbooden, 1999. Alternate land use systems in the Sahel, West Africa: The case of Lagassagou, Mali. Management of Arid Ecosystem. Arid, India 42: 315-323.

Sauerborn, J., 1991. The economic importance of the phytoparasites *Orobanche* and *Striga*. In: J.K. Ransom, L.J. Musselman, A.D. Worsham and C. Parker (Eds), Proceedings, 5th International Symposium on Parasitic Weeds, Nairobi, 1991. CIMMYT, Nairobi, pp. 137-143.

Scherr, S.J., 1999. Soil degradation: A threat to developing-country food security by 2020. Food, Agriculture, and the Environment Discussion Paper No 27. International Food Policy Research Institute, Washington DC.

Sédogo, P.M., 1993. Evolution des sols ferrugineux lessivés sous culture: Incidence des modes de gestion sur la fertilité. PhD Thesis, University of Abidjan, Ivory Coast, 343 pp.

Seligman, N.G., H. van Keulen and C.J.T. Spitters, 1992. Weather, soil conditions and interannual variability of herbage productions and nutrient uptake on annual Mediterranean grasslands. Agric. Forest. Meteorology 57: 265-269.

Shetty, S.V.R., B. Keita, A. Coulibaly and I. Kassambara, 1987. Cultures associées au Mali. Progrès de la recherche agronomique. In: Proceeding of the Seminar on 'Les cultures Associées au Mali', Bamako 15-17 Sept. 1987. ICRISAT/IER, Mali, 31-51 pp.

Shetty, S.V.R., N.F. Beninati and S.R. Beckerman, 1991. Strengthening sorghum and pearl millet research in Mali. International Crops Research Institute for the Semi-Arid Tropics, Pantancheru, A.P. 502 324, India.

Shetty, S.V.R., N. van Duivenbooden, A. Bationo and M.V.K. Sivakumar, 1998. Stratégies agronomiques pour l'intensification des systèmes de productions au Sahel. In: H. Breman (Ed.), L'intensification agricole au Sahel: Mythe ou réalité? Karthala, Paris.

Sissoko, K., 1999. Et demain l'agriculture? Option technique et mesures politiques pour un développement agricole durable en Afrique subsaharienne. Cas du Cercle de Koutiala. Doc. Sur la Gestion des Ressources Tropicales No 23. Thèse du Doctorat présenté à l'Université de Wageningen aux Pays-Bas, 184 pp.

Sivakumar, M.V.K., 1989. Drought spells frequencies in West Africa. Research Bulletin No 13. ICRISAT, Patancheru, India, 340 pp.

Sivakumar, M.V.K. and J.L. Hatfield, 1990. Spatial variability of rainfall at an experimental station in Niger, West Africa. Theoretical Applied Climatology 42: 33-39.

Sivakumar, M.V.K. and J.B. Wills (Eds), 1995. Combating land degradation in sub-Saharan Africa: Summary. Proceedings of the International Planning Workshop for a Desert Margins Initiative, 23-26 January 1995, Nairobi, Kenya. Patacheru

502324, Andhra Pradesh, India.

Sivakumar, M.V.K, A. Maidoukia and R.D. Stern, 1993. Agrometeorology of West Africa: Niger. ICRISAT Informat. Bulletin No 5. ICRISAT, Patencheru, Andhra Pradesh 502 324, India, 108 pp.

Smaling, E.M.A. (Ed.), 1998. Nutrient balances as indicators of productivity and sustainability in sub-Saharan African agriculture. Agric. Ecos. Envir.71 (1,2,3), 283 pp.

Smaling, E.M.A. and B.H. Janssen, 1993. Calibration of QUEFTS, a model predicting nutrient uptake and yields from chemical soil fertility indices. Geoderma 59: 21-44.

Smaling, E.M.A. and C. Toulmin, 2000. The itinerary of soil nutrients in Africa: Destination anywhere? Outlook on agriculture 29: 193-200.

Smaling, E.M.A., A. Stein and P.H.M. Sloot, 1991. A statistical analysis of the influence of *Striga hermonthica* on maize yields in fertilizer trials in Southwestern Kenya. Plant and Soil 138: 1-8.

Smaling, E.M.A., J.J. Stoorvogel and A. de Jager, 2002. Decision making on integrated nutrient management through the eyes of the scientist, the land-user and the policy maker. In: B. Van Lauwe, J. Diels, J. Sanginga and R. Merckx (Eds), Integrated plant nutrient management in sub-Saharan Africa: from concept to practice. CAB International, Wallingford, Oxon, UK.

Spencer, D.S.C. and M.V.K Sivakumar, 1987. Pearl millet in African agriculture. Proceedings of the International Pearl Millet Workshop, 7-11 April 1986. ICRISAT Center, India, Patancheru, India.

Ssali, H. and S.O. Keya, 1986. The effects of phosphorus and nitrogen fertilizer level on nodulation, growth and di-nitrogen fixation on three bean cultivars. Trop. Agric. 63: 105-109.

Stein, A., J. Brouwer and J. Bouma, 1997. Methods of comparing spatial variability patterns of millet and soil data. Soil Sci. Soc. of Amer. J. 63: 861-870.

Stern, W.R., 1993. Nitrogen fixation and transfer in intercrop systems. Field Crops Res. 34: 335-356.

Stomph, T.J., L.O. Fresco and H. van Keulen, 1994. Land use system evaluation; concept and methodology. Agric. Systems 44: 243-245.

Stoorvogel, J.J. and E.M.A. Smaling, 1990a. Assessment of nutrient depletion in sub-saharan Africa: 1983-2000. Vol. I. Main report. 2nd Ed., Report No. 28, the Winand Staring Centre for Integrated Land Soil and Water Research SC-DLO, Wageningen, The Netherlands.

Stoorvogel, J.J. and E.M.A. Smaling, 1990b. Assessment of nutrient depletion in sub-saharan Africa: 1983-2000. Vol. III. Literature review and description of land use systems. 2nd Ed., Report No. 28, the Winand Staring Centre for Integrated Land.

Soil and Water Research, Wageningen, The Netherlands.

Stoorvogel, J.J., E.M.A. Smaling and B.H. Janssen, 1993. Calculating soil nutrient balances in Africa at different scales. I. Supra-national scale. Fert. Res. 35: 227-235.

Swinkels, R.A., S. Franzel, K.D. Shepherd, E. Ohlsson and J.K. Ndufa, 1997. The economics of short rotation improved fallows: Evidence from areas of high population density in western Kenya. Agric. Systems 55: 99-121.

Tarawali, R., M.A. von Kaufman and M. Saleem, 1992. The role of livestock-based cropping systems for developing sustainable food production in the sub-Saharan Africa. In: T. Bezeneh, M. Kamuaanaga, T. Kibrah and J.O. Olukosi (Eds), SAFGRAD. Ouagadougou, Burkina Faso.

Témé, B., H. Breman and K. Sissoko, 1995. Intensification agricole au Sahel: Mythe ou réalité? Rapport de synthèse du colloque international sur l'intensification agricole au Sahel; Bamako (Mali), Déc. 1995, 28 pp.

Tessougué M., P.C. Trench and P. Woodhouse, 1998. Terre, eau et administration locale au Mali: La riziculture et gestion des ressources naturelles dans la vallée du Sourou, Cercle de Bankass. Mopti, Mali, 141 pp.

Thenkabail, P.S. and C. Nolte, 1995. Mapping and characterizing inland valley agro-ecosystems of West and Central Africa. A methodology integrating Remote Sensing, Global Positioning Systems, and Ground-truth data in a Geographic Information Systems framework. RCP Research Monograph 16, Ibadan, Nigeria, International Institute of Tropical Agriculture, 52 pp.

Thibout, F., Traoré, M.F., Piéri, C., Pichot, J., 1980. Utilisation agricole des phosphates naturels de Tilemsi (Mali). Synthèse des résultats de la recherche agronomique sur les cultures vivrières et oléagineuses. Agronomie Tropicale 35: 240-249.

Thomas, G.W., 1982. Exchangeable cations. In: A.L. Page, R.H. Miller and D.R. Keeney (Eds), Methods of soil analysis, Part 2. Second edition, American Society of Agronomy, pp. 159-164.

Traoré, H. and O. Quédraogo, 1996. Research activities into integrated *Striga* management of pearl millet and sorghum in Burkina Faso - 1990 to 1995. Report on the ICRISAT Sector Review for *Striga* Control in Sorghum and Pearl millet. 27-28 May 1996, ICRISAT-Bamako, Mal, pp. 89-94.

Trenbath, B.R., 1993. Intercropping for the management of pest and diseases. Field Crop Research 34: 381-405.

Turco, R.F., M. Bischoff, D.P. Breakwell and D.R. Griffith, 1990. Contribution of soil-born bacteria to the rotation effect in corn. Plant and Soil 122: 115-120.

van Ast, A., L. Bastiaans, Z.J.L. Sanogo, A.H. Pieterse and M.J. Kropff, 2003. Longevity of *Striga hermonthica* seed under field and laboratory conditions (in

preparation).
van Duivenbooden, N., 1992. Suistainability in terms of nutrient elements with special reference to West Africa. Report 160 CABO-DLO, Wageningen, The Netherlands, 261 pp. (and annexes)
van Duivenbooden, N., 1993. Impact of inorganic fertilizer availability on land use and agricultural production in the Fifth Region of Mali. II. Scenario definition and results. Fertilizer Research 35: 205-216.
van Duivenbooden, N., 1997. Exploitation de la variabilité multi-échelle des sytèmes d'utilisation des terres afin d'améliorer la gestion des ressources naturelles dans la zone soudano-sahélienne de l'Afrique de l'Ouest (MUSCLUS). Méthodologie et Plan de Travail. Integrated Systems Project. Report Series No 2. Niamey, Niger, ICRISAT Centre Sahélien.
van Duivenbooden, N. and F.R. Veeneklaas, 1993. Impact of inorganic fertilizer availability on land use and agricultural production in the fifth region of Mali. Fertilizer Res. 35: 193-204.
van Duivenbooden, N. and L. Cissé, 1993. Fertilization of millet cv. Souna III in Senegal: Dry matter production and nutrient uptake. Fertilizer Res. 35: 217-226.
van Duivenbooden, N. and P.N. Windmeijer, 1995. Manual for semi-detailed characterization of inland valley agro-ecosystems. Characterization of rice-growing environments in West Africa. Technical Report No 4. Wageningen, The Netherlands, SC-DLO, 85 pp.
van der Pol, F., 1992. Soil mining: An unseen contributor for farm income in southern Mali. Bull. 325, Royal Tropical Institute, Amsterdam, The Netherlands, 47 pp.
van der Pol, F., 1993. Etude sur la relation entre pratique d'amélioration des sols et variables socio-économiques dans la zone Mali-Sud. CMDT/KIT/IER, 26 pp.
van Reuler, H. and B.H. Jansen, 1989. Nutrient constraints in secondary vegetation and upland rice in southwest Ivory Coast. In: J.H. Proctor (Ed.), Mineral nutrients in tropical forest and Savanna ecosystems. Special publication No 9 of the British Ecological Society, Blackwell Scientific publications, Oxford, England, pp. 71-382.
van Reuler, H. and W.H. Prins, 1993. The role of plant nutrients for sustainable food crop production in sub-Saharan Africa. Vereniging van Kunstmest Producenten, Leidschendam, The Netherlands, 259 pp.
Veeneklaas, F.R., S. Cissé, P.A. Gosseye, N. van Duivenbooden and H. van Keulen, 1990. Compétition pour des ressources limitées: Le cas de la cinquième région du Mali. Scenarios de Developpement. Rapport 4. CABO/ESPR, Wageningen, Pays-Bas, 182 pp.
Veeneklaas, F.R., S. Cissé, P.A. Gosseye, N. van Duivenbooden and H. van Keulen, 1990. Compétition pour des ressources limitées: Le cas de la cinquième région du

Mali. Rapport No 4. Scénarios de développement. Mopti. CABO-DLO, Wageningen, 180 pp.

Windmeijer, P.N. and W. Andriesse (Eds), 1993. Inland valleys in West Africa. An agro-ecological characterization of rice growing environments. Publication 52. International Institute for Land Reclamation and Improvement, Wageningen, The Netherlands, 160 pp.

World Bank, 1984. Toward sustained development in Sub-Saharan Africa. World Bank, Washington DC, USA.

World Bank, 1992. Annual report. World Bank, Washington DC, USA.

World Bank, 1984. Toward sustained development in sub-Saharan Africa. World Bank, Washington DC, USA.

Wortmann, C.S. and C.K. Kaizzi, 1998. Annual soil improving legumes: Agronomic effectiveness, nutrient uptake, nitrogen fixation and water use. Agric. Ecosys. and Environ. 71: 115-129.

Yamoah, C.F., A. Bationo, B. Shapiro and S. Koala, 2002. Trend and stability analyses of millet yields treated with fertilizer and crop residues in the Sahel. Field Crops Res. 75: 53-62.

Yossi, H., 1998. Utilisation optimale des ligneux à usages multiples pour l'amélioration des jachères au Mali. Rapport de recherche, IVème session du Comité de Programme, 5-19 Octobre 1998, IER, Bamako, Mali, 38 pp.

Young, A., 1989. Agroforestry for soil conservation. CAB International, Wallingford and ICRAF, Nairobi.

Summary

The agricultural sector in the Sahelian zone of West Africa is mainly based on subsistence rainfed cereal (sorghum and millet) cropping often associated with animal husbandry. In the driest zones, pearl millet (*Pennisetum glaucum* (L.) R. Br.) is the most important rainfed staple crop. As a result of increasing population pressure in the Sahel of West Africa in the past decades, the cultivated area has been increasing. At the same time crop yield per hectare hardly increased and remained at a very low level in most countries. This pressure on land has led to shorter fallow periods and continuous cereal cropping systems without or with few external inputs. Application of inorganic fertilizers is constrained by lack of access to capital while the use of organic inputs is limited by their low availability. This results in declining soil fertility and increased weed infestation. The main limitations to crop production are the low soil fertility, the variable and low rainfall levels and the parasitic weed *Striga* in many major crops. The aim of this study was to increase our understanding of the millet-based cropping systems in the Sahelian zone of Mali by identifying constraints and to search for intervention points to make millet cropping systems more productive and sustainable.

In this study, it was shown that indeed decreasing fertility is a crucial factor in the bush areas of the villages where no fertilizers or manure are applied. Increasing grain production in these low-input farming systems must be based on improved soil and crop management technologies that impact on the nutrient stocks and flows, on natural nutrient accumulation in short-term fallows, and on ways to reduce the yield-limiting effect of the parasitic weed *Striga hermonthica*. The research programme consisted of two parts: (*i*) analysis of the millet-cropping system at the macro/region, meso/zone and the micro/village scale and (*ii*) experimental analyses of different integrated management strategies for millet-based cropping systems with variable fallow periods, rotations and intercrops with legumes and the use of fertilizers.

The multi-scale characterization (Chapter 2) was conducted to determine opportunities and major constraints to millet production at the regional, district and village level in the Fifth Region of Mali. For the first two levels mainly secondary data were used, while at the village level additional data were collected. Field surveys were conducted to explore variation in yield and soil fertility between village territories and within the villages. The multi-scale analysis covered different administrative scale levels in the Fifth Region of Mali using the Bankass district within the region, with emphasis on the Séno-Bankass zone and Lagassagou village within the district. At each level, constraints to millet-based production systems were identified. The major

constraint identified at the regional level is the distance to major markets and the lack of an agro-industry related to products from millet-based production systems. The low and erratic rainfall is a characteristic of the agro-ecological zone but this major limitation at the district level is beyond control. At the village level, soil poverty and *Striga* infestation in large parts of the village territory are the major limiting factors for improved millet productivity. Diversification into cash crops is not an issue as long as markets and processing facilities are not available at the district or regional level.

On the basis of this study, a quantitative analysis of millet-based cropping systems was made in the district to determine spatial variation of fertility, *Striga* infestation and millet yield between and within village territories (Chapter 3). Results showed that homefields (< 200 m from the edge of the compounds) were more fertile than bushfields (> 200 m) because of application of (small amounts of) fertilizers and manure and animal penning around the village. The reasons for this type of localised application were the low amounts of manure produced and the lack of transport means to carry organic fertilizer further away. Millet grain yield and *Striga* infestation were consistent with these gradients along a transect from the border of the village to the center of the village. Yields increased from 520 kg ha^{-1} in bushfield to 1060 kg ha^{-1} in homefields and *Striga* infestation decreased from 11,800 plants ha^{-1} in bushfields to 2,000 plants ha^{-1} in homefields. Regression analysis showed that millet yield was negatively correlated with *Striga* infestation and positively with soil fertility.

In a 4-years study from 1998 to 2001, different integrated crop management systems for millet-based cropping systems in West Africa were evaluated (Chapters 4 and 5). The experiment was conducted on a sandy soil in the village Lagassagou in northern Mali using a factorial split-plot design with as main plot treatments four fallow periods (0, 2, 5, and 7 years). Sub-plot treatments were three cropping systems: (1) continuous cultivation of millet from 1998 to 2001, (2) cowpea in 1998 followed by three years of a millet crop and (3) cowpea in 1998 followed by three years of a millet/cowpea intercrop. Chapter 4 describes the results of the treatments without fertilizers and Chapter 5 describes the results of different P fertilizers on the performance of the cropping systems as described in Chapter 4.

Without additional fertilizers, the cowpea crop that was grown in 1998 had a positive effect on subsequent millet yield and on soil nitrogen levels (Chapter 4). Soil C levels remained higher after growing cowpea in 1998 in several treatments than after growing millet in 1998. An increased fallow length had a positive effect on millet grain yield varying on average from 300 kg ha^{-1} with continuous millet to 450–470 kg ha^{-1} with 2–7 years fallow. Growing a cowpea crop in 1998 reduced infestation of millet with the parasitic weed *Striga hermonthica* in 1999 but this effect could not be detected anymore in 2001 in millet monoculture. In the mixed cropping system, a

reduction of *Striga hermonthica* was observed in 2001. A longer fallow period reduced the infestation of the fields by *S. hermonthica* more strongly, both in 1999 and 2001.

In the treatments with P fertilizers (Chapter 5), the grain legume cowpea, grown in 1998, had a positive effect on subsequent millet yield and on soil N levels in the first year after the cowpea crop but not in subsequent years. The addition of P fertilizer enhanced yields strongly in all treatments. This effect was independent of the use of cowpea in rotation or as an intercrop and of the duration of the fallow period. Only in 2001 an interaction between fallow duration and P fertilizer was observed. An annual application of 100 kg ha^{-1} TSP (triple super phosphate) resulted in comparable yields to those obtained after a one time application of 300 kg ha^{-1} of TRP (Tilemsi Rock Phosphate) followed by an annual application of 100 kg ha^{-1}. Both these treatments were superior to a one-time application of 300 kg ha^{-1} of TRP. Application of P resulted in maintenance of soil organic C content during years of cultivation whereas soil N content and *Striga* infestation were not affected by P fertilizer application.

P fertilizer in a continuous monoculture of millet has a similar effect on yield as introducing a fallow period of up to 7 years in a non fertilized plot and a stronger effect than the inclusion of cowpea in rotation or as an intercrop without fertilizer. The combination of P fertilizer, fallow and cowpea in the cropping system could even boost yield from 250 kg ha^{-1} to a level of 1200 kg ha^{-1} in bushfields in 2001. This is comparable to the yields in manured homefields.

The relationships between soil fertility, fertilizer application, nutrient uptake and grain yields were assessed using the model QUEFTS (Quantitative Evaluation of the Fertility of Tropical Soils) in Chapter 6. The model shows that total N, P-Bray and exchangeable K are able to explain a substantial part of the potential supply of N, P and K to millet plants. Adding other soil test values did not increase the percentage explanation of potential supplies. Nitrogen (N) and phosphorus (P) recovery fractions from the fertilizers were 73 and 17%, respectively. Yield ranges were obtained from the relationship between N, P and K contents in the aboveground plant components and millet grain yield. The correlation between measured and calculated yields showed that on average yields in homefields corresponded very well. However, individual data points showed large deviations. Comparison of measured and calculated millet yields in *Striga* infested bushfields showed a yield gap of 39%. The model should be operationalized in agricultural research services and laboratories. But, sound validation requiring inputs parameters from other millet cropping environments are needed to improve its predictive value for a wider range of environments.

In Chapter 7, all the results in the previous Chapters are integrated and further discussed. In this study, the main focus was to evaluate the combined effects of cropping systems on the basis of identified constraints and to develop a decision support tool to evaluate and scale up the relationship between fertility parameters, nutrient uptake and millet grain yield. The main results revealed that, as land is becoming scarce, cowpea as a legume crop in rotation with millet could replace short (2 years) fallow as a means to improve grain yields in environments similar to the Séno-Bankass zone. Including a millet/cowpea intercrop in the rotation system will further minimize food security risk in years with poor rainfall. The sustainability and productivity of the system will be increased by the use of P fertilizers, or, in the absence of biologically-fixed nitrogen, the combined use of N and P fertilizers. The latter may even be profitable if farmers could sell surplus produce during the food scarcity period. For this to become reality though, farm gate prices of inputs and outputs should be known by farmers and made more attractive to enable them to change their practices of soil mining and to invest in the long-term fertility of their soils. This, however, can hardly succeed without targeted policy intervention at higher levels of organization (e.g., government, donors, national and international financial institutions).

Résumé

La pression démographique dans le Sahel de l'Afrique de l'Ouest a considérablement réduit la durée des jachères et remplacé ce système mil-jachère dans certaines localités, par des cultures continues des céréales avec peu ou sans apport d'intrants. L'utilisation d'intrants chimiques est restreinte par leur prix et l'utilisation des amendements organiques est limitée par leurs faible disponibilité. Cette pratique, a contribuée, à son tour, à la baisse de la fertilité des sols, à la prolifération des adventices (par exemple *Striga hermonthica*) et à la baisse des rendements des cultures. Ainsi les principales contraintes sont la pauvre fertilité du sol, la faible pluviométrie et la présence de *Striga*. Cette étude a pour objective d'améliorer la compréhension du système de culture à base du mil dans la zone sahélien du Mali à travers l'identification des contraintes et la recherche des points d'intervention en vue de pouvoir rendre le système plus productive et plus durable. Cette étude a été entièrement centrée sur le système de culture à base du mil (*Pennisetum glaucum* (L.) R. Br.). L'amélioration à long terme de la productivité de ce système, demande d'intégrer un ensemble de méthodes culturales incluant la gestion du sol et des cultures et leur impact sur la fertilité du sol, sur l'accumulation des nutriments pendant des jachères de courte durée, et la réduction de l'effet de *Striga* sur le rendement du mil. La recherche se décompose en deux parties. Premièrement, une caractérisation multi-échelle a été conduite pour déterminer les principales opportunités et contraintes de production du mil au niveau de la région, du district et du village. Une telle analyse a été nécessaire pour mieux comprendre le système en vue de développer et proposer des techniques de production durable. Deuxièmement, des études de terrain ont été menées, pour déterminer les causes de la variabilité spatiale des rendements des cultures et de la fertilité des sols entre les champs du terroir villageois. Une attention particulière a été accordée à l'évaluation de l'effet des différentes techniques culturales et de la mise en place des jachères, sur les rendements, la fertilité des sols et la présence de *Striga hermonthica*.

Dans le Chapitre 2, l'analyse multi-échelle des systèmes de production a couvert les unités administratives à différents niveaux d'échelle dans la Cinquième Région du Mali. La zone agro-écologique du Séno-Bankass a été choisie pour la caractérisation à l'échelle régionale, le district de Bankass pour l'analyse à l'échelle du district et le village de Lagassagou pour la caractérisation au niveau du village. A chaque échelle, des contraintes de la production du mil ont été identifiées. A l'échelle de la région et du district, l'insuffisance de budgets d'investissement pour des infrastructures (routes, agro-industries), l'absence des marchés et de subvention (intrants, équipements) provoquent l'augmentation des prix des intrants et la réduction des prix des productions agricoles pour les producteurs par rapport aux prix pratiquées dans les centres urbains. Le faible niveau de la fertilité des sols et l'infestation accrue des champs par *Striga* réduisent la production du mil au niveau village entraînant des problèmes de sécurité alimentaire dans le district et la région. Une possible diversification et l'introduction des cultures de rentes n'apporteraient pas d'opportunités nouvelles tant qu'il n'y a pas de marchés ni des industries de transformation au niveau de la région ou du district.

Les résultats des études menées dans le District de Bankass (Chapitre 3) sur la base des contraintes identifiées, ont montrés que les champs de case (10–200 m à partir de la limite des concessions) sont beaucoup plus fertiles que les champs de brousse (> 500 m). Ceci est du à l'apport des fumures organiques et au parcage des animaux à proximité du village. Les raisons d'une telle pratique d'application localisée des fumures, sont surtout leur faible disponibilité et le manque de moyen pour transporter les fumiers produits loin du village. La production du mil et l'infestation du *Striga* varient en fonction de ces gradients de fertilité avec une augmentation de rendements grain de mil de 520 kg ha^{-1} dans les champs de brousse à 1060 kg ha^{-1} dans les champs de case, et une diminution du nombre de *Striga* de 11800 plantes ha^{-1} dans les champs de brousse à 2000 plantes ha^{-1} dans les champs de case. La régression statistique effectuée a montrée, que la corrélation entre le rendement de mil et l'infestation du *Striga* était négative alors qu'entre le rendement et la fertilité du sol celle-ci était positive. Ceci semble indiquer que l'infestation due à *Striga* et le manque de la fertilité des sols sont liés.

Dans les chapitres 4 et 5, une série d'options pour une gestion intégrée de la fertilité des sols et de *Striga hermonthica* a été testée au cours de quatre années d'expérimentation (1998–2001). L'expérimentation a été conduite sur un sol sableux à Lagassagou comme 'split-plot'. Les traitements principaux étaient quatre périodes de jachères (0, 2, 5 et 7 ans). Les sous-traitements étaient trois systèmes culturaux: (1) mil pure continu 1998-2001, (2) niébé 1998, suivi par trois années de mil pur, (3) niébé 1998, suivi par trois années d'association mil-niébé.

Les résultats ont montré que les systèmes de cultures ont un effet significatif sur le rendement du mil. La culture du niébé en rotation avec le mil, sans apport de fumure (Chapitre 4), améliore le rendement grain du mil et le niveau d'azote du sol seulement à la première année de rotation et maintient le niveau du carbone organique contenu dans le sol pendant trois ans.

Une augmentation de la durée de la jachère a amélioré le rendement de mil de 300 kg ha^{-1} en moyenne en système de mil pur et continu à 450–470 kg ha^{-1} avec 2–7 ans de jachère. Les deux systèmes de cultures (mil pur ou mil/niébé en rotation avec le niébé) réduisent l'infestation du *Striga* par rapport à la culture continue du mil seulement la première année (1999), bien qu'une tendance à la baisse du nombre de *Striga* ait été constatée avec l'association mil/niébé lors de la troisième année (2001).

Des jachères des longues durées ont eu un impact plus important sur la présence de *Striga*, en 1999 et aussi en 2001. Augmenter la durée des jachères à 7 ans réduit davantage le nombre de *Striga,* spécialement dans les années où le niveau d'infestation est plus élevé.

L'application de la fumure phosphatée entraîne une augmentation du rendement moyen du mil, indépendamment de l'incorporation du niébé en rotation ou association et de la durée de la jachère (Chapitre 5). Quand le niébé a été cultivé en 1998 avec la fumure phosphatée, le rendement du mil et le niveau d'azote dans le sol ont été positivement influencé pendant la première année après application mais pas dans les années suivantes. L'application annuelle de 100 kg ha^{-1} de superphosphate triple (TSP) pendant trois années, a un effet positif sur les rendements et il est comparable à celui d'une dose de 300 kg ha^{-1} de phosphate naturel de Tilemsi (TRP) la première année suivi par une dose annuel de 100 kg ha^{-1} de TRP. La dose unique de 300 kg ha^{-1} de TRP a donné un résultat inférieur. Ceci indique que la dose de 300 kg ha^{-1} de TRP, apportée une seule fois, semble ne pas être suffisante pour assurer une productivité durable du système de culture à base du mil. L'application de la fumure phosphatée entraîne une augmentation du rendement du mil et du niveau de carbone organique du sol sans avoir des effets notoires sur la teneur en azote et l'infestation par *Striga*. L'application de fumure phosphatée dans une culture de mil pure et continue a permis une augmentation du rendement similaire à celle obtenue après 7 ans de jachère et supérieur à celle obtenue lors de l'addition de niébé en association ou en rotation. La combinaison de fertilisation avec P, jachère et niébé dans le système de culture a montré la possibilité d'augmenter le rendement de 250 kg ha^{-1} à 1200 kg ha^{-1} dans les champs de brousse (2001). Ce rendement est comparable à celui dans les champs de case.

Dans le Chapitre 6, les relations entre la fertilité du sol, le recouvrement des éléments nutritifs apportés par l'application des fumures et le rendement du mil ont été évaluées avec le model QUEFTS (Evaluation Quantitative de la Fertilité des Sols Tropicaux). Le model a indiqué que l'azote (N) total, le phosphore assimilable (P-BrayI) et le potassium échangeable (K) sont capables d'expliquer une part substantielle de l'offre potentiel de N, P et K au mil. L'addition d'autres paramètres du sols n'a pas permis d'améliorer l'explication. Les fractions de recouvrement de N et P à partir des fumures appliquées ont été respectivement de 73 et 17%. La relation entre les rendements observés et calculés est forte pour les rendements du mil dans les champs de case. Néanmoins les points individuels montraient une grande déviation (écart).

L'écart entre rendements observés et calculés dans les champs de brousse infestés par *Striga* à été de125 kg ha^{-1} (39 %) et a été attribué à l'infestation par *Striga.* Toutefois, une validation du model avec des paramètres provenant de plusieurs autres localités adaptées à la culture du mil, sont nécessaires pour améliorer sa valeur prédictive à grande échelle.

Tous les résultats présentés dans les Chapitres précédents ont été intégrés et discutés davantage dans le Chapitre 7. L'objectif global était d'évaluer les effets combinés des systèmes de cultures sur la base des contraintes identifiées et de développer un outil d'aide à la décision pour évaluer et extrapoler les résultats à d'autres environnements similaires et plus larges. Les résultats ont montré que la culture pure du niébé en rotation avec le mil peut remplacer les jachères de 2 ans dans les conditions similaires de celles du Séno-Bankass. L'association mil/niébé dans le système, permet d'accroître le rendement global et minimiser le risque d'échec des cultures dans les années de mauvaise pluviométrie. La durabilité du système peut être davantage assurée par l'apport de fumure phosphatée ou, en absence de fixation biologique d'azote atmosphérique, par l'apport d'une combinaison de N et P. La dernière option peut être bénéfique quand le paysan peut vendre le surplus produit pendant les périodes de manque de la nourriture. Une telle pratique n'est possible qu'avec des mesures politiques incitatrices des prix des intrants et des produits agricoles en faveurs des producteurs. Les prix des intrants et des produits agricoles au niveau des exploitations doivent être connus et incitatifs pour pouvoir motiver les paysans à atténuer les contraintes évoquées notamment par des investissements dans la fertilité de leurs sols. Une politique d'intervention des autorités à l'échelle nationale et régionale dans ce domaine est nécessaire.

Samenvatting

De landbouw in de West Afrikaanse Sahel is grotendeels gebaseerd op de regen-afhankelijke zelfvoorzieningsverbouw van graangewassen (sorghum en parelgierst) die meestal wordt gecombineerd met veeteelt. In de droogste zones is parelgierst het belangrijkste hoofdvoedselgewas. Door de toenemende bevolkingsdruk in de afgelopen decennia is de productie van voedsel toegenomen door een toename van het landbouwareaal. De gewasopbrengst per hectare is echter op een uiterst laag niveau gebleven en in bijna alle landen in de Sahelzone nauwelijks gestegen. De intensivering van het grondgebruik heeft geleid tot een verkorting van de braakperiode en tot de permanente teelt van graangewassen waarbij geen of slechts zeer geringe hoeveelheden externe inputs zoals meststoffen worden gebruikt. Het gebruik van kunstmest is extreem laag door het gebrek aan financiële middelen, en het gebruik van organische meststoffen is beperkt vanwege de kleine hoeveelheden die beschikbaar zijn. Dit heeft geresulteerd in een afnemende bodemvruchtbaarheid en een toenemende onkruiddruk. De belangrijkste groeibeperkende factoren voor de gewassen zijn de lage bodemvruchtbaarheid, de hoeveelheid en variabiliteit van de regenval en het parasitaire onkruid *Striga hermonthica*. Het doel van deze studie is inzicht verkrijgen in het functioneren van teeltsystemen met parelgierst als hoofdgewas, door vast te stellen wat de belangrijkste beperkende factoren zijn, en door te zoeken naar mogelijkheden om deze teeltsystemen productiever en duurzamer maken.

Uit deze studie blijkt dat de afnemende bodemvruchtbaarheid de grootste beperkende factor is voor de gewasgroei in de verder van het dorp gelegen percelen waar geen organische mest of kunstmest wordt toegepast. Een toename in graanproductie in deze systemen is alleen mogelijk als er technieken voor bodem- en gewasmanagement worden ontwikkeld die de natuurlijke toename van de bodemvruchtbaarheid tijdens de korte braakperiode verhogen, en die opbrengstverliezen door het parasitaire onkruid *Striga hermonthica* beperken. Het onderzoeksprogramma is opgebouwd uit twee onderdelen: (*i*) inventarisatie en analyse van parelgierstteeltsystemen op regioniveau (macroschaal), op het niveau van de agro-ecologische zone (mesoschaal) en op dorpsniveau (microschaal) en (*ii*) experimentele analyse van verschillende geïntegreerde strategieën voor de teelt van parelgierst als hoofdgewas. Daarin werden de effecten van de duur van de braakperiode, de gewasrotatie, het telen in monocultuur of in mengteelt met vlinderbloemigen en met of zonder gebruik van kunstmest geanalyseerd.

De giersteeltsystemen in de Vijfde Regio in Mali zijn beschreven in Hoofstuk 2 op verschillende schaalniveaus: de regio zelf, het district Bankass met nadruk op de Séno-

Bankass zone en het dorp Lagassagou. Voor elk van de drie niveaus, regio-, districts- en dorpsniveau, zijn de mogelijkheden van en de belangrijkste beperkingen voor de gierstproductie vastgesteld. Voor de eerste twee niveaus zijn voornamelijk bestaande gegevens gebruikt. Voor de beschrijving op dorpsniveau zijn er aanvullende gegevens verzameld. Veldstudies zijn uitgevoerd om de variatie in opbrengst, bodem-vruchtbaarheid en *Striga*-dichtheid tussen dorpen en binnen dorpen in kaart te brengen. De afstand tussen productiegebieden en markt en het ontbreken van een verwerkings-industrie voor landbouwproducten van de gierstteeltsystemen werden als belangrijkste knelpunten op regionaal niveau geïdentificeerd. De lage en onzekere regenval is een kenmerk van de agro-ecologische zone maar deze factor is op districtsniveau niet beïnvloedbaar. Op dorpsniveau zijn de lage bodemvruchtbaarheid en de hoge aan-tasting van de gewassen met *Striga* de belangrijkste knelpunten. Uitbreiding van het teeltsysteem met een handelsgewas is geen oplossing zolang markten en verwerkings-mogelijkheden uitblijven op regio- en districtsniveau.

Een kwantitatieve analyse van de teeltsystemen in het district is uitgevoerd om de ruimtelijke variatie in bodemvruchtbaarheid, *Striga*-dichtheid en gierstopbrengst binnen en tussen dorpen vast te stellen (Hoofdstuk 3). Percelen die dicht bij het dorp liggen (< 200 m verwijderd van de dichtstbijzijnde huizen) zijn vruchtbaarder dan verder verwijderde percelen (> 200 m). Dit is het gevolg van het gebruik van (kleine hoeveelheden) kunstmest en organische mestgebruik op percelen rond het dorp en het laten overnachten van beesten op deze percelen. Reden voor dit zeer lokaal toedienen van organische mest is de beperkte hoeveelheid die geproduceerd wordt in elk dorp en het gebrek aan vervoersmiddelen waarmee organische mest verderop kan worden verspreid. De opbrengst van gierst en de *Striga*-dichtheid waren sterk gecorreleerd met de vruchtbaarheidsgradiënt langs een transect van de dorpskern naar de rand van het dorpsgebied. Opbrengsten namen toe van 520 kg ha^{-1} in de ver verwijderde percelen tot 1060 kg ha^{-1} in de percelen direct rond het dorp en de *Striga*-dichtheid nam af van 11800 planten ha^{-1} in de verder verwijderde percelen tot 2000 planten ha^{-1} in de percelen direct rond het dorp. Uit regressieanalyse bleek dat de gierstopbrengst negatief gecorreleerd was met *Striga*-dichtheid en positief gecorreleerd was met de bodemvruchtbaarheid.

In een vierjarig experiment (van 1998 tot en met 2001) zijn verschillende geïntegreerde teeltsystemen met gierst als hoofdgewas geëvalueerd (Hoofdstukken 4 en 5). De proef is als een factoriële blokkenproef uitgevoerd op een diepe zandbodem in het dorp Lagassagou in noord Mali met als hoofdfactor vier braakperiodes (0, 2, 5 en 7 jaar). Sub-factoren waren drie teeltsystemen: (1) teelt van gierst tussen 1998 en 2001, (2) *Vigna unguiculata* (L.) (cowpea) in 1998 gevolgd door drie jaar gierst en (3) *V. unguiculata* in 1998 gevolgd door drie jaar mengteelt van gierst en *V. unguiculata*.

In Hoofdstuk 4 zijn de resultaten gegeven van de behandelingen zonder kunstmest en in Hoofdstuk 5 zijn deze resultaten vergeleken met die van dezelfde behandelingen uitgevoerd bij een drietal fosfaatbehandelingen. Deze behandelingen waren: (*i*) 300 kg ha^{-1} rotsfosfaat toegediend in 1998 als éénmalige dosis, (*ii*) 300 kg ha^{-1} rotsfosfaat toegediend in 1998 als éénmalige dosis gevolgd door een jaarlijkse dosis van 100 kg ha^{-1} van hetzelfde rotsfosfaat tussen 1999 en 2001 en (*iii*) geen bemesting in 1998 gevolgd door een jaarlijkse bemesting met 100 kg ha^{-1} supertriplefosfaat tussen 1999 en 2001.

Zonder toevoeging van bemesting had de in 1998 verbouwde *V. unguiculata* een positief effect op de opbrengst van het erop volgende gierstgewas en op het stikstofniveau in de bodem (Hoofdstuk 4). In diverse behandelingen bleef het C niveau in de bodem op een hoger niveau na de teelt van *V. unguiculata* in 1998 dan na verbouw van gierst in 1998. Een langere braakperiode had een positief effect op de gierstopbrengst, deze liep op van 300 kg ha^{-1} in de behandeling zonder braak tot 450–470 kg ha^{-1} na 2–7 jaar braak. De teelt van *V. unguiculata* in 1998 verminderde de aantasting door *Striga* in 1999, maar dit effect was niet langer meetbaar in 2001 in de gierst monocultuur. In het in mengteelt verbouwde gierst/*V. unguiculata* gewas was de *Striga* aantasting lager in 2001. Een langere braakperiode verminderde de aantasting met *Striga hermonthica* zowel in 1999 als in 2001.

In de behandelingen met fosfaatbemesting (Hoofdstuk 5) had het in 1998 verbouwde vlinderbloemige gewas *V. unguiculata* een positieve uitwerking op de opbrengst van het erop volgende gierstgewas en op het stikstofniveau in de bodem in het eerste jaar na de teelt van *V. unguiculata*. In de daaropvolgende jaren was dit effect verdwenen. De toevoeging van fosfaatbemesting verbeterde de gewasopbrengst aanmerkelijk in alle behandelingen. Het effect was onafhankelijk van het gebruik van *V. unguiculata*, zowel als tussengewas in rotatie met gierst als in het gierst/*V. unguiculata* mengteeltsysteem en onafhankelijk van de duur van de braak voorafgaande aan de teelt van gierst. Slechts in 2001 werd een interactie waargenomen tussen de effecten van braakperiode en die van fosfaatbemesting. Een jaarlijkse dosis van 100 kg ha^{-1} triplesuperfosfaat (TSP) leidde tot een vergelijkbare opbrengst als behaald met de combinatie van een éénmalige dosis van 300 kg ha^{-1} rotsfosfaat uit Tilemsi (TRP) en een jaarlijkse dosis van 100 kg ha^{-1} TRP in de daaropvolgende jaren. Deze beide behandelingen leverden een hogere opbrengst dan de éénmalige dosis van 300 kg ha^{-1} TRP. Bij toediening van fosfaatkunstmest nam het koolstofniveau in de bodem minder sterk af dan zonder toediening, terwijl het stikstofniveau in de bodem niet beïnvloed werd door de toediening van fosfaat.

Gebruik van fosfaatkunstmest in een continue teelt van gierst had een vergelijkbaar effect op de opbrengst als het gebruik van een braakperiode in een onbemest veld en een groter effect dan het telen van één jaar *V. unguiculata* in rotatie met gierst of het invoeren van een gierst/*V. unguiculata* mengteelt beiden zonder gebruik van kunstmest. De combinatie van P-kunstmest, korte braak en *V. unguiculata* in één teeltsysteem kan de opbrengst van de gierst opvoeren tot 1200 kg ha^{-1} in de verder van het dorp verwijderde velden in plaats van de gebruikelijke 250 kg ha^{-1} bij langdurige teelt van gierst in een monocultuur. Deze verbeterde opbrengst is vergelijkbaar met de opbrengst die gehaald wordt op de velden direct rond het dorp waar organische mest is toegediend.

De relatie tussen bodemvruchtbaarheid, kunstmestgift, voedingstoffenopname en korrelopbrengst zijn onderzocht met het model QUEFTS (kwantitatieve evaluatie van de vruchtbaarheid van tropische bodems) in Hoofdstuk 6. Het model laat zien dat totaal stikstof, P-Bray en uitwisselbaar kalium samen een groot deel kunnen verklaren van de potentiële bodembeschikbaarheid van N, P en K voor gierst. Toevoeging van waardes uit andere bodemchemische testen leidde niet tot een verhoging van het verklaarde percentage van de potentiële beschikbaarheid. Van de middels kunstmest toegediende stikstof (N) en fosfaat (P) werd respectievelijk 73 en 17% in het gewas terug gevonden. Ordes van grootte van opbrengst zijn bepaald middels de relatie tussen N, P en K gehaltes in de bovengrondse plantendelen en de korrelopbrengst van de gierst. De overeenstemming tussen gemeten en berekende opbrengsten was redelijk goed voor de percelen dicht bij het dorp. Desalniettemin vertoonden de datasets een grote spreiding. De vergelijking van gemeten en berekende gierstopbrengsten op met *Striga*-besmette veldjes uit de verder van het dorp gelegen velden lieten een onverklaard deel van de variantie in opbrengst zien van 39%. Het model QUEFTS moet verder operationeel gemaakt worden door landbouwkundige diensten en laboratoria. Een grondige validatie is nodig om de voorspellende waarde van het model te verbeteren. Daarvoor zijn gegevens uit meer verschillende productie-omstandigheden nodig.

In Hoofdstuk 7 worden alle uitkomsten van de eerste hoofdstukken geïntegreerd en nader besproken. Deze studie was gericht op het beoordelen van de gecombineerde effecten van teeltsystemen op grond van de beperkende factoren en een beslissings-ondersteunend middel te ontwikkelen waarmee de relatie tussen gegevens over bodemvruchtbaarheid, meststoffenopname en korrelopbrengst van gierst kan worden beoordeeld en opgeschaald. De belangrijkste resultaten laten zien dat *V. unguiculata* als vlinderbloemig gewas in rotatie met gierst bij toenemende schaarste van grond evenveel effect heeft als een korte (2 jaar) braak als middel om graan-opbrengsten te verbeteren in vergelijkbare omstandigheden met die in de Séno-Bankass zone. Een gierst/*V. unguiculata* mengteelt in deze rotatie vermindert de risico's in jaren met een lage regenval. De duurzaamheid en productiviteit van het teeltsysteem zal verder toenemen als fosfaatkunstmest wordt gebruikt of, bij gebrek aan natuurlijke stikstofbinding, de combinatie van N en P kunstmest. Deze laatste combinatie is met name economisch rendabel wanneer de boeren hun gierst kunnen verkopen tijdens de periode met het laagste voedselaanbod op de markt aan het begin van het regenseizoen. Hiertoe moeten prijzen van zowel ingekochte als verkochte producten bekend zijn bij de boeren, en moeten deze lucratiever worden gemaakt waarmee het interessanter wordt voor de boeren de bestaande methodieken die leiden tot uitputting van de bodem te veranderen en te investeren in de vruchtbaarheid van die bodems op lange termijn. De kansen hiervoor zijn echter gering als er geen gerichte ingreep plaatsvindt op politiek niveau in Mali (bijvoorbeeld de overheid, donoren en nationale en internationale financiële instanties).

Curriculum vitae

Odiaba Samaké was born in Dialakoroba (Kati), Mali in 1 January 1953. After completing basic studies in Dialakoroba and Sanankoroba, he was admitted at the high school (Lycée Askia Mohamed) in Biological Science in Bamako where he got the Baccalaureate first and second degrees in June 1974 and June 1975, respectively. Then, he attended 'l'Institut Polytechnique Rurale (IPR) de Katibougou' from October 1975 to December 1979 where he was rewarded with a Bachelor of Science in agronomy. After graduation, he started his professional carrier as a research scientist at the 'Institut d'Economy Rurale (IER)', the national agricultural research institute of Mali where he served as agronomist on the groundnut and soybean research programme (1980–1981) in Sotuba (Bamako). A year later, he was based in Sikasso in the southern region of Mali where he continued his work on tea and became head of the Research Section of Tea and Tobacco (1982–1987). In July 1997, he attended Texas A&M University where he received a degree of Master of Science in agronomy (soil fertility) in May 1990. Back to Mali, he restarted working for IER as agronomist in the research programmes of tea (1990–1991), lowland and upland rice (1991–1992), millet and cowpea (1993–1994). He was head of the 'Station de Recherche Agonomique de Sikasso/Longorola', the main research station of IER in the Southern Mali (1992–1993) and regional supervisor of the 'Programme National de Vulgarisation Agricole' for the same Institute in Mopti, a northern region of Mali (1994–1997). In January 1998, he began working for a PhD degree in agronomy through a sandwich programme under the direction of Prof. Dr. Martin Kropff, Prof. Dr. Eric Smaling and Dr. TjeerdJan Stomph at Wageningen University, the Netherlands. During his research carrier, he attended several training on various aspects on agronomy and technology transfer to farmers. He was also involved in regional, national and international network activities. He was rewarded the 'Gender Price' of IER in 1999.

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