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Effect of ramial wood amendment on sorghum production and topsoil quality in a Sudano-Sahelian ecosystem (central Burkina Faso)

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Abstract In Sudano-Sahelian agriculture, organic amendments are often limited by resource availability. Small branches (ramial wood, RW) represent an organic resource found in many landscapes but little is known about their effects. This field trial (2007–2009) studied the effects of RW or straw at low application rate (0.69 Mg C ha^{-1} $year^{-1}$) on topsoil carbon (C), nitrogen (N) and available phosphorus (P, P_{av}), termite cast abundance, and sorghum yield. Straw and RW were chopped and either buried (StBu, WoBu) or mulched (StMu, WoMu). Mineral fertilizers were added to straw so that RW- and straw-amended plots received similar applications of C, N, P, and potassium. Another treatment had RW buried with additional N (WoBuN), and there was a control (Ctrl). Branches came from *Piliostigma reticulatum*, very common in the area. The treatments had little significant effect on topsoil and crop, owing to the low application rate and spatial variability. However, P_{av} was significantly lower with buried than mulched amendments in 2009, and decreased significantly over time in Ctrl and with buried amendments. Topsoil C also decreased significantly with time in WoMu. Significantly more termite casts were observed with RW. The sorghum yield averaged 0.87 Mg DM ha^{-1} in 2007 and then decreased. The treatments affected yield significantly in 2008 only: it was higher in WoBuN and StBu than in Ctrl. In 2009, the yield was mainly affected by initial topsoil P_{av}. These results suggest that RW stimulated biological activity, leading to P immobilization and C mineralization, but had little effect on yields.

Keywords Organic amendments · Branches · Soil carbon · Soil phosphorus · Termites · Tropical dry Africa

Abbreviations

Ctrl	Control treatment (no inputs)
P_{av}	Available phosphorus

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RW	Ramial wood (small branches)
StBu	Treatment with buried straw
StMu	Treatment with straw mulch
WoBu	Treatment with buried ramial wood
WoBuN	Treatment with buried ramial wood and additional mineral nitrogen
WoMu	Treatment with ramial wood mulch

Introduction

Natural and cultivated ecosystems differ in the degree of closure of biogeochemical cycles, due to differences in structural and functional complexity (Odum 1969; Perry et al. 1989). Agrosystems are particularly open systems for energy and nutrient balance: their viability depends strongly on external soil management to compensate for nutrient and carbon (C) losses whereas the resilience of natural ecosystems is achieved largely through self-sustained processes of biological maintenance. The conventional management of agrosystems generally aims at maintaining some soil physical and chemical properties within acceptable ranges based on "substitution maintenance" (sensu Izac and Swift 1994). Indeed, tillage and mineral fertilizers may compensate for soil physical degradation and nutrient losses, respectively; but they may also have detrimental agronomic and environmental effects, such as soil erosion and degradation, groundwater pollution, eutrophication of aquatic habitats, greenhouse gas emissions, etc. (Tilman et al. 2002). Furthermore, in many instances, tillage and fertilizers are unable to avoid soil degradation, which has been estimated to affect more than 560 Mha of agricultural land (Lal 2001). Soil degradation involves physical, chemical and/or biological processes, which all result in the decline in soil organic C; but some of these processes may be reversed by increasing soil organic C (Lal 2004). This has important consequences for the ecosystem services provided by soils: for example, increasing topsoil organic C by 1 Mg ha^{-1} may increase cereal grain production by 32 Mt in developing countries, where there is a need to increase production by 477 Mt between 2000 and 2025 to meet human food demand (Lal 2006).

With the development of soil ecology, which underlines the role of biological factors in soil functioning, the application of organic amendments has regained interest as a sustainable alternative for agrosystem management by improving soil physical, chemical and biological properties (Manlay et al. 2007). However, this practice is often limited by the availability and competition for use of organic resources, transportation costs, and the delicate control of decomposition dynamics and nutrient bioavailability (Kumar and Goh 2000). The emergence of agroecology as a scientific discipline responds to the need to overcome these limitations, among others (Altieri 2002). One basic hypothesis in agroecology is that the sustainability of natural ecosystems relies on structural and functional features that are largely specific to local environmental conditions; and that, once strategies to imitate these features have been developed, they can be transferred to agrosystems to enhance their sustainability (Ewel 1999). The grassland ecosystem served as a model for perennial grain cropping in North America (Jackson 2002) and for direct seeding mulch-based cropping systems CIRAD 1999). Forest ecosystems served as model for agroforestry. The strategy of using tree branches, or ramial wood (RW), as soil amendment also mimics tree ecosystems.

The use of RW for soil amendment has been developed in Canada for over 20 years and then in other countries (Lemieux 1996). It consists in burying small-diameter tree branches in the upper layer of cultivated soils in a "sink" (target) agroecosystem. The initial recommendations, established under cool climate conditions, mentioned the use of branches less than 7 cm in diameter, which were chipped, hence the expression "ramial chipped wood" to describe the material itself and the technique. The aim of applying RW is to improve the organic and biological status of the sink soils so that it becomes closer to that of the forest soils from which they would derive (although the ecosystem preceding cropping is not necessarily forest). The developers of this technique claim that applying RW would increase crop yields by modifying the soil physical and chemical properties, and, to a greater extent, stimulating soil biological activities, especially by encouraging fungi at the expense of bacteria. Applying RW may also buffer the impact of climate on plant performance, which is of special interest for smallholder farmers in the dry tropics (De Vries et al. 2012).

However, rather little statistical information is available in the literature on the effects of RW amendments on crops and soil, according to a review by Barthès et al. (2010). All studies in temperate conditions reviewed in this paper were carried out in Canada, on coarse-textured soils, and involved burying chipped RW. The few studies carried out under tropical conditions often involved the application of roughly fragmented or unfragmented RW, which was buried or sometimes used as mulch. On the whole, the review indicated that RW application increases the soil nutrient and organic matter content, stimulates soil biological activities, especially those of fungi, which in turn improves nutrient availability for crops. However, owing to high carbon-to-nitrogen and carbon-to-phosphorus ratios, RW application might lead to nitrogen (N) and phosphorous (P) immobilization in the year of application, and thus to a decrease in the yield of the following crop. This has been observed when RW was buried in sandy soils, particularly in temperate conditions, but research is required to extend this result to tropical conditions (Barthès et al. 2010). However, the review reported that N immobilization could be offset by additional N input; and that applying RW tends to increase the yields of subsequent crops, even with repeated RW application. Furthermore, the application of RW, especially as mulch, improves soil physical properties (moisture, porosity, structure, etc.), which, in semi-arid conditions, is closely linked with termite activity. There has not been any report of possible effects on crop pests and diseases.

The effects of RW application can be affected by several factors such as the tree species and amendment characteristics, including quantity, frequency, and chip size, but the available information cannot be used to draw up precise recommendations. Furthermore, there is little information on the advantages of using RW rather than organic, non-woody amendments (Barthès et al. 2010).

Most of the studies reviewed tested the application of RW at rates higher than 5 Mg ha^{-1} (dry matter basis, DM), which may raise concerns about the availability of ramial resources and about transportation and possible chipping of RW, especially in conditions where no machines are available.

The objective of the study was to assess the effects of amendment with RW or straw, buried or mulched, at a low application rate, on some topsoil chemical properties, on termite cast coverage (as a proxy of their activity), and on sorghum production, in a manual cropping system under semi-arid conditions.

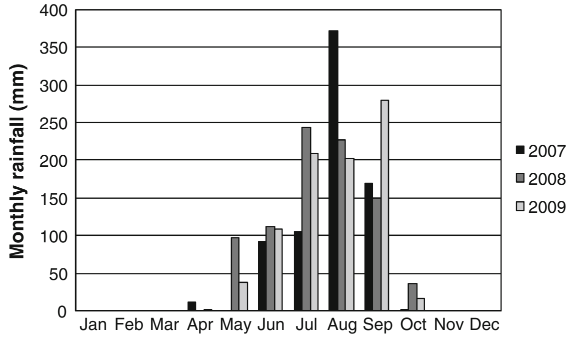

Fig. 1 Monthly rainfall at Gampéla from 2007 to 2009

Materials and methods

Study site

The study was carried out in 2007, 2008 and 2009, at the experimental station of Gampéla (12°24′35″N, 01°21′05″W), 15 km east of Ouagadougou, in the central region of Burkina Faso.

In the area, rainfall is between 600 and 900 mm year^{-1}, from May to October (INERA 1995). In 2007, 2008 and 2009, the annual rainfall at Gampéla was 751, 865 and 854 mm year^{-1}, respectively, which was higher than the mean of the previous ten years (692 mm year^{-1}). The rainfall distribution was well-balanced in 2008, whereas 2009 was characterized by major flooding on September 1st, with 233 mm rainfall within a few hours (Fig. 1), when the sorghum was at flowering stage. The mean annual temperature is 28 °C.

The landscape is slightly undulating, with a slope less than 2 %, and is developed on granites and migmatites (Hottin and Ouedraogo 1992). The soil at the experimental station is an endogleyic Acrisol (IUSS Working Group WRB 2006). The texture is silty sand in the topsoil and silty clay in the subsoil. This soil type is common in Burkina Faso (Hien et al. 2010). Most of the land around the experimental station is cultivated. The main crops are cereals such as sorghum, millet and maize, and legumes such as niebe (black-eyed pea) and peanut.

Experimental design

The trial was set up in an area that had been under natural fallow for four years, and then uniformly cropped with sorghum for one season in 2006 before starting the trial (manual cropping, no organic or nutrient inputs). The trial had a randomized complete block design, with four blocks perpendicular to the main slope. Each block had six 6×5 m^2 plots, which were separated by 1 m wide alleys.

The experiment compared six types of applications, located at random in each block, all plots being cropped with sorghum [*Sorghum bicolor* (L.) Moench, var. Sariasso]. Three treatments involved the application of RW from *Piliostigma reticulatum* (DC.) Hochst, which is a non-nitrogen-fixing Caesalpiniaceae shrub that is very common in the Sudano-Sahelian area (Arbonnier 2002). After being cut when the land is cleared, it regenerates rapidly when the land is left fallow (Yelemou et al. 2007). The experiment used leafy branches less than 2 cm in diameter, collected in late May. Their composition was determined on five composite samples, each comprising 12 branches cut from several places on each of five shrubs more than 10 m apart (see analytical methods in the next section). These Piliostigma branch samples (including leaves) had mean (± standard error, n = 5) C, N, P and potassium (K) contents of 46.2 (±0.2), 1.31 (±0.02), 0.088 (±0.005) and 0.88 (±0.09) g 100 g^{-1} DM, respectively (C/N = 35.3); water content was 49 % (as measured after drying at 50 °C until constant mass was achieved). These branches were cut into small pieces (<5 cm long) using a machete and applied immediately to the plots concerned. Other treatments involved the application of dry sorghum straw, in which C, N, P and K contents averaged 43.2, 0.59, 0.042 and 0.82 g 100 g^{-1} DM, respectively (C/N = 73.2); water content was 2 %. Straw was also cut into small pieces. The six treatments studied were:

- *Ctrl (control)*: sorghum cropping according to local practices, without any input; the soil was hoed manually to a depth of 5 cm at the beginning of June and sorghum was sown in late June or early July, when the soil moisture was considered appropriate; the plots were then hoed manually every two weeks for six weeks to weed and break the crust caused by heavy rains on the silty soil; the sorghum was harvested in October or November, and crop residues were removed;
- *WoBu (wood buried)*: as for Ctrl but RW was applied at a rate of 1.5 Mg DM ha^{-1} $year^{-1}$ (i.e. 0.69 Mg C ha^{-1} $year^{-1}$); in late May the RW was collected, chipped, applied the same day, and buried at a depth of 5 cm using a hoe;
- *WoMu (wood mulched)*: as for WoBu but RW was mulched and lightly covered with soil from the plot to avoid dispersal by wind or runoff;
- *WoBuN (wood buried with N)*: as for WoBu with an additional application of 9.6 kg N ha^{-1} $year^{-1}$ as urea two weeks after emergence; the aim was to offset possible N immobilization by soil microorganisms;
- *StBu (straw buried)*: as for WoBu but the 1.5 Mg DM ha^{-1} $year^{-1}$ of RW was replaced by straw at a rate of 1.6 Mg DM ha^{-1} $year^{-1}$ (i.e. 0.69 Mg C ha^{-1} $year^{-1}$, as for RW) with the addition of 10.47 N, 0.65 P and 0.75 K kg ha^{-1} $year^{-1}$ applied as mineral fertilizer (14.23.14) and urea, two weeks after emergence; this mineral complement aimed at achieving similar C, N, P and K application rates in WoBu and StBu;
- *StMu (straw mulched)*: as for StBu but the straw was mulched and lightly covered with soil to avoid dispersal by wind or runoff.

The application rate of 1.5 Mg DM ha^{-1} for ramial wood was selected as being between the rates of 1 and 2 Mg DM ha^{-1} tested by Wezel and Böcker (1999) in neighbouring Niger.

Measurements and analyses

Sorghum grain and straw production were measured every year at harvest in the central 16.4 m^2 (out of 30 m^2) of every plot. The two outside rows and the two end sheaves on the rows were not taken into account. The grains and straw were weighed after air drying for 2 months and oven drying of aliquots at 60 °C for 2 days (until constant mass was achieved). In 2008 and 2009, the weight of 1,000 seeds was determined on an aliquot of air-dried grains. The grain yield and weight of 1,000 seeds were used to calculate the number of seeds per hectare. The seed number and the weight of 1,000 seeds have been proposed as indicators of cereal yield limiting factors: the former would reflect water and nutrient availability during the vegetative phase of the crop cycle, and the latter, possible water stress and/or pest and disease intensity during the period from flowering to maturity (Doré et al. 2008).

Composite soil samples were collected on each plot in April 2007, before starting the trial, at 0–5 cm depth, and again at harvest in 2008 and 2009, at 0–5 and 5–15 cm depth, using an auger. Three separate samples were taken from sorghum rows in different parts of the plot and mixed thoroughly to form the composite sample. The soil samples were air-dried and then gently broken up using a pestle and mortar, and sieved at 2 mm. Aliquots were ground to 0.2 mm for further analyses.

The C and N concentrations in the soil and plant samples were determined on 0.2 mm ground aliquots by dry combustion using an elemental analyzer (CHN Fisons/Carlo Erba NA 2000, Milan, Italy). However, in 2007, the soil N could not be determined owing to analytical problems. As all of the soils were carbonate-free, total C was equal to organic C. The soil available P (P_{av}) concentration was determined on 0.2 mm ground aliquots using the Olsen procedure for samples collected in 2007 and 2008 (extraction using sodium bicarbonate at pH 8.5), and the Olsen-Dabin procedure for samples collected in 2009 (extraction using sodium bicarbonate and ammonium fluoride at pH 8.5), both with colorimetric assay. The latter procedure, which complexes iron and aluminum, tends to extract more P and has sometimes been considered more suitable for soils from tropical regions (Pansu and Gautheyrou 2006). The P and K concentrations in plant samples were determined after dry mineralization by inductively coupled plasma atomic emission spectrometry (ICP-AES; Pansu and Gautheyrou 2006).

Termite activity was characterized at the beginning of the cropping season in 2008 by semi-quantitative assessment of the abundance of termite casts on the soil surface. On each plot, a 1 × 1 m square frame with one hundred 10 × 10 cm squares was put on the soil, and the number of squares with termite casts was counted. The count was replicated 10 times on the plot, along two perpendicular transects. The count was carried out seven days after applying RW or straw and again one and two weeks later. It was not possible subsequently because the termite casts were destroyed by rainfall.

Statistical analyses

An analysis of covariance (ANCOVA; Yang and Juskiw 2011) was carried out to determine the significance of treatment effects on sorghum grain and straw production, and on topsoil C, N and P_{av} (at $p < 0.05$). An analysis of variance (ANOVA) was carried out to determine the significance of treatment effects on the interannual variations of grain yield and on the abundance of termite casts (at $p < 0.05$). ANOVA considered block and treatment as explicative variables. ANCOVA additionally considered the initial (April 2007) C and P_{av} contents at 0–5 cm as explicative variables, in order to remove possible effects of initial topsoil conditions. The significance of explicative variables was assessed by type III sum-of-square. A Duncan's paired test was used to assess the significance of differences between treatments at a given date, and a Student's paired test was used to assess the significance of differences between dates for a given treatment. The correlation coefficient was calculated between the initial C and P_{av} contents at 0–5 cm. The correlation coefficient between the weight of 1,000 seeds and number of seeds per hectare was calculated over two years (data were available for 2008 and 2009); although less informative due to the small number of plots, it was also calculated per year. All analyses were carried out using the XLSTAT 2008 v6.01 software (Addinsoft, Paris).

Results

Effects of treatments on soil total carbon, total nitrogen, and available phosphorus

At the start of the trial (April 2007), the total C and P_{av} at 0–5 cm depth were significantly higher upslope than downslope (block effect), and were significantly correlated ($r = 0.43$, $p < 0.05$; Table 1). This was the reason for using initial C and P_{av} as additional explicative variables in ANCOVA when studying treatment effects.

There were few significant differences between treatments (Table 1). Firstly, in 2008 at 5–15 cm, C was significantly lower in WoBuN than in most other treatments, and significantly lower in StBu than in WoBu. Secondly, in 2009 at 0–5 cm, P_{av} was significantly lower when the amendments were buried (WoBu, WoBuN, StBu) than when they were mulched (WoMu, StMu); for this date and depth layer, differences between plots were significantly affected by initial P_{av}, and to a lesser extent, by initial C and block.

Few significant changes in topsoil C and N were observed over time: C decreased in WoMu at 0–5 cm

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Table 1 Effects of treatments on the total carbon (C), total nitrogen (N), and available phosphorus (P_{av}; mean ± standard error) in the topsoil as estimated by ANCOVA

Variable	Date	Depth	Treatments						Probability of an effect of			
		(cm)	Ctrl	WoBu	WoMu	WoBuN	StBu	StMu	Treatment	Block	C at T_0	P_{av} at T_0
C	April 2007 (T_0)	0–5	3.30 ± 0.22[a]	3.59 ± 0.23[a]	3.41 ± 0.19[a]	3.33 ± 0.20[a]	3.29 ± 0.18[a]	3.56 ± 0.18[a]	0.504	0.003	ND	ND
($g\ kg^{-1}$)	Harvest 2008	0–5	3.12 ± 0.13[a]	3.19 ± 0.11[a]	3.20 ± 0.12[a]	3.08 ± 0.25[a]	3.13 ± 0.19[a]	3.30 ± 0.23[a]	0.905	0.045	0.728	0.869
	Harvest 2008	5–15	3.64 ± 0.14[ab]	3.67 ± 0.16[a]	3.47 ± 0.13[ab]	3.04 ± 0.12[c]						
	3.33 ± 0.09[bc]		3.46 ± 0.22[ab]	0.020	0.115	0.966	0.559					
	Harvest 2009	0–5	3.05 ± 0.21[a]	3.13 ± 0.12[a]	3.00 ± 0.20[a]	2.90 ± 0.27[a]	3.01 ± 0.14[a]	3.35 ± 0.21[a]	0.412	0.036	0.512	0.291
	Harvest 2009	5–15	3.52 ± 0.12[a]	3.37 ± 0.10[a]	3.49 ± 0.30[a]	3.16 ± 0.19[a]	3.48 ± 0.30[a]	3.37 ± 0.17[a]	0.722	0.330	0.869	0.323
N	April 2007 (T_0)	0–5	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
($mg\ kg^{-1}$)	Harvest 2008	0–5	220 ± 7[a]	220 ± 7[a]	233 ± 10[a]	228 ± 14[a]	230 ± 8[a]	238 ± 15[a]	0.703	0.281	0.372	0.832
	Harvest 2008	5–15	243 ± 8[a]	240 ± 7[a]	235 ± 14[a]	218 ± 6[a]	223 ± 3[a]	235 ± 14[a]	0.243	0.226	0.956	0.748
	Harvest 2009	0–5	248 ± 28[a]	245 ± 12[a]	245 ± 19[a]	228 ± 17[a]	228 ± 5[a]	253 ± 14[a]	0.813	0.141	0.849	0.834
	Harvest 2009	5–15	273 ± 13[a]	248 ± 11[a]	260 ± 21[a]	233 ± 19[a]	260 ± 31[a]	243 ± 3[a]	0.184	0.031	0.078	0.150
P_{av}	April 2007 (T_0)	0–5	7.61 ± 0.77[a]	8.46 ± 0.21[a]	7.83 ± 0.68[a]	7.82 ± 0.42[a]	7.98 ± 0.37[a]	7.89 ± 0.59[a]	0.363	<0.001	ND	ND
($mg\ kg^{-1}$)	Harvest 2008	0–5	11.41 ± 1.24[a]	13.22 ± 1.46[a]	14.75 ± 1.26[a]	10.01 ± 1.39[a]						
	10.17 ± 0.81[a]		11.27 ± 1.25[a]	0.228	0.704	0.594	0.342					
	Harvest 2008	5–15	11.67 ± 1.10[a]	13.56 ± 2.22[a]	9.71 ± 0.36[a]	12.46 ± 2.02[a]						
	10.47 ± 0.82[a]		13.25 ± 2.47[a]	0.507	0.415	0.204	0.364					
	Harvest 2009	0–5	5.75 ± 1.03[ab]	4.50 ± 0.87[b]	7.00 ± 1.08[a]	4.75 ± 0.25[b]	4.50 ± 0.65[b]	6.50 ± 0.96[a]	<0.001	0.022	0.013	<0.001
	Harvest 2009	5–15	3.75 ± 1.89[a]	1.50 ± 0.50[a]	2.75 ± 0.85[a]	3.00 ± 1.35[a]	3.50 ± 1.85[a]	3.25 ± 0.95[a]	0.462	0.963	0.940	0.099

For a given variable and date, different letters indicate significant differences between treatments ($p < 0.05$). T_0 stands for the start of the experiment (April 2007)

ND not determined

from April 2007 to the 2009 harvest, and N increased in StBu at 5–15 cm from the 2008 harvest to the 2009 harvest (Table 1). By contrast, P_{av} decreased significantly and noticeably at 0–5 cm in Ctrl and in treatments with buried amendment (WoBu, WoBuN, StBu) from April 2007 to the 2009 harvest, although not monotonically: it increased between April 2007 (dry season) and the 2008 harvest and then decreased. Partial data at the 2007 harvest even suggested that P_{av} increased strongly between April 2007 and the 2007 harvest and then decreased (data not shown). At 5–15 cm the P_{av} decrease over time was significant for all treatments. It is worth noting that the method used for determining P_{av} involved procedures that tended to extract more P in 2009 than in 2007 and 2008; so the decrease in P_{av} from 2007 to 2009 might be underestimated.

Effects of treatments on crop production

The mean overall yields in 2007, 2008 and 2009 were 0.87, 0.37 and 0.28 Mg DM ha^{-1} for grain, and 3.18, 1.94 and 0.72 Mg DM ha^{-1} for straw, respectively. Grain yields were low, and both yields decreased noticeably with time (Table 2). Using ANCOVA, the mean grain and straw yields and the mean total aboveground biomass (sum of grain and straw yields) did not differ significantly between treatments in 2007. In 2008, the mean grain and straw yields were significantly lower in Ctrl than in WoBuN and StBu, although ANCOVA showed that the treatments had little effect on grain yield ($p = 0.1$); nevertheless it showed that the total aboveground biomass was significantly lower in Ctrl than in WoBuN and StBu (data not shown). In 2009, there was no significant effect of treatment on yields but there were significant effects of block and initial topsoil P_{av}, which was not the case in 2007 and 2008. The mean three-year cumulative grain and straw yields were not affected significantly by the treatment; but, as in 2007 and 2008, there was an overall trend towards lower grain and straw yields in Ctrl and WoBu than in the other treatments (Table 2). The interannual variation in the grain yield was not significantly dependant on the treatment.

The mean weight of 1,000 seeds was significantly lower in Ctrl than in the other treatments in 2008, but was not significantly affected by the treatments in 2009. The mean number of seeds per hectare was also significantly smaller in Ctrl than in WoBuN and StBu in 2008 (13 vs. 38 and 36 x 10^6 seeds ha^{-1}, respectively; data not shown), and was significantly higher in StMu than in StBu in 2009 (21 vs. 11 x 10^6 seeds ha^{-1}; data not shown). Taking 2008 and 2009 together, there was a negative relation between seed weight and seed number ($R = -0.52$, $p < 0.1$), particularly if the data for Ctrl in 2008 were removed ($R = -0.74$, $p < 0.01$), and, to a lesser extent, if the data for WoBu in 2008 were also removed ($R = -0.85$, $p < 0.01$; Fig. 2). However, there was a positive correlation between the seed weight and number for 2008 on its own ($R = 0.81$, $p < 0.1$), and no significant correlation for 2009 on its own ($R = -0.36$, $p > 0.1$); but this was less informative owing to the small number of plots per year. There were more grains in 2008 than in 2009 but these were smaller. For both years, the seed weight was highest for StBu and smallest for Ctrl.

Termite cast abundance

According to ANOVA, the number of 10 × 10 cm squares with termite casts at the beginning of the cropping season in 2008 was 4–18 times higher for treatments with RW (8–11 % of the total number of squares, standard error < 2 %) than for the other treatments (0.6 % for Ctrl, 1.2 % for StBu, 2.1 % for StMu, standard error < 1 %), the difference being very significant ($p < 0.001$).

Discussion

Topsoil C, N and P_{av}

The main significant differences in the topsoil properties between the treatments were: (i) C at 5–15 cm at the 2008 harvest, which was lower in WoBuN than in the other treatments (the trend was also noticeable at 0–5 cm and in 2009), and (ii) P_{av} at 0–5 cm at the 2009 harvest, which was lower when the amendment was buried than when it was mulched. The aboveground biomass production tended to be higher in WoBuN than in the other treatments in 2007 and 2008 (this was significant only in 2008 when compared to Ctrl). The aboveground residues were exported, but it is likely that root production and thus plant C input into the soil were also higher in WoBuN, especially in

Table 2 Effects of treatments on grain and straw yield and on the weight of 1,000 seeds (mean ± standard error) as estimated by ANCOVA

Year and variable	Treatments						Probability of an effect of			
	Ctrl	WoBu	WoMu	WoBuN	StBu	StMu	Treatment	Block	C at T_0	P_{av} at T_0
Year 2007										
Grain yield (Mg DM ha^{-1})	0.74 ± 0.21^a	0.81 ± 0.11^a	0.88 ± 0.04^a	0.99 ± 0.11^a	0.92 ± 0.17^a	0.87 ± 0.18^a	0.804	0.439	0.261	0.505
Straw yield (Mg DM ha^{-1})	2.79 ± 0.56^a	2.98 ± 0.27^a	3.39 ± 0.33^a	3.47 ± 0.21^a	3.25 ± 0.34^a	3.21 ± 0.45^a	0.738	0.299	0.124	0.401
1,000 seeds (g DM)	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
Year 2008										
Grain yield (Mg DM ha^{-1})	0.16 ± 0.06^b	0.25 ± 0.06^{ab}	0.38 ± 0.10^{ab}	0.52 ± 0.19^a	0.49 ± 0.10^a	0.43 ± 0.13^{ab}	0.108	0.337	0.811	0.642
Straw yield (Mg DM ha^{-1})	0.99 ± 0.21^b	1.38 ± 0.14^{ab}	2.02 ± 0.39^{ab}	2.64 ± 0.69^a	2.50 ± 0.43^a	2.11 ± 0.51^{ab}	0.045	0.261	0.765	0.933
1,000 seeds (g DM)	11.6 ± 0.5^b	13.0 ± 0.5^a	13.5 ± 0.3^a	13.5 ± 0.4^a	13.7 ± 0.1^a	12.9 ± 0.7^a	0.025	0.101	0.409	0.142
Year 2009										
Grain yield (Mg DM ha^{-1})	0.28 ± 0.18^a	0.17 ± 0.05^a	0.36 ± 0.13^a	0.27 ± 0.07^a	0.24 ± 0.04^a	0.38 ± 0.11^a	0.075	0.010	0.112	0.003
Straw yield (Mg DM ha^{-1})	0.68 ± 0.37^a	0.51 ± 0.13^a	0.78 ± 0.25^a	0.70 ± 0.16^a	0.71 ± 0.07^a	0.93 ± 0.21^a	0.146	0.012	0.079	0.004
1,000 seeds (g DM)	15.8 ± 1.1^a	17.2 ± 0.6^a	18.2 ± 1.8^a	16.9 ± 2.1^a	20.9 ± 1.1^a	17.3 ± 2.3^a	0.426	0.523	0.458	0.474
Years 2007 to 2009 (cumulative)										
Grain yield (Mg DM ha^{-1})	1.18 ± 0.38^a	1.23 ± 0.13^a	1.63 ± 0.17^a	1.78 ± 0.34^a	1.65 ± 0.26^a	1.67 ± 0.42^a	0.287	0.204	0.288	0.202
Straw yield (Mg DM ha^{-1})	4.46 ± 0.96^a	4.86 ± 0.25^a	6.19 ± 0.63^a	6.81 ± 0.84^a	6.46 ± 0.75^a	6.24 ± 1.13^a	0.112	0.101	0.143	0.208

For a given variable and period, different letters indicate significant differences between treatments ($p < 0.05$). T_0 stands for the start of the experiment (April 2007), C and P_{av} for total carbon and available phosphorus, respectively, at 0–5 cm depth

ND not determined

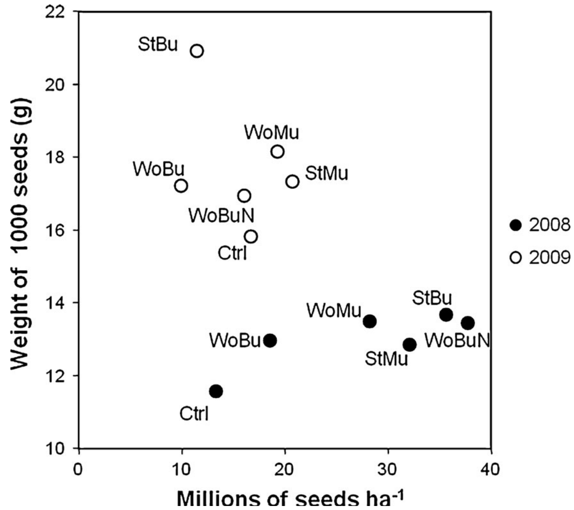

Fig. 2 Relationship between the number of seeds per hectare and the weight of 1,000 seeds for each treatment in 2008 and 2009

2008. It could thus be expected that topsoil C would be higher with this treatment than with the others, but this was not the case. Furthermore, soil C at 0–5 cm tended to decrease in all treatments over the three-year experiment, and the decrease was significant for WoMu, indicating that mulching did not prevent soil C loss.

An increase in topsoil C has often been reported in RW experiments. However, there are very few studies for sandy soils in dry tropical regions and these are much less conclusive (Barthès et al. 2010). At the second tomato harvest after burying RW at a rate of 8–31 Mg DM ha^{-1}, Soumare et al. (2002) observed that topsoil C did not differ significantly from the control (though 40 % higher) and did not depend on the RW application rate (±4 % variation). Taken in conjunction with our results, this suggests that adding high rates of fresh organic matter to sandy soils, at least in semi-arid conditions, has no clear effect on topsoil C, and that adding low rates causes the topsoil C to decrease. This may be explained by the weak protection of organic matter against mineralization (Barthès et al. 2008), and also probably by priming effect (Kuzyakov et al. 2000; Fontaine et al. 2003).

In this study, topsoil N was not significantly affected by the treatments. This does not agree with the results reported by Soumare et al. (2002) in a sandy soil under tomato in Senegal (similar climate and soil conditions to the present study), where burying RW (8 to 31 Mg DM ha^{-1}) caused the topsoil N to increase tenfold compared to the control. This positive effect might be attributed to the much higher RW application rates than in the present study, as well as the much higher N content in RW. High RW application rates are not necessarily sufficient to increase topsoil N: for wetter conditions and a more clayey soil, topsoil N under banana plantation was not significantly affected two years after applying woodchip mulch at a high-rate (50 Mg DM ha^{-1}; Salau et al. 1992).

The low application rates might also explain the limited effects of treatments on topsoil P_{av} in 2007 and 2008. Nevertheless, in 2009, topsoil P_{av} was lower in treatments involving burying, which might be explained by P immobilization by soil microorganisms. This immobilization might result from repeated treatments over three years (the topsoil P_{av} decreased from harvest 2007 to harvest 2009) and/or from the major flooding in September 2009, which might have stimulated mycelial proliferation. The burying of RW at a high rate (>18 Mg DM ha^{-1} $year^{-1}$) in a sandy soil under potato in Canada also caused topsoil P_{av} to be significantly lower than in the control, which was attributed to P immobilization (Tremblay and Beauchamp 1998). A significant difference in topsoil P_{av} was also observed under tomato in Senegal between the control and plots where RW had been buried at rates of 8 to 31 Mg DM ha^{-1}, and, according to analyses of P concentration in leaves, it was similarly attributed to microbial immobilization (Soumare et al. 2002). However, the topsoil P_{av} was not clearly affected in more clayey soils in humid tropics, with RW or ligneous inputs either buried or applied as mulch at a rate between 5 and 50 Mg DM ha^{-1} $year^{-1}$ (Obiefuna 1991; Salau et al. 1992; Kwabiah et al. 2003).

It should be borne in mind that the soil C, N and P_{av} contents were very low at the site studied here, as is often the case in central Burkina Faso: over the three years, on the composite samples analyzed (not averaged over blocks), C ranged from 2.2 to 4.3 g kg^{-1}, N from 0.17 to 0.31 g kg^{-1}, and P_{av} from 1 to 20 mg kg^{-1}. This study did not characterize repeatability or reproducibility for soil C, N and P_{av} analyses; nevertheless, especially for C and N, the differences between the treatments or dates were not much greater than analytical precision (e.g. around 0.5 g kg^{-1} for C), which limited the interpretation of results.

Crop production

Few differences in the crop properties studied were significant between treatments, probably due to the low application rates and to spatial heterogeneity. However, some significant differences in yield were recorded in 2008: more grain and straw were harvested in WoBuN and StBu than in Ctrl. The lower yield in Ctrl might be explained by the lack of inputs. By contrast, for both WoBuN and StBu the amendment was buried and mineral N was added, which probably resulted in higher nutrient bioavailability. The grain yield in 2008 varied mainly according to the number of grains (cf. Fig. 2), which depends on water and nutrient availability during flowering; whereas the grain weight was low, suggesting that the water supply was limiting during the grain-filling period (Doré et al. 2008). It should be noted that rainfalls in August and September were low in 2008 in comparison with 2007 and 2009 (cf. Fig. 1). The trend changed in 2009: the yield seemed to depend firstly on P_{av}, which was significantly lower in treatments where the amendment was buried (see discussion on soil properties). Despite fairly high seed weight, the grain yield was very low due to the low number of grains (cf. Fig. 2), which confirms that the supply of minerals was a limiting factor. Significantly smaller grains in Ctrl than in the other treatments in 2008 suggests that straw and RW amendments had a general positive effect on late season conditions, during the grain-filling period, probably owing to a better water supply (see discussion regarding termites).

The lack of any significant effect of treatment on the cumulative grain and straw yield over the three years suggested that the experimental design (in particular the number of blocks) might not be appropriate for assessing the impact of a low organic matter application rate. Furthermore, the lack of any significant effect of RW application on interannual yield variation might indicate either that the RW application was not effective at buffering climatic variations, or that the experimental conditions (duration and design) were not suitable for showing any buffering effect. However, the strong decrease in yield from 2007 to 2009 seemed to be caused by nutrient depletion, very possibly a lack of P, rather than by interannual variations. Unnoticed pest attacks might also have affected the yield from year to year.

According to the literature (cf. review from Barthès et al. 2010), burying chipped RW in coarse-textured soils decreases the yield of the first crop after application, as observed in Canada (N'dayegamiye and Dubé 1986; Beauchemin et al. 1990, 1992; Larochelle 1994; the crops studied were cereals and potato) and in the only peer-reviewed paper reporting RW burying in sandy soils under tropical conditions (Soumare et al. 2002, for tomato). The trend appears, therefore, to be well established for temperate conditions but unconfirmed for tropical conditions, and it is not confirmed by the present study. The lower first yield with buried RW has been attributed to the decrease in N uptake by crops after N immobilization by soil microorganisms (N'dayegamiye and Dubé 1986; Beauchemin et al. 1990), and additionally, in tropical conditions, to P immobilization (Soumare et al. 2002). The latter point has been discussed in the previous section. However, published papers have reported that the yield of the subsequent crops tends to be higher with the application of RW than without, even when RW has been applied repeatedly (N'dayegamiye and Dubé 1986; Gasser et al. 1995; Soumare et al. 2002). Burying chipped RW in less sandy soils or mulching RW, even in sandy soils, increases crop yields from the first season, as observed in tropical conditions (Aman 1996; Wezel and Böcker 1999; Gómez 2003; the crops studied were maize and millet). However, most of the studies referred to above applied RW at much higher rates than the present study (4–50 Mg DM ha^{-1} $year^{-1}$ vs. 1.5 Mg DM ha^{-1} $year^{-1}$ here), which very probably explained the greater effects on crop yield. It should be noted that the only study carried out in conditions similar to the present study (two cereal cropping seasons after one 1 or 2 Mg DM ha^{-1} application of mulched RW on a sandy soil in semi-arid Niger) was not very conclusive (Wezel and Böcker 1999): the millet grain yield was higher with the application of RW than without (+80 % in average) but this was hardly significant owing to soil variability; furthermore, the grain yield did not vary to any great extent when the RW application rate was doubled (+6 % in average).

Termites as ecosystem engineers?

The application of RW promoted termite activity markedly and significantly, and to a much greater extent than the application of straw. The positive effects of the presence of dead woody material on termite colonization have already been reported in wet tropical conditions (Davies et al. 1999). By contrast, Rouland et al. (2003) found that more termite casts were produced on straw than on woody material in an experiment in Senegal during the dry season, under drier conditions than in the present study. Since they also showed that litter preference was strongly driven by termite species, further characterisation of termite diversity in Gampéla would be needed for further comparison with other works. Mando (1997) demonstrated on crusted, uncropped soils in Burkina Faso that the positive role of mulches (straw or/and branches) on soil porosity, infiltration and water status was mainly due to their stimulation of termite activity. The rate of RW application was higher than in the present study (6 vs. 1.5 Mg DM ha^{-1}), but it is likely that the RW mulch also had a positive but less marked effect on the soil hydrophysical properties in the present study.

Ecological intensification due to ramial wood?

This experiment was set up to determine the specificity of woody amendment (vs. herbaceous amendment) by applying similar amounts of C, N, P and K to plots with RW and straw amendment. To compensate for the lower nutrient content of straw, small amounts of mineral N, P and K were applied in addition to the straw. Actually this was not very relevant because these elements were much more easily available for plants than in the organic amendments, which probably favoured the crops in the straw-amended treatments, distorting the comparison with RW-amended treatments.

The strong mediation of RW by termites in this study suggests that patterns of soil improvement previously observed using woody amendment (involving the stimulation of a diffuse fungal network in the topsoil; Barthès et al. 2010) could not be reproduced under the experimental protocol of this study. There were probably beneficial effects through improved soil hydrophysical properties and soil biochemical and nutrient enrichment by casts. However, termite foraging results in the partial transfer of applied organic matter to their nests, and thus in its partial removal from the crop-soil organo-mineral balance, and in heterogeneous shaping of the foodweb. Establishing fungi-mediated soil improvement patterns would probably require RW to be applied at the onset of the rainy season, when termite activity is at its lowest (Manlay et al. 2004). However, this would not only suppress any positive benefit from termite foraging but might also decrease nutrient (especially N and P) availability to plant due to microbial immobilization.

Conclusion and perspectives

Over the three years of the experiment, burying or mulching ramial wood or straw at a rate of 0.69 Mg C ha^{-1} $year^{-1}$ had little significant effect on topsoil C, N and P_{av} or on sorghum grain and straw yields. This was mainly attributed to the low application rate, which was probably so low that the effects were masked by spatial heterogeneity, particularly that of the soil. Nevertheless, at the third harvest, the topsoil P_{av} in treatments with buried amendment was significantly lower than in the other treatments, and lower than at the start of the experiment, both probably due to P immobilization by soil microorganisms. The low application rate was not sufficient to increase topsoil C, N, and P_{av}, which, on the contrary, tended to decrease, due to the mineralization of soil organic matter and probably to priming effect and transfer of organic matter by termites to their nests. Further studies may be needed to take account of the spatial patterns of redistribution of organic matter inputs by termites. Indeed, termite activity was strongly stimulated by the application of ramial wood.

Yields were low, particularly the grain yield, and decreased with time, suggesting that the treatments studied were not sustainable. On the whole, the application rate was not sufficient to cause significant differences in yields between treatments. Nevertheless, at the second harvest, Ctrl produced significantly less than some of the other treatments; it also produced significantly fewer, smaller grains than all other treatments. This suggested that organic applications had a beneficial effect on grain filling, probably owing to better water supply at the end of the cropping season, which is usually rainless. This also suggested that organic applications had a beneficial effect on grain initiation (number of grains per cropping area) when rainfall was limited during the flowering season.

Larger application rates need to be tested, but this will raise issues about the availability of the branches, which also have to be studied. Long-term studies, involving farm- and territory-scales, are also needed to address both the application efficiency and the availability of resources.

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ERRATUM

Erratum to: Effect of ramial wood amendment on sorghum production and topsoil quality in a Sudano-Sahelian ecosystem (central Burkina Faso)

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Unfortunately, in the original publication of the article, Table 1 layout has appeared incorrectly. The correct version of Table 1 is provided in this erratum.

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Table 1 Effects of treatments on the total carbon (C), total nitrogen (N), and available phosphorus (P_{av}; mean ± standard error) in the topsoil as estimated by ANCOVA

Variable	Date	Depth (cm)	Treatments						Probability of an effect of			
			Ctrl	WoBu	WoMu	WoBuN	StBu	StMu	Treatment	Block	C at T_0	P_{av} at T_0
C (g kg^{-1})	April 2007 (T_0)	0–5	3.30 ± 0.22[a]	3.59 ± 0.23[a]	3.41 ± 0.19[a]	3.33 ± 0.20[a]	3.29 ± 0.18[a]	3.56 ± 0.18[a]	0.504	0.003	ND	ND
	Harvest 2008	0–5	3.12 ± 0.13[a]	3.19 ± 0.11[a]	3.20 ± 0.12[a]	3.08 ± 0.25[a]	3.13 ± 0.19[a]	3.30 ± 0.23[a]	0.905	0.045	0.728	0.869
	Harvest 2008	5–15	3.64 ± 0.14[ab]	3.67 ± 0.16[a]	3.47 ± 0.13[ab]	3.04 ± 0.12[c]	3.33 ± 0.09[bc]	3.46 ± 0.22[ab]	0.020	0.115	0.966	0.559
	Harvest 2009	0–5	3.05 ± 0.21[a]	3.13 ± 0.12[a]	3.00 ± 0.20[a]	2.90 ± 0.27[a]	3.01 ± 0.14[a]	3.35 ± 0.21[a]	0.412	0.036	0.512	0.291
	Harvest 2009	5–15	3.52 ± 0.12[a]	3.37 ± 0.10[a]	3.49 ± 0.30[a]	3.16 ± 0.19[a]	3.48 ± 0.30[a]	3.37 ± 0.17[a]	0.722	0.330	0.869	0.323
N (mg kg^{-1})	April 2007 (T_0)	0–5	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	Harvest 2008	0–5	220 ± 7[a]	220 ± 7[a]	233 ± 10[a]	228 ± 14[a]	230 ± 8[a]	238 ± 15[a]	0.703	0.281	0.372	0.832
	Harvest 2008	5–15	243 ± 8[a]	240 ± 7[a]	235 ± 14[a]	218 ± 6[a]	223 ± 3[a]	235 ± 14[a]	0.243	0.226	0.956	0.748
	Harvest 2009	0–5	248 ± 28[a]	245 ± 12[a]	245 ± 19[a]	228 ± 17[a]	228 ± 5[a]	253 ± 14[a]	0.813	0.141	0.849	0.834
	Harvest 2009	5–15	273 ± 13[a]	248 ± 11[a]	260 ± 21[a]	233 ± 19[a]	260 ± 31[a]	243 ± 3[a]	0.184	0.031	0.078	0.150
P_{av} (mg kg^{-1})	April 2007 (T_0)	0–5	7.61 ± 0.77[a]	8.46 ± 0.21[a]	7.83 ± 0.68[a]	7.82 ± 0.42[a]	7.98 ± 0.37[a]	7.89 ± 0.59[a]	0.363	< 0.001	ND	ND
	Harvest 2008	0–5	11.41 ± 1.24[a]	13.22 ± 1.46[a]	14.75 ± 1.26[a]	10.01 ± 1.39[a]	10.17 ± 0.81[a]	11.27 ± 1.25[a]	0.228	0.704	0.594	0.342
	Harvest 2008	5–15	11.67 ± 1.10[a]	13.56 ± 2.22[a]	9.71 ± 0.36[a]	12.46 ± 2.02[a]	10.47 ± 0.82[a]	13.25 ± 2.47[a]	0.507	0.415	0.204	0.364
	Harvest 2009	0–5	5.75 ± 1.03[ab]	4.50 ± 0.87[b]	7.00 ± 1.08[a]	4.75 ± 0.25[b]	4.50 ± 0.65[b]	6.50 ± 0.96[a]	< 0.001	0.022	0.013	< 0.001
	Harvest 2009	5–15	3.75 ± 1.89[a]	1.50 ± 0.50[a]	2.75 ± 0.85[a]	3.00 ± 1.35[a]	3.50 ± 1.85[a]	3.25 ± 0.95[a]	0.462	0.963	0.940	0.099

For a given variable and date, different letters indicate significant differences between treatments ($p < 0.05$). T_0 stands for the start of the experiment (April 2007)

ND not determined