Nutr Cycl Agroecosyst (2008) 82:89–105
DOI 10.1007/s10705-008-9172-4

RESEARCH ARTICLE

Is soil quality improvement by legume cover crops a function of the initial soil chemical characteristics?

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Received: 11 June 2007 / Accepted: 19 February 2008 / Published online: 18 March 2008

Abstract The aim of this study, which was conducted in a humid savannah zone of central Côte d'Ivoire, was to examine changes in the quality of soil cultivated with herbaceous legume cover crops as a function of initial soil characteristics. *Mucuna pruriens* var *utilis* and *Pueraria phaseoloides* were used in a two side-by-side location experiment: a shrubby savannah (the savannah site or "SAV") and a natural fallow dominated by *Chromolaena odorata* (the fallow site or "FAL"). The latter was mainly characterized by higher organic matter [organic carbon (C) 10 vs. 7.5 mg kg^{-1}; total nitrogen (N) 0.8 vs. 0.5 mg kg^{-1}) and total phosphorus (P) (282.3 vs. 168.3 mg kg^{-1}) contents in the upper soil layer (0–10 cm). After 8 months of growth, biomass production by *M. pruriens* was found to be 6.5 and 4.9 t dry matter (DM) ha^{-1} at FAL and SAV, respectively. For *P. phaseoloides*, the values were 7.2 and 6.4 t DM ha^{-1}, respectively, in approximately the same period. The quantities of nutrients released by decomposing legume litter were higher at FAL than at SAV. Between-site differences in soil quality improvement were most noticeable in terms of available P, microbial biomass carbon (MBC) and MBC:total carbon (TC) ratio. The FAL site experienced a faster improvement of soil parameters under both legume species: available P increased from 18 to 58 mg kg^{-1} under *M. pruriens*, and from 19 to 52 mg kg^{-1} under *P. phaseoloides*; MBC increased from 88 to 185 mg kg^{-1} under *M. pruriens*, and from 127 to 192 mg kg^{-1} under *P. phaseoloides*. In contrast, the parameters remained constant over time at SAV. Soil C and N contents as well as C mineralization showed similar trends at both sites. Based on these results, we conclude that soil quality

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improvement under cover crops appears to be faster when the initial soil organic C, total N and P contents are adequate. These findings will be useful in assisting governmental decision-making on approaches to be taken for restoring soil fertility in low-input agricultural systems in West Africa.

Keywords Côte d'Ivoire · Herbaceous legumes · Humid savannah · Initial soil characteristics · Low-input agriculture · Soil quality improvement

Introduction

Soils from the West African savannah areas are generally characterized by an inherent low-fertility level, due mainly to the presence of low-activity clays (Oorts et al. 2003). In central Côte d'Ivoire, soil organic matter and phosphorus (P) contents are known to be very low, thereby limiting plant growth (Riou 1974). A policy of improved fallows has been widely implemented throughout the tropics with the aim of addressing this problem. These man-made fallows have the potential to improve soil organic matter and P levels as well as physical parameters (Azontonde et al. 1998; Carsky et al. 2001; Cong and Merckx 2005**;** Okpara et al. 2005; Koné et al. 2008). In addition, biological processes are enhanced, resulting in increased nutrient cycling when compared to natural fallow systems (Tian et al. 2001; Kolawole et al. 2003). Among the plants that have been proposed as green manures, *Mucuna pruriens* and *Pueraria phaseoloides* have been suggested as promising candidates for West African savannah soil fertility restoration (Tian et al. 2000; Okpara et al. 2005). These species are widespread in the region, although the introduction of the former is still relatively restrained in Côte d'Ivoire.

Soil quality is a key factor that governs yield, food security and the sustainability of agricultural systems under humid tropics (Schjonning et al. 2004). Most indicators of soil quality are influenced by plant biomass and organic matter turnover (Albiach et al. 2000). The main advantage of these indicators is that they are more sensitive to environmental stress and, consequently, may provide a more rapid and accurate assessment of changes in soil quality than whole soil organic matter per se (Emmerling et al. 2002; Dinesh et al. 2004).

Biomass production by herbaceous legumes and its impact on soil chemistry and biology are well documented in the literature (Carsky et al. 2001; Tian et al. 2001; Dinesh et al. 2004; Anthofer and Kroschel 2005). Good correlations have been found between soil characteristics and plant residue quality (Chadwick et al. 1998; Bernhard-Reverat et al. 2000). Changes in soil nutrient contents are often related to some specific soil parameters; for instance, P availability in soil has been reported to be closely related to pH and texture as well as Al and Fe contents (Nwoke et al. 2003; Cong and Merckx 2005). It is also known that soil organic matter and nutrient contents are best improved in soils with a high clay content (Feller and Bear 1991; Hassink 1997; Six et al. 2002). However, investigations are still needed about changes in the quality characteristics of soil following the establishment of herbaceous legume cover crops as a function of the initial soil characteristics.

This study deals with changes in the quality characteristics of two soils, differing in terms of initial chemical and biological characteristics, cultivated with legumes. To address this question, we examined the dynamics of soil organic matter carbon (C), nitrogen (N) and P contents as well as microbial biomass carbon (MBC), the microbial biomass C to total C (MBC:TC) ratio, carbon mineralization (C_{min}) and specific soil respiration. Our hypothesis was that initial soil characteristics play a key role in the improvement of soil quality following the establishment of legume cover crops.

Material and methods

Study site

The study site was located in the buffer zone of the Lamto Reserve (6°13′N and 5°20′W), a forest–savannah transition zone in central Côte d'Ivoire. The climate is of a subequatorial type with four seasons: a long dry season from December to February, a long wet season from March to July, a short dry season in August and a short wet season from September to November. During the study period (2003–2004), mean annual rainfall was 1305 mm, and the constant temperature averaged 27°C.

Trials were conducted concurrently at two sites located side by side (about 30 m apart). The sites were representative of the different agroecosystems of the area: Site 1, referred to as "Savannah" or "SAV", was established in a shrubby natural savannah, with a woody stratum dominated by *Bridelia ferruginea* and *Crossopteryx febrifuga* and a herbaceous stratum with *Hyparrhenia diplandra*. Site 2, referred to as "Fallow" or "FAL", was established in a 17-year-old fallow that had been colonized by the invading weed *Chromolaena odorata* following yam cropping of the shrubby natural savannah. Soils at both sites were Alfisols, with a sandy loam upper layer (0–30 cm) and overlying sandy clay (30–70 cm) and stony (>70 cm) horizons.

Experimental layout

Two different experiments were carried out at the two sites in order to monitor changes in soil characteristics. At SAV, plots were planted either with legumes or with maize, while the FAL plots were planted only with legumes. The experimental design at each site consisted of a randomized-complete block, with three replications. The blocks were separated by 4-m-wide alleys, and the 192-m^2 (24 × 8 m) plots were separated by 2-m alleys. Each plot was further divided into three subplots for specific parameter measurements. Soil parameters and plant biomass production were measured in the same subplot. Plots with the same legume species at both sites were monitored for 12 months: *Mucuna pruriens* var. *utilis* and *Pueraria Phaseoloides*. Thus, for a given species, changes in soil characteristics that occurred after legume establishment were compared between sites.

Cropping activities

Prior to setting up the experiment, both sites were cleared and then hoe-weeded. Legume seeds were hand-sown at 0.5-m spacing during the rainy season (June 2003) at both sites. Non-germinated seeds were replaced at approximately 2 weeks after sowing. In order to facilitate plant growth, the plots were hoe-weeded twice following seedling emergence, with a 1-month interval between weeding; thereafter, the weeds were left on the soil surface.

Sampling

Plant biomass

Plant biomass was determined at two stages of legume development: (1) when 50% of plants had flowered, and (2) when 50% of plants carried dry pods. Aboveground biomass sampling was carried out within a 1 × 1-m quadrat, at three points distributed over the defined subplot, for a total of nine replicate samples per treatment. Fine roots were sampled as follows: soil monoliths 25 × 25 × 40 cm in size were collected within the 1-m^2 quadrat defined above. The monoliths then were sorted successively by passage through 5- and 2-mm mesh sieves and the roots (dead and alive) removed. Roots were separated into two size classes (diameter < 2 and > 2 mm, respectively) using a calliper square. In general, fine roots collected from plots were assumed to belong to the established legume. This assumption is highly probable because *M. pruriens* and *P. phaseoloides* were grown for 5 and 8 months, respectively, attaining complete soil coverage and, consequently, suppressing other plant species. Plant samples were oven-dried at 60°C for 72 h, then weighed. A 20-g subsample of each plant material was finely ground and stored in a plastic bag for further analyses.

Soil

At each site, soil sampling was conducted at three periods in the same subplot: before land clearing and at 6 and 12 months after sowing. All samples were collected from the 0–10 cm soil layer at nine different points distributed over the subplot during the rainy season (April and October 2003, then in early May 2004) using an auger. Prior to this sampling, non-decomposed plant residues were carefully removed from soil surface. Samples from each block were thoroughly mixed into a composite sample. They were then air-dried at ambient temperature, crushed and passed through a 2-mm sieve before being stored in plastic bags for further analyses.

Soil bulk density was determined on core samples obtained using an auger (diameter 3.6 cm, height 10 cm). Samples were collected in the first 10-cm soil layer, oven-dried at 105°C for 48 h and then weighed.

Laboratory analyses

Plant materials

Organic C was determined after mineralization of plant residues using a sulfochromic solution (Walkley and Black 1934), and N was determined using the standard Kjeldahl digestion method. Phosphorus was determined by colorimetry following nitriperchloric acid digestion and subsequent molybdenum-blue colour development. Major cations were extracted using ammonium acetate buffer (pH 7) and determined by means of atomic absorption spectrophotometry techniques.

Soil parameters

Organic C and total N were determined in the ground and in 0.2-mm sieved soil samples using near-infrared reflectance spectroscopy (NIRS). The method was based on a close relationship between the biochemical composition of a sample and its spectral absorbance (Dalal and Henry 1986; Morra et al. 1991; Ludwig et al. 2002; McCarthy et al. 2002). The samples were analysed using a FOSS 5000 model spectrophotometer (Foss NIR Systems, Silver Spring, MD) to measure their reflectance between 1100 and 2500 nm. The spectral data obtained were expressed as the logarithm of the inverse of reflectance [log(1/R)]. The data were then processed using WINISI III ver. 1.50e software (Foss NIRSystems). A reference set was selected using the most representative samples identified with the internal algorithm WINISI software (Shenk and Westerhaus 1991). These samples were then analysed in an elemental micro-analyser CHN Carlo Erba (CE Instruments, Milan, Italy) to determine total C and N. In the absence of carbonates, total C was assumed to be organic C. Finally, the calibration model of a reference set was applied to the spectral data from all soil samples to predict C and N contents.

Microbial biomass C was determined using the chloroform fumigation–extraction method (Vance et al. 1987; Horwath and Paul 1994). Samples obtained from the first 10 cm of the soil layer were either humidified (80% field capacity) and fumigated with an ethanol-free chloroform solution for 24 h (20 g) or not fumigated and kept in a desiccator in a dark room as controls (10 g). Carbon from the fumigated and control samples was then extracted with a 0.5 *M* K_2SO_4 solution following shaking, centrifugation and filtration of the soil suspension through Whatman filter paper. Dissolved organic C (DOC) in the soil extracts was determined by measuring the chemical oxygen demand (COD) using a spectro-colorimeter DR/700 (Hach method). Microbial biomass C was determined by taking the difference between the DOC of the fumigated and non-fumigated soil samples.

Soil C_{min} was measured according to the dynamic closed chamber method (Bekku et al. 1997). A 70-g sample of dry soil was brought to 80% field capacity with distilled water and put into a jar with open pipes to allow aeration. The jars were incubated in an oven at a constant temperature of 30°C, and CO_2 was measured at 7, 14, and 21 days following incubation. The readily degradable C was determined using an infrared CO_2 meter (Dräger Polytron IR CO_2; Dräger Safety, Luebeck, Germany). Specific soil respiration was calculated by dividing evolved C–CO_2 by microbial biomass C.

Water pH measurements were conducted in a soil:water (1:2.5) suspension. Available P was extracted according the Olsen–Dabin method (in a mixture of $NaHCO_3$ and NH_4F, at pH 8.5), and total P was extracted in a mixture of HNO_3 and $HClO_4$ (Olsen and Sommers 1982). The two extracts were then analyzed for P by colorimetry at 660 nm (Murphy and Riley 1962). Total soil P was calculated as follows:

$$\text{Total P (kg ha}^{-1}) = \text{Core weight (kg ha}^{-1}) \times \text{Total soil P content (mg kg}^{-1}) \times 10^6.$$

Exchangeable bases were extracted using the standard ammonium acetate (pH 7) buffer and measured by atomic absorption spectrometry. Cation exchange capacity (CEC) was obtained using standard methods (Anderson and Ingram 1993). Soil texture was determined using the standard Na-hexametaphosphate suspension method. Organic matter was destroyed using hydrogen peroxide. The coarse soil fraction was then obtained by means of sieving, and the fine particles (clay and silt) were determined using the Robinson pipette method (Anderson and Ingram 1993).

Statistical analyses

In order to ascertain that trends observed for one legume species are repeated with the other, we made between-site comparisons at the species level. Due to the low number of soil sample replications ($n = 3$ for

each soil variable studied), mean comparisons were carried out using non-parametric tests. For a given site and soil characteristic, differences between the mean values recorded over time (before sowing, 6 and 12 months after sowing) were tested using the Kruskal–Wallis test. For a given legume species, between-site differences in soil parameters were also analysed using the Mann–Whitney test. Between-site comparisons of plant biomass were carried out using the Student *t* test following verification of the normality and homogeneity of variances with the Shapiro–Wilk and Levene's tests, respectively. These statistical analyses were processed using the STATISTICA ver. 6.0 software programme (Statistica, Tulsa, OK).

Multiple regressions using GLM (General Linear Model) procedures (SAS ver. 6 software; SAS Institute, Cary, NC) were also performed on the data to test relationships between variables. All results were significant when $p < 0.05$.

Results

Initial soil characteristics

Soils were slightly acidic, with similar mean water pH values (6.6–6.7). Between-site differences in the fine fraction amount were not significant. Organic C and total N were significantly higher at FAL than at SAV ($p = 0.004$). In contrast, the C:N ratio was significantly lower at FAL (Table 1). While available P was similar at both sites, total P was in general significantly higher ($p = 0.03$) at FAL than at SAV. The CEC and exchangeable bases did not show any significant between-site differences; however, in plots to be cultivated with *P. phaseoloides*, the values were significantly higher at FAL.

In general, there were no significant between-site differences in soil microbial parameters (Table 2). However, the MBC and MBC:TC ratios were somewhat higher at SAV, whereas C_{min} and specific soil respiration were higher at FAL.

Biomass production and relationships with initial soil parameters

Total biomass production by *M. pruriens* increased over time at both sites. However, the increase was significant ($p = 0.01$) only at FAL, where total biomass varied from 3.7 to 6.5 t ha^{-1} (Fig. 1a). Likewise, leaf-litter biomass increased significantly ($p = 0.02$) between the two stages of development at that site, varying from 0.8 to 2.2 t ha^{-1} (Fig. 1b). In contrast, fine root biomass decreased between the two

Table 1 Main initial soil (0–10 cm layer) characteristics of the study sites

	Mucana pruriens[a] ($n = 3$)		*Pueraria phaseoloides*[a] ($n = 3$)	
	Savannah	Fallow	Savannah	Fallow
Clay + silt (mg kg^{-1})	186 (10) a	156 (10) a	171 (8) a	190 (22) a
Bulk density (kg m^{-3})	1148 (23) a	1026 (54) a	1226 (34) a	1065 (25) a
pH water	6.6 (0.1) a	6.7 (0.1) a	6.6 (0.1) a	6.6 (0.1) a
Organic C (g kg^{-1})	7.7 (0.1) a	10 (0.8) b	7.3 (0.2) a	10 (0.5) b
Total N (g kg^{-1})	0.5 (0.0) a	0.8 (0.1) b	0.5 (0.0) a	0.8 (0.0) b
C:N ratio	14.3 (0.1) a	12.9 (0.3) b	14.3 (0.2) b	12.8 (0.2) a
Total P (mg kg^{-1})	216.3 (7.3) a	277.3 (4.3) a	120.3 (19) a	287.3 (43) b
Available P (mg kg^{-1})	18.7 (1.8) a	18 (9) a	16.7 (3.2) a	19.3 (9.1) a
CEC (cmol$_c$ kg^{-1})	5.5 (0.7) a	4 (0.3) a	3.7 (0.3) a	5.7 (1.3) b
Ca (cmol$_c$ kg^{-1})	1.9 (0.2) a	2.7 (0.8) a	2.1 (0.2) a	3.8 (1.1) b
K (cmol$_c$ kg^{-1})	0.3 (0.1) a	0.2 (0.0) a	0.2 (0.0) a	0.2 (0.0) a
Mg (cmol$_c$ kg^{-1})	0.7 (0.0) a	1.2 (0.4) a	0.7 (0.1) a	1.9 (0.3) b

CEC, Cation exchange capacity

All values are given as the mean ± standard error (in parenthesis). For a specific soil parameter, means with the same letter are not significantly different at the 5% level

[a] Initial plots to be converted to *M. pruriens* and *P. phaseoloides* cover crops

Table 2 Initial soil biological characteristics (0–10 cm layer) of the study sites

	M. pruriens[a] ($n = 3$)		*P. phaseoloides*[a] ($n = 3$)	
	Savannah	Fallow	Savannah	Fallow
MBC (mg kg^{-1})	115 (27.5) a	88.3 (11.7) a	130 (42.7) a	126.7 (11) a
MBC:TC (%)	1.5 (0.4) a	0.9 (0.1) a	1.8 (0.5) a	1.3 (0.1) a
Evolved CO_2 (mg g C_{org}^{-1})	108.3 (12) a	119.4 (27.6) a	92 (3.8) a	148.2 (28.6) b
Specific respiration (mg CO_2 g^{-1} MBC)	1.1 (0.3) a	1.4 (0.3) a	0.8 (0.2) a	1.2 (0.4) a

MBC, Microbial biomass carbon; MBC:C, ratio of microbial biomass C to total C

All values are given as the mean ± standard error (in parenthesis). For a specific soil parameter, means with the same letter are not significantly different at the 5% level

[a] Initial plots to be converted to *M. pruriens* and *P. phaseoloides* cover crops

stages at both sites (Fig. 1c), although the decrease was significant only at SAV ($p = 0.02$). Although the between-site variation in total biomass with *M. pruriens* was not significant, values were higher at FAL than at SAV. Leaf-litter and fine root biomasses, however, were higher at SAV than at FAL, at the flowering stage, but a significant difference ($p = 0.04$) was observed with leaf-litter only.

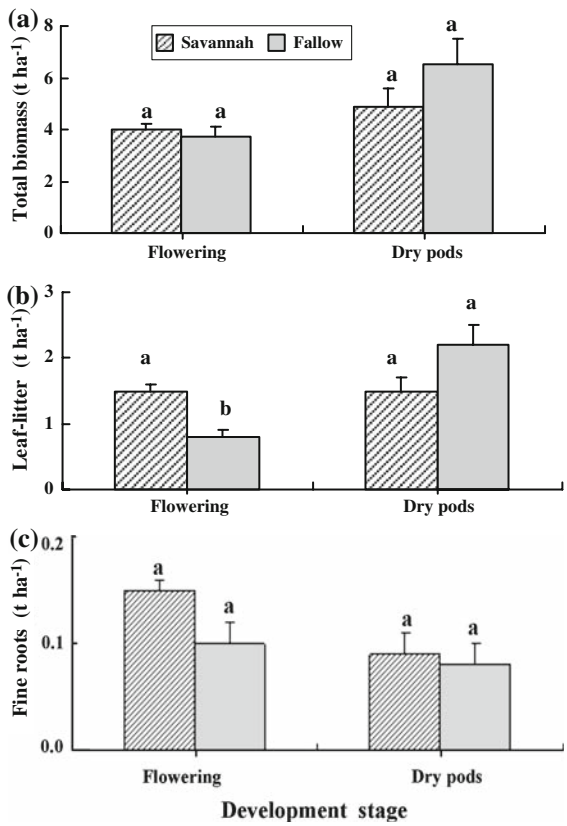

Fig. 1 Biomass production by *Mucuna pruriens*: (**a**) total biomass, (**b**) leaf-litter, (**c**) fine roots. For the same developmental stage, *means with the same letter* are not significantly different at the 5% level. *Vertical bars* denote standard errors, $n = 9$

With *P. phaseoloides*, total biomass production (Fig. 2a), and leaf-litter quantity increased over time at both sites (Fig. 2b), although the increase was significant only with leaf-litter ($p = 0.001$ at SAV, $p < 0.001$ at FAL). In contrast to *M. pruriens*, fine root biomass (Fig. 2c) significantly increased ($p < 0.001$) between the two stages of development at both sites. Total biomass production and leaf-litter quantity were higher at FAL, with a significant difference in terms of leaf-litter at the dry pod stage ($p = 0.04$). Fine root biomass did not show any significant between-site difference.

Biomass production by *M. pruriens* was not significantly influenced by the initial soil chemical parameters (multiple regression test). For *P. phaseoloides*, however, all of the categories of biomass were significantly influenced by these soil parameters (leaf-litter $R^2 = 0.63$, $F = 4$, $p = 0.02$; fine roots $R^2 = 0.55$, $F = 3$, $p = 0.05$; total biomass $R^2 = 0.71$, $F = 6$, $p = 0.007$). Amongst these, only Ca was significantly (and positively) related to biomass production and, in particular, to total biomass ($\beta = 2.3$, $p = 0.04$). When data from both species were combined, only leaf-litter and total biomasses exhibited significant relationships with the initial soil chemical parameters (leaf-litter $R^2 = 0.6$, $F = 6.95$, $p < 0.001$; total biomass $R^2 = 0.45$, $F = 3.91$, $p = 0.005$). These categories were significantly and positively related only to soil Ca ($\beta = 0.61$, $p = 0.02$ with leaf-litter; $\beta = 1.63$, $p = 0.01$ with total biomass).

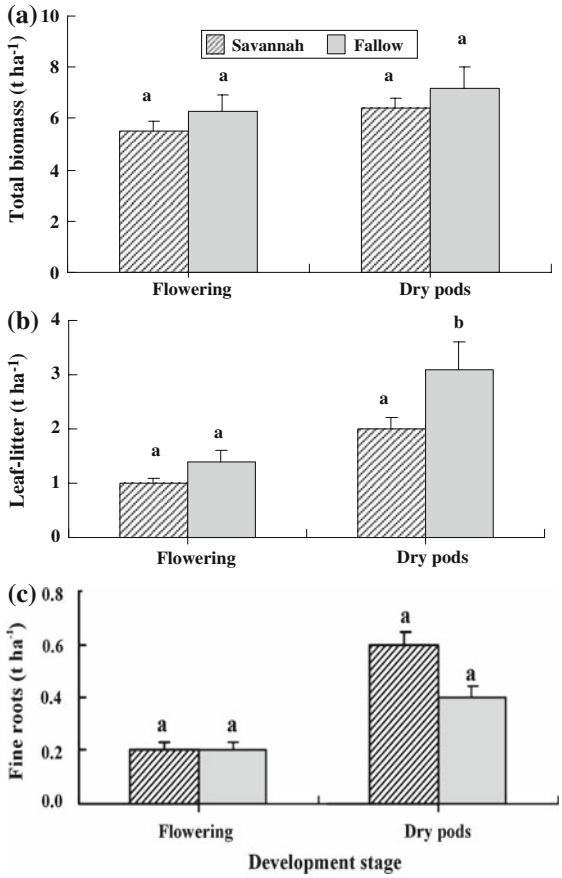

Fig. 2 Biomass production by *Pueraria phaseoloides*: (**a**) total biomass, (**b**) leaf-litter, (**c**) fine roots. For the same development stage, *means with the same letter* are not significantly different at the 5% level. *Vertical bars* denote standard errors, $n = 9$

Quality of organic residues and nutrient stocks

Quality of organic residues

Leaf-litter from *M. pruriens* at FAL was of a higher quality (higher P, K, Ca, Mg contents) compared to that at SAV, although significant between-site difference was observed only for Mg (Table 3). The C:P ratio of the leaf-litter was significantly lower at FAL than at SAV. Fine roots from *M. pruriens* planted at FAL also were of a higher quality, with significantly higher N and Ca contents and a lower C:N ratio.

Except for Ca, nutrient concentrations in *P. phaseoloides* leaf-litter from FAL were higher than those of SAV (Table 3). However, between-site significant differences were observed only in P and K contents. Both the C:N and C:P ratios were

Table 3 Leaf-litter and fine root quality (at pod stage)

Legume parts	Sites	C (% dry matter)	N (% dry matter)	P (% dry matter)	K (% dry matter)	Ca (% dry matter)	Mg (% dry matter)	C:N	C:P
M. pruriens									
Leaf litter	Savannah	54.1 (0.2) a	1.7 (0.1 a	0.1 (0.0) a	0.9 (0.0) a	1.3 (0.0) a	0.22 (0.0) a	31 (1.2) a	513.9 (43) a
	Fallow	53.5 (0.2) a	1.6 (0.1) a	0.13 (0.0) a	1.3 (0.2) a	1.5 (0.1) a	0.27 (0.0) b	33 (1.7) a	424.7 (20) b
Fine roots	Savannah	54.6 (0.2) a	1.0 (0.1) a	0.06 (0.0) a	0.8 (0.1) a	2.4 (0.2) a	0.26 (0.0) a	56.3 (5.6) a	857 (30) a
	Fallow	54 (0.4) a	1.5 (0.1) b	0.05 (0.0) a	1.0 (0.1) a	5 (0.1) b	0.32 (0.0) a	36.4 (2.9) b	945 (62.5) a
P. phaseoloides									
Leaf litter	Savannah	52.7 (0.4) a	0.8 (0.1) a	0.07 (0.0) a	1 (0.03) a	1.8 (0.05) a	0.35 (0.0) a	65.3 (4.4) a	690.5 (35) a
	Fallow	52.6 (0.2) a	1.1 (0.1) a	0.1 (0.0) b	1.4 (0.1) b	1.7 (0.05) a	0.37 (0.0) a	47.4 (5.6) b	584.5 (22) b
Fine roots	Savannah	51.7 (1.5) a	0.9 (0.1) a	0.05 (0.0) a	0.8 (0.03) a	3.2 (0.15) a	0.17 (0.0) a	64 (7.7) a	1182 (259) a
	Fallow	51.6 (1.5) a	1 (0.1) a	0.05 (0.0) a	0.8 (0.04) a	4.5 (0.6) a	0.17 (0.0) a	57.5 (6.2) a	1054 (138) a

All values are given as the mean ± standard error (in parenthesis); $n = 5$. For a specific parameter, means with the same letter are not significantly different at the 5% level

significantly lower at FAL. No between-site differences were observed for fine roots, however, in terms of nutrient contents or the C:N and C:P ratios.

Nutrient stocks in organic residues

Nutrient stocks in *M. pruriens* leaf-litter were significantly higher at FAL than at SAV, except for N (Table 4). The nutrient stocks in the fine roots were not different from one site to the other, except for P, which was higher at SAV. For *P. phaseoloides*, the nutrient stocks in the leaf-litter at FAL were nearly twofold higher than those at SAV. In terms of fine roots, no significant between-site difference was observed (Table 4).

Total nutrient uptake by both the legume species at FAL was higher than at SAV. Between-site differences were more pronounced with *M. pruriens* than with *P. phaseoloides*. Indeed, total K and Ca uptake by the former species was significantly higher at FAL than at SAV (Table 4).

Soil quality

Organic matter content and C:N ratio

Under *M. pruriens*, soil organic C (SOC) and total N contents increased over time at SAV ($p = 0.04$) (Table 5). The same trends were observed at FAL, but changes were not significant. Nevertheless, they were as high as (N), or even higher (C) than, those at SAV. The C:N ratio decreased significantly at SAV, and only slightly at FAL (Table 5). The dynamics of C, N and C:N ratio, under *P. phaseoloides*, were consistent with those observed under *M. pruriens* at both sites.

Soil phosphorus

Total soil P concentration varied significantly with time under *M. pruriens* cultivation at FAL only ($p = 0.03$), showing a decrease between 0 and 6 months after sowing and an increase thereafter between 6 and 12 months. The final value was similar to the initial one (Fig. 3a). In addition, total P concentration at FAL was still significantly higher after 6 ($p = 0.04$) and 12 months ($p = 0.04$) of *M. pruriens* growth, as compared to values from SAV. Under *P. phaseoloides* cultivation, total P concentration remained almost constant over time at SAV, while it varied significantly at FAL ($p = 0.03$), decreasing between 0 and 6 months after sowing and increasing thereafter between 6 and 12 months (Fig. 3b). The significant between-site difference remained constant up to 12 months after *P. phaseoloides* establishment.

Table 4 Carbon, N and nutrient stocks in legume parts (at pod stage)

Legume parts	Sites	C (kg ha^{-1})	N (kg ha^{-1})	P (kg ha^{-1})	K (kg ha^{-1})	Ca (kg ha^{-1})	Mg (kg ha^{-1})
M. pruriens							
Leaf litter	Savannah	838 (127) a	27.1 (4.1) a	1.7 (0.26) b	14.6 (2.2) b	20.6 (3.1) b	3.4 (0.5) b
	Fallow	1,198 (179) a	36.5 (5.5) a	2.9 (0.43) a	29.3 (4.4) a	34.5 (5.2) a	6 (0.9) a
Fine roots	Savannah	16.2 (2.4) a	0.3 (0.04) a	0.02 (0.00) a	0.2 (0.03) a	0.7 (0.1) a	0.1 (0.01) a
	Fallow	11.9 (1.8) a	0.3 (0.05) a	0.01 (0.00) b	0.2 (0.04) a	1.1 (0.2) a	0.1 (0.01) a
Total biomass	Savannah	–	101.5 (15) a	4.4 (0.6) a	46.7 (6.9) b	113 (16.6) b	11.7 (1.7) a
	Fallow	–	138.3 (22) a	5.8 (0.9) a	70.1 (11.2) a	242 (38.6) a	17.3 (2.8) a
P. phaseoloides							
Leaf litter	Savannah	1,067 (87) a	16 (1.6) b	1.58 (0.13) b	20 (1.6) b	34.5 (2.8) a	7.1 (0.6) b
	Fallow	1,671 (280) a	35.2 (6) a	2.78 (0.5) a	45 (7.4) a	52.2 (8.7) a	11.4 (1.9) a
Fine roots	Savannah	63 (6.3) a	1.0 (0.1) a	0.06 (0.01) a	0.9 (0.1) a	3.9 (0.4) a	0.2 (0.02) a
	Fallow	46 (5.4) a	0.8 (0.1) a	0.04 (0.01) a	0.7 (0.1) a	4 (0.5) a	0.1 (0.02) a
Total biomass	Savannah	–	86.4 (5.6) a	4.3 (0.3) a	61.5 (3.9) a	205.2 (13) a	19.5 (1.3) a
	Fallow	–	109.5 (112) a	5.0 (0.5) a	75.9 (8.1) a	237.5 (25) a	23.8 (2.6) a

All values are given as the mean ± standard error (in parenthesis); $n = 5$. For a specific element, means with the same letter are not significantly different at the 5% level

Table 5 Dynamics of soil organic C, total nitrogen and C:N ratio at each site

Site	Soil organic C (g kg^{-1})			Total N (g kg^{-1})			C:N		
	0 month[a]	6 months	12 months	0 month[a]	6 months	12 months	0 month[a]	6 months	12 months
M. pruriens									
Savannah	7.7 (0.1)	8.1 (0.2)	8.2 (0.2)	0.5 (0.0)	0.6 (0.0)	0.6 (0.0)	14.3 (0.1)	13.7 (0.1)	13.4 (0.1)
Fallow	10 (0.8)	10.4 (0.4)	10.9 (0.4)	0.8 (0.1)	0.8 (0.0)	0.9 (0.0)	12.9 (0.3)	12.4 (0.3)	12.5 (0.2)
P. phaseoloides									
Savannah	7.3 (0.2)	7.7 (0.2)	8 (0.2)	0.5 (0.0)	0.6 (0.0)	0.6 (0.0)	14.3 (0.2)	13.7 (9.1)	13.4 (0.1)
Fallow	10 (0.5)	10.6 (0.9)	11.2 (1)	0.8 (0.0)	0.9 (0.1)	0.9 (0.1)	12.8 (0.2)	12.1 (0.3)	12.3 (0.2)

All values are given as the mean ± standard error (in parenthesis); $n = 3$

[a] Initial sampling time, before experimental set-up

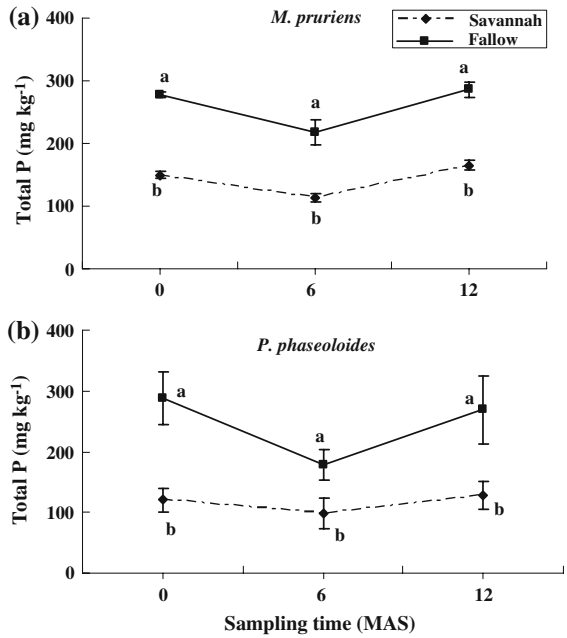

Fig. 3 Dynamics of total soil (0–10 cm) P concentration in soil under legume cultivation: (**a**) *M. pruriens*, (**b**) *P. phaseoloides*. For the same sampling time, *means with the same letter* are not significantly different at the 5% level. *Vertical bars* denote standard errors, $n = 3$. *MAS* Months after sowing

At both sites and under the cultivation regimes of both legume species, the evolution pattern of total soil P stocks was similar to that of total P concentration, and the variations were not statistically significant. At SAV, total P stocks first decreased from 172.4 and 146.4 kg ha^{-1} to 143.1 and 116.4 kg ha^{-1}, and then increased to 175.5 and 140.3 kg ha^{-1} under *M. pruriens* and *P. phaseoloides*, respectively. At FAL, it first decreased from 297.6 and 308.3 kg ha^{-1} to 260.5 and 220.6 kg ha^{-1} and then increased to 285.4 and 295.3 kg ha^{-1} under *M. pruriens* and *P. phaseoloides*, respectively. Thus, at SAV, changes in total P stock during the two periods (0–6 and 6–12 months, respectively) were of the same magnitude, i.e., about 30 kg ha^{-1} under both legumes. At the other site, however, the magnitude of the variations was different from one species to the other and was, on average, 30 kg ha^{-1} under *M. pruriens* cultivation while it peaked at 75 kg ha^{-1} under *P. phaseoloides* cultivation.

Under *M. pruriens* cultivation, available P increased significantly over time ($p = 0.02$) at FAL only (Fig. 4a), varying from 18 to 58 mg kg^{-1} between 0 and 12 months. The values were significantly higher than those at SAV at 6 and 12 months ($p = 0.04$ for both) after sowing. Under *P. phaseoloides* cultivation, changes in available P at FAL were consistent with those under *M. pruriens*, as it increased significantly from 19 to 52 mg kg^{-1} between 0 and 12 months (Fig. 4b). At SAV, however, variations over time were not significant, as revealed by the Kruskal–Wallis test. Consequently, values were higher at FAL than at SAV 6 and 12 months ($p = 0.04$ for both) after sowing (Fig. 4b).

Microbial biomass C and MBC:TC ratio

Under *M. pruriens* cultivation, the changes in MBC were not significant over time at SAV, whereas they varied significantly at FAL ($p = 0.04$), increasing particularly between 6 and 12 months (Fig. 5a). Significant between-site differences ($p = 0.04$) were observed 12 months after legume establishment, with a higher value (185 mg kg^{-1}) at FAL than at SAV (102 mg kg^{-1}). Although no significant between-site

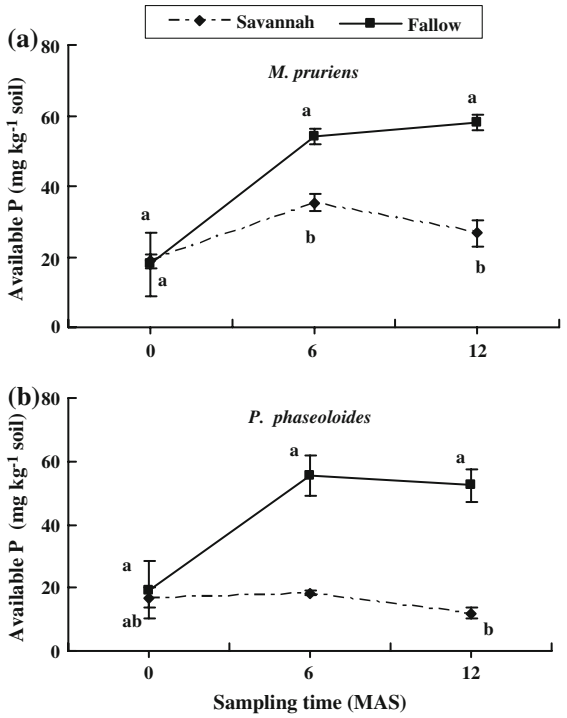

Fig. 4 Dynamics of soil (0–10 cm) available P under legume cultivation: (**a**) *M. pruriens*, (**b**) *P. phaseoloides*. For the same sampling time, *means with the same letter* are not significantly different at the 5% level. *Vertical bars* denote standard errors, $n = 3$. *MAS* Months after sowing

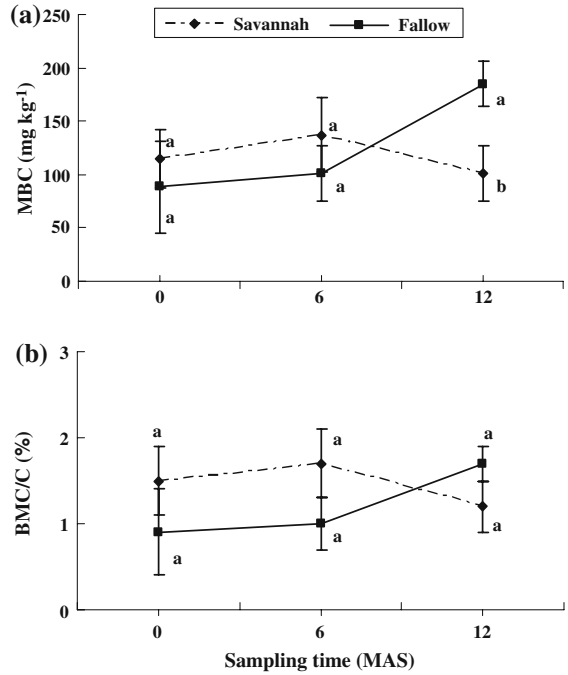

Fig. 5 Dynamics of soil (0–10 cm) microbial biomass-C (*MBC*) (**a**) and MBC:C ratio (**b**) in soil under *M. pruriens* cultivation. For the same sampling time, *means with the same letter* are not significantly different at the 5% level. *Vertical bars* denote standard errors, $n = 3$. *MAS* Months after sowing

difference in MBC:TC ratio was found, regardless of sampling periods, significant increases were observed over time at FAL (Fig. 5b).

Similarly to *M. pruriens*, soil MBC under *P. phaseoloides* cultivation increased significantly over time at FAL only ($p = 0.04$). Moreover, a significant between-site difference was reached earlier, i.e. 6 months after sowing, with values of 202 and 105 mg kg^{-1} at FAL and SAV, respectively (Fig. 6a). The ratio of MBC:TC also showed the same trend as with *M. pruriens* (Fig. 6b).

Multiple regressions showed that the MBC obtained 6 months after sowing was significantly influenced by leaf-litter nutrient stocks ($R^2 = 0.77$, $F = 4.2$, $p = 0.05$), although only the P partial regression coefficient was significant ($\beta = 4487.1$, $p = 0.03$). This was not the case for data obtained 12 months after sowing. Amongst the nutrient stocks, P and Mg impacted (positively) the most on the MBC, whatever the period after sowing. The MBC:TC ratio was found not to be significantly influenced by leaf-litter nutrient stocks during the study period.

Carbon mineralization and soil specific respiration

Under *M. pruriens* cultivation, the C mineralization (C_{min}) dynamic was similar at both sites, varying over time ($p = 0.04$). After a decrease between 0 and 6 months, C_{min} increased only slightly between 6 and 12 months (Fig. 7a). Between-site differences were not significant. The same trend was observed with soil-specific respiration (Fig. 7b).

Under *P. phaseoloides*, C_{min} also varied significantly with time at both sites ($p = 0.04$), with almost similar trends: first a decrease between 0 and 6 months, followed by an increase between 6 and 12 months (Fig. 8a). After *P. phaseoloides* establishment, C_{min} did not show any significant between-site difference. As with *M. pruriens*, soil-specific respiration decreased between 0 and 6 months and then increased between 6 and 12 months, regardless of site (Fig. 8b).

Carbon mineralization (C_{min}) was significantly influenced by leaf-litter nutrient stocks, although this

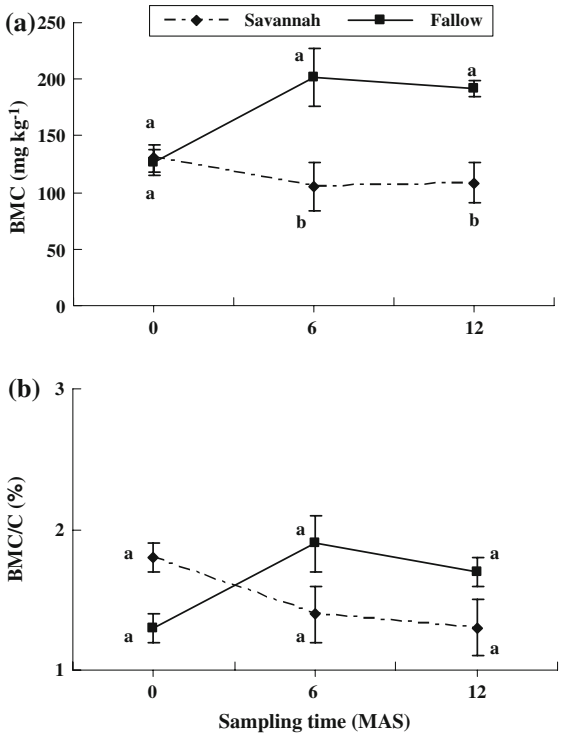

Fig. 6 Dynamics of soil (0–10 cm) microbial biomass C (*MBC*) (**a**) and MBC: total C ratio (**b**) in soil under *P. phaseoloides* cultivation. For the same sampling time, *means with the same letter* are not significantly different at the 5% level. *Vertical bars* denote standard errors, $n = 3$. *MAS* Months after sowing

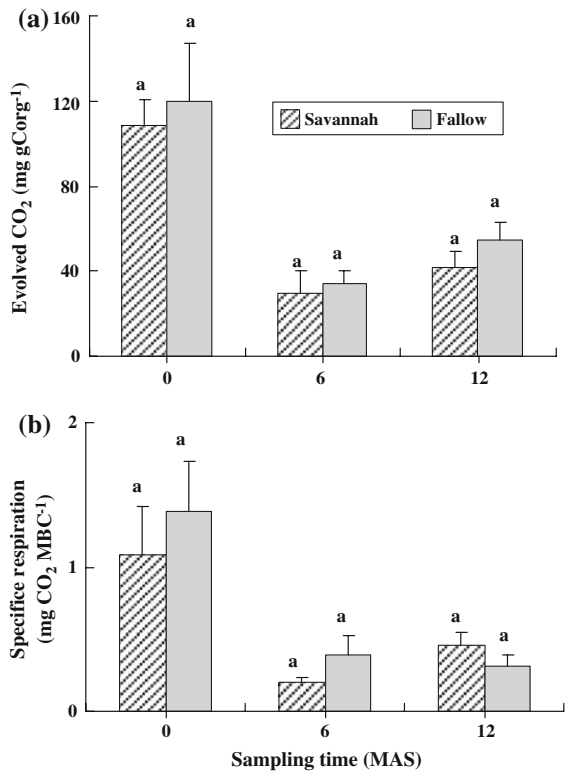

Fig. 7 Dynamics of soil (0–10 cm) C mineralization (**a**) and specific soil respiration (**b**) (21 days incubation) in soil under *M. pruriens* cultivation. For the same sampling time, *means with the same letter* are not significantly different at the 5% level. *Vertical bars* denote standard errors, $n = 3$. *MAS* Months after sowing

was observed only for the 12 months after the sowing period ($R^2 = 0.99$; $F = 265.2$; $p > 0.001$). Furthermore, C_{min} was significantly related to each nutrient stock (N: $\beta = 1.95$, $p < 0.001$; P: $\beta = -963.2$, $p = 0.002$; K: $\beta = 56$, $p = 0.002$; Ca: $\beta = 150$, $p = 0.001$; Mg: $\beta = -666.6$, $p = 0.001$) for the same period. As in the case of MBC, leaf-litter P and Mg stocks were the most important determining factors in carbon mineralization, regardless of sampling period. In contrast, soil-specific respiration did not show any significant relationship with leaf-litter nutrient stocks and seemed to be influenced mostly by P and Mg.

Discussion

For the ease of understanding, this research must be considered as a case study since it consisted of comparing nutrient dynamics at two singles sites.

Biomass production

In addition to total plant biomass, fine root and leaf-litter biomasses were monitored because of their direct impact on soil chemical and microbiological processes during decomposition (Balesdent and Balabane 1996; Tian et al. 2001; Dinesh et al. 2004). For example, fine roots are less suberized, but higher in nutrient contents (Berish and Ewel 1988) and, therefore, more likely to be readily decomposed than coarse roots.

Previous studies (Carsky et al. 2001; Houngnandan et al. 2001) have stressed the importance of soil P content in biomass build-up by legumes. This relationship did not appear in our data, although both biomass production and total P were higher at FAL. However, multiple regression analysis in general showed the significant influence of initial soil chemical characteristics on biomass production by

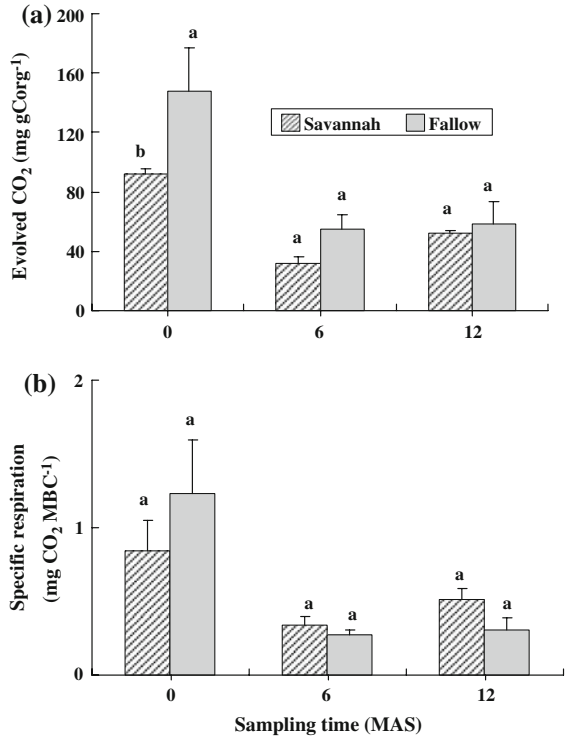

Fig. 8 Dynamics of soil (0–10 cm) C mineralization (**a**) and soil-specific respiration (**b**) (21 days incubation) in soil under *P. phaseoloides* cultivation. For the same sampling time, *means with the same letter* are not significantly different at the 5% level. *Vertical bars* denote standard errors, $n = 3$. *MAS* Months after sowing

legumes. Soil Ca content appeared to be the major soil parameter that influenced legume growth and was, therefore, responsible for the higher biomass production observed at FAL. Consequently, we can conclude that biomass production by the herbaceous legumes was somewhat determined by the initial soil fertility level.

By restricting sampling to only the top 40 cm of soil, the fine root biomass may have been underestimated. However, it has been reported that the bulk of the roots of most herbaceous plant species (approx. 80%) are to be found in the top 20 cm layer of mineral soil (Blair and Perfecto 2001; Tian et al. 2001). A number of researchers have reported the effects of soil characteristics on fine root biomass. Gower (1987) reported an increase in fine root biomass with increased soil P and Ca, whereas Maycock and Congdon (2000) found a decrease with increased soil N. Our results did not show any significant relationships between legume fine root biomass and soil chemical parameters. At the end of its life cycle (flowering), the annual *M. pruriens* species probably experienced increased root decay, which may explain the significant decrease in fine root biomass between the two development stages. In contrast, *P. phaseoloides*, which is a perennial species, was still growing, therefore increasing its fine root biomass.

Quality of organic materials and nutrient stocks

Chadwick et al. (1998) observed that leaf-litter was of a higher quality on the most fertile soils. Our results are consistent with this observation. Therefore, we conclude that the status of soil fertility can explain the observed between-site difference in organic material quality. As fine roots are closely linked to soil particles, the observed higher nutrient contents in *M. pruriens* fine roots at FAL were probably due to a higher soil fertility status.

In terms of the nutrient stocks in legume species, leaf-litter exhibited greater between-site differences than fine roots. Although the initial soil fertility status influenced nutrient contents in legume parts (Table 3), nutrients stocks may be more related to plant biomass. We found that, given similar nutrient contents at both sites (e.g. leaf-litter from *M. pruriens*), nutrient stocks were significantly higher at FAL because of its higher biomass.

Changes in soil quality

Organic matter and C:N ratio dynamics

The site effect was great on initial soil organic matter (SOM) content. According to Feller and Beare (1991), the SOM content is likely to be controlled by the finer soil particles, particularly in sandy soils, such as the ones used in our study, and which are known to contain low-activity clays. Thus, the capacity of the soils in our plots to stabilize SOM was low despite increased organic residue inputs. This could explain why there was no further significant increase in SOM at FAL. The same trend was observed at SAV, probably because of the reasons mentioned above (low fine particle content, low-activity clays). In general, soil C and N increased to the same extent (slightly) at both sites. The significance observed in SOM increase at SAV was simply

due to the lower spatial soil heterogeneity at this site relative to FAL (Table 5).

Our data shows that the soil C:N ratios decreased gradually at both sites, possibly due to N-richer organic residue (litter, decaying nodules) additions to the soil by legumes as compared to the native vegetation. Changes in vegetation at a site have been reported to bring about a gradual decline in organic matter at that site as well as a constant replenishment with new plant residue inputs (van Noordwijk et al. 1997).

Total and available phosphorus

The decrease in total P between 0 and 6 months and the subsequent increase could be an indication that P uptake by the legumes was more significant during the first stages of their life cycles, as was observed by Kolawole et al. (2003) in natural fallow and planted *P. phaseoloides* plots. In our study, litter accumulation started 2 months after *M. pruriens* establishment and 4 months after *P. phaseoloides* establishment. In the plots under *M. pruriens* cultivation, for example, litterfall increased suddenly after the flowering stage, i.e., 4 months after sowing. Thus, important quantities of high-quality litter from *M. pruriens* had been decomposed for at least 4 and 10 months prior to the first and second sampling periods, respectively. For *P. phaseoloides*, 2 and 8 months elapsed prior to the same sampling periods; consequently, nutrients had been released to the soil, allowing total P to increase after an initial decrease. Nevertheless, the magnitude of total soil P stock variations was much higher than legume P uptake, with total soil P stock variations consisting of about 30 kg ha^{-1} at SAV (under both species) and 30 (under *M. pruriens*) to 75 kg ha^{-1} (under *P. phaseoloides*) at FAL, while P uptake by legumes varied from 4.3 to 6 kg ha^{-1}. Even if pods P were taken into account, total P uptake by legumes would have hardly reached 10 kg ha^{-1}, as total pod biomass was, by far, lower than total plant biomass. Hence, the decrease in total P between 0 and 6 months could also be attributed to losses through surface run-off and leaching out of the 0-10 cm soil layer. This layer was found to be very sandy (>80% coarse particles), and rainfall was high during the first 3 months of the trial when the plots were denuded. The increase in total P between 6 and 12 months may be explained by the mechanism of continuous P cycling from deeper to surface layers by roots of established legumes. The fact that changes in total soil P were greater at FAL could be attributed to the lower soil bulk density at this site.

The increase in available P only at FAL, which was independent of initial content, was likely due to a higher nutrient quantity and faster turnover of organic residues at that site. Organic materials from both legume species at FAL had, in general, higher N (fine roots from *M. pruriens*, leaf-litter from *P. phaseoloides*), P (leaf-litter from both species) and cation (leaf-litter from both species, fine roots from *M. pruriens*) contents than those at SAV (Table 3). In addition, lower C:N (leaf-litter from *P. phaseoloides*, fine roots from both species) and C:P ratios (leaf-litter from both species) were found at FAL. Consequently, these materials decomposed and released more P at this site (result not shown). However, the fact that total P decreased while available P increased during the same period is due to unknown factors, given the similarities in the P curves obtained for both species at the two sites.

According to McGrath et al. (2000), the higher the C:P ratio, the slower the P release from decomposing plant materials. Indeed, with high C:P ratios, P is likely to be immobilized by microorganisms. Hence, at SAV, the low P concentration in organic materials, which was probably due to the lower initial soil P content, may explain the lack of increase in available P after legume establishment.

Thus, the mechanism of the soil P content increase seems to be the following: the higher initial soil fertility caused a higher legume biomass and the production of better quality residues, resulting in faster litter decomposition and P release in soil. The fact that soil-available P improved as a function of initial soil fertility status may be one of the most significant findings of our study, since P is the second most limiting nutrient in soils from moist savannah zones of West Africa (Nwoke et al. 2003).

Microbial biomass C and MBC:TC ratio

Changes in soil MBC at each site were consistent with soil-available P. Thus, our results agree with the findings of Wick et al. (1998) on P-poor soils. As indicated by the multiple regression test, the increase in MBC was probably determined primarily by litter P. The importance of P in regulating soil microbial

processes has also been stressed in previous studies (Cleveland et al. 2004; Böhme and Böhme 2006). In a study dealing with organic matter decomposition conducted in microcosms, in which plant residues were separated from the soil, Ha et al. (2007) observed that available P increased at the residue–soil interface. They also observed that microbial P experienced an increase in the same area, relative to the control, suggesting that some of the P released was taken up by the microorganisms. Demoling et al. (2007) showed that nutrients, such as N and P, may limit bacterial growth. In a pot experiment, these authors found that P addition significantly increased bacterial growth in some soil samples as compared to the control. Thus, the greater increase in soil microbial biomass observed at FAL following legume establishment may best be explained by both higher P quantities in leaf-litter and higher soil-available P at this site. The increase in soil P was probably due to the mineralization of plant residues, with subsequent P release into soil. However, no increase in MBC was observed at SAV under *M. pruriens* cultivation, although there was some increase in available P. This result could be due to the low-soil N content as N may constitute a limiting factor for bacterial growth (Wardle 1992; Demoling et al. 2007).

The MBC:TC ratio is an indication of the quality and availability of organic residues as well as C turnover in soil, which is useful in determining changes in organic matter over time (Sparling 1997). Since MBC forms part of the TC, its rapid increase at FAL in comparison to TC, is the reason why the MBC:TC ratio increased significantly. The MBC increased by 109 and 50.3% between 0 and 12 months under *M. pruriens* and *P. phaseoloides*, respectively, while TC increased only by 9 and 12%, respectively, during the same period. As with MBC, the increase in the MBC:TC ratio could be explained primarily by P quantities in leaf-litter. In this study, the MBC:TC ratios ranged from 0.9 to 1.91%, which is nearly within the 1–5% range reported by Jenkinson and Ladd (1981).

Overall, the mechanism of microbial biomass increase seems to be the following: the higher initial soil fertility induced a higher legume biomass and a higher quality of residue products, resulting in the faster decomposition of the residue and, consequently, a faster supply of nutrients to the soil. Among these, P and Mg enhanced microbial growth the most. However, the increase in microbial biomass seemed to be not only under the control of the higher quality residues but also to be associated with an initial soil N threshold.

The best method for determining MBC is to carry out measurements on freshly collected soil from field. Drying was one method to stop microbial growth until measurements could be made, as soil samples were analysed in laboratories some distance from the experiment field. There is some possibility that changes occurred in the MBC during the drying and rewetting, but it is unlikely that this altered the observed trends in our study, as all measurements were carried out in the same manner.

Soil carbon mineralization and specific respiration

Soil C mineralization (C_{min}) and specific respiration changes showed the same decreasing trends at both sites. Kramer and Gleixner (2006) reported that C sources used by soil microorganisms vary according to the group of microorganisms and that plant-derived C is prominent when input from plant residues into the soil is high. Surprisingly, in our experiment, soil C_{min} and specific respiration decreased after the legumes had established, even though N-rich plant inputs were high. In addition, the parameters decreased, although MBC increased significantly at FAL. Both MBC and C_{min} were influenced the most by P and Mg quantities in leaf-litter, but in different ways. The MBC increased with the nutrient stocks, while C_{min} decreased. To explain the decrease in C_{min}, we hypothesize the following: (1) a gradual change in the composition of the soil microbial community over time (Böhme and Böhme 2006) (indeed, the decrease in C_{min} should not necessarily be interpreted as a negative effect of the nutrients on microbial activity per se); (2) nutrient deficiency; (3) rapid feeding on the initial soil microorganism population by other organisms from the soil food web; (4) the addition of an inhibitor into soil, such as phenolic compounds. The decrease in soil-specific respiration, which is relatively more important at FAL than at SAV, could be attributed to the greater increase in MBC. However, further studies are needed to confirm these conflicting findings.

Drying the soil samples unavoidably made soil microorganisms dormant as low-water content is known to limit microbial activity. This was the

approach we used to stop the C mineralization process until we were able to carry out our analyses. However, rewetting the soil samples prior to C_{min} measurements may have stimulated microorganism respiration, resulting in more CO_2 production, as in the "priming effect" phenomenon (Fontaine et al. 2003). Thus, the C_{min} values obtained in our study could have been lower, had we not carried out the drying–rewetting cycle. Nonetheless, it is unlikely that the method used altered the observed trends in the data as all C_{min} determinations were carried out in the same manner during all sampling periods.

Conclusion

In the research reported here, we studied the influence of initial soil characteristics on short-term changes in soil quality subsequent to the establishment of a legume cover crop. Our study revealed that soil quality parameter dynamics were related to the initial soil fertility level. The improving effect of legume cover crops on soil quality is likely to be more easily obtained when the soil is initially high in organic C, total N and total P. Available P, MBC and the MBC:TC ratio appear to be the soil quality parameters that clearly showed—in the short run—between-site differences following legume establishment. The mechanism of the improvement seems to be the following: (1) the higher initial soil fertility induced higher legume biomass production and a higher quality of residue product, resulting in (2) faster residue decomposition, greater nutrient turnover in soil and higher microbial biomass. (3) The increase in microbial biomass seemed to be not only under the control of the higher quality residues but also an initial soil N threshold. The improvement in soil-available P in the soil under legume cover crops as a function of initial soil fertility status can be considered to be a very important finding of this study, since plant-available P is the second most limiting nutrient in soils from moist savannah zones of West Africa. These findings may be useful in assisting (governmental) decision-making on the approaches to be taken to restore soil fertility in low-input agricultural systems in West Africa.

Acknowledgements This work was funded by the International Foundation for Science (IFS) and the "Service de Coopération et d'Action Culturelle" (SCAC) at the French Embassy in Abidjan (Côte d'Ivoire). The authors are grateful to Dr. Martine Tahoux (Director of the Ecological Research Centre (CRE), University of Abobo-Adjamé) and Dr. Souleymane Konaté (Director of the Lamto Ecological Research Station) for facilitating the field work, and Prof. Tié-bi Tra (ESA, INP-HB, Yamoussoukro, Côte d'Ivoire) for samples analyses and collaboration. They also thank Yao N'Goran, Konan N'Guessan Jean and Loucou Kouakou Martin (supporting staff of Lamto) for their assistance during field experiments.

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