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Improving the productivity of millet based cropping systems in the West African Sahel: Experiences from a long-term experiment in Niger

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ABSTRACT

Resource-poor farmers who are living in the harsh environments of the West African Sahel (WAS) depend on subsistence orientated, low-input farming systems for meeting their livelihood needs. These largely extractive farming systems have resulted in nutrient depletion, soil fertility decline, low productivity and land degradation. A study conducted over 25 years in Niger, aimed to evaluate the long-term effects of organic and mineral fertilizers, cropping systems (CS) of millet and cowpea on crop productivity. The traditional millet/cowpea intercrop system without P fertilizer (TrM/C) was compared with four improved CS receiving P fertilizer: sole millet (MM), millet/cowpea intercrop (M/C), millet-cowpea rotation (M-C), and M/C and rotation with cowpea (M/C-C). Nitrogen fertilizer (N) and the residues of millet (CR) were applied alone or in combination in all five cropping systems. CR were always applied as mulch. The traditional system (TrM/C) produced the lowest millet grain yields (GY) (0.02–0.43 t/ha). All the four improved CS (MM, M/C, M-C and M/C-C) increased GY compared with the traditional system (TrM/C). The M/C and MM systems increased millet GY 3 and 3.3 times compared with the TrM/C, respectively. The M/C-C and M-C systems produced 4 and 4.2 times more GY than that of the TrM/C system, respectively. The lowest revenue was obtained with the TrM/C system. Except for the TrM/C, the revenue of the MM system was lower compared with combined cultivation of millet and cowpea. Compared with the TrM/C system, M/C and M/C-C provided 2 times more revenue. By providing 2.4 times more revenue than the TrM/C system, the M-C system was the most productive system. Cowpea provided from 54% and 56% of the revenue in M/C-C and M-C system, respectively. Soil organic carbon decreased in all the CS from 46% to 63% compared with the soil kept under natural vegetation fallow. The improved CS increased soil P from 3.4 to 4 times. Over the 25 years of cropping, the highest millet yields were obtained with the lower levels of rainfall indicating the role of nutrients in the system. The four improved systems maintained millet yields over the 25 years of cropping. By improving water and nutrient use efficiency, integrated management of mineral fertilizers, CR and cowpea affected more crop productivity than the rainfall. We concluded that cereal-legume based cropping systems treated with small doses of mineral fertilizers and CR could be used for sustainable management of soil fertility in low-input farming systems.

1. Introduction

The population of Africa is projected to double by 2050 as compared to 2010. Food insecurity and poverty remain major challenges to feed this growing population. At the same time sub-Saharan Africa (SSA) in general and the West African Sahel (WAS) in particular, are facing high pressures on its fragile resources of lands, which are prone to degradation. The original poverty of soils, low soil organic carbon (SOC) and clay content, the rapid loss of SOC with cropping activities, soil erosion, acidification, nutrient mining and frequent droughts or flooding in the context of climate change, are all serious constraints to agriculture in the WAS (Bationo and Buerkert, 2001; Bado and Bationo, 2018). Sustainable and productive agricultural technologies and integrated management systems are needed to improve agricultural productivity

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and nutrition, reduce poverty and contribute towards food security (Bekunda et al., 2010). Achieving the Sustainable Development Goals (SDGs) of the United Nations established in 2015, demands that solutions to these environmental and social challenges are found. In 2001, at the founding of the African Union's New Partnership for Africa's Development (NEPAD), African heads of state declared that improved agricultural performance is a prerequisite of economic development on the continent (Bekunda et al., 2010). Considering the important role of fertilizer as powerful productivity-enhancing input for agricultural development, the Africa Fertilizer Summit of African Head of States recommended to increase the fertilizer use from 8 to 50 kg/ha, as a key driver of crop productivity and attaining food security and rural well-being (Bekunda et al., 2010).

In much of SSA, although farmers are aware as to the potential beneficial impacts from fertilizer application, they lack access to appropriate fertilizer products. However, the high cost of fertilizers compared with the limited resources of farmers, the limited market for both fertilizers and agricultural products are the main constraints that limit the utilization of mineral fertilizers. With the demise of the traditional fallow systems (10–15 years fallow followed by a 3–5 years cropping) which to some extent maintained soil fertility, new farming systems are required to meet the high demands for lands due to a growing population (Pichot et al., 1981; Pieri, 1989; Bationo and Mokwunye, 1991b; Steiner, 1991; Bado et al., 1997; Bationo et al., 2006; Bado and Bationo, 2018). It is estimated that more than 70% of African soils are degraded by agricultural practices and human and animal pressure (Bationo and Mokwunye, 1991a, 1991b; Bationo et al., 2006). Therefore, smallholder farmers are trapped in a vicious cycle of land degradation and poverty (Tittonell and Giller, 2013).

Many concepts have been developed over the years, aiming to improve the productivity of smallholder's farming systems. The paradigm of "external input" of the 1960 s and 1970 s focusing on fertilizers associated with improved germplasm has certainly boosted agricultural production in Asia and Latin America in the form of the first "Green Revolution." However, this approach did not start a "Green Revolution" in Africa, due to a lack of the 'enabling environment' and also related to high fertilizer costs. The low external input sustainable agriculture (LEISA) approach of the 1990 s considered the importance of organic resources, while the concept of integrated nutrient management (INM) combined organic and mineral fertilizers (Vanlauwe, 2004). These approaches have been more successful as farmers are more able to afford small quantities of mineral fertilizer. The mid-1980 s to the mid-1990 s saw a shift in paradigm toward the combined use of organic and mineral inputs accompanied by the "participatory" movement, which emphasized on involving various stakeholders in the process of research and development. Considering that farmers' decision-making process is not merely driven by soil and climate but by a large set of factors cutting across the biophysical, socioeconomic, and political domain, the integrated natural resource management (INRM) approach was developed (Izac, 2000). With experiences gained from different approaches and changes in the overall social, economic, and political environment, the integrated soil fertility management (ISFM) approach was developed to include an integral part of the INRM approach with a focus on appropriate management of natural resources, farmers' capacities to afford technologies, and the complexity of cropping systems in line with local policies (cost, availability, and affordability of fertilizer and credit). The ISFM approach aims at adapt locally relevant soil fertility management practices of farmers to optimize agronomic efficiency of mineral fertilizers and organic inputs and to increase the productivity of cropping systems. The ISFM is defined as a set of soil fertility management practices of fertilizer, organic inputs and improved germplasm. Combined with the knowledge of how to adapt practices to local conditions, the ISFM aims to maximize agronomic use efficiency of the applied nutrients and improve crop productivity (Vanlauwe, 2004; Vanlauwe et al., 2010). The ISFM recognizes the important role of social, cultural, and economic processes regulating soil fertility management strategies. This approach is broader than the INM approach as it recognizes the need of an appropriate physical and chemical environment for plants to grow optimally, besides a sufficient and timely supply of available nutrients (Vanlauwe, 2004). This paradigm is closely related to the wider concepts of INRM, thereby representing a significant step beyond the earlier narrower concept and approach of nutrient replenishment/recapitalization to enhance soil fertility (Sanchez et al., 1997). The ISFM approach integrates the roles of soil and water conservation; land preparation and tillage; organic and inorganic nutrient sources; nutrient recycling; pests and diseases; livestock; rotation and intercropping; multipurpose role of legumes; and integrating the different research methods and knowledge systems. Legume integration such as legume–cereal intercropping or rotation are important components of ISFM technologies. The cropping systems of smallholder farmers comprise many N_2-fixing legume crops, such as groundnut (*Arachis hypogaea* L.) and cowpea (*Vigna unguiculata* (L) Walp), which are usually rotated or intercropped with cereals (Bado et al., 2006a). Farmers commonly intercrop to secure food production by averting risk, and to maximize utilization of land and labour (Mucheru-Muna et al., 2010). N_2-fixing legumes contribute to addition of N in cropping systems through biological nitrogen fixation. Legumes as intercrops perform well in low-input farming systems (Bationo and Ntare, 2000; Bado et al., 2006b; Nelson et al., 2021).

Organic amendments such as farmyard manure and crop residues are also important components of ISFM technologies. The positive impact of organic fertilizers alone or combined with mineral fertilizers is well documented in previous works (Bationo and Mokwunye, 1991ab; Akponikpe et al., 2008; Suzuki et al., 2016). However, the amount of farmyard manure usually recommended by research and extension is out of reach for most smallholder farmers (Mando et al., 2005). There is also a competition for crop residues between household needs and animal feeding. Alternative management options of the different components of ISFM technologies are necessary to improve their efficiency and affordability to smallholder farmers. This research aims at investigating alternative management options of ISFM technologies to develop cropping systems that sustainably improve crop production. This study investigates the effects of small doses of mineral fertilizer with or without crop residues on the productivity of the popular millet-cowpea based cropping systems. The goal was to identify alternative cropping systems that sustainably improve soil fertility, crop yields, and agricultural productivity.

2. Materials and method

2.1. Experimental site

The experiment was established in 1986 at the agronomic research station of International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) Sahelian Center, located at Sadore, 45 km from Niamey in Niger, West Africa (13° 15′N, 2° 18′E) at an altitude of 240 m a.s.l. The climate is characterized by a short rainy season (90 days) from June to September. The average rainfall is 560 mm, occurs irregularly, and normally comes in the form of thunderstorms. Monthly rainfall during the period of the experiment is presented in Fig. 1. Maximum temperatures range from 30° to 40°C during the cropping season and potential evapotranspiration (PET) exceeds the total rainfall in all months except July-August, which is the peak of the rainy season (Subbarao et al., 2000).

Fig. 1.

The site is located on a sandy plain of 2–8 m in depth covering one of a series of stepped surfaces comprised of cemented laterite gravels (West et al., 1984). The surface horizon (25–30 cm in depth) of the soil is yellowish red sand underlain by a thick (>1 m) red loam or red sand horizon. The soil is acidic in nature (pH_{H2O} 4.5–5.0), coarse textured, with sand content exceeding 95%, low in both nutrients (cation exchange capacity = 1.5 cmol kg^{-1}), water holding capacity (<10%), and

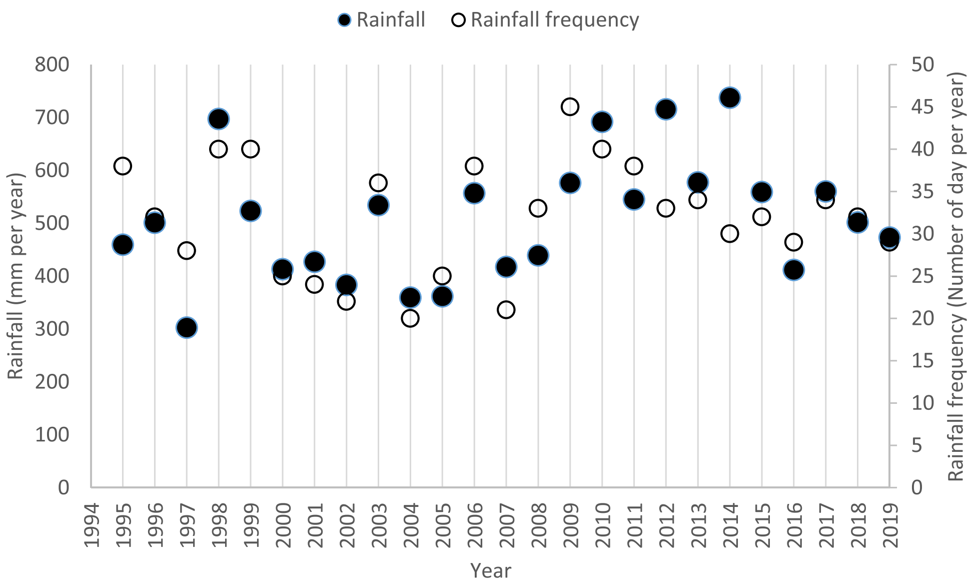

Fig. 1. Annual rainfall: (A) in mm per year and, (B) rainfall frequency in number of days per year, over the 25 years of the experiment.

organic matter content (0.4%) (Subbarao et al., 2000). The main properties of the soil of the experiment are presented in Table 1.

2.2. Agronomic experiment

Established in 1986, a field trial was laid out as a randomized complete block design with five cropping systems replicated four times, involving hand cultivation and ridging with animal traction and planting on ridges. The traditional pearl millet/cowpea intercropping system (Tr-M/C) without fertilizer was compared with four improved cropping systems receiving 13 kg P/ha: sole millet (MM), millet/cowpea intercrop (M/C), millet-cowpea rotation (M-C), and millet/cowpea intercrop and rotation with cowpea (M/C-C) (Table 2). Plot size was initially 500 m^2 (50 m x 10 m). One plot was a reference treatment and was kept under natural fallow without any fertilizer application or weeding during throughout the experiment.

In 1989, another factor was added. Management of crop residues (millet straw retained as mulch) was introduced by dividing each main plot in half creating two sub-plots, thereby creating two treatments of crop residues (CR) (with and without CR). The size of the sub-plot was 250 m^2 (25 m x 10 m). In 1994, N treatment (15 kg N/ha as calcium ammonium nitrate) was introduced by further dividing each sub-plot in half (two sub-sub-plots), thereby creating two treatments of N fertilizer (with and without N). The size of the sub-sub-plots is 125 m^2 (25 m x 5 m). The experimental design became a factorial 5 × 2×2 in a split-split plot arrangement with 5 cropping systems in the main plots, 2 treatments of CR (with and without CR) in sub-plots, and 2 treatments of N (with and without N) in the sub-sub plots. The details of treatments are

Table 1
Soil properties in 2019 after 25 years of cultivation as affected by the application of millet residues with and without nitrogen fertilizer in the traditional millet/cowpea intercropping system (TrM/C) and the four improved cropping systems compared with the soil under fallow.

Cropping systems	Crop residues	Nitrogen fertilizer	pH H_2O	pH-KCl	Organic C (g/kg)	N-total (mg/kg)	P-Bray1 (mg/kg)	K^+ ($cmol^+$/kg)
Traditional Millet/Cowpea intercrop (TrM/C)	CR0	N0	5.1^a	4.0	1.21	94.1	6.8^b	0.11
		N1	4.6^{bc}	3.8	1.16	99.5	6.3^b	0.09
	CR1	N0	5.1^a	4.1	1.16	85.5	5.5^b	0.11
		N1	4.7^b	3.8	1.47	116.5	10.6^a	0.11
Millet/Cowpea intercropping	CR0	N0	5.0^b	4.1	1.11	145.2	37.4	0.17
		N1	4.8^c	3.9	1.15	112.1	33.8	0.13
	CR1	N0	5.3^a	4.2	1.58	145.3	28.8	0.16
		N1	4.9^{ab}	3.9	1.59	149.5	26.7	0.14
Millet/Cowpea intercropping and rotation with cowpea (M/C-C)	CR0	N0	5.0^a	3.9	1.14	89.0	33.3	0.14
		N1	4.7^b	3.8	1.08	88.1	31.4	0.13
	CR1	N0	5.1^{ab}	4.0	1.22	108.3	30.4	0.13
		N1	4.7^b	3.8	1.34	102.8	28.5	0.12
Millet-Millet (MM)	CR0	N0	5.4^a	4.3^a	1.17	94.7	27.7	0.13
		N1	4.9^b	3.9^b	1.24	102.8	33.0	0.16
	CR1	N0	5.6^a	4.3^a	1.17	96.5	25.5	0.13
		N1	4.9^b	3.9^b	1.37	124.8	22.4	0.13
Millet-Cowpea rotation (M-C)	CR0	N0	5.0^a	4.1^a	1.04^b	85.6^b	26.4	0.12
		N1	4.7^b	3.9^b	1.24^b	104.8^{ab}	21.7	0.12
	CR1	N0	5.0^a	4.0^a	1.26^b	107.1^{ab}	34.0	0.13
		N1	4.7^b	3.8^b	1.57^a	120.5^a	30.7	0.12
Soil under Fallow			5.8	5.1	3.25	256.0	6.4	0.13
Standard error			0.28	0.22	0.34	34.38	11.6	0.03

CR0: No Cropping residues, CR1: With Cropping residues; N0: No Nitrogen fertilizer, N1: With Nitrogen fertilizer. Values affected by the same superscripted letter on the same column for the same cropping system are not significantly different at $p < 0.05$, according to the test of Student-Newman-Keuls. The lack of superscripted letter means no significant differences.

Table 2
List cropping systems and treatments of the experiment.

Cropping systems	Fertilizer treatments		Year of cultivation	
	Crop Residues	Nitrogen	Year1	Year2
Traditional Millet/Cowpea (TrM/C)	CR0	N0	TrM/C	TrM/C
		N0	TrM/C	TrM/C
	CR1	N1	TrM/C	TrM/C
		N1	TrM/C	TrM/C
Sole millet (MM)	CR0	N0	M	M
		N1	M	M
	CR1	N0	M	M
		N1	M	M
Millet/Cowpea intercropping (M/C)	CR0	N0	M/C	M/C
		N0	M/C	M/C
	CR1	N1	M/C	M/C
		N1	M/C	M/C
Millet-Cowpea rotation (M-C)*	CR0	N0	M	C
		N0	C	M
	CR1	N1	M	C
		N1	C	M
Millet/Cowpea intercropping and rotation with cowpea (M/C-C)*	CR0	N0	M/C	C
		N0	C	M/C
	CR1	N1	M/C	C
		N1	C	M/C
Fallow	–	–	–	–

CR1, CR0: with and without crop residues, respectively
N1, N0: with and without nitrogen, respectively
* For M-C and M/C-C, each element of the rotation is present each year by millet (M), cowpea (C) or M/C (Year 1 and year 2)

presented in Table 2.

Millet and cowpea were always planted in hills on separate lines at 3 and 2 plants per hill, respectively. In the TrM/C, millet and cowpea were planted at the spacing of 2.0 m x 1.5 m, and the plant density was 9999 plants/ha (3333 hills/ha) and 6666 plants/ha (3333 hills/ha), respectively. In the improved cropping systems, sole millet (M) and sole cowpea (C) were planted at the spacing of 1.0 m x 1.0 m and 1.0 m x 0.5 m, respectively. Thus, the plant density was 30,000 plants/ha (10,000 hills/ha) and 40,000 plants/ha (20,000 hills/ha) in sole millet and sole cowpea, respectively. Millet and cowpea were planted at the spacing of 1.5 m x 1.0 m each, and the plant density was 19,998 plants/ha (6666 hills/ha) and 13,332 plants/ha (6666 hills/ha) in the improved cropping system.

Millet and cowpea as sole crops were planted after 20 mm of rain was received at the start of the growing season. Cowpea in intercrop treatments was planted 2 weeks after millet. Several seeds were planted per hill to allow subsequent thinning to the desired plant density. Two or three weeks after planting, millet was thinned to 3 plants per hill.

For control plots cultivated by the traditional system, no fertilizer was applied. For all the improved cropping systems, a dose of P fertilizer (13 kg P ha^{-1}) was annually applied using triple superphosphate (1986–1988) or single superphosphate (1989–2019). Phosphorus fertilizer was broadcasted by hand at the beginning of the growing season. Nitrogen fertilizer was also broadcasted by hand at the first weeding (10 days after sowing). Since 1994, Sadore Local, which is a local landrace of millet and cowpea variety TM 578 was used in all the treatments.

The field was kept weed-free by manual hoeing. Sole cowpea was protected from insects using a mixture of cypermethrin and dimethoate (as Cymbush Super ED ®) at least twice during the cropping season. At maturity, within each plot, an area of 125 m^2 was harvested manually. Crops were air-dried for 60 days, and grain yield (GY) and total dry matter (TDM) was determined. The TDM is the total aboveground biomass and grain yield. Except the roots and senescence leaves, the aboveground parts of cowpea residues (grain and fodder) were removed in all the treatments. Similarly, the aboveground parts of millet were removed except the treatments where millet residues are recycled as mulch (Table 2). Data of the first 11 years (1986–1996) have been published (Subbarao et al., 2000). This paper will be focused on data collected over the 26 years from 1994 to 2019 since the introduction of the two new factors (application of millet residues (CR) with or without N fertilizer) with hand cultivation, which is the most popular method used by farmers. However, millet yield data from 1994 were lost and, hence, 25 years of data (1995–2019) is presented. Furthermore, limited data collection of the cowpea yield component limited the analysis to four consecutive years (2017–2020).

2.3. Sampling and analysis

Yearly data for GY and TDM were subjected to analysis of variance as per RCBD using four factors: Year (Y), cropping system (CS), crop residues (CR) and nitrogen (N) treatments. Water use efficiency (WUE) by millet was calculated as the ratio GY to the total rainfall during the season (kg grain per mm of rainfall). A combined analysis of random effects, treatments and interactions between factors was applied on all data by including year (Y) as a factor (Gomez and Gamez, 1983). The test of Student Newman-Keuls test was used for multi comparison of means (Gomez and Gamez, 1983; GENSTAT 5 Committee, 1993).

2.3.1. Soil sampling

After the 25 years of cropping, soil samples were collected from the 0–20 cm layer in all plots, including the soils under fallow since the installment of the experiment (as original soil). Ten sub-samples were randomly taken from each sub-plot, and mixed to prepare a composite sample for laboratory analysis. Soils were analyzed for pH (McLean, 1983), P (Bray-I) (Bray and Kurtz, 1945), and organic C (OC) (Nelson and Sommers, 1983). Soil exchangeable K was extracted with 1 M NH4OACc solution (Helmke and Sparks, 1996) and determined by flame photometry.

2.3.2. Stability analysis

The method of Finlay and Wilkinson (1963) was used to analyze the stability of treatments over years of cropping. This approach was originally developed to assess the stability of a genotype's productivity based on multi-location evaluations. Similarly, millet grain yields (GY) or water use efficiency (WUE) of treatments were regressed on an environmental mean (EM), which is the average of GY or WUE in a given year (Raun et al., 1993; Subbarao et, 2000).

2.3.3. Economical analysis

The productivity of cropping systems was evaluated by calculating the annual global revenues provided by the two crops (millet and cowpea) in each cropping system. Because of the irregularity of yield data of cowpea, we have used the available data of both millet and cowpea on four consecutive years (2017–2020) to calculate the annual revenues per crop and per cropping system. The prices of grain, stover (millet) and fodder (cowpea) at local markets were used to evaluate the productivity of cropping system. Labor cost was not integrated into this evaluation.

3. Results

3.1. Changes in soil properties

Data of the original soil kept under fallow and soil properties after 25 years of cropping are presented in Table 1. Across the five cropping systems, the applications of CR and N fertilizer consistently affected soil pH. The application of N with or without CR always decreased ($P < 0.05$) soil pH, while cropping system treatment decreased soil pH from 0.2 to 1.2 units compared with the pH of soils under fallow. The applications of CR and N fertilizer affected SOC and soil N, only in the M/C-C system. The highest levels of SOC and N were obtained with CR and N fertilizer (CR1N1) treatment, whereas the lowest values were obtained in the control without CR or N fertilizer (CR0N0). However, SOC and N were decreased in the five cropping systems compared with the original soil. Compared with the soil under fallow, N decreased between 46% and 62% and SOC decreased between 58% and 63% depending on cropping system.

Fertilizer treatments and cropping systems significantly affected soil P. In the TrM/C system, soil P was maintained or decreased with the applications of N and CR alone compared with the fallow plot. There were no differences between fertilizer treatments for P in the four improved cropping systems (MM, M/C, M-C and M/C-C).

3.2. *Millet yield*

Considering the global analysis of variance of grain yield (GY) and total dry matter (TDM) yield, both were affected ($P < 0.001$) by the four factors: N fertilizer (N), crop residues (CR), cropping system (CS) and year (Table 3). There were significant interactions between N and year ($P < 0.01$), CR and year ($P < 0.01$), and CS and year ($P < 0.01$), indicating the impact of seasonal variability on treatments (N, CR, and CS). There were also two interactions between N and CS ($P < 0.01$) and between CS and CR ($P < 0.05$) for TDM, indicating that millet response to N and CR depended on the cropping system. However, there was no interaction between CR and N.

Yearly analysis of GY confirmed that millet GY was affected by N, CR, and CS over the 25 years, except for 2012 and 2013 for CR and CS, respectively (Table 4). Interactions were observed between N and CS in 2 years (2003 and 2009) and between CR and CS in 3 years (2001–2003) out of the 25 years. The yearly analysis also confirmed that there was no interaction between CR and N.

Across the five cropping systems, the combined application of N fertilizer associated with CR (CR1N1) produced the highest GY over the 25 years, whereas the lowest GY was obtained with the control without fertilizer (CR0N0) (Fig. 2). Millet responses to N or CR alone depended on the cropping system. Owing to the seasonal variability of yields associated with different interactions between factors (N fertilizer, CR, CS, and year), data could not be presented by factor without taking into account the influence of other factors. Therefore, we presented the yield data by cropping system.

The improved systems produced the highest yields, whereas the TrM/C system produced the lowest yields. Within the improved systems, the highest yields were obtained when millet was rotated with cowpea (M-C), followed by millet/cowpea intercrop and rotation with cowpea (M/C-C).

The mean grain and dry matter yield produced over the 25 years are presented in Table 5, enabling a long-term comparison of treatments. The traditional system (TrM/C) produced the lowest yield (0.02–0.43 t/ha), and there were no significant differences between fertilizer treatments. The cumulative GY of the combined application of N and CR (CR1N1) increased millet GY by 77% compared with the control without N and crop residues (CR0N0) in the TrM/C system. The applications of N or CR alone did not affect millet yields in the TrM/C system, and there were no significant differences between the two treatments. The CR1N1 treatment increased millet GY by 115% compared with CR0N0 in the M/C system.

Compared with CR0N0, the application of N or CR alone also increased millet GY by 61% and 67%, respectively, in the M/C system. With MM system, the CR1N1 treatment increased millet GY 123% compared with CR0N0. Compared with CR0N0, the application of CR or N alone also increased millet GY by 51% and 69%, respectively, in the MM system, (Table 5). The CR1N1 treatment increased millet GY by 61% compared with CR0N0 in the M-C system. Compared with CR0N0, the application of N or CR alone also increased millet GY by 28% and 35%, respectively, in the M-C system. The CR1N1 treatment increased millet GY by 70% compared with CR0N0 in M/C-C system. Compared with CR0N0, the application of N or CR alone also increased millet GY by 32% and 40%, respectively, in the M/C-C system.

All the four improved cropping systems (MM, M/C, M-C and M/C-C) that received P fertilizer had an increased GY compared with the traditional system (TrM/C) without P fertilizer. The MM also produced 3.3 times more GY than that of the TrM/C system. The highest GY were obtained when millet was intercropped or rotated with cowpea. The M/C-C and M-C cropping systems produced 4 and 4.2 times more GY than that of the TrM/C system, respectively.

Table 3
Combined analysis of variance for millet grain and total dry matter yield as a function of cropping system, crop residue management and nitrogen fertilization over 25 years (1998–2019).

Source of variation	dl	Variance Ratio (F value)	
		Grain yields	Total Dry Matter
Years (Y)	24	44.3 * *	79.9 * *
Cropping System (CS)	4	325.3 * *	266.0 * *
Crop Residues (CR)	1	242.3 * *	212.8 * *
Nitrogen fertilizer (N)	1	202.1 * *	214.8 * *
Y * CS	96	6.6 * *	6.4 * *
Y * CR	24	2.3 * *	2.4 * *
Y * N	24	2.3 * *	2.7 * *
CS * CR	4	6.6 * *	6.7 * *
CS * N	4	9.4 * *	6.0 * *
CR * N	1	0.1	0.2
Y * CS * CR	96	0.6	0.6
Y * CS * N	96	0.6	0.4
Y * CR * N	24	0.3	0.5
CS * CR * N	4	0.3	0.9
Y * CS * CR * N	96	0.6	0.5

* and * *: Significance at 0.05 and 0.01 P levels, respectively, according to the test of Student Newman-Keuls

Table 4
Analysis of variance for millet grain yields (1998–2019).

Year	Variance Ratio (F value)						
	Nitrogen fertilizer (N)	Crop residue (CR)	Cropping system (CS)	Interactions between N, CR, and CS			
				N x CR	N x CS	CR x CS	N x CR x CS
1995	0.34	0.9	2.9 *	0.1	0.5	0.5	0.2
1996	13.7 * *	5.5 *	5.3 * *	0.01	0.2	0.4	0.01
1997	42.3 * *	60.7 * *	115.4 * *	0.1	2.0	2.0	0.1
1998	26.8 * *	33.1 * *	141.8 * *	0	0.8	0.9	0.1
1999	29.4 * *	48.1 * *	62.9 * *	0	0.8	2.4	0.1
2000	25.8 * *	48.0 * *	133.4 * *	0.5	0.5	0.9	0.2
2001	9.4 *	34.9 * *	91.0 * *	0	0.9	4.6 *	0.1
2002	17.5 * *	68.9 * *	77.4 * *	0.7	0.7	2.8 *	0.1
2003	21.0 * *	27.7 * *	34.9 * *	0.6	3.4 *	3.8 *	0.5
2004	25.3 * *	19.0 * *	70.9 * *	0.5	1.3	1.3	0
2005	20.4 * *	30.2 * *	32.6 * *	0.7	1.1	2	0.3
2006	8.5 *	7.8 *	29.1 * *	0.2	0.9	2.4	0.4
2007	13.8 * *	22.1 * *	41.5 * *	1.3	1.1	2.4	0.2
2008	21.9 * *	8.1 *	23.1 * *	0.3	1.2	0.9	0.6
2009	72.6 * *	18.7 * *	20.4 * *	0.1	4.3 *	0.9	0.3
2010	27.4 * *	14.4 * *	24.1 * *	0	1.8	1.2	0.3
2011	26.5 * *	5.8 *	5.3 * *	0.1	0.9	0.1	0.1
2012	9.3 *	1.3	17.7 * *	0.5	0.7	0.8	0.1
2013	8.6 *	15.2 * *	0.4	0.8	0.3	0.5	0.7
2014	10.8 *	16.4 * *	15.6 * *	0	0.5	1.1	0
2016	18.6 * *	15.5 * *	16.0 * *	0	0.3	1.1	0
2017	15.5 * *	21.2 * *	22.6 * *	1	1.3	1.5	1.3
2018	23.9 * *	20.6 * *	15.5 * *	0	0.9	0.7	0
2019	13.0 * *	14.7 * *	8.5 * *	0.6	0.6	1.3	0.1

NxCR, NxCS, and CRxCS: Interaction between * and * *: Significant decrease of yields at 0.05 and 0.01 P levels, respectively, according to the test of Student Newman-Keuls

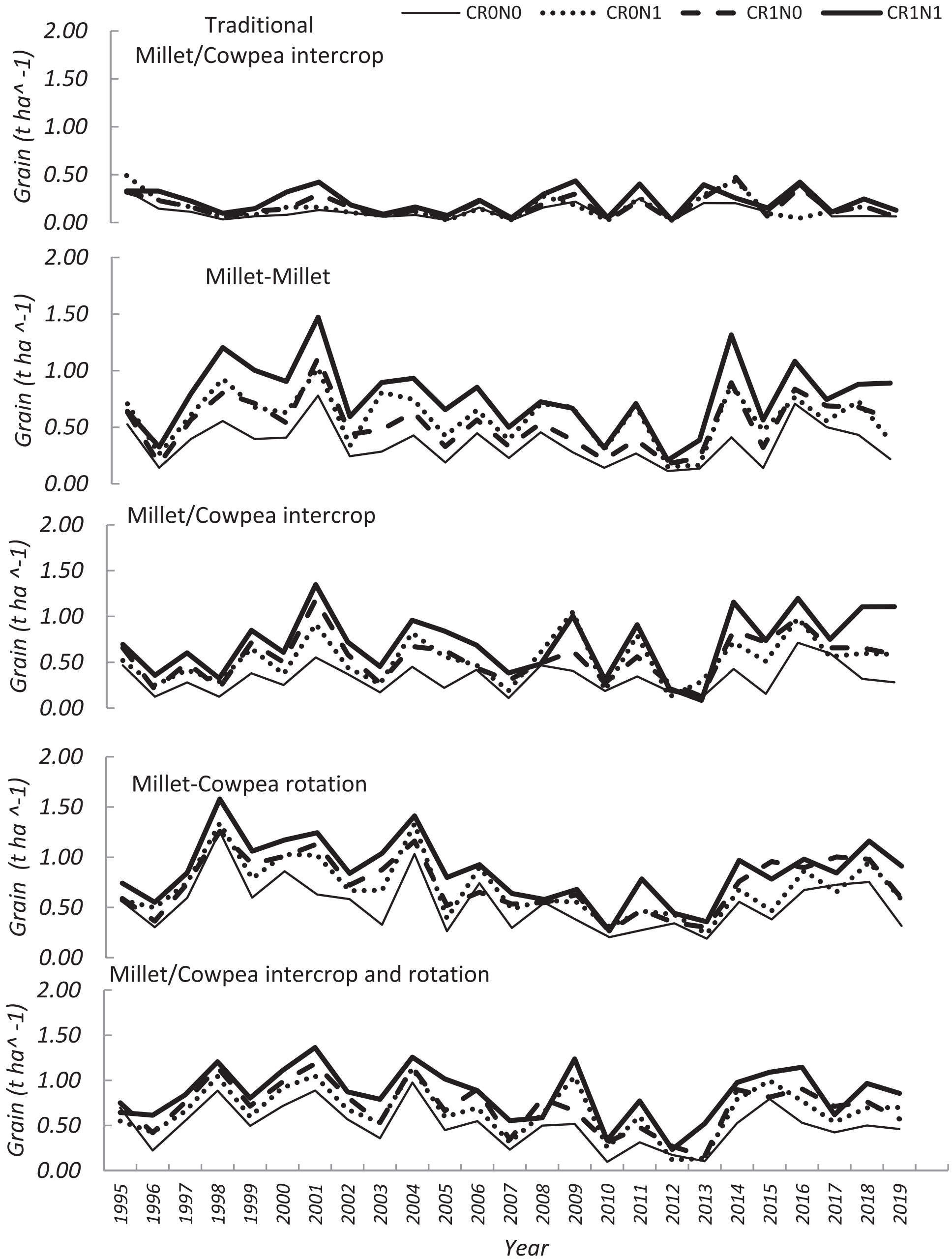

Fig. 2. Effects of fertilizer treatments with and without crop residues and cropping systems on millet grain yields over 25 years (1995–2019). Except the traditional M/C intercrop, P fertilizer was applied at 13 kg P/ha on the four improved cropping systems. CR0N0: control without crop residues and N fertilizer; CR1N1: crop residues and N fertilizer; CR1N0 and CR0N1: crop residues without N fertilizer and N fertilizer without crop residues, respectively.

3.3. *Rainfall, yield stability and water use efficiency*

3.3.1. *Rainfall and yields*

The variations in rainfall (total and frequency) over the 25 years of cropping are presented in Fig. 1. The rainfall (total and frequency) was associated with variations in millet GY by significant linear correlations. The parameters of the linear correlations between the rainfall and GY for all the treatments (fertilizers and cropping systems) are presented in Table 6. A graphical representation indicated that the highest GY was obtained with the lowest rainfalls (less than 350 mm) (Fig. 3).

The highest GY and TDM yields were obtained with the lowest rainfalls (total and frequency) in the improved cropping systems, whereas the variations of rainfall did not affect millet GY in either the TrM/C system or the sole millet system (MM) (Fig. 3). Similarly, the lowest GYs were obtained with the highest rainfall across all fertilizer treatments in the improved cropping systems (M-C, M/C, M/C-C) (Table 6). Low GY associated with higher rainfall were mainly observed in treatments with N fertilizer (N1), CR (CR1), or the combined application of CR and N fertilizer (CR1N1). Any significant correlation was not observed between rainfall and GY for any fertilizer treatments in both the traditional system (TrM/C) and the sole millet system (MM) (Table 6).

3.3.2. *Yield stability and water use efficiency by Millet*

The millet grain yields to environment mean ratio (GY/EM-R) of the five cropping systems were significantly related by linear correlations (Fig. 4). The TrM/C system was the less responsive to environment (slope= 0.24; r = 0.34), meaning that the TrM/C system responded less to the variation in environmental factors. In contrast, the four improved systems were responsive to environment, with the correlation (slope and

Table 5
Mean yields (t.ha-1) of 25 years cultivation of millet as affected by the application of millet residues with and without nitrogen fertilizer in the traditional millet/cowpea intercropping system (TrM/C) and the four improved cropping systems.

Cropping systems	Crop residues	Nitrogen	Grain yields t/ha	Grain yields (%)	Total dry matter yields t/ha	Total dry matter yields (%)
Traditional Millet/ Cowpea intercrop (TrM/C)	CR0	N0	0.13^{b}	100	0.93^{c}	100
		N1	0.15^{ab}	115	1.26^{ab}	136
	CR1	N0	0.17^{ab}	131	1.14^{b}	123
		N1	0.23^{a}	177	1.57^{a}	170
	Mean		0.17	100	1.22	100
Sole Millet (MM) Mean	CR0	N0	0.35^{c}	100	2.29^{c}	100
		N1	0.59^{b}	169	3.32^{b}	145
	CR1	N0	0.53^{bc}	151	3.00^{b}	131
		N1	0.78^{a}	223	4.23^{a}	185
	Mean		0.56	332	3.21	262
Millet/Cowpea intercropping (M/C)	CR0	N0	0.33^{c}	100	1.99^{c}	100
		N1	0.53^{b}	161	2.80^{b}	140
	CR1	N0	0.55^{b}	167	3.07^{b}	154
		N1	0.71^{a}	215	3.85^{a}	193
	Mean		0.53	311	2.94	240
Millet-Cowpea rotation (M-C)	CR0	N0	0.54^{c}	100	2.99^{c}	100
		N1	0.69^{b}	128	3.95^{b}	132
	CR1	N0	0.73^{b}	135	3.89^{ab}	130
		N1	0.87^{a}	161	4.40^{a}	147
	Mean		0.71	415	3.79	310
Millet/Cowpea intercropping and rotation with cowpea (M/C-C)	CR0	N0	0.50^{c}	100	2.66^{c}	100
		N1	0.66^{b}	132	3.37^{b}	127
	CR1	N0	0.70^{b}	140	3.63^{b}	136
		N1	0.85^{a}	170	4.54^{a}	170
	Mean		0.68	399	3.55	290

CR1, CR0: with and without crop residues, respectively; N1, N0: with and without nitrogen, respectively. Values affected by the same superscripted letter on the same column for the same cropping system are not significantly different at $p < 0.05$, according to Student Newman-Keuls test. The lack of superscripted letter means no significant difference.

coefficient) varying from 1.1 to 1.3 and from 0.73 to 0.77, respectively. The highest variations of GY/EM-R were obtained with the M/C-C system.

The water use efficiency by millet to environmental mean ratio (WUE/EM-R) is presented in Fig. 5. Similar to GY/EM-R, the TrM/C system was the less responsive to environment (slope= 0.22; r = 0.24). With the improved systems, the correlation (slope, coefficient) varied from 0.54 to 1.3 and from 0.55 to 0.70, respectively. Similarly to GY/EM-R, the highest variations of WUE/EM-R were obtained with the M/C-C system.

3.4. *Productivity of the cropping systems*

The available yield data of cowpea during four consecutive years (2017–2020) and the yields per crop (millet and cowpea) and per cropping system and the global production (yields in t/ha and the value in $US) are presented in Table 7. Similarly with millet, the applications of CR alone or associated with N fertilizer produced the highest yields while the lowest yields were obtained in the control treatment without fertilizers (Fig. 6). The highest yields of cowpea were obtained in the M-C system while the lowest yields were obtained in the intercrop systems (TrM/C and M/C). Sole cultivation of cowpea in M-C system explains the higher productivity of cowpea.

The lowest production was obtained with the TrM/C system. The MM system produced more than the TrM/C system ($p < 0.05$). Except for the TrM/C, the production of the MM system was lowest compared to the cropping systems that included cowpea. The highest production (US $1781) was obtained with millet-cowpea rotation (M-C). Cowpea provided the highest contribution (56%) to the revenue of M-C system. This could be explained by the high yields of pure cowpea in M-C system and the highest prices of cowpea grain and fodder. The M/C and M/C-C produced more compared with the MM system but there were no significant differences between these two cropping systems in term of revenue., The M/C and M/C-C produced 2 times more compared with The TrM/C system. The M-C system was the most productive.

Table 6
Parameters of the linear regressions that describe the relationships between millet grain yields (t/ha) and rainfall (total and frequency) as affected by fertilizer treatments in the improved cropping systems (sole millet, millet/cowpea intercrop, millet-cowpea rotation, millet/cowpea intercrop and rotation) that received P fertilizer and the traditional millet/cowpea intercrop which did not receive P fertilizer over 25 years (1995–2019).

Treatments			Rainfall (mm/year)			Rainfall frequency (days/year			Rainfall (mm/year)			Rainfall frequency (days/year)		
Cropping system	Crop residue	N Fertilizer	Slope	Intercept	r	Slope	Intercept	r	Slope	Intercept	r	Slope	Intercept	r
Traditional Millet/Cowpea intercrop	CR0	N0	-0.05	0.15	0.03	2.40	0.15	0.07	-0.06	0.20	0.03	2.65	0.08	0.08
	CR0	N1	0.03	0.14	0.02	1.56	0.12	0.05						
	CR1	N0	0.02	0.16	0.01	3.30	0.05	0.11						
	CR1	N1	-0.22	0.33	0.12	3.32	0.02	0.12						
Millet-Millet	CR0	N0	-0.25	0.48	0.14	-6.05	0.96	0.11	-0.24	0.68	0.08	-2.23	0.63	0.05
	CR0	N1	-0.14	0.65	0.05	-4.54	0.68	0.10						
	CR1	N0	-0.22	0.65	0.09	3.07	0.49	0.07						
	CR1	N1	-0.38	0.96	0.12	-1.56	0.41	0.05						
Millet/Cowpea intercrop	CR0	N0	-0.33	0.50	0.17	-13.25	0.12	0.23 *	-0.54	0.81	0.18 * *	-5.03	0.69	0.10 *
	CR0	N1	-0.53	0.80	0.20 *	-9.78	1.02	0.17						
	CR1	N0	-0.58	0.85	0.21 *	-10.51	1.02	0.20 *						
	CR1	N1	-0.75	1.10	0.23 *	-4.48	0.69	0.09						
Millet-Cowpea Rotation	CR0	N0	-0.18	0.63	0.07	-9.99	1.04	0.17	-0.54	0.96	0.17 * *	-9.39	0.98	0.18 * *
	CR0	N1	-0.58	0.98	0.19 *	-9.50	0.86	0.20 *						
	CR1	N0	-0.58	1.00	0.18	0.00	0.53	0.00						
	CR1	N1	-0.84	1.25	0.26 *	-1.21	0.37	0.04						
Millet/Cowpea intercrop Rotation	CR0	N0	-0.61	0.82	0.22 *	-10.67	1.18	0.18	-0.60	0.98	0.18 * *	-8.22	0.94	0.14 *
	CR0	N1	-0.50	0.91	0.16	-8.11	0.96	0.15						
	CR1	N0	-0.50	0.95	0.16	-4.66	0.80	0.08						
	CR1	N1	-0.79	1.24	0.24 *	-9.53	0.81	0.20						

CR1, CR0: with and without crop residues, respectively. N1, N0: with and without nitrogen, respectively. * and * *: Significant decrease of yields at 0.05 and 0.01 P levels, respectively, according to the test of Student Newman-Keuls

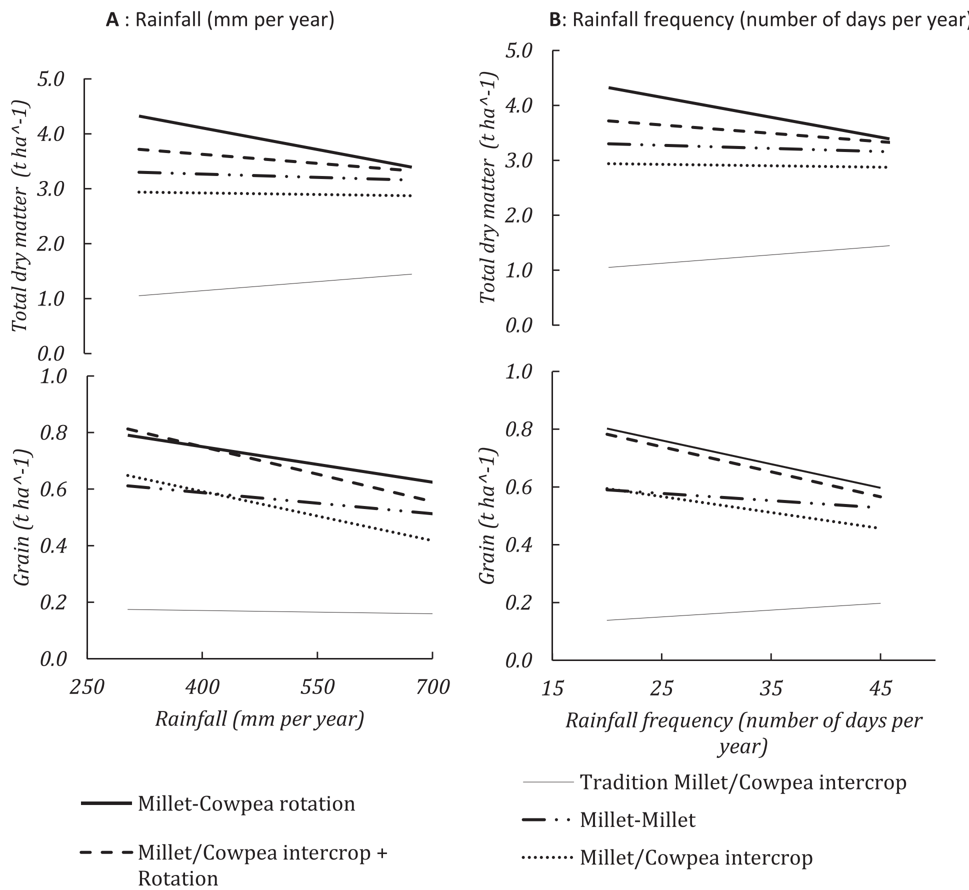

Fig. 3. Relationship between (A) total rainfall (mm per year) and millet yields (total dry matter and grain yields) and (B) rainfall frequency (number of days per year) and millet yields (total dry matter and grain yields) over 25 years of cropping. Except the traditional M/C intercrop, P fertilizer was applied at 13 kg P/ha in the four improved cropping systems.

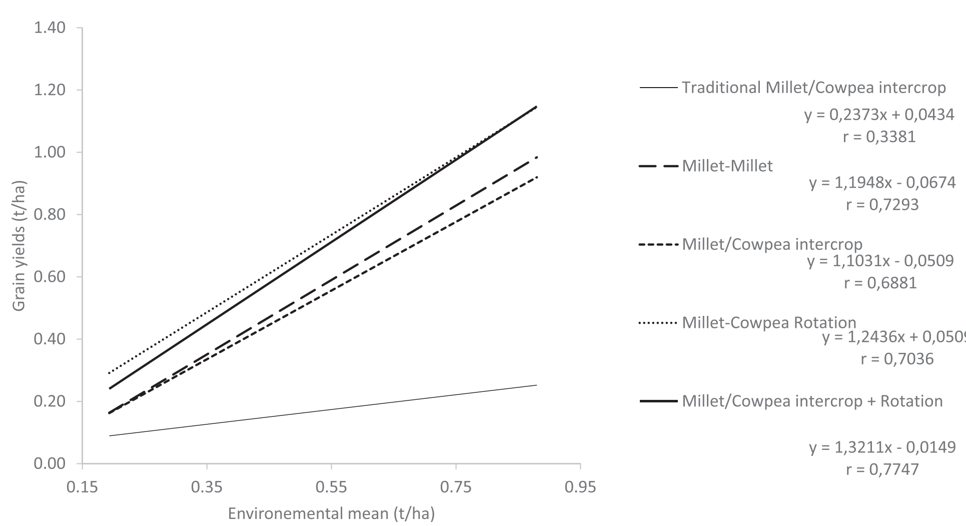

Fig. 4. Regression of millet grain yields (t/ha) on the environmental mean (t/ha) over 25 years (1995–2019) of cropping for the: (i) traditional millet/cowpea intercrop; (ii) millet-millet monocropping; (iii) millet/cowpea intercrop; (iv) millet-cowpea rotation and; (v) millet/cowpea intercrop and rotation with cowpea. Except the traditional M/C intercrop, P fertilizer was applied at 13 kg P/ha in the four improved cropping systems.

4. Discussion

The aim of this research was to identify integrated management options for smallholder farmers that sustainably improve soil fertility, crop yields and the productivity of the low-input cropping systems. Using millet as test crop to compare the cropping systems, our data revealed management options of nutrients and crop residues that could sustainably improve the productivity of cropping systems. But the different factors of the system (mineral fertilizers, crop residues and N_2-fixing cowpea) play different roles with interactions between factors. It is not easy to separate and quantify the effect of specific factor on the productivity of the global productivity of cropping systems. However,

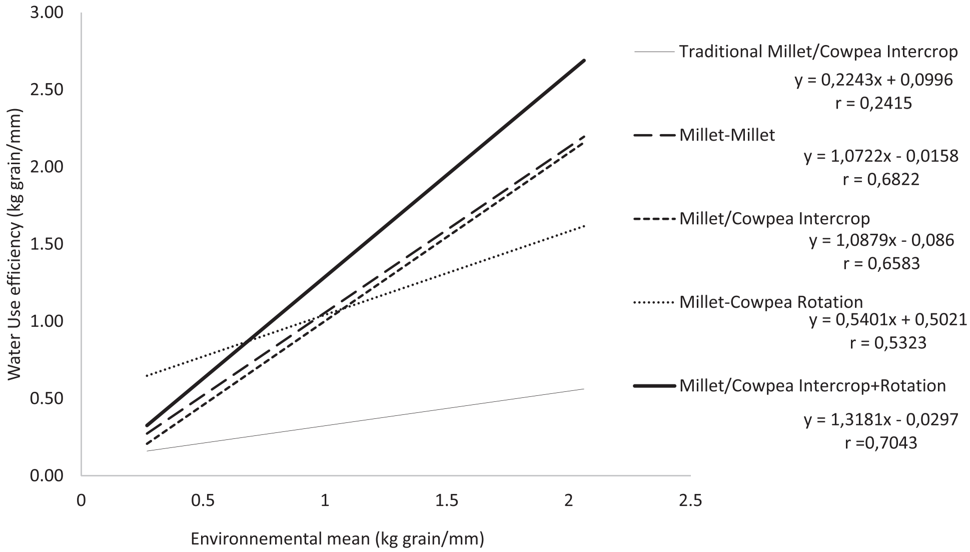

Fig. 5. Regression of water use efficiency by millet (kg grain/mm of water) on the environmental mean (kg grain/mm of water) over 25 years (1995–2019) of cropping for the: (i) traditional millet/cowpea intercrop; (ii) millet-millet monocropping; (iii) millet/cowpea intercrop; (iv) millet-cowpea rotation and; (v) millet/cowpea intercrop and rotation with cowpea. Except the traditional M/C intercrop, P fertilizer was applied at 13 kg P/ha in the four improved cropping systems.

Table 7
Annual and total production in yields (t.ha-1) and value ($US) of millet (grain and stover) and cowpea (grain and fodder) in the five cropping systems over 4 years (2017–2020).

		Years				Global production		
Cropping system	Crop	2017	2018	2019	2020	Yields (t/ha) (4 years)	Value ($US) (per crop)	Value ($US) (per cropping system)
Traditional Millet/Cowpea (TrM/C)	Cowpea grain	0.040	0.079	0.073	0.126	0.318	337[b]	778[e]
	Cowpea fodder	0.125	0.239	0.211	0.253	0.828		
	Millet grain	0.135	0.265	0.175	0.256	0.831	441[a]	
	Millet stover	0.425	0.702	0.647	0.65	2.424		
Sole millet (MM)	Millet grain	0.529	0.655	0.533	0.734	2.451	1211[a]	1211[d]
	Millet stover	1.188	1.371	1.193	1.441	5.193		
Millet/Cowpea intercropping (M/C)	Cowpea grain	0.026	0.088	0.074	0.119	0.307	351[b]	1540[bc]
	Cowpea fodder	0.089	0.302	0.25	0.301	0.942		
	Millet grain	0.573	0.636	0.544	0.632	2.385	1189[a]	
	Millet stover	1.400	1.373	1.207	1.312	5.292		
Millet-Cowpea rotation (M-C)	Cowpea grain	0.358		0.384		0.742	1023[a]	1830[a]
	Cowpea fodder	2.077		1.165		3.241		
	Millet grain		0.921		0.722	1.643	807[b]	
	Millet stover		1.894		1.476	3.37		
Millet/Cowpea intercropping and rotation with cowpea (M/C-C)	Cowpea grain (M/C)		0.019		0.037	0.056	895[a]	1594[b]
	Cowpea fodder (M/C)		0.089		0.191	0.28		
	Cowpea grain (C)	0.257		0.334		0.591		
	Cowpea fodder (C)	1.687		0.877		2.564		
	Millet grain(M/C)		0.816		0.603	1.419	699[b]	
	Millet stover(M/C)		1.696		1.268	2.964		

The prices of millet grain and stover were $US 0.388 and $US0.045/kg, respectively. The prices of cowpea grain and fodder were $US 0.588 and $US0.181/kg, respectively. Within a column, values affected by the same letter are not significantly different at $p < 0.05$ according to the Newman-Keuls test.

the relative impact of the different factors on the productivity of cropping systems can be discussed.

4.1. Mineral N and P fertilizers

The four improved cropping systems (MM, M/C, M-C and M/C-C) that received P fertilizer, increased millet GY from 3.3 to 4.2 times compared with the traditional system (TrM/C) without P fertilizer. As a consequence of P addition, all four improved cropping systems increased available soil P from 3.4 to 4 times compared with the soil under fallow (Table 1). At the same time, P applied by mineral fertilizers dramatically increased soil P. This means that P applied by mineral fertilizer feeds as well the plants as the soil, indicating that P-saturation is by far not reached and that the current low status of P probably points to long term mining of nutrients. The residual effects of P fertilizer in the improved cropping systems could explain these high levels of soil P compared with the TrM/C system, which did not receive P fertilizer. Therefore, the lowest yields and the decline of yields over time in the TrM/C system could be mainly attributed to the absence of P fertilizer. The mining of P by crops from these soils, which are inherently low in P, could explain

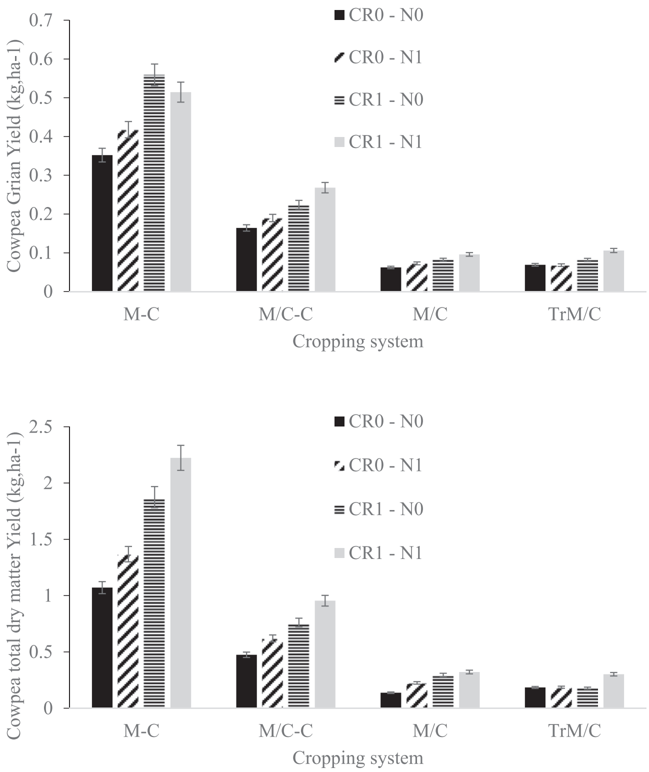

Fig. 6. Cowpea grain and total dry matter yields (kg/ha) in the five cropping systems over 4 consecutive years of cropping (2017–2020). TrM/C: Traditional Millet/Cowpea intercrop (without P fertilizer); M/C: Millet/Cowpea intercropping; M-C: Millet-Cowpea rotation; M/C-C: Millet/Cowpea intercropping and rotation with cowpea. CR0: No Cropping residues, CR1: With Cropping residues; N0: No Nitrogen fertilizer, N1: With Nitrogen fertilizer.

the low productivity of the TrM/C system and its decline over time. This is a confirmation of the important role of P as the main limiting nutrient on the weakly acid sandy soils of West Africa Sahel (WAS) as reported in previous works (Bationo et al., 2003; Sahrawat et al., 1997; Subbarao et al., 2000; Bado et al., 2010, 2021). As a consequence of nutrient deficiency, the beneficial impact of N and P fertilizers on crop productivity are widely demonstrated (Bado et al., 2010; Bationo et al., 2003a; Bado et al., 2018). Bationo et al. (2006) reported that P is the main limiting nutrient on the degraded soils of WAS. They showed that pearl millet yield could be increased by 376% by adding a small dose of 13 kg/ha P as we done in this experiment and the combined application of N and P fertilizers increased pearl millet yield by 600%. However, the efficiency of fertilizer nutrients varies with soil types and ecologies. For instance, while N deficiency is the most limiting factor than P in the humid forest zones (Sahrawat et al., 1997), P deficiency is more important in the savannah zones, the savanna-forest transition zones, and the arid and semiarid zones (Bationo et al., 2006, 2012).

However, data from many long-term experiments in upland soils reveal yield declines over time as a consequence of decreasing SOC, soil acidification, and decreasing nutrient use efficiency Pichot et al. (1981); Bationo and Mokwunye (1991a); Bationo and Mokwunye (1991b); Bado et al., 1997; Pieri (1989); Bationo et al. (2003a). In many cases, liming is frequently required to neutralize soil acidity induced by the continuous application of mineral fertilizer (Bado et al., 1997; Bationo et al., 2012). In our experiment, the application of N with or without CR always decreased soil pH from 0.2 to 1.2 units compared with the soil under fallow. However, this was not associated with significant decline of yield.

4.2. *Crop residues*

Our data indicated that the application of the residues of millet (CR) as mulch alone or associated with N fertilizer increased millet yields up to 40% and 80%, respectively compared with the control treatment. The beneficial impact of CR on millet yield was associated with an increase of both water use efficiency and the ratio of yield/environment means in the improved systems with cowpea (M-C, M/C, M/C-C) (Figs. 4 and 5). Even SOC decreased in all the treatments compared with the soil under fallow, the highest levels of SOC were obtained when N fertilizer was associated with CR. Mineral N from fertilizer has probably contributed to better mineralization of N from CR, improvement of microbial activity, leading to better level of SOC. compared with treatments without CR+N-fertilizer.

A combined effect of higher SOC associated with mineral N and CR has probably contributed to water retention with positive impact on millet production (Whitbread et al., 2003). This effect is also probably associated with the contribution of cowpea in soil protection as cover crop in intercropping systems. The incorporation of organic materials with a high C/N ratio (e.g., millet residues) sometimes induces yield decrease due to temporal immobilization of N by soil microorganisms. This was not the case in our experiment over the 25 years.

Crop residues are usually leftovers from grazing by livestock after the cropping season, which are removed by farmers for other purposes. The direct consequence is the exposure of soils in this dry environment to evaporation of water, increases in diurnal fluctuations in soil temperature, runoff or soil erosion, reductions in input of organic carbon, formation and stability of aggregates, hydraulic conductivity, and air permeability (Bationo et al., 1993; Blanco-Canqui and Lal, 2009). The removal of CR could also limit the development of earthworm populations and microbial C and N biomass (Blanco-Canqui and Lal, 2009). Through the mulching of CR, some of these residues were incorporated while protecting the soil surface, leading to the reduction of evapotranspiration, improved water retention and infiltration, and increases in water use efficiency (WUE). Similar results were reported in previous studies on the same site (Ibrahim et al., 2015a, 2015b). Buerkert et al. (2000) reported that the residue effects on weakly buffered Sahelian soils were due to a decrease in peak temperatures by 4 °C, increased water availability, improved P availability, and protection of seedlings against wind erosion. Better quality of organic amendments, such as farmyard manure, could be combined with the mulching of CR and mineral fertilizer. Similar results were reported by Yamoah et al. (2002) who found that CR significantly improved both water and nutrient-use efficiency of the applied fertilizer in the same site. Suzuki et al. (2016) also reported that the combined applications of fertilizer and crop residue increased N use efficiency (NUE), probably because CR had more potential than cattle manure to enhance the effect of fertilizers. This is supported by previous works on the important role of CR on improvement of available P, increasing K, crop roots elongation, decreasing of soil firmness, improving soil water content and reducing soil temperature, preserving the soil surface; improvement of NUE and a gradual C source (Bostick et al., 2007) that capture more nutrients in sandy soils, leading to better use of N with limited losses of N (Buerkert et al., 2000; Bationo and Buerkert, 2001; Whitbread et al., 2003; Liu et al., 2010; Suzuki et al., 2016). Mulching of CR along with inorganic fertilizer also increased microbiological activities. Our study confirms the previous work of Suzuki et al. (2016) who concluded that pearl millet residue had more potential to enhance the effect of fertilizer on crop growth and yield than cattle manure in West Africa Sahel.

4.3. *Effect of cowpea and productivity of the systems*

Although the plant density of millet in the improved millet-cowpea intercropping systems (M/C, M/C-C) was lower than that of the mono cropping of millet (MM) system, the M/C and MM produced similar yields, and the M/C-C system produced higher yields, compared with the

MM system (Fig. 4). This reflects the beneficial impact of cowpea on millet productivity. In our study, the productivity of cowpea was limited in the intercropping systems probably because of competition between the two crops for light, water and nutrients, similar to findings of Nelson et al. (2021). In general, cereals has a competitive advantage because their roots occupy both shallow and deeper soil layers and have a superior ability to recover soil mineral N, whereas root systems of legumes are smaller and confined to the upper soil layer (Hardter and Horst, 1990; Hauggaard-Nielsen et al., 2001).

Many studies have reported that cereals benefit from association or in rotation with legumes. Bado et al. (2006a) reported that legume increase cereal yields up to 50–350% in cereal-legume based systems. In the semiarid zone of West Africa, Bationo and Ntare (2000) reported that cowpea increased the succeeding pearl millet yields by 58–100%. The N-effect of N_2-legume crops was found to be the main factor that explains the beneficial effect of legumes. Within the sole cowpea treatment in the M-C and M/C-C systems, high quality residues of cowpea (senescent leaves and underground biomass) have contributed to improving soil mineral N and fertilizer use efficiency by succeeding millet crops (Bagayoko et al, 2000; Bado, 2002; Bado et al., 2006a). For example, Bado et al. (2006b), (2011) reported that sole cowpea could increase soil mineral N by 52% and the yields of succeeding sorghum by 300%. In rotation with sorghum, cowpea could provide an equivalent of 42 kg N/ha to the succeeding sorghum (Bado et al, 2012; Bado et al., 2013). The beneficial effects of these two sources of N (organic and mineral) also contributed to the highest performances of M-C and M/C-C systems. Other beneficial effects of cowpea include its role as cover crop that reduce soil erosion, nutrient leaching, weed control, improve water retention, reduce water evaporation. Although such the beneficial effects are there, intercropping systems are inherently more labour intensive. For example, Rusinamhodzi et al. (2012) reported that maize-legume intercropping required 36% more labor cost for weeding compared with the mono cropping. We did not quantify the labor cost in our study. But the relative contributions from crops revealed that cowpea contributed for 27% and 56% to the global of M/C and M-C system, respectively. The high contribution of cowpea comes from the highest value of cowpea grain and fodder.

4.4. The relationship between rainfall and millet performance

An important observation was that millet produced the lowest yields with intensive rainfalls (total and frequency) when cowpea was included in the cropping system with P fertilizer. Other factors, including nutrient availability and uptake, could have contributed to yield variations. With the difference between the two types of cropping systems (traditional and improved systems) being the absence of P fertilizer in TrM/C system, the lowest yields regardless of the rainfall levels indicated that limited availability of soil nutrients, especially P and N was the limiting factor, not rainfall (Bationo and Mokwunye, 1991a; Bado et al., 2021). Without P application, yield increase could not be expected regardless the level of rainfall. From its good quality residues (roots and leaves), cowpea provides mineral N early in the cropping season to the subsequent millet (Bado et al., 2006a). High rainfall could be associated with heterogeneous distribution over seasons with occasional increased runoff and leaching, leading to a low availability of soil nutrients. For example, low GY was observed in 1998 even though rainfall was high. Conversely, high GY was obtained in year 2001 with low rainfall (Fig. 1).

While it is common for farmers in low rainfall regions to be underfertilising due to perceptions related to risk (Monjardino et al., 2013), fertilization may be risk-neutral or even risk-reducing (Bationo et al., 2020). For example, P fertilizer and shorter-duration millet varieties speed millet growth, earlier mature, leading to the reduction the risk to damage from and exposure to drought (ICRISAT, 88, 1985). Several scientists have reported that in the dry land of the Sahel, the most limiting factors to crop production is nutrient and not water (Twomlow et al., 2010). On the same site in Niger where the annual average rainfall is 560 mm, Bationo et al. (2020), reported an increase of WUE by millet from 1.24 kg/mm (without fertilizer) to 4.14 kg/mm with the application of mineral fertilizer. While water is necessary to improve fertilizer use efficiency, fertilizers are a key to improved water use efficiency.

As observed with the stability analysis in our study, variations in the environment may come from the effects of fertilizers, changes in soil chemical and physical properties and partly from rainfall variations (Ripoche et al., 2015). This explains the efficiency of water harvesting techniques on the improvement of the fertilizer use efficiency (Bationo et al., 2020). For example, the widely adoption of Zaï technology that combines water harvesting and micro dosing of fertilizers (Ibrahim et al., 2015a) in West Africa confirms the need for integrated management of both water and nutrients in the drylands. In the context of climate change, this can be considered as a strategic adaptation for resilience.

4.5. Implication for farming systems

The main objective of this research was to investigate realistic and sustainable management options of cropping systems of poor soils with the low-input systems of smallholder farmers. Our strategic approach was based on the concept of Integrated Soil fertility Management (ISFM) to improve crop productivity. The challenge was to identify integrated management options of poor soils under the low-input systems of smallholder farmers with small quantities of fertilizer (15 kg N/ha; 13 kg P/ha) for sustainable improvement of crop yields and productivity of cropping systems. The four improved cropping systems were inspired by farmers' practices: multi-cropping systems with small doses of fertilizers. This study suggested interesting management options to improve millet cowpea based system productivity with small doses of fertilizers. We identified three interesting cropping systems with cowpea (M/C intercrop, M/C+ rotation, and M-C rotation) with 15 and 13 kg/ha of N and P, respectively, and if possible, the mulching of millet residues. The M/C intercrop could be considered as the best system in terms of productivity of millet and its consistency with the practices of farmers. The M/C-C is an inclusion of rotation with sole cowpea in the M/C system. More than M/C system, the potential production of cowpea grain and fodder in M/C-C and M-C systems could be of great interest to many farmers.

The presence of cowpea in the three systems has many advantages in the context of WAS where smallholder farmers make their livelihoods from livestock and farming. The common feed sources for livestock are open grazing and crop residues (sorghum, millet, groundnut haulms, and cowpea hay) (Ayantunde et al., 2007; Umutoni et al., 2021; Umutoni et al., 2021). The better use of N from soil and cowpea residues with the low rainfalls (well distributed), compared to the losses of N through run-off and leaching with intensive rainfalls, suggest future research is needed to improve N use efficiency in cropping systems containing cowpea. For example, an adjustment of plant density could optimize the recovery of N from fertilizers and mineral N from residues of cowpea. An increase in millet plant density on the rows of millet in the M/C system without reducing plant spacing could also be an option to improve N use efficiency in the system. Improved technologies of management of fertilizers could be associated to improve the productivity of the low-input cropping systems of farmers. For example, the hill placement of mineral and organic fertilizers through the technology of micro dosing could help improving fertilizer use efficiency and the productivity of the systems (Tabo et al., 2008, 2015b). Cowpea is both a staple and a cash crop that provides an income and quality feed for livestock. This is one of the justifications of the popularly use of millet-legume based system in West Africa Sahel. The productivity of farming systems could be improved through an integrated management approach in line with the concept of integrated soil fertility management (ISFM) that includes the use of fertilizers, organic inputs, and improved germplasm, combined with knowledge on how to adapt these practices to local conditions and farming systems (Waddington et al., 2007; Vanlauwe et al., 2010). In the context small holder's farming systems, farmyard manure, composts and other sources of available organic residues could be alternatives to crop residues. Cereal-legume based systems offer diverse benefits for food security and the resilience of smallholder farmer's farming systems (Whitbread et al. (2015).

This study also point out the need to improve rainwater use efficiency in the drylands of West Africa Sahel and how the application of small doses of mineral fertilizer with or without CR could contribute to improve water use efficiency (WUE) and crop yields. As observed in the stability analysis, the traditional system (without NP fertilizers) did not respond to the variation in environmental factors both for yields and WUE, while the four improved systems strongly responded to environment for the two factors (yields and WUE) (Figs. 4 and 5). The stability analysis of millet yields also indicated that a minimum of 350 mm of rainfall was enough to obtain the highest production with the improved cropping systems (Fig. 3). But less than this minimum of 350mn of annual rainfall was obtained only during 4 years out the 25 years of the experiment (Fig. 1). This means that the traditional system was not able to exploit the production potential of the system despite the good rainfalls. In the general opinion, rainfall is most of the time considered as the first limiting factor of agricultural production in WAS. As revealed by previous works (Bationo et al., 2020), soil poverty is probably the first limiting factor before rainfall. This calls for development of strategies to improve farmer's access to fertilizers and fertilizers recommendations, enabling a better use of rainwater in the dry ecologies.

5. Conclusion

This study showed that millet-cowpea rotation; millet/cowpea intercrop, or millet/cowpea intercrop and rotation were the most productive cropping systems. The applications of 15 and 13 kg/ha of N and P fertilizers, respectively, improved and maintained millet yields with at least 350 mm of annual rainfall during 25 days of rain over the cropping season. Poor availability of P and N were the main limiting factor in the cropping systems. We concluded that cereal-legume based cropping systems (e.g., millet and cowpea) treated with small doses of N and P could be used for sustainable management of soil fertility and the productivity of low-inputs cropping systems. Considering that in seasons with higher rainfall are associated with runoff and leaching of mineral N, future research should investigate different options, including increasing plant density for better recovery of N from fertilizers, soil, and residues of cowpea to increase the productivity of the system.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

Akponikpe, P.B., Michels, K., Bielders, C.L., 2008. Integratednutrient management of pearl millet in the Sahel combining cattle manure, crop residue and mineral fertilizer. Exp. Agric. 44, 453–472. https://doi.org/10.1017/S001447970800673X.

Ayantunde, A.A., Delfosse, P., Fernandez-Rivera, S., Gerard, B., Dan Gomma, A., 2007. Supplementation with groundnut haulms for sheep fattening in the West African Sahel. Trop. Anim. Health Prod. 39, 207–216. https://doi.org/10.1007/s11250-007-9009-1.

Bado, B.V., 2002. Rôle des légumineuses sur la fertilité des sols ferrugineux tropicaux des zones guinéenne et soudanienne du Burkina Faso (Doctoral dissertation, Université Laval).

Bado, B.V., Bationo, A., Cescas, M.P., 2006a. Assessment of cowpea and groundnut contributions to soil fertility and succeeding sorghum yields in the Guinean savannah zone of Burkina Faso (West Africa). Biol. Fertil. oil 43, 171–176. https://doi.org/10.1007/s00374-006-0076-7.

Bado, B.V., Cescas, M.P., Bationo, A., Sedogo, M.P., Traore, T., 2013. Influence of legumes on nitrogen (N) fertilizer recommendations for succeeding sorghum in the Guinea Savannah of West Africa. Afr. J. Agric. Res. 8, 6416–6421.

Bado, B.V., Lompo, F., Bationo, A., Segda, Z., Sedogo, M.P., Cescas, M.P., Mel, V.C., 2012. Nitrogen recoveries and yields improvement in cowpea sorghum and fallow sorghum rotations in West Africa Savannah. J. Agric. Sci. Technol. B2 (7B), 758–767.

Bado, B.V., Lompo, F., Sedogo, M.P., Cescas, M.P., 2010. Establishment of the critical limit of soil available Phosphorous for maize production in low acidic ultisols of West Africa. Commun. Soil Sci. Plant Anal. 41.8, 968–976. https://doi.org/10.1080/00103621003646055.

Bado, B.V., Sawadogo, A., Thio, B., Bationo, A., Cescas, M.P., 2006b. How do cowpea and groundnut improve soil fertility and succeeding sorghum yields in the Guinean Savannah Zone of Burkina Faso West Africa. Proc. Ser. 287–305. https://doi.org/10.1007/s00374-006-0076-7.

Bado, B.V., Sawadogo, A., Thio, B., Bationo, A., Traoré, K., Cescas, M.P., 2011. Nematode infestation and N-effect of legumes on soil and crop yields in legume-sorghum rotations. Agric. Sci. Vol.2 (No.2), 49–55. https://doi.org/10.4236/as.2011.22008.

Bado, B.V., Sedogo, M., Lompo, F., Maman Laminou, S.M., 2018. Biological nitrogen fixation by local and improved genotypes of cowpea in Burkina Faso (West Africa): total nitrogen accumulated can be used for quick estimation. Article ID 9641923 Adv. Agric. vol. 2018, 1–8. https://doi.org/10.1155/2018/9641923.

Bado, B.V., Sédogo, M.P., Cescas, M.P., Lompo, F., Bationo, A., 1997. Effet à long terme des fumures sur le sol et les rendements du mais au Burkina Faso. Cah. Agric. 6, 571–575.

Bado, B.V., Whitbread, A., Manzo, M.L.S., 2021. Improving agricultural productivity using agroforestry systems: performance of millet, cowpea, and Ziziphus-based cropping systems in West Africa Sahel. Agric. Ecosyst. Environ. 305, 107175 https://doi.org/10.1016/j.agee.2020.107175.

Bado, V.B., Bationo, A., 2018. Integrated management of soil fertility and land resources in Sub-Saharan Africa: involving local communities. In: Adv. Agron, 150. Academic Press,, pp. 1–33. https://doi.org/10.1016/bs.agron.2018.02.001.

Bagayoko, M., Buerkert, A., Lung, G., Bationo, A., Römheld, V., 2000. Cereal/legume rotation effects on cereal growth in Sudano-Sahelian West Africa: soil mineral nitrogen, mycorrhizae and nematodes. Plant Soil 218, 103–116. https://doi.org/10.1023/A:1014957605852.

Bationo, A., Buerkert, A., 2001. Soil organic carbon management for sustainable land use in Sudano-Sahelian West Africa. Nutr. Cycl. Agroecosys 61, 131–142. ⟨https://doi.org/10.1023/A:1013355822946⟩.

Bationo, A., Christianson, B.C., Klaij, M.C., 1993. The effect of crop residue and fertilizer use on pearl millet yields in Niger. Fert. Res. 34, 251–258. https://doi.org/10.1007/BF00750571.

Bationo, A., Hartemink, A., Lungu, O., Naimi, M., Okoth, P., Smaling, E., Thiombiano, L., 2006. African soils: their productivity and profitability of fertilizer use. In: Background paper prepared for the African Fertilizer Summit, vol. 2006. Abuja,, Nigeria, p. 25. June 9–13.

Bationo, A., Mokwunye, A.U., 1991a. Alleviating soil fertility constraints to increased crop production in West Africa: the experience of the Sahel. Fertil. Res. 29, 95–115. https://doi.org/10.1007/BF01048992.

Bationo, A., Mokwunye, A.U., 1991b. Role of manures and crop residues in alleviating soil fertility constraints to crop production: with special reference to the Sahelian and Sudanian zones of West Africa. Fert. Res. 29, 117–125. https://doi.org/10.1007/BF01048993.

Bationo, A., Mokwunye, U., Vlek, P.L.G., Koala, S., Shapiro, B.I., 2003. Soil fertility manage- ment for sustainable land use in the West African Sudano-Sahelian Zone. In: Gichuru, M.P., Bationo, A., Bekunda, M.A., Goma, H.C., Mafongonya, P.L., Mugendi, D.N., Murwira, H.M., Nandwa, S.M., Nyathi, P., Swift, M.J. (Eds.), Soil Fertility Management in Africa: A Regional Perspective. Academy Science Publishers, Nairobi, pp. 253–292.

Bationo, A., Ntare, B.R., 2000. Rotation and nitrogen fertilizer effects on pearl millet, cow- pea and groundnut yield and soil chemical properties in a sandy soil the semi-arid tropics, West Africa. J. Agric. Sci. 134, 277–284. https://doi.org/10.1017/S0021859699007650.

Bationo, A., Singh, U., Dossa, E., Wendt, J., Agyin-Birikorang, S., Lompo, F., Bindraban, P., 2020. "Improving Soil Fertility through Fertilizer Management in Sub-Saharan Africa. In: Rattan Lal (Ed.), Soil and Fertilizers: Managing the Environmental Footprint. CRC Press, pp. 67–102.

Bationo, A., Singh, U., Dossa, E., Wendt, J., Agyin-Birikorang, S., Lompo, F., Bindraban, P., 2020. "Improving Soil Fertility through Fertilizer Management in Sub-Saharan Africa. In: Rattan Lal (Ed.), Soil and Fertilizers: Managing the Environmental Footprint. CRC Press, pp. 67–102.

Bationo, A., Waswa, B., Adamou, A., Bado, V., Bonzi, M., Iwuafor, E., Kibunja, C., Kihara, J., Mucheru, M., Mugendi, D., Mugwe, J., Mwale, C., Okeyo, J., Olle, A., Roing, K., Sedego, M., 2012. Overview of long-term experiments in Africa. In: Bationo, A., Waswa, B., Kihara, J., Adolwa, I., Vanlauwe, B., Saidou, K. (Eds.), Lessons Learned From Long-Term Soil Fertility Management Experiments in Africa. Springer, Dordrecht, The Netherlands, pp. 1–26. 〈https://doi.org/10.1007/978-94-007-2938-4_1〉.

Bekunda, M., Sanginga, N., Woomer, P.L., 2010. Restoring soil fertility in sub-Sahara Africa. Adv. Agron. 108, 183–236.

Blanco-Canqui, H., Lal, R., 2009. Crop residue removal impacts on soil productivity and environmental quality. Crit. Rev. Plant Sci. 28, 139–163. https://doi.org/10.1080/07352680902776507.

Bostick, W.M., Bado, V.B., Bationo, A., Soler, C.T., Hoogenboom, G., Jones, J.W., 2007. Soil carbon dynamics and crop residue yields of cropping systems in the Northern Guinea Savanna of Burkina Faso. Soil Tillage Res. 93, 138–151. https://doi.org/10.1016/j.still.2006.03.020.

Bray, R.H., Kurtz, T., 1945. Determination of total, organic and available forms of phosphorus in soils. Soil Sci. 59, 39–46. https://doi.org/10.1097/00010694-194501000-00006.

Buerkert, A., Bationo, A., Komlan Dossa, K., 2000. Mechanisms of residue mulch-induced cereal growth increases in West Africa. SOIL Sci. Soc. Am. J. 64, 346–358.

Finlay, K.W., Wilkinson, G.N., 1963. The analysis of adaptation in a plant breeding programme. Aust. J. Agric. Res. 14, 742–754.

GENSTAT 5 Committee, 1993. GENSTAT 5 Reference Manual. Release 3. Clarendon Press, Oxford, UK.

Gomez, K.A., Gamez, A.A., 1983. Statistical procedure for agri- cultural research, 2nd edn..,. IRRI, Los Banos.

Hardter, R., Horst, W.J., 1990. Nitrogen and phosphorus use in maize sole cropping and maize/cowpea mixed cropping systems on an Alfisol in northern Guinea Savannah of Ghana. Biol. Fertil. Soils 10, 267–275.

Hauggaard-Nielsen, H., Ambus, H., Jensen, E.S., 2001. Temporal and spatial distribution of roots and competition for nitrogen in pea-barley intercrops; a field study employing 32P technique. Plant Soil 236, 63–74.

Helmke, P.A., Sparks, D.L., 1996. Lithium, sodium, potassium, rubidium and cesium. In: Bigham, J.M. (Ed.), Method of soil analysis. Part 3. Chemical methods. Soil Science Society of America/American Society of Agronomy, Madison, WI, pp. 551–574.

Ibrahim, A., Abaidoo, R.C., Fatondji, D., Opoku, A., 2015a. Integrated use of fertilizer micro dosing and *Acacia tumida* mulching increases millet yield and water use efficiency in Sahelian semi-arid environment. Nutr. Cycl. Agroecosys. 103, 375–388. https://doi.org/10.1007/s10705-015-9752-z.

Ibrahim, A., Abaidoo, R.C., Fatondji, D., Opoku, A., 2015b. Hill placement of manure and fertilizer micro-dosing improves yield and water use efficiency in the Sahelian low input millet-based cropping system. Field Crop Res. 180, 29–36. https://doi.org/10.1016/j.fcr.2015.04.022.

ICRISAT, 1985–1988. ICRISAT Sahelian Center Annual Report, 1984. International Crops Research Institute for the Semi-Arid Tropics,, Patancheru, India.

Izac, A.-M.N. 2000. "What Paradigm for Linking Poverty Alleviation to Natural Resources Management?" IN Proceedings of an International Workshop on Integrated Natural Resource Management in the CGIAR: Approaches and Lessons, August 21–25, 2000, Penang, Malaysia.

Liu, E., Changrong, Y., Xurong, M., Wenqing, H., Bing, S.H., Ding, L., Liu, Q., Liu, S., Fan, T., 2010. Long-term effect of chemical fertilizer, straw, and manure on soil chemical and biological properties in northwest China. Geoderma 158, 173–180. https://doi.org/10.1016/j.geoderma.2010.04.029.

Mando, A., Ouattara, B., Somado, A.E., Wopereis, M.C.S., Stroosnijder, L., Breman, H., 2005. Long-term effects of fallow, tillage and manure application on soil organic matter and nitrogen fractions and on sorghum yield under Sudano-Sahelian conditions. Soil Use Manag. 21 (1), 25–31.

McLean, E.O., 1983. Soil pH and lime requirement. In: Page, A.L., Miller, R.H., Keeney, D.R. (Eds.), Methods of Soil Analysis. Part 2. Chemical and microbiological properties, Second edition.,. American Society of Agronomy and Soil Science Society of America, Madison, WI., pp. 199–223. https://doi.org/10.2134/agronmonogr9.2.2ed.c12

Monjardino, M., McBeath, T.M., Brennan, L., Llewellyn, R., 2013. Are farmers in low-rainfall cropping regions under-fertilising with nitrogen? A risk analysis. Agric. Syst. 116, 37–51 doi.org/10.1016/j.agsy.2012.12.007.

Mucheru-Muna, M., Pypers, P., Mugendi, D., Kung'u, J., Mugwe, J., Merckx, R., Vanlauwe, B., 2010. A staggered maize–legume intercrop arrangement robustly increases crop yields and economic returns in the highlands of Central Kenya. Field Crops Res. 115 (2), 132–139.

Nelson, D.W., Sommers, L.E., 1983. Total carbon, organic carbon and organic matter. In: Page, A.L., Miller, R.H., Keeney, D.R. (Eds.), Methods of Soil Analysis. Part 2. Chemical and microbiological properties, Second edition.,. American Society of Agronomy and Soil Science Society of America, Madison, WI, pp. 538–578.

Nelson, W.C.D., Hoffmann, M.P., Vadez, V., Rötter, R.P., Koch, M., Whitbread, A.M., 2021. Can intercropping be an adaptation to drought? A model based analysis for pearl millet– cowpea. J. Agron. Crop Sci. 00, 1–18. https://doi.org/10.1111/jac.12552.

Pichot, J., Sédogo, M.P., Poulain, J.F., 1981. Évolution de la fertilité d'un sol ferrugineux tropical sous l'influence des fumures minérales et organiques. Agron. Trop. 036, 122–133.

Pieri, C., 1989. Fertilité des terres de savane. Bilan de 30 années de recherche et de développement agricoles au sud du sahara. Agridoc-International. Ministère de la coopération et CIRAD-IRAT, Paris, p. 444.

Raun, W.R., Barreto, H.J., Westerman, R.L., 1993. Use of stability analysis for long-term soil fertility experiments. Agron. J. 85, 159–167.

Ripoche, A., Crétenet, M., Corbeels, M., Affholder, F., Naudin, K., Sissoko, F., Tittonell, P., 2015. Cotton as an entry point for soil fertility maintenance and food crop productivity in savannah agroecosystems–Evidence from a long-term experiment in southern Mali. Field Crops Res. 177, 37–48.

Rusinamhodzi, L., Corbeels, M., Nyamangara, J., Giller, K.E., 2012. Maize–grain legume intercropping is an attractive option for ecological intensification that reduces climatic risk for smallholder farmers in central Mozambique. Field Crops Res. 136, 12–22.

Sahrawat, K.L., Jones, M.P., Diatta, S., 1997. Extractable phosphorous and rice yield in an Ultisol of the humid forest zone in West Africa. Commun. Soil Sci. Plant Anal. 28, 711–716.

Sahrawat, K.L., Jones, M.P., Diatta, S., 1997. Extractable phosphorous and rice yield in an Ultisol of the humid forest zone in West Africa. Commun. Soil Sci. Plant Anal. 28, 711–716. https://doi.org/10.1080/00103629709369823.

Sanchez, P.A., Shepherd, K.D., Soule, M.J., Place, F.M., Buresh, R.J., Izac, A.-M.N., Mokwunye, A.U., Kwesiga, F.R., Ndiritu, C.G., Woomer, P.L., 1997. Soil Fertility Replenishment in Africa: An Investment in Natural Resource Capital. In: Buresh, R.J., Sanchez, P.A., Calhoun, F. (Eds.), Replenishing Soil Fertility in Africa. SSSA Special Publication, No. 51. Soil Science Society of America, Madison, WIisconsin, pp. 1–46.

Steiner, K.G., 1991. Overcoming soil fertility constraints to crop production in West Africa: Impact of traditional and improved cropping systems on soil fertility. In: Mokwunye, A.U. (Ed.), Alleviating Soil Fertility Constraints to Increased Crop Production in West Africa. Kluwer Academic Publishers, Dordrecht, the Netherlands, pp. 69–91. 〈https://doi.org/10.1007/978-94-011-3224-4_7〉.

Subbarao, G.V., Renard, C., Payne, W.A., Bationo, A., 2000. Long-term effects of tillage, phosphorus fertilization and crop rotation on pearl millet-cowpea productivity in the West-African Sahel. Exp. Agric. 36, 243–264. https://doi.org/10.1017/S0014479700002106.

Suzuki, K., Matsunaga, R., Hayashi, K., Matsumoto, N., Tobita, S., Bationo, A., Okada, K., 2016. Long-term effects of fertilizer and organic matter application on millet in Niger. Agron. J. 108 (2), 873–883.

Tabo, R., Bation, A., Hassane, O., Amadou, Fosu, M., Sawadogo-Kabore, S., Fatondji, D., Korodjouma, O., Abdou, A., Koala, S., 2008. Fertilizer microdosing for the prosperity of resource poor farmers: a success story. Proceedings of the Workshop on Increasing the Productivity and Sustainability of Rainfed Cropping Systems of Poor, Smallholder Farmers, Tamale, Ghana, 22–25 September 2008.

Tittonell, P., Giller E., K., 2013. When yield gaps are poverty traps: the paradigm of ecological intensification in African smallholder agriculture. Field Crops Res. 143, 76–90. https://doi.org/10.1016/j.fcr.2012.10.007.

Twomlow, S., Rohrbach, D., Dimes, J., Rusike, J., Mupangwa, W., Ncube, B., Hove, L., Moyo, M., Mashingaidze, N., Mahposa, P., 2010. Micro-dosing as a pathway to Africa's Green Revolution: evidence from broad-scale on-farm trials. Nutr. Cycl. Agroecosystems 88, 3–15. https://doi.org/10.1007/s10705-008-9200-4.

Umutoni, C., Bado, V., Whitbread, A., Ayantunde, A., 2021. Assessment of stovers of dual-purpose pearl millet varieties as feed for goats in the West African Sahel. Int. J. Livest. Res. 11 (12), 37–43.

Umutoni, C., Bado, V.B., Whitbread, A.M., Ayantunde, A., Gangashetty, P., 2021. Evaluation of chemical composition and in vitro digestibility of stovers of different pearl millet varieties and their effect on performance of sheep in the West African Sahel. Acta Agriculturae Scandinavica, Section A — Animal Science (SAGA),. https://doi.org/10.1080/09064702.2021.1919193.

Vanlauwe, B., 2004. Integrated soil fertility management research at TSBF: the framework, the principles, and their application. In: Bationo, A. (Ed.), Managing Nutrient Cycles to Sustain Soil Fertility in Sub-Saharan Africa. Academy Science Publishers, Nairobi, Kenya.

Vanlauwe, B., Bationo, A., Chianu, J., Giller, K.E., Merckx, R., Mokwunye, U., Ohiokpehai, O., Pypers, P., Tabo, R., Shepherd, K.D., Smaling, E.M.A., Woomer, P.L., Sanginga, N., 2010. Integrated soil fertility management. Operational definition and consequences for implementation and dissemination. Outlook Agric. 39, 17–24. https://doi.org/10.5367/000000010791169998.

Waddington, S.R., Mekuria, M., Siziba, S., Karigwindi, J., 2007. Long-term yield sustainability and financial returns from grain legume–maize intercrops on a sandy soil in subhumid north central Zimbabwe. Exp. Agric. 43 (4), 489–503.

West, L.T., Wilding, L.P., Landeck, J.K., Calhoun, F.G., 1984. Soil Survey of the ICRISAT Sahelian Center, Niger, West Africa. Tropsoils, Texas A&M University,, College Station, TX.

Whitbread, A.M., Davoren, C., Gupta, V.V.S.R., Llewellyn, R., Roget, D., 2015. Long-term cropping system studies support intensive and responsive cropping systems in the low rainfall Australian Mallee. Crop Pasture Sci. 66, 553–565. DOI10.1071/CP14136.

Whitbread, A., Blair, G., Konboon, Y., Lefroy, R., Naklang, K., 2003. Managing crop residues of rice and wheat cropping systems in Thailand and Australia. Agric. Ecosyst. Environ. 100, 251–263. https://doi.org/10.1016/S0167-8809(03)00189-0.

Yamoah, C.F., Bationo, A., Shapiro, B., Koala, S., 2002. Trend and stability analyses of millet yields treated with fertilizer and crop residues in the Sahel. Field Crop. Res. 75, 53–62. https://doi.org/10.1016/S0378-4290(02)00008-4.