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ORIGINAL PAPER

Integrated pearl millet management in the Sahel: Effects of legume rotation and fallow management on productivity and *Striga hermonthica* infestation

O Samaké · T. J. Stomph · M. J. Kropff · E. M. A. Smaling

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Abstract Increasing population density and food needs in the Sahel are major drivers behind the conversion of land under natural vegetation to arable land. Intensification of agriculture is a necessity for farmers to produce enough food. As manure is scarce and fertilizers expensive, this study looks into the potential role of cowpea (*Vigna unguiculata* L.) and short duration fallow in maintaining soil fertility and productivity and in reducing the major weed problem *Striga hermonthica* (Del.) Benth. The research was carried out 'on-farm' in a traditional millet (*Pennisetum glaucum* (L.) R.Br.) growing area in the Malian Sahel, near Bankass. The four year experiment combined 0, 2, 5, and 7 years of preceding fallow with (i) 4 years of millet, (ii) 1 year of cowpea + 3 years of millet, and (iii) 1 year of cowpea + 3 years of millet/cowpea inter-cropping. Total millet production (4 years) was 1440 kg ha^{-1} for all systems with 2, 5 or 7 years of preceding fallow against 1180 kg ha^{-1} for systems without fallow. Cowpea grain production showed no significant differences between fallow treatments. Over 4 years, all cropping systems produced similar total amounts of millet grain, implying that the millet 'lost' during the year with a pure cowpea crop in treatments (ii) and (iii) was compensated within three years, while the cowpea grain production was an additional benefit. Such compensation was however not observed for increasing number of preceding fallow years, showing that there is no additional production benefit in 5–7 years of fallow as compared to 2 years.The soil organic carbon content decreased more slowly in treatments with a cowpea pure crop in 1998 than in the millet pure crop, while overall higher contents were observed after preceding fallow also after four years of cropping. *Striga hermonthica* infestation decreased linearly with duration of preceding fallow, but also after seven years of fallow and one year of cowpea the hemi-parasitic weed still re-appeared. Overall the intensification

Treatments used in the experiments reported here are indicated by the following abbreviations, for further details see text below.

O Samaké
Institut d'Economie Rurale (IER), BP. 208, Bamako, Mali

T. J. Stomph (✉) · M. J. Kropff
Plant sciences, Crop and Weed Ecology Group, Wageningen University, P.O. Box 430, 6700 AK Wageningen, The Netherlands
e-mail: Tjeerdjan.Stomph@wur.nl

E. M. A. Smaling
International Institute for Geo-Information Science and Earth Observation (ITC), P.O.Box 6, 7500 AA Enschede, The Netherlands

E. M. A. Smaling
Plant Sciences, Plant Production Systems Group, Wageningen University, P.O. Box 430, 6700 AA Wageningen, The Netherlands

through a cowpea pure crop and cowpea intercrop in these millet-based systems improved production and a number of other characteristics of the system, making it more viable.

Keywords Cowpea · Intercropping · Rotation · Sahel · Sub-Saharan Africa

Abbreviations

F0	no fallow preceding the 4 years experiment
F2, F5 and F7	respectively, 2, 5 and 7 years fallow preceding the 4 years experiment
4*M	4-years cropping of a pearl millet monocrop
C-3*M	a cowpea crop in the first year followed by 3 years of pearl millet monocrop
C-3*M/C	a cowpea crop in the first year followed by 3 years of a pearl millet/cowpea intercrop

Introduction

Increasing population density in the West-African Sahel requires increased food production. Production increases during the past decades have been obtained mainly through an increase in land area under cultivation, at the expense of natural vegetation and long-term fallows (Dixon et al. 2001).Using FAO statistics for Senegal, Gambia, Mauritania, Mali, Niger Chad and Burkina Faso of two 5-year periods (1988–1992 and 1998–2002), Samaké (2003) found an increase in area under cultivation of 17.3% (from 8010 to 9400 km^2) against 4.9% increase in per unit area production (from 507 to 532 kg ha^{-1}). To sustain the population living on millet-based diets, intensification is needed as the current rate of agricultural area expansion cannot be maintained for lack of uncultivated land. Also, further area expansion is undesirable from a global environmental perspective.

Bationo et al. (1995) reported that continuous cultivation of cereals in the Sahel zone has led to a drastic reduction in organic matter contents and a subsequent soil acidification. In northern Nigeria, Jones (1971) found that during 18 years of continuous cropping, soil organic matter declined at a rate of 3–5% per annum. Continuous cereal cropping systems negatively influence soil physical characteristics like crusting (Juo and Lal 1977; Piéri 1989; Valentin et al. 2004) and the incidence of the hemiparasitic weed *S. hermonthica* is linked with short fallow rotations and continuous cropping at low inputs. *S. hermonthica* is reported to be one of if not the most important and persistent weed problems in sub-Saharan Africa (Oswald 2005).

Several studies (e.g., Prudencio 1993; Smaling et al. 1996) have shown that traditionally farmers in large parts of West Africa apply all available organic fertilizers in fields around the village compounds (the so-called home fields). Also in Kenya differential fertilisation exists between fields closer and at some distance from homestead (Tittonell et al. 2005). A recent survey in the Seno zone in northern Mali showed that this fertilized area represents only approximately 1% of the village territory (Samaké et al. 2005). Reasons for this localized application include the low amount of manure produced and the lack of transport means to apply organic fertilizers further away (i.e. in bush fields). Samaké et al. (2005) report soil organic carbon contents of 5.5 vs. 1.5 g kg^{-1} and 8.4 vs. 2.5 mg P kg^{-1} soil, for home fields and bush fields, respectively. Millet grain yields were about 1000 kg ha^{-1} in home fields and declined to 250 kg ha^{-1} in bush fields. *S. hermonthica* infestation was more severe in bush fields (between 6000 and 32000 plants ha^{-1}) than in home fields (zero to 1000 plants ha^{-1}, Samaké et al. 2005).

A combination of mineral and organic fertilizers may restore soil fertility and increase crop yields (Bationo et al. 1998; Piéri 1989; Van Reuler and Janssen 1989), but organic fertilizers often are in short supply, and mineral fertilizers often prohibitively expensive and poorly available (Samaké et al. 2005; Témé et al. 1995). Therefore, technologies not based on fertilizers for bush fields require attention, improving soil and grain productivity and keeping *S. hermonthica* infestation at tolerable levels under reduced fallow duration.

One option to enhance system productivity is the introduction of legume crops in rotation or as an intercrop with millet after short-term fallow. Sanginga et al. (2003) described the successful introduction of dual-purpose cowpea in the savannas of Nigeria. In this article, dual-purpose cowpea is tested as a starter for intensification. The overall hypothesis is that inclusion of a legume in the rotation directly following short duration fallow can improve system productivity, i.e. the productivity in terms of yield during the full duration of a rotation (cf. Klaij et al. 1994; Fresco et al. 1994). Earlier studies have shown that cereal–legume rotations and intercrops improve soil chemical characteristics (Bagayoko et al. 1992; Gakale and Clegg 1987; Reddy et al. 1990, 1992) and reduce *S. hermonthica* infestation (Reddy et al. 1994). However, Bationo and Ntare (2000) found that fallow–millet rotations supplied more mineral N than legume–millet rotations. There is however, little quantitative information on the combination of system productivity, *S. hermonthica* infestation and soil chemical characteristics in fallow–millet, fallow–legume–millet and fallow–legume–millet/legume intercrop rotations under Sahelian agro-climatic conditions. In this study we focused our research on improvement of the cropping systems on bush fields, because of the relative importance of the bush-field area and the larger fertility and weed problems.

Hence, the objective of this study is to evaluate system productivity over a period of four cropping seasons for combinations of the following management options:

- the range of fallow periods currently encountered in the study area, i.e. 0, 2, 5 and 7 years (Samaké et al. 2005), and
- four years cultivation of a millet sole-crop (4*M), three years cultivation of a millet pure crop after a cowpea sole-crop (C-3*M), or three years of a millet/cowpea intercrop after a cowpea sole-crop (C-3*M/C). From these combinations, options for system intensification can be derived.

Materials and methods

Experimental site

A four-year on-farm study was conducted between 1998 and 2001 in Lagassagou, a village located in the Sahelian zone of Mali, Bankass area (between 3°15′ to 4°05′ W and 13°10′ to 14°15′ N). Soils were homogeneously sandy with a low organic matter and nutrient content. 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.

Treatments

The basic experimental set-up was a split-plot design with four lengths of the fallow period (0, 2, 5, and 7 years, respectively, F0, F2, F5 and F7) as main plot treatments. Prior to all these fallow treatments the fields had been cropped for 3–5 years with millet. For each fallow period, there were four replicates in the bush fields of the village territory, so a total of 16 fields were used. All fields had been infested by *Striga hermonthica* (Del.) Benth. 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 or heterogeneity of the infestation in the different fields could be given by the farmers. Previous investigations in the area (Samake et al. 2005) have shown that as the duration of the fallow period increased from 1 to 7 years the density of trees and shrubs increased gradually from 560 to 777 plants ha^{-1}. The total above-ground herbaceous biomass of these fallow fields was largest in fallow of 4–6 years. Graminaceous species such as *Pennisetum pedicellatum* and the leguminous species *Alysicarpus ovalifolius* dominated in the early years, while other leguminous species (*Cassia mimosoide* and *Zornia glochidiata*) catch up somewhat in year 6 and 7.

The three sub-plot treatments were different rotations: four years of pearl millet (*Pennisetum glaucum* (L.) R.Br.) monocrop (4*M), one year of cowpea (*Vigna unguiculata* L.) followed by three years of pearl millet monocrop (C-3*M) and one year of cowpea followed by three years of a pearl millet/cowpea intercrop (C-3*M/C) (Table 1). The main plots were 300 m^2 and sub-plots 100 m^2.

Table 1 Schedule of cropping sequence in the tested crop rotations

Cropping systems	Crops cultivated			
	1998	1999	2000	2001
4*M	Millet	Millet	Millet	Millet
C-3*M	Cowpea	Millet	Millet	Millet
C-3*M/C	Cowpea	Millet/Cowpea	Millet/Cowpea	Millet/Cowpea

Crop husbandry

In 1998, monocultures of well-adapted local cultivars of pearl millet (cv. Toroniou) and cowpea (cv. IT89DK-245) were sown after the first major rainfall event on ridges to avoid seedling mortality by sand-blasting. The same cultivar of millet was homogeneously planted in all plots in the following three seasons. Plots were planted following the first major rainfall event in all years (cf. Fig. 1), 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 1.0 m between and within rows and thinned to three plants per hill 15 days after emergence. Cowpea in the pure crop was sown at 0.5 m by 0.25 m spacing. In the intercropped millet, cowpea was sown 15 days after millet emergence 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. Cowpea hills were sown at 3–6 grains and thinned to two plants at 20 days after sowing. At harvest crop residues were removed for feeding to animals, as would be the case under standard farming practice, but animals were not allowed to graze on the plots. No fertilizers or pesticides were applied, in conformity with current cropping practices in the area. All plots were kept weed-free by manual hoeing until 35 days after emergence of millet and before the apparition of *S. hermonthica*.

Observations and analyses

Prior to sowing in 1998, soil samples were taken from the first 15 cm of the soil profile in a 2 by 2 m grid and bulked per replication of each fallow treatment. A sub-sample was analysed for soil organic C and soil N, P and K content. The other years, before planting soil samples were taken from each sub-plot at 0–15 cm depth in a 2 by 2 m grid, and bulked per sub-plot. A sub-sample was analysed for soil organic C and soil N content. At maturity, heads of millet and pods of cowpea were harvested from each plot, sun-dried for two weeks to around 10% moisture content, threshed and weighed to determine grain yield. Total vegetative above-ground dry matter was determined by collecting all remaining above-ground biomass from the same plots. This material was cut into short pieces, weighed and a 2 kg sub-sample was weighed and dried in a force-draught oven at 60°C for 72 h and weighed again to determine moisture percentage. For each plot the

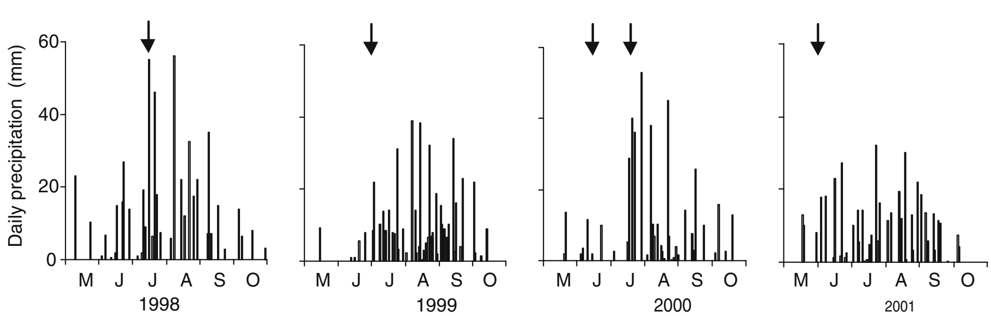

Fig. 1 Daily rainfall (May–October) in Lagassagou village in 1998–2001, the arrows indicate the sowing dates. In 2000 the millet had to be sown a second time after the early season drought

remaining biomass was sun-dried for two weeks and sampled to determine N concentration. The number of *S. hermonthica* shoots was counted in all plots two weeks prior to harvesting.

Chemical analyses were carried out at the national soil and plant laboratory of Sotuba in Bamako, Mali. Soil organic C was determined using the Walkley–Black method (Nelson and Sommers 1982), soil and plant total N was determined as described by Nelson and Sommers (1980).

Analysis of variance were carried out using Genstat version 8 and post-hoc testing of treatment differences was done using the Student–Newman–Keuls procedure at $P < 0.05$. For system productivity analysis, single degree of freedom orthogonal contrast were tested. First we compared the two systems with cowpea in 1998 with the system without cowpea, thereafter, we compared the system with the millet cowpea intercropping with the pure millet after cowpea system. The effect of fallow was analysed using orthogonal contrasts also comparing the no-fallow treatment with the fallow treatments (one degree of freedom) and thereafter comparing the three treatments with fallow among each other (two degrees of freedom).

Results

Rainfall

Seasonal rainfall in 1998 was 581 mm, which is close to the 10-year average (1992–2001) rainfall of 570 mm in Lagassagou (Samake 2003). In 1999, 2000 and 2001, precipitation was less than this 10-year average with 522 mm, 438 mm and 460 mm, respectively. Rainfall distribution (Fig. 1) was favorable for crop growth in 1998, 1999 and 2001. In 2000, a long period of 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 yields

The 1998-cowpea crop (C-3*M) increased millet grain yield in 1999 and 2001 significantly ($P < 0.05$) by 37% and 34%, respectively, compared with millet grown after the 1998 millet crop (4*M), and independent of the fallow treatment (Table 2). Overall millet yields obtained in 2000 were much smaller than in 1999 and 2001 and no significant differences ($P > 0.05$) were observed between the different cropping systems. The low grain yields occurred after late replanting as the first sowing failed due to early season drought.

The millet yield in the millet/cowpea intercrop in 1999 and 2000, sown on plots with a cowpea monocrop in 1998 (C-3*M/C) was similar to the yield in the millet monocrop sown after a cowpea monocrop (C-3*M) (Table 2). In the third growing season (2001), millet yield was 25% greater in C-3*M/C than C-3*M and 69% higher than in the continuous millet treatment (4*M).

No interactions ($P > 0.05$) were observed between length of the fallow period and the cropping system treatments. In all years, millet yields were less on the no-fallow plots than on the fallowed plots as indicated by the tested orthogonal contrasts. 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.

Cowpea grain yields in all years were similar for all treatments (Table 3). Data on the 2001 cowpea grain yields are missing as the cowpea beans were taken by the farmers prior to observations to solve food shortages after the disastrous 2000 yields.

System productivity

Total millet production over the three years millet/cowpea intercrop following the pure cowpea crop in 1998 (C-3*M/C) was the same (Table 2) as the total produced in four years of continuous millet monoculture (4*M), and only 7% less when no intercrop was sown (C-3*M). In addition to the millet, farmers could, on average, harvest 949 kg cowpea grain from the rotation and the intercropping in three years. The same effect was observed for all fallow treatments. Total millet production differed between fallow durations (Table 2) with the highest productivity for the longer fallow duration, but no clear trend with an

Table 2 Effects of fallow–cowpea–millet rotation systems on millet production in 1998, 1999, 2000 and 2001, on total millet production between 1998 and 2001 and on millet production per year of the cropping system, calculated over cropping and fallow period together

Cropping systems	1998 (kg ha^{-1})	1999 (kg ha^{-1})	2000 (kg ha^{-1})	2001 (kg ha^{-1})	Total millet production 1998–2001 (kg ha^{-1})	Average system millet productivity (kg. ha^{-1}. year^{-1})
Cropping system (CS)						
4*M	–	433 ^{b,*}	240 ^{b}	323 ^{c}	1400 ^{a}	207 ^{a}
C-3*M	–	590 ^{a}	257 ^{a}	434 ^{b}	1310 ^{a}	191 ^{a}
C-3*M/C	–	585 ^{a}	247 ^{ab}	545 ^{a}	1420 ^{a}	213 ^{a}
SED^{A}		56.2	6.2	37.8	64.5	10.1
$P > F^{B}$		0.014	0.05	< 0.001	0.22	0.11
Fallow duration (F)						
F0 (no fallow)	339 ^{a}	375 ^{a}	203 ^{a}	361 ^{ab}	1180 ^{b}	289 ^{a}
F2 (2 year fallow)	372 ^{a}	556 ^{a}	282 ^{a}	509 ^{a}	1470 ^{a}	245 ^{b}
F5 (5 year fallow)	400 ^{a}	601 ^{a}	250 ^{a}	319 ^{b}	1300 ^{ab}	145 ^{c}
F7 (7 year fallow)	418 ^{a}	612 ^{a}	258 ^{a}	546 ^{a}	1560 ^{a}	141 ^{c}
SED	53.5	89.9	32.4	71.7	99.5	18.2
$P > F$	0.51	0.09	0.18	0.03	0.02	< 0.001
Interactions CS × F						
$P > F$	–	0.94	0.08	0.33	0.26	0.07

The letter combinations to indicate cropping systems are explained in Table 1

[A]Standard error of the difference

[B]Probability of treatment effects (level of significance)

*Means within a column and treatment comparison followed by the same letter are not significantly different

Table 3 Effects of fallow–cowpea–millet rotation systems on cowpea production in 1998, 1999, 2000, on total cowpea production between 1998 and 2000 and on cowpea production per year of the cropping system, calculated over cropping and fallow period together

Cropping systems	1998 (kg ha^{-1})	1999 (kg ha^{-1})	2000 (kg ha^{-1})	Total 1998–2000 (kg ha^{-1})	Average system cowpea productivity^{C} (kg ha^{-1} year^{-1})
Cropping system (CS)					
C-3*M	–	–	–	419 ^{b}	78 ^{b}
C-3*M/C	–	198	332	949 ^{a}	179 ^{a}
SED^{A}	–			31.1	5.2
$P > F^{B}$	–	–	–	< 0.001	< 0.001
Fallow duration (F)					
F0 (no fallow)	400 ^{a}	208 ^{a}	333 ^{a}	671 ^{a}	224 ^{a}
F2 (2 year fallow)	408 ^{a}	181 ^{a}	356 ^{a}	676 ^{a}	135 ^{b}
F5 (5 year fallow)	446 ^{a}	194 ^{a}	313 ^{a}	700 ^{a}	88 ^{c}
F7 (7 year fallow)	421 ^{a}	208 ^{a}	326 ^{a}	689 ^{a}	69 ^{c}
SED	64.6	55.7	57.7	43	9.1
$P > F$	0.89	0.95	0.9	0.9	< 0.001
Interactions CS × F					
$P > F$	–	–	–	0.98	< 0.001^{D}

The letter combinations to indicate cropping systems are explained in Table 1

[A]Standard error of the difference

[B]Probability of treatment effects (level of significance)

[C]The averages are calculated for the period 1998–2000 plus the preceding fallow period, excluding the year 2001 for which data are lacking (see text)

[D]For further information on this interaction see Fig. 2

increase in fallow duration was observed as the F5 treatment consistently had a low millet production in 2001 as mentioned above. Total cowpea production on the contrary was not affected by the duration of the fallow preceding the experiment (Table 3).

When the average productivity per year was considered, compensating for the duration of the fallow period, productivity gradually fell with an increase in fallow duration for both the millet (Table 2) and the cowpea (Table 3), indicating that the higher productivity in some of the fallow treatments did not compensate for the fallow years in which no millet or cowpea was produced. For the average cowpea system productivity an interaction ($P < 0.05$) was observed between cropping system and fallow duration (Fig. 2). At longer fallow duration the difference in system productivity is smaller than at shorter fallow duration, but the interaction does not compromise the main effects.

Nitrogen uptake

Nitrogen uptake in millet above-ground dry matter was higher ($P < 0.05$) in 1999 and 2001 when millet followed cowpea (C-3*M and C-3 M/C) than when it followed millet (4*M) (Table 4). No significant differences ($P > 0.05$) between N uptake from the different cropping systems were observed in 2000. A significant ($P < 0.05$, Table 4) increase in N uptake was observed after fallow (F2–F7) compared to the no-fallow treatment (F0). In all three years increasing fallow duration did not ($P > 0.05$) increase millet N uptake. Increased N uptake was accompanied by an increase in the N mass fraction (data not shown). In other words both total N yield and above ground biomass N mass fraction increased providing more and better quality fodder for the farm animals.

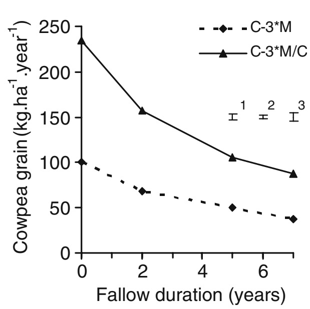

Fig. 2 Interaction between the effects of cropping systems and of the fallow duration on cowpea grain production per year, calculated over the total of cropping and fallow period. Error bars show standard error of the difference between means for comparisons of (1) fallow duration treatments, (2) cropping system treatments, (3) all treatments combined. Letters indicating cropping systems are explained in Table 1

Table 4 Effects of fallow–cowpea–millet rotation systems on millet nitrogen uptake (kg ha^{-1}) in the village Lagassagou in northern Mali

Cropping systems	1999	2000	2001
Cropping system (CS)			
4*M	22.1 ^{c,*}	13.1 ^{a}	13.2 ^{b}
C-3*M	30.9 ^{a}	15.0 ^{a}	21.0 ^{a}
C-3*M/C	27.0 ^{b}	12.9 ^{a}	23.7 ^{a}
SED^{A}	0.98	0.97	1.82
$P > F^{B}$	< 0.001	0.251	0.001
Fallow duration (F)			
F0 (no fallow)	21.0 ^{b}	9.6 ^{b}	12.4 ^{b}
F2 (2 year fallow)	27.5 ^{a}	15.4 ^{a}	19.2 ^{a}
F5 (5 year fallow)	28.8 ^{a}	15.2 ^{a}	22.4 ^{a}
F7 (7 year fallow)	29.4 ^{a}	14.4 ^{a}	23.2 ^{a}
SED	1.14	1.12	2.1
$P > F$	< 0.001	0.002	0.003
Interactions CS × F			
$P > F$	0.24	>0.99	0.99

The letter combinations to indicate cropping systems are explained in Table 1

[A]Standard error of the difference

[B]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

At the start of the experiment the soil carbon and N content differed between the no-fallow and fallow treatments, but not between the 2, 5 and 7 year fallow plots (Table 5). In all cropping systems the carbon and N content decreased between 1998 and 2001. The rate at which soil carbon was lost differed ($P < 0.05$) between the cropping systems (Fig. 3) and fallow treatments (Table 5), and there were interactions between these treatments (Table 5).

The difference in soil organic C between the no-fallow plots and the plots where a fallow period preceded the experiment persisted until 2001

Table 5 Effects of fallow–cowpea–millet rotation systems on organic carbon and total nitrogen content (g kg^{-1}) in the soil. CS stands for cropping systems

Treatments	Soil organic C				Soil N			
	1998	1999	2000	2001	1998	1999	2000	2001
Fallow duration								
F0 (no fallow)	1.64 ^{b,*}	1.92 ^{b}	1.61 ^{c}	1.31 ^{b}	0.14 ^{b}	0.19 ^{a}	0.17 ^{c}	0.12 ^{b}
F2 (2 year fallow)	2.57 ^{a}	2.25 ^{ab}	2.17 ^{b}	2.20 ^{a}	0.20 ^{a}	0.21 ^{a}	0.19 ^{b}	0.14 ^{b}
F5 (5 year fallow)	2.78 ^{a}	2.64 ^{a}	2.59 ^{a}	2.17 ^{a}	0.21 ^{a}	0.23 ^{a}	0.21 ^{ab}	0.18 ^{ab}
F7 (7 year fallow)	2.92 ^{a}	2.51 ^{a}	2.23 ^{b}	2.03 ^{a}	0.24 ^{a}	0.23 ^{a}	0.23 ^{a}	0.20 ^{a}
SED[A]	0.15	0.16	0.1	0.08	0.01	0.02	0.01	0.02
$P > F$[B]	0.001	0.02	< 0.001	< 0.001	0.013	0.52	0.009	0.006
Interactions CS × F P > F	–	0.56	0.59	0.15	–	0.51	0.998	0.42

[A]Standard error of the difference

[B]Probability of treatment effects (level of significance)

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

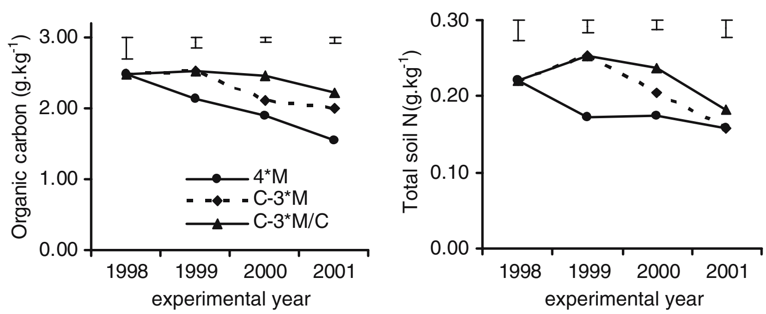

Fig. 3 Effects of cropping systems on organic carbon and total nitrogen contents in the top soil 0–15 cm, between 1998 and 2001. The letters indicating the cropping systems are explained in Table 1

(Table 5). No major and consistent differences were observed between the plots with a fallow. The soil N content differences observed at the start of the experiment between the no-fallow and fallow plots were gradually reduced during the four years of cropping, though some differences still persisted in 2001 (Table 5).

The 1998 cowpea crop seemed to improve both the soil N content and maintain the soil C content between the start of the 1998 and the start of the 1999 rainy season (Fig. 3). The significant difference ($P < 0.05$, Fig. 3) in soil N content in 1999 is an indication of the positive role of the cowpea mono-crop in enhancing soil N content. Sowing an intercrop in 1999 further maintained the soil N content at a higher level in 2000, while no differences ($P > 0.05$) were observed in 2001. Soil organic carbon seemed to be lost more slowly when a cowpea mono-crop was included in the system and yet more slowly when also a cowpea intercrop was included when millet was grown (Fig. 3). In 1999 the cowpea intercrop had a positive effect on soil organic C maintenance, as soil organic C content was higher ($P < 0.05$) at the start of the 2000 rainy season compared to the C-3*M treatment. However, no differences ($P > 0.05$) were observed between these treatments at the start of the 2001 rainy season so the treatment did not have a consistent effect over time.

Effects on S. hermonthica

S. hermonthica plants were only observed in 1998, 1999 and 2001, in 2000 no *S. hermonthica* was observed in the experiment or in farmers fields in the village. No differences ($P > 0.05$) were observed in *S. hermonthica* infestation between the different cropping systems in either 1999 or 2001 (Fig. 4).

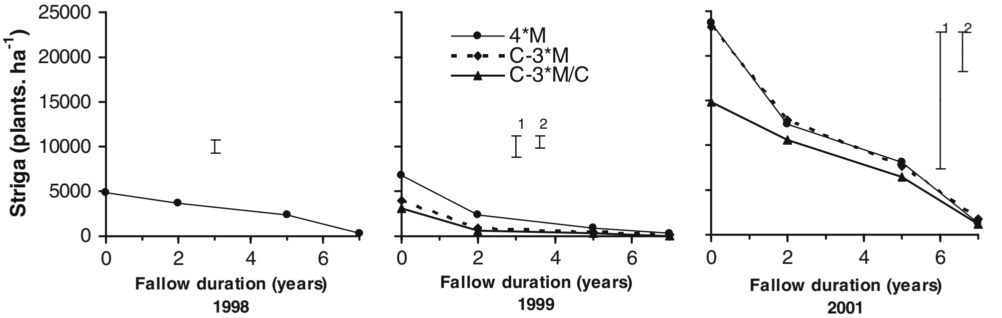

Fig. 4 Influence of cropping system and fallow duration on *S. hermonthica* infestation (plants ha^{-1}) in 1999 and 2001 Note that the levels of *S. hermonthica* infestation differ between years and no *S. hermonthica* was observed in 2000. Error bars show standard error of the difference between means for comparisons of (1) fallow duration treatments and (2) cropping system treatments at a same level of fallow treatment. The letters indicating the cropping systems are explained in Table 1

Fallow duration affected *S. hermonthica* infestation ($P < 0.05$, Fig. 4). In all three years, inclusion of a polynomial contrast for fallow duration gave a significant linear term ($P < 0.001$, $P = 0.005$ and $P = 0.03$, respectively for 1998, 1999 and 2001) and no significant ($P > 0.05$) quadratic term. Interaction in 1999 and 2001 between the cropping systems and the linear term of the polynomial contrast indicated that the slope of the decrease in *Striga hermonthica* numbers with increasing fallow duration was higher ($P < 0.05$) for the millet monocrop (4*M) than for the two other cropping systems in 1999, while the slope for the millet–cowpea intercropping (C-3*M/C) treatment was less steep ($P < 0.05$) in 2001 than for the two other treatments.

Discussion

Inclusion of soil organic matter, soil nitrogen or *Striga hermonthica* populations as covariates in the analysis of millet production appeared to provide no further explanation of experimental error. These have therefore not been presented in the above tables.

The sample size of the soil samples may not have been sufficient to provide sound enough estimates of soil parameters at individual plot levels for inclusion as covariates. At the level of treatment means it is observed that the higher millet production in 1999 and 2001 after inclusion of cowpea in the rotation is accompanied by a slightly higher soil organic matter in 1999, but not consistently in 2001. Also *Striga hermonthica* infestation tended to follow the same differences as observed for millet production, but again not providing a real explanation for the observed millet differences. Hence, the exact processes through which the productivity is enhanced in the cropping systems in which cowpea was included or in which a longer fallow period was preceding the millet crops have not been elucidated in this study.

Cowpea rotation and intercrop effects

Inclusion of cowpea in rotation with millet increased millet yield by 37, 0 and 34% in the three years following one-year cowpea monocrop (C-3*M) over yield in continuous millet monocrop (4*M). The observed increase is comparable to results obtained in studies by Bagayoko et al. (1992) and Kouyate et al. (2000) who found sorghum and millet yield increases between 20% and 40% when cereals followed, respectively, a soybean or cowpea crop compared to continuous cereal cropping. In other studies, though, two-fold (Subbarao et al. 2000) and even three-fold (Reddy et al. 1994) increases in pearl millet yield grown in rotation with cowpea on sandy soils have been reported in the first year of millet cropping. In both these studies, however, P fertilizer had been used, and in the former study millet and cowpea were alternated yearly and animal traction was used to make ridges, while in the latter study millet followed three years of consecutive cowpea monocropping. The much higher increases therefore seem to be found only when more intensive cultivation practices are applied.

Next to the enhanced millet yield also the N mass fraction in the vegetative biomass was enhanced by the cowpea crop and soil organic carbon content remained higher in the three years following the cowpea crop (both the C-3*M and C-3*M/C treatment), when compared to the system with continuous millet production (4*M). This increase of both N uptake and millet N mass fraction has also been found by Reddy et al. (1992) after three years of cowpea crop, but contrasts with Reddy et al. (1994) who found a 25% decrease in N mass fraction at an increased N-uptake after three years of cowpea. In both studies P fertilizer was used on the cowpea crop, with the higher P fertilization applied in the 1994 study in which a decrease was observed. In other words the improved N mass fraction can be expected in otherwise low fertility conditions, but not necessarily in more fertile systems.

Including a cowpea intercrop in alternate-row configuration with millet in the years following the cowpea (C-3*C/M) did not affect ($P > 0.05$) millet grain yield compared to a millet monocrop in the first and the second year after the cowpea crop. Millet yields were not lower in the presence of additional cowpea despite the extra competition, a phenomenon observed more often in the Sahel at the applied planting densities and with delayed sowing of cowpea (e.g., Subbarao et al. 2000; Reddy et al. 1992, 1994). By the third growing season, millet yield in the intercrop even increased by 22% over the sole crop, possibly taking advantage of the higher soil fertility as indicated by the higher soil organic C content. Soil N content did not seem to be correlated with the differences in millet production between treatments but as soil nitrogen content is strongly influenced by early rains and not all samples were always taken prior to the first rains, the differences between years are difficult to interpret.

The observed soil quality differences between the cropping systems indicate that including a cowpea sole-crop improves the soil thus enabling a longer cropping period. From this four years experiment the exact prolongation cannot be determined. Moreover, the positive influence we observed does not correspond with effects found by Subbarao et al. (2000) in their 11 years experiment on similar sandy soils in Niger. They observed an average linear decrease of soil organic carbon of 0.02% per year in all tested cropping systems (sole millet, millet-cowpea rotation and millet/cowpea intercropping). Their systems started off at a higher organic C content (almost 0.4%) and ended at comparable contents as we found (just under 0.2%). The decrease rate in our study ranged from 0.03% to 0.01% per year and given the shorter period is difficult to compare. It cannot be concluded whether the positive effect reported here would be maintained over a much longer period.

Striga hermonthica

The data on *Striga hermonthica* are less conclusive than the data on millet production and soil organic C content. The inclusion of cowpea as sole or intercrop into the millet production system did not seem to have any effect on this noxious weed. This conflicts with the *S. hermonthica* suppression Reddy et al. (1994) reported after three years of cowpea sole crop and which they attributed to the effect of the N input into the soil. Their observed suppression may in fact have also been the effect of three years without a host and it was not seen here after a single year of cowpea sole crop. A trend of lower infestation when cowpea was grown in intercrop with millet (C-3*M/C) was expected and seems to be there, but the overall variability was too large to allow us to distinguish between treatment means (CV was 32% and 58% in 1999 and 2001, respectively). The rather high variability is inherent to *S. hermonthica* research when experiments are carried out using existing infestation. The lack of *S. hermonthica* infestation in 2000 in all treatments (and farmers' fields) might be due to the late re-sowing of the millet crop in that year, as farmers claim that late sowing always is accompanied by low infestation or absence of *S. hermonthica*, a phenomenon also observed by Bielders and Michels (2002).

The only option to reduce *S. hermonthica* infestation, as observed in this study, is to include longer fallow duration. However, this would reduce the per unit land area productivity and is therefore only an option under lower land pressure or on small areas. Whether other management options such as intensive weeding or several years of cowpea on infected (patches of) fields would work requires further study. Current infection levels in the experimental fields cannot be expected to trigger large attention from farmers as there is no clear correlation between the degree of infestation and yield of a plot.

Intensification options for millet based cropping systems

The objective of our study was to analyse the overall productivity of the different systems in farmers' bush fields. We conclude that total millet produced in three years after one year cowpea crop was the same as the total millet produced in a 4-years period with millet only (Table 2). In other words if farmers would grow cowpea on 25% of a field and millet or a millet–cowpea intercrop on the remaining 75% and would rotate the area under cowpea they would produce the same amount of millet (roughly 320 kg ha^{-1} $year^{-1}$) as when they would only grow millet on the same field. In addition, farmers could harvest roughly 330 kg ha^{-1} $year^{-1}$ of cowpea grain from the rotation and the intercrop. Further advantages are higher quality millet fodder and a substantial amount of cowpea fodder for animal feed. Especially when increasing land pressure will lead to less fallow land for grazing, this enhanced production of animal feed should help intensification, maintaining availability of animal manure for home fields. This component of the farming system cannot easily be quantified from our data and will need further quantification in terms of improved system productivity and security for a full understanding of intensification options. Yields of cowpea in the millet/cowpea intercrop were higher in 2000 than in 1999, 340 vs. 200 kg ha^{-1}, respectively, and only 20% lower than the yields in the 1998 pure cowpea (420 kg ha^{-1}). Such an enhanced cowpea yield during a poor rainy season when millet performed badly was also reported by Bielders and Michels (2002), who attributed this to lower pest incidence. It seems logical also that the poor millet growth was compensated by a better cowpea performance as the cowpea crop was able to exploit resources not used by the cereal. Both effects may have played a role. The relatively good cowpea production in the year 2000 with poor rainfall should also help to reduce food security risks. The role an intercrop can play in food security during the 'hunger' period preceding a new millet harvest was also indicated by the 'disappearance' of cowpea grain from the experimental plots in 2001.

Fallow duration

When land is the single, most-scarce resource farmers can be expected to optimise the output per unit area of land, but when land is not as scarce farmers can be expected to optimise their production per unit of labour. When optimisation is also on labour short fallow is a sensible technology as total productivity in the four years of cultivation was clearly superior compared to production when no fallow was used. Although labour was not quantified it can be roughly said that the higher production of the plots after fallow will lead to higher productivity per unit labour. If land scarcity increases farmers will reduce fallow length and optimise on per unit area productivity (or land productivity) including the none productive area (under fallow) rather than on per unit area productivity of cropped land (which is equal to labour productivity) only.

Concluding remarks

Land is becoming so scarce in the Malian Sahel that farmers have to increase cropping intensity in order to produce enough to feed their families. Inclusion of cowpea after 2 years of bush-fallow in rotation with 3 years millet/cowpea intercrop in bush fields seems a viable option for resource poor farmers. Even when land is still available, the decision to let the fields rest for more than 2 years is only necessary if *S. hermonthica* infestation levels are very high. In our study we found that:

- The productivity of the system in terms of millet grain (257 kg ha^{-1} $year^{-1}$) almost equals that of continuous millet production

(310 kg ha^{-1} $year^{-1}$) despite the three years of zero millet production during fallow and pure cowpea production;

- Additional cowpea grain production (190 kg ha^{-1} $year^{-1}$) makes the system superior from a food system point of view;
- Further advantages of the system are the enhanced quantity and quality of the produced fodder, as, next to grain, the cowpea also produces fodder of better quality than millet fodder while also the millet fodder nitrogen mass fraction is improved;
- Also the soil quality has improved in terms of soil carbon and N content at the end of the 6 year rotation.The higher soil quality and higher millet productivity during the last year of the rotation seem to imply that the crop production period in this system could possibly be extended, thereby increasing the total millet productivity. Where less fallow land is available this seems to open up possibilities for a longer period of millet/cowpea intercrop cultivation or a second cycle of one year cowpea and three years millet/cowpea intercrop, without intermittent fallow.

A few important uncertain elements remain for further study as they were not included here, i.e. the implications of land tenure arrangements for management of the rotation, implication for the animal production component of the farming systems and long term effects on other soil characteristics like soil P, K, and micronutrients. The higher productivity potentially leads to increased mining of these elements for which then a further input will be needed in the course of intensification.

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