Received: 29 March 2017 | Revised: 23 May 2018 | Accepted: 27 May 2018
DOI: 10.1002/ldr.3033

SPECIAL ISSUE ARTICLE

WILEY

# Ramial wood amendments (*Piliostigma reticulatum*) mitigate degradation of tropical soils but do not replenish nutrient exports

**Georges F. Félix**[1] | **Cathy Clermont-Dauphin**[2,3] | **Edmond Hien**[4,5] | **Jeroen C.J. Groot**[1] | **Aurélien Penche**[2,4] | **Bernard G. Barthès**[2] | **Raphaël J. Manlay**[2,6] | **Pablo Tittonell**[1,7] | **Laurent Cournac**[2,3]

[1] Wageningen University & Research, Farming Systems Ecology, Wageningen, The Netherlands
[2] Eco&Sols, Univ Montpellier, CIRAD, INRA, IRD, Montpellier SupAgro, Montpellier, France
[3] LMI IESOL, Dakar, Senegal
[4] LMI IESOL, Ouagadougou, Burkina Faso
[5] Université Ouaga I Pr Joseph Ki-Zerbo, UFR Sciences de la Vie et de la Terre, Ouagadougou, Burkina Faso
[6] AgroParisTech, Paris, France
[7] INTA, Natural Resources and Environment Program, Bariloche, Argentina

**Correspondence**
Georges F. Félix, Farming Systems Ecology, Wageningen University & Research, Wageningen, The Netherlands.
Email: gfelix@protonmail.com

**Funding information**
European Union Seventh Framework Programme; AgroParisTech

## Abstract

Restoring degraded soils to support food production is a major challenge for West African smallholders who have developed local innovations to counter further degradation. The objective of this study was to evaluate a local farmer's technique that uses ramial wood (RW) as soil amendment (*Piliostigma reticulatum* shrub). Three treatments were applied in an experimental plot in Burkina Faso: control (no amendment), low RW (3 Mg fresh mass·ha$^{-1}$·yr$^{-1}$), and high RW (12 Mg fresh mass·ha$^{-1}$·yr$^{-1}$). RW was chipped to <5-cm pieces and either buried or mulched. Topsoil carbon (C), nitrogen (N), and phosphorus (P) in control and low-RW treatments declined after 7 years of continuous sorghum cultivation. Use of high-RW amendment stabilized soil C content while N and P declined, thus not replenishing nutrient exports. Net contribution to soil C in the layer measuring 0–15 cm was 15% of the applied C in the high-RW amendments. Although biomass and grain yields were higher in high-RW treatments, crop productivity declined throughout the experiment for all treatments. Termite casts on RW treatments evidenced the potential role of wood-foraging termites in diluting the impact of RW on soil fertility build-up and soil water content. We conclude that mitigating soil degradation under semiarid conditions in Burkina Faso would require large amounts of woody amendments, particularly if the level of termite activity is high. Additional nutrient sources would be needed to compensate for removal in exported products so that biomass and grain production can be stabilized or increased.

KEYWORDS
adaptation, farmer innovation, Sahel, shrub material, termites

## 1 | INTRODUCTION

The majority of the rural population of West Africa cultivates the soil to produce crops for self-subsistence, using small amounts of external inputs and no irrigation (Douxchamps et al., 2015; Masse et al., 2011). Historically, these farming systems relied on fallow periods to restore soil fertility (Hiernaux et al., 2009). The regrowth of native woody and herbaceous vegetation in fields left as fallow for 10 to 20 years would be eventually cut down, burnt on site, used as fuelwood, or more rarely, reincorporated in the soil, restoring soil carbon and nutrients

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(Hiernaux et al., 2009; Wezel & Haigis, 2002). Fallow and agricultural fields would alternate and rotate in time in these savanna ecosystems. Shortened fallow periods have been observed all over the region in the last few decades, associated with increased demographic pressure and the introduction of cash crops (CSFD, 2015; Diarisso, Corbeels, Andrieu, Djamen, & Tittonell, 2015). High demand for agricultural land has provoked a shift towards continuous cultivation, leading to severe soil degradation ranging from 2% to 3% (in Niger, Mali, and Burkina Faso) and up to 9–17% (in Nigeria, Gambia, and Senegal) of the agricultural soils in the region (Bai, Dent, Olsson, & Schaepman, 2008).

When vegetation is cleared by people to address the need for land, scarce cover makes semiarid West Africa (SWA) soils prone to degradation (Couteron & Kokou, 1997; Savadogo, Tigabu, Sawadogo, & Odén, 2007; Sop & Oldeland, 2013). In particular, wind and water erosion and decreasing organic matter and nutrient contents in soils (Ganry, Feller, Harmand, & Guibert, 2001; Roose & Barthès, 2001) may lead to the formation of physical crusts on topsoil layers (Bationo, Kihara, Vanlauwe, Waswa, & Kimetu, 2007; Mando & Stroosnijder, 2006). Intensive plot-level management is required to counter land degradation at landscape level. Experience in the region indicates that soil structure and fertility could be rehabilitated by (a) reducing water runoff and land erosion through creation of permeable microdykes (e.g., stone bunds or grass strips), (b) re-establishing macroporosity of soil and deep rooting capacity through localized tillage (e.g., *zaï* or half-moons), (c) stabilizing porosity by incorporation of organic matter, (d) revitalizing surface horizon by application of composted organic matter (e.g., domestic waste compost and animal manure), (e) increasing soil pH over 5 to reduce Al and Mg toxicity, and, finally, (f) ensuring balanced crop nutrition by complementing organic amendments with nitrogen (N) and phosphorus (P) inputs (Kathuli & Itabari, 2015; Roose, Kaboré, & Guénat, 1999).

Organic matter resources play a central role in soil rehabilitation (Mando, 1997; Zougmoré, Zida, & Kambou, 2003), as long as minimum effective doses are not in short supply. Organic resources traditionally used to restore soil fertility, such as crop residues, compost, and animal manure, are subject to competing uses within smallholder farming systems (Erenstein, Gérard, & Tittonell, 2015). Woody perennial species such as shrubs and trees are often present in these landscapes, providing numerous ecosystem services to farming families (Bayala, Sanou, Teklehaimanot, Kalinganire, & Ouédraogo, 2014; Sinare & Gordon, 2015; Sop, Oldeland, Bognounou, Schmiedel, & Thiombiano, 2012). In dryland agroecosystems, trees, and especially shrubs, may supply renewable quantities of branches and leaves useable to amend degraded soils (Breton, Crosaz, & Rey, 2016; Hueso-González, Martínez-Murillo, & Ruiz-Sinoga, 2016; Lahmar & Yacouba, 2012). Several studies on the use of such soil amendments, known as ramial chipped wood (in French, *bois raméal fragmenté*), were conducted in temperate regions, and they showed potential to restore soil functions, particularly of soil fungi and microbial communities (Barthès, Manlay, & Porte, 2010; Breton, Crosaz, & Rey, 2016; Breton, Rey, & Crosaz, 2015). To what extent can soil productivity be restored in this way, how long will it take to rehabilitate severely degraded soils in a semiarid tropical environment, and at what costs for farming families are questions that remain poorly explored in the context of SWA. In a study assessing effects of the native shrub amendments (*Piliostigma reticulatum* DC. Hochst.) on soils and crops, Barthès et al. (2015) reported no significant yield differences with application of 3 Mg fresh mass (FM) $ha^{-1}\cdot yr^{-1}$ of buried or mulched material on sorghum yields, as compared with control or crop residue application. From that experience, conducted between 2007 and 2009 at Gampéla, Burkina Faso, the experiment described in this paper was partly modified by introducing higher rates of ramial wood (RW) application in 2010 (12 Mg $FM\cdot ha^{-1}\cdot yr^{-1}$), incorporated or as mulch, and continued until 2013.

Here, we present an analysis of the complete data series, from 2007 to 2013, to evaluate the potential of RW amendments to cope with agricultural soil degradation. RW consists of small branches and leaves of a native shrub species (*P. reticulatum* DC. Hochst.) as soil cover, at the onset of rainy season. We hypothesized that application of RW as soil amendment has beneficial impacts on both soil quality and plant growth conditions, translating in crop yield increases, a necessary condition to ensure farmers' adoption of this soil rehabilitation technique. Specifically, we studied the effect of two application rates (3 and 12 $Mg\cdot ha^{-1}$) with two modes of application (mulched or mixed in the soil profile) of woody amendments on topsoil organic matter and nutrient stocks and on sorghum yields in a continuously cultivated system (cereal monoculture).

## 2 | MATERIALS AND METHODS

### 2.1 | Study site

The experiment was conducted on the field station of Gampéla (12°24′35″N, 01°21′05″W), located 15 km north-east of Ouagadougou, Burkina Faso (Figure 1a). Elevation is approximately 300 m asl and climate is of the Sudano-Sahelian type, with rainfall concentrated in one short rainy season, ranging between 700 and 1,000 $mm\cdot yr^{-1}$, and generally distributed from May through October (Figure 1b). The annual rainfall during the experimental period between 2007 and 2013 averaged 823 $mm\cdot yr^{-1}$ and was lowest in 2011 (728 mm) and highest in 2012 (973 mm). Mean annual temperature in the region is 28°C, with the highest temperature usually occurring by April (40–43°C), before the planting season starts, and the lowest temperatures occurring around December (18°C), when crops have already been harvested.

The Gampéla field station is located in a slightly undulating landscape, with a slope steepness of on average 2%. Savanna-type vegetation surrounds the experimental plot. Naturally occurring species composition varies according to landscape features, as described in Table 1. Soils on the station are classified as endogleyic Acrisols, presenting silty sand texture in the topsoil and silty clay in the subsoil (FAO, 2015). A large proportion of the land area of Burkina Faso is characterized by this soil type (Hien, Kaboré, Masse, & Dugué, 2010), which is generally suitable to grow crops such as sorghum, millet, maize, cowpea, and groundnut, as evidenced on the neighbouring fields around the Gampéla experimental field station.

### 2.2 | Experimental design

The trial was implemented on a field that had been under natural herbaceous fallow during 4 years (2001 through 2005). In 2006, the field was uniformly sown with sorghum (manual cropping, no inputs). Experimental set-up consisted of a randomized complete block design,

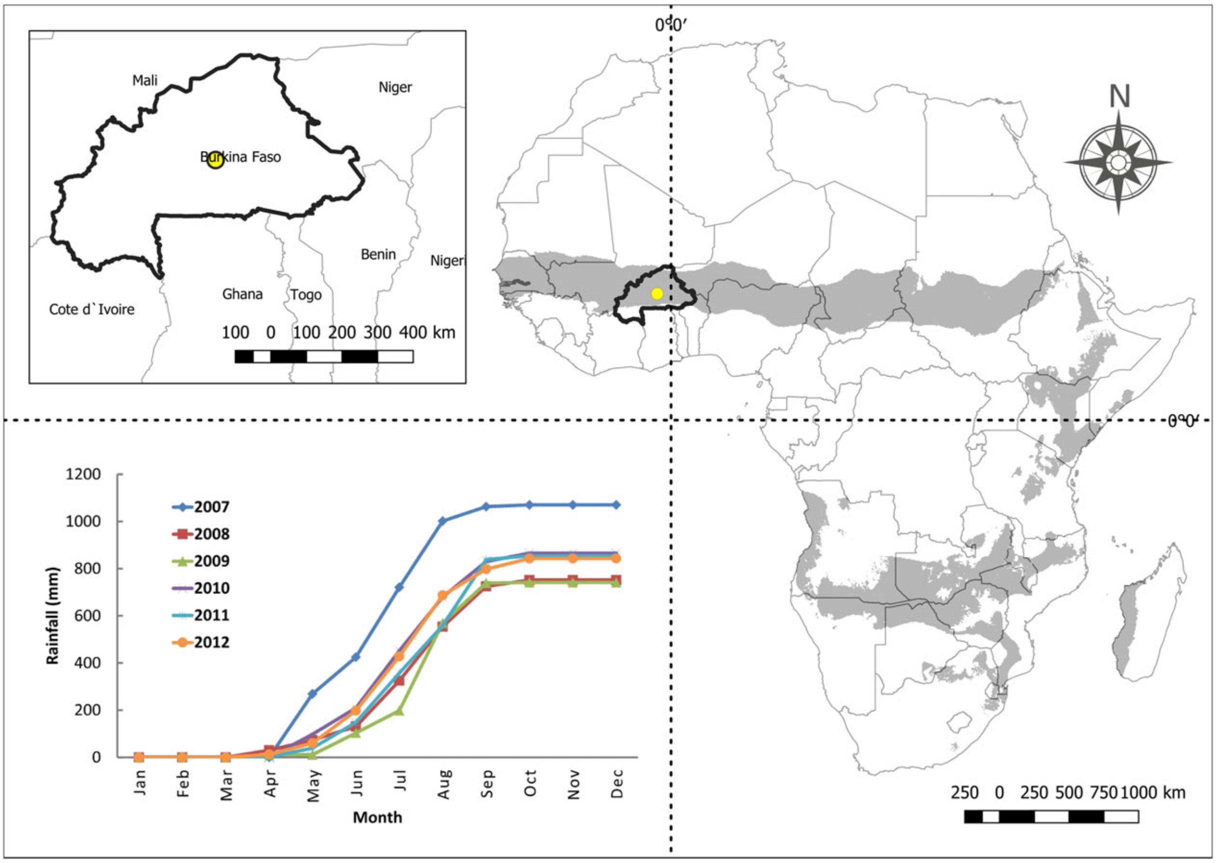

**FIGURE 1** Geographical location and rainfall patterns (2007–2012) at Gampéla experimental field station (yellow dot), within semiarid West Africa (shaded area). Agroecological zones available at: https://harvestchoice.org/data/aez5_clas.Rainfalldata:EdmondHien,IRD Ouagadougou [Colour figure can be viewed at wileyonlinelibrary.com]

**TABLE 1** Vegetation types surrounding Gampéla experimental field station and key species

| Landscape feature | Trees | Shrubs | Herbaceous |
|---|---|---|---|
| Lowland and riverbed | *Anogeissus leiocarpus* (DC.) Guill. & Perr.<br>*Mitragyna inermis* (Willd.) K. Schum. | | *Vetiveria nigritana* Retz. |
| Open savanna | *Balanites aegyptiaca* (L.) Del.<br>*Combretum glutinosum* Perr.<br>*Parkia biglobosa* (Jacq.) R.Br.<br>*Sclerocarya birrea* (A. Rich.) Hochst.<br>*Vitellaria paradoxa* C.F.Gaertn. | *Acacia gourmaensis* A. Chev.<br>*Acacia macrostachya* Reichenb.<br>*B. aegyptiaca* (L.) Del.<br>*C. glutinosum* Perr.<br>*Guiera senegalensis* J.F.Gmel.<br>*Piliostigma reticulatum* (DC.) Hochst.<br>*Ziziphus mauritiana* Lam. | *Andropogon gayanus* Kunth.<br>*Ctenium elegans* Kunth.<br>*Eragrostis tremula* (L.) Hochst.<br>*Loudetia togoensis* (Pilg.) C.E.Hubb.<br>*Pennisetum pedicellatum* Trin. |
| Close to household compounds | *Azadirachta indica* A.Juss.,<br>*Eucalyptus* sp. L'Hér.<br>*Mangifera indica* L. | *Cassia sieberiana* DC.<br>*Combretum micranthum* G. Don.<br>*P. reticulatum* (DC.) Hochst. | *A. gayanus* Kunth. |

with four blocks oriented perpendicularly to the main slope. Each block comprised six 6 × 5 $m^2$ plots, each separated by 1-m aisles, and the total experimental area covered 972 $m^2$. All treatments were homogeneously cropped with *Sorghum bicolor* L. Moench. (var. *Sariasso*) as sole crop with a row distance of 0.8 m, distance of 0.4 m within rows, and a plant density of 31,250 plants·$ha^{-1}$.

Across the whole study, treatments that included woody amendments involved the application of *P. reticulatum* DC. Hochst. RW as branches < 2 cm in diameter, with their leaves chipped with machete in pieces ≤5 cm long. This non-nitrogen-fixing plant (Fabaceae family, formerly Cesalpinaceae) is common in Sudano-Sahelian areas (Arbonnier, 2002). *P. reticulatum* was selected as soil amendment for (a) its high abundance in the surrounding landscape (cf. Table 1) and (b) its characteristic fast renewal of vegetative organs upon land clearing even under continuous soil cultivation (Ky-Dembele, Tigabu, Bayala, Ouédraogo, & Odén, 2007; Yélémou, Bationo, Yaméogo, & Millogo-Rasolodimby, 2007). From 2007 through 2009, the experimental set-up included treatments with the application of 3 Mg FM·$ha^{-1}$·$y^{-1}$ of woody shrub (*P. reticulatum* DC. Hochst.) material or sorghum (*S. bicolor* L. Moench.) straw, either mulched (treatments WoMu3t and StMu) or buried (WoBu3t and StBu, see Table 2 for a detailed description of treatments, including fertilization).

Synthetic fertilizers were added to the straw treatments so that nutrient supply in wood and straw treatments was the same (2007–2009). One additional treatment with buried woody material received extra synthetic N (WoBu3t+N), and there was an untreated control

**TABLE 2** Description of experimental treatments

| Treatment | Cropping system description |
|---|---|
| Ctrl | 2007–2013 (*control*) Cropping system mimicking local farming practices, without any inputs and manually operated. Soils were hoed at 5-cm depth early June and sown uniformly with sorghum (*Sorghum bicolor*) 3 to 4 weeks later, when rains were providing enough water to revive adequate soil moisture content for plant growth. Plots were then manually weeded using a hoe and harvested in October or November, when grain was mature. |
| WoMu3t | 2007–2013 (*3t ha$^{-1}$ wood mulched, without N*) Similar to Ctrl with addition of 1.5 Mg DM·ha$^{-1}$·yr$^{-1}$ ramial woody shrub material (*Piliostigma reticulatum*), manually chipped with machete, mulched on surface, and covered with small amounts of soil to prevent biomass dispersal by wind or water runoff. |
| WoBu3t | 2007–2013 (*3t ha$^{-1}$ wood buried, without N*) Similar to WoMu3t with incorporation of woody shrub material (small branches and leaves) at a rate of 1.5 Mg DM·ha$^{-1}$·yr$^{-1}$ and manually buried at 5-cm depth using a hand hoe. |
| WoBu3t+N | 2007–2013 (*3t ha$^{-1}$ wood buried, with N*) Similar to WoBu3t with addition of 9.6 kg N·ha$^{-1}$·yr$^{-1}$ as urea, applied 2 weeks after emergence of sorghum seedlings, in one time. |
| WoMu12t | 2010–2013 (*12t ha$^{-1}$ wood mulched*) Similar to WoMu3t but instead with four-times the amount of fresh woody shrub material, an equivalent of 6 Mg DM·ha$^{-1}$<br>(Previous treatment) 2007–2009 *(StMu; straw mulched, with NPK)* Mulched straw from sorghum crop residues at a rate of 1.6 Mg DM·ha$^{-1}$·yr$^{-1}$, covered with small amounts of soil to prevent biomass dispersal by wind or water runoff, and completed with mineral fertilizer (14–23–14) and urea, 2 weeks after emergence of sorghum seedlings. This fertilization aimed at achieving similar C, N, P, and K applications in both wood and straw treatments. Thus, N, P, and K doses under straw treatments were close to 10.47, 0.65, and 0.75 kg·ha$^{-1}$·yr$^{-1}$, respectively. |
| WoBu12t | 2010–2013 (*12t ha$^{-1}$ wood buried)* Similar to WoBu3t but instead with four-times the amount of fresh woody shrub material, an equivalent of 6 Mg DM·ha$^{-1}$<br>(Previous treatment) 2007–2009 *(StBu; straw buried, with NPK)* Similar to StMu with a modification: Crop residues were incorporated into topsoil at 5-cm depth using a hand-hoe. |

*Note*. Average dry matter wood input (Wo) quality was 46.2% of C, 1.31% of N, 0.088% of P, 0.88% of K, a C/N ratio of 35, and a water content of 49% (years 2007–2013). Average sorghum biomass (St) tissue quality was 43.2% of C, 0.59% of N, 0.042% of P, 0.82% of K, a C/N ratio of 73, and a water content of 2% (years 2007–2009).

plot (results reported in Barthès et al., 2015). From 2010 through 2013, the experimental layout remained the same, but the focus of the experiment shifted from an objective of comparing effects of two sources of organic amendments (straw vs. wood) to an objective of comparing two different rates of the same source of organic matter (only woody material), featuring a "low-RW" rate of 3 Mg FM·ha$^{-1}$·yr$^{-1}$ (3t) versus "high-RW" rate of 12 Mg FM·ha$^{-1}$·yr$^{-1}$ (12t). Treatments with mulched or buried sorghum straw (StMu and StBu) were replaced in 2010 with high-RW mulched or buried (treatments WoMu12t and WoBu12t). The results of the experiment during the 2007–2009 period showed that the effects of RW and straw additions on topsoil properties and sorghum yields were similar (Barthès et al., 2015). As, in addition, minerals added to straw (to provide similar amounts of N, P, and K as RW) rendered comparison between both amendments difficult (because mineral N, P, and K were in a much more available form), it was decided to address the question of amendment rate rather than continue studying the question of its woody versus herbaceous nature. Thus, our analysis takes into account this shift as described in Table 2, by analysing two separate periods:

(1) a 7-year experiment (2007–2013) with four treatments conducted throughout the whole period (WoMu3t, WoBu3t, WoBu3t+N, and Ctrl) and

(2) a 4-year experiment (2010–2013) including two new treatments (WoMu12t and WoBu12t) following practices of sorghum straw application (treatments StMu and StBu). Treatments tested from 2007 to 2009 had little significant effects on topsoil properties, especially the woody versus herbaceous nature of the organic amendment (Barthès et al., 2015): Considering soil C, N, and available P ($P_{av}$) concentrations at depths of 0–5 and 5–15 cm at the 2009 harvest, the only parameter significantly affected by the treatments was $P_{av}$ at 0–5 cm, which was lower in WoBu, WoBuN, and StBu than in WoMu and StMu (and intermediate in Ctrl), also as a significant result of initial $P_{av}$ (2007), though it did not differ significantly between treatments to be set up. Thus, we considered that the two new treatments and the four old ones had comparable backgrounds in 2010 and the analysis could be conducted over the following experimental period.

## 2.3 | Data collection

### 2.3.1 | Soil parameters

Soil samples were collected before the onset of this trial in April 2007 at the depth of 0–5 cm, and from 2008 through 2013 after harvest at depths of 0–5 and 5–15 cm. Sampling depth corresponded to approximate soil disturbance depth in the region with the use of manual tools, at which most soil transformations occur. Each soil sample resulted from thoroughly mixing three subsamples diagonally distributed across each plot (e.g., near two corners of the plot and in the centre). After air-drying during 48 hr, aggregates in soil samples were gently crushed using pestle and mortar and sieved through 2 mm. Aliquots were then ground at 0.2 mm, packed in plastic jars, and transported to Dakar, Senegal, for analysis at the LAMA facilities in *Laboratoire Mixte International IESOL* (LMI IESOL; http://lama.ird.sn/prestations/index.htm). Total soil C and N were measured by dry combustion using an elemental analyser (CHN Fisons/Carlo Erba NA 2000, Milan, Italy). On carbonate-less soils, total C equals organic C. Soil mineral N ($NO_3$ and $NH_4$) was extracted by potassium chloride (KCl) and then was measured by colorimetry. Total soil P was extracted by acid mineralization using a boiling mixture of chlorhydric (2/3) and nitric (1/3) acids and then was measured by colorimetry. 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 from 2009 onwards (extraction using sodium bicarbonate and ammonium fluoride at pH 8.5), both with colorimetric assay.

### 2.3.2 | Crop productivity

Sorghum grain and aboveground biomass weight was measured every year at harvest (October–November) on each plot by taking into account only the central zone of each plot, corresponding to 16.4 m$^2$ (out of 30 m$^2$). The sampling scheme intended to minimize possible border effects on outer rows of each plot. At harvest, grain and total aboveground biomass were weighed after air-drying in the shade for a period of at least 10 days. Mean yields (plus or minus standard deviation) are provided in dry matter (DM) per hectare. Harvest data of 2013 were not included because drought and bird predation led to complete crop failure.

### 2.3.3 | Termite foraging activity

As a proxy to termite activity, cast abundance was characterized at the beginning of planting seasons in 2010 and 2011. On each 30-m$^2$ plot (*n* = 24), 10 repetitions across the plot were conducted using a 1-m$^2$ square frame including a grid of 100 squares of 10 cm$^2$ each. The number of squares with cast presence was counted to determine the relative abundance, expressed as a percentage of total number of squares in the grid. Observations were averaged per plot and per year, one measure being conducted in 2010 and two in 2011, prior to planting but after RW application.

## 2.4 | Data analyses

Statistical analyses were performed using the R software v3.3.2 (RCoreTeam, 2016). We conducted stepwise multiple regression and analyses of variance to assess effects of explanatory factors (block, year, treatment) on response variables (crop yields, soil carbon, and nutrient contents). Grain, total aboveground biomass, and termite cast presence were considered response variables. Soil C, total N, mineral N, total P, and P$_{av}$ (depths of 0–5 and 5–15 cm) were considered as response variables to treatments and as explanatory variables for crop productivity and termite cast presence. Possible interactions (Year: Treatment) and quadratic terms (Year$^2$) were additionally assessed for changes in residual sum of squares on individual response

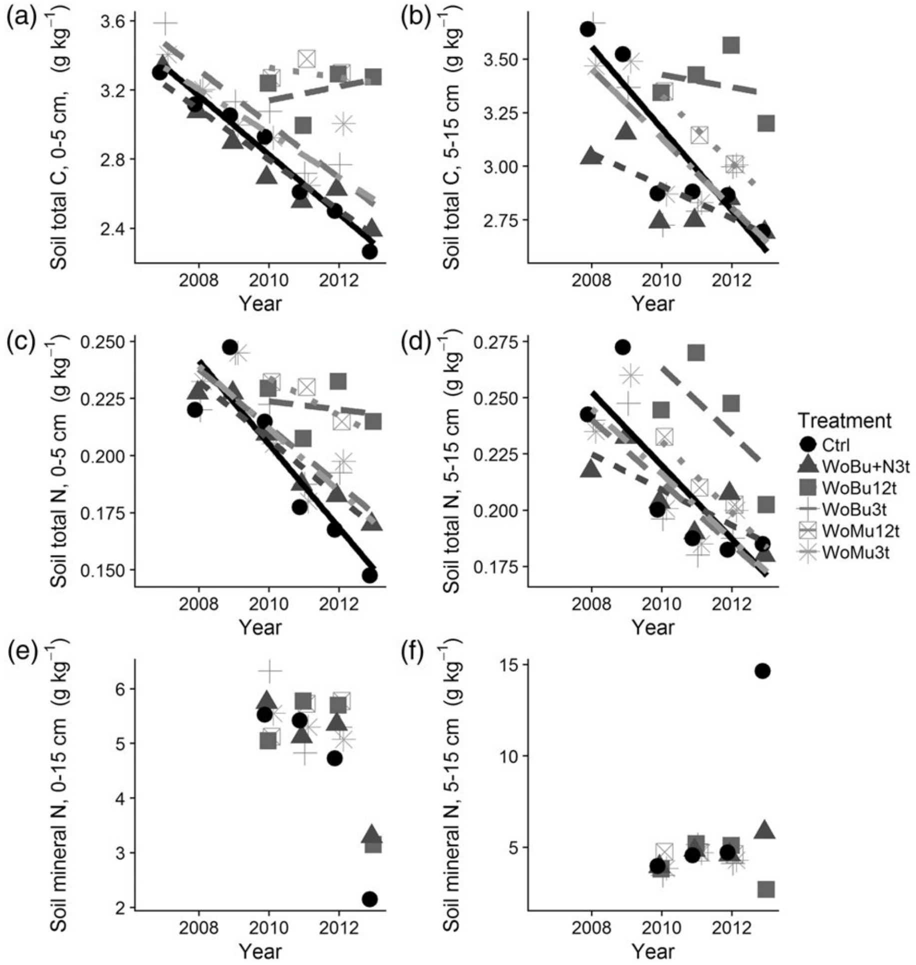

**FIGURE 2** Topsoil content of carbon (C; a and b), total nitrogen (N; c and d), and mineral nitrogen ($NO_3 + NH_4$; e and f) as affected by absence (Ctrl) or low rates of woody amendment application (either mulched: WoMu3t or buried: WoBu3t, or buried with nitrogen fertilizer added: WoBu3t+N) from 2007 to 2013, and high rates of amendment application (WoMu12t and WoBu12t) from 2010 to 2013, at depths of 0–5 cm (a, c, e) and 5–15 cm (b, d, f). Lines indicate trends; details of the regression analysis are provided in Table 3 [Colour figure can be viewed at wileyonlinelibrary.com]

variables, using *AddTerm*, a forward model selection function in R (package MASS). Terms were added to the model provided they resulted in a significant ($p < 0.05$) reduction in the residual mean square.

## 3 | RESULTS

### 3.1 | Effect of ramial wood on topsoil carbon and nutrient content

Soil C content at depths of 0–5 cm and 5–15 cm declined linearly when no (Ctrl) or low rates of RW (WoMu3t, WoBu3t, and WoBu3t+N) were applied during the 7-year period of the trial (Figure 2a,b). Initial C content at 0–5 cm prior to planting in 2007 was on average 3.4 ± 0.4 g·kg$^{-1}$. After the seventh year of continuous sorghum cultivation, soil C content at harvest in 2013 had decreased to an average of 2.4 ± 0.4 g·kg$^{-1}$, with a significantly higher C content for treatment WoBu3t compared with other low-RW and control treatments (Figure 2a). When high-RW treatments (WoMu12t and WoBu12t) were introduced in 2010, their effect resulted in stabilization of soil C content at depth of 0–5 cm to 3.2 ± 0.4 g·kg$^{-1}$ in average, over the last 4-year period. Soil C content declined linearly at depth of 5–15 cm and for all treatments, except for buried high RW (WoBu12t), which maintained C contents over time (Figure 2b; Table 3).

In the studied horizons (0–15 cm), total soil C stock (Mg·ha$^{-1}$) declined by an estimate 5.3%·y$^{-1}$ for control and WoBu3t and WoMu3t treatments, by 2.7% for both WoBu3t+N and WoMu12t treatments, and by 0.7% for WoBu12t treatment. WoMu12t and WoBu3t+N treatments were partly able to compensate the C degradation whereas WoBu12t treatment was able to compensate C loss almost completely, as compared with control. The net addition of buried high-RW rates (2.8 Mg C·ha$^{-1}$·y$^{-1}$) is thus equal to the decline in C without any amendment. C loss in control was 0.4 Mg SOC·ha$^{-1}$·y$^{-1}$, meaning that an equivalent 15% of buried C input at high-RW rates (WoBu12t) remained on the plot and was enough to compensate for soil C losses as observed in control plots for the layer with depth of 0–15 cm.

Total soil N ($N_{tot}$) content in both depths of 0–5 and 5–15 cm decreased over time and for all treatments (Figures 2c,d; Table 3). Soil N content at depth of 0–5 cm for low-RW treatments and control declined from 0.23 ± 0.02 g·kg$^{-1}$ after the second harvest to 0.16 ± 0.03 g·kg$^{-1}$ after the seventh harvest. Under high-RW application rates, soil N content was higher than that under low RW but declined linearly as well (Figures 2c,d). The mode of RW application (buried or mulched) did not result in significant N differences at depth of 0–5 cm. At 5–15 cm, the $N_{tot}$ content for WoBu12t was higher than that for the other treatments ($R^2 = 0.1$, $p < 0.001$). Treatment WoMu12t $N_{tot}$ contents were only slightly but significantly higher ($R^2 = 0.4$, $p < 0.1$) than those of the control and low-RW treatments. Annual $N_{tot}$ decline for the studied period and soil horizons (0–15 cm) was on average 4.7% (all treatments), with the lowest decline observed for WoBu3t+N (4%) and strongest for WoMu12t (5.5%).

Mineral N ($N_{min}$), measured at harvest, was variable between years with a tendency to slightly increase during the first years of the experiments and decline after the fourth year of measurement. $N_{min}$ contents were homogeneous between all treatments, and at both studied depths (Figures 2e,f; Table 3).

**TABLE 3** Contributions to the variance and $R^2$ (%) explained in the multiple regression analysis for soil attributes as affected by blocks, year, treatment effects, rainfall, year quadratic, and year-to-treatment interactions

| | Soil attribute and sampling depth (cm) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Factors | Total C (0–5 cm) | Total C (5–15 cm) | Total N (0–5 cm) | Total N (5–15 cm) | Mineral N (0–5 cm) | Mineral N (5–15 cm) | Total P (0–5 cm) | Total P (5–15 cm) | Available P (0–5 cm) | Available P (5–15 cm) |
| 2007–2013: Treatments with low amendment applications (Ctrl, WoMu3t, WoBu3t, WoBu3t+N) | | | | | | | | | | |
| Block | 0.12*** | | 0.11*** | | | | | | | |
| Year (Y) | 0.43*** | 0.36*** | 0.43*** | 0.40*** | 0.41*** | | 0.16** | | 0.35*** | 0.31*** |
| Treatment (T) | 0.04* | | | | | | | | | |
| $Y^2$ | | 0.04** | | | 0.08** | 0.13** | 0.05. | 0.10** | 0.12*** | 0.16*** |
| Y:T | | | | | | | | | | |
| Rainfall | | 0.14*** | 0.08** | 0.16*** | 0.12** | 0.13* | | 0.14** | 0.23*** | 0.41*** |
| Total ($R^2_{adj}$) | 0.59 | 0.54 | 0.62 | 0.56 | 0.60 | 0.25 | 0.21 | 0.25 | 0.70 | 0.88 |
| 2010–2013: RW treatments (i.e., with high amendment applications WoMu12t and WoBu12t) | | | | | | | | | | |
| Block | 0.15*** | 0.09** | 0.13*** | 0.06. | | | 0.10. | | | |
| Year (Y) | 0.04** | | 0.12*** | 0.07** | 0.35*** | 0.06* | | 0.04. | 0.08* | 0.20*** |
| Treatment (T) | 0.36*** | 0.30*** | 0.23*** | 0.27*** | | | | 0.22** | | |
| $Y^2$ | | 0.02. | | | 0.14*** | 0.18*** | | | | |
| Y:T | | | | | | 0.10. | | | | |
| Rainfall | | 0.03. | | | 0.17*** | 0.18*** | | | | |
| Total ($R^2_{adj}$) | 0.56 | 0.44 | 0.48 | 0.39 | 0.67 | 0.53 | 0.10 | 0.25 | 0.08 | 0.20 |

*Note*. Treatments with low amendment applications (2007 through 2013): control (Ctrl), ramial wood (RW) mulched 3 Mg·ha$^{-1}$ (WoMu3t), RW buried 3 Mg·ha$^{-1}$ (WoBu3t), and RW buried 3 Mg·ha$^{-1}$ with synthetic fertilizer (WoBu3t+N). Treatments featuring high amendment applications (from 2010 through 3013): RW mulched 12 Mg·ha$^{-1}$ (WoMu12t) and RW buried 12 Mg·ha$^{-1}$ (WoBu12t).

***$p < 0.001$. **$p < 0.01$. *$p < 0.05$, . $p < 0.1$.

Variability in topsoil total P ($P_{tot}$) per treatment and per year content was observed (Figures 3a,b). Nevertheless, at depth of 0–5 cm, $P_{tot}$ declined for low-RW application and control while general stability was observed for high-RW application (Figure 3a; Table 3). At depth of 5–15 cm, high-RW application resulted in significant increase in time in soil $P_{tot}$ content, whereas the mulched RW (WoMu12t) treatment showed higher $P_{tot}$ contents than did buried amendments (WoBu12t; Figure 3b; Table 3).

$P_{av}$ content at depth of 0–5 cm before planting in 2007 averaged 7.9 ± 1.0 ppm and declined strongly during the first years of the experiment but then stabilized at an average 4.9 ± 3.6 ppm (Figure 3c; Table 3). At both studied depths, $P_{av}$ declined over time without significant differences between treatments (Figures 3c,d).

## 3.2 | Effect of ramial wood on crop productivity

Sorghum grain production declined for subsequent years, and for all treatments, although significant differences were found between treatments (Figure 4a). Control and low-RW treatments yielded an average 0.8 ± 0.3 Mg·ha$^{-1}$ at the first grain harvest and declined after 6 years of continuous cropping, to an average 0.2 ± 0.2 Mg·ha$^{-1}$, in 2012. Aboveground total biomass for control and low RW followed a similar trend as grain yields, declining from 4.0 ± 0.9 to 0.5 ± 0.4 Mg·ha$^{-1}$ (Figure 4b).

Treatment WoBu3t+N yielded slightly higher than did other treatments during the period 2007 through 2012 (Table 4). When high-RW treatments were introduced in 2010, crop productivity with mulched RW (WoMu12t) yielded significantly more than did control and low-RW treatments but less than buried RW (WoBu12t). In fact, high-RW treatments always yielded higher than the control, whereas low-RW treatments in some cases throughout the study yielded less than did control plots (Figures 4c,d).

## 3.3 | Effect of ramial wood on termite activity

Termites and termite cast abundance was visible to the naked eye in the field (Figure 5a–d). Observation of termite cast presence in 2010 was done after a short rain event, which partly 'erased' the casts from the surface, explaining the strong contrast between years (Figure 6). Trends between termite cast presence and treatments were however clear in both years. Percentage of termite casts was significantly higher for high-RW treatments as compared with low RW and control but was not significantly affected by RW mode of application (buried or mulched).

# 4 | DISCUSSION

In this study at Gampéla, Burkina Faso, a working hypothesis was that RW application as soil amendment would have beneficial short-term effects on both soil quality and plant growth conditions. The practice of mulching RW amendments from native woody shrubs is a farmer innovation (see Lahmar, Bationo, Dan Lamso, Guéro, & Tittonell, 2012), here tested during 7 years, in on-station field conditions, and featuring several treatments (i.e., control versus high or low RW, and mulched versus buried). Results show differences between treatments, featuring low and declining yields but consistently higher yields and enhanced soil conditions when high-RW rates were used (WoBu12t ≥ WoMu12t > WoBu3t+N > WoMu3t = WoBu3t = Ctrl). Treatment effects on soil C, soil nutrients, and crop productivity followed similar trends, suggesting that the highest yields obtained

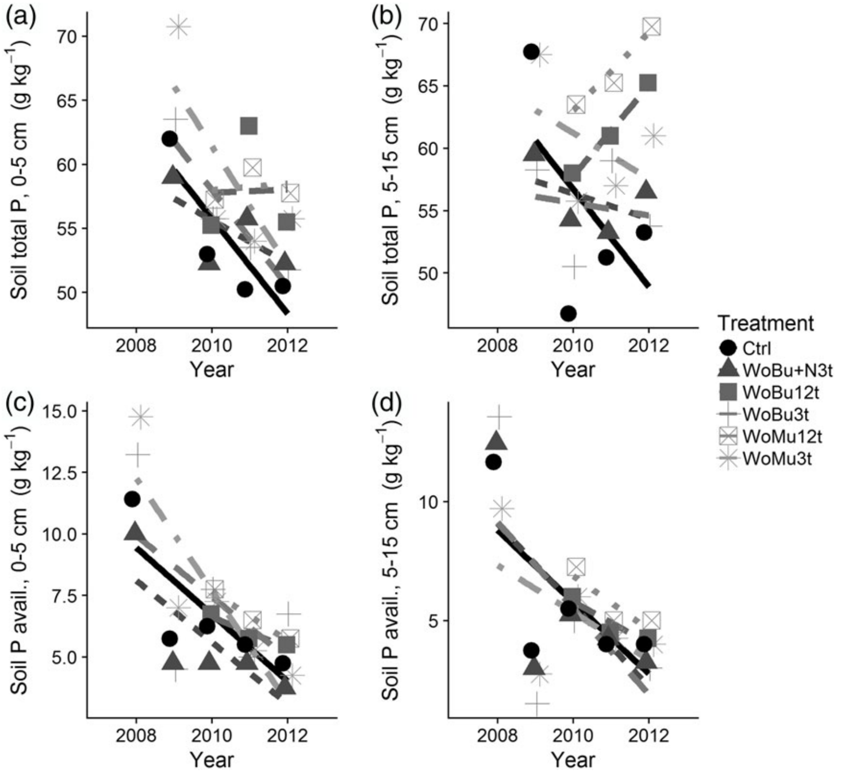

**FIGURE 3** Trends for topsoil total phosphorus (P; a and b) and available P ($P_{av}$; c and d) as affected by no (Ctrl) or low rates of woody amendment application (WoMu3t, WoBu3t, or WoBu+N3t) from 2007 to 2013, and high rates of amendment application (WoMu12t and WoBu12t; dash and dots line) from 2010 to 2013, at depths of 0–5 cm (a, c) and 5–15 cm (b, d). Lines indicate trends; details of the regression analysis are provided in Table 3 [Colour figure can be viewed at wileyonlinelibrary.com]

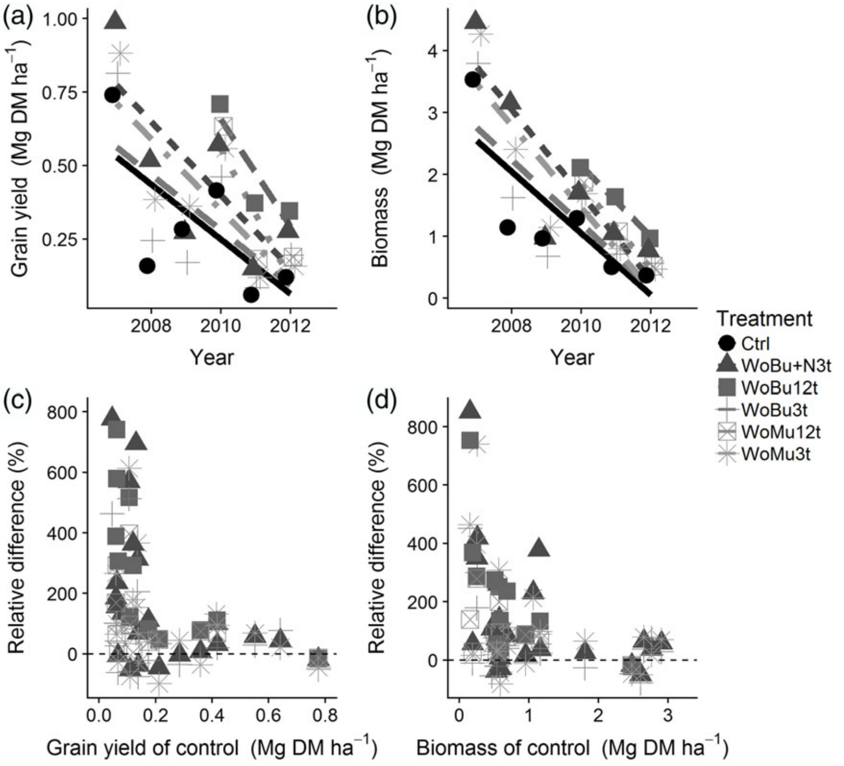

**FIGURE 4** Average crop productivity results per treatment and year for sorghum grain yield (a) and total aboveground biomass (b) indicate a declining trend for all treatments and significantly higher yields with the use of high-RW rates (each data point is the average of four observations per year). Treatments yield relative to control (in %) for sorghum grain (c) and total aboveground biomass (d) show that high-RW rates of application never yielded lower than did control, whereas low-RW rates in some cases yielded less than did control (each data point is an observation, as compared with the yield recorded for control of that block per year) [Colour figure can be viewed at wileyonlinelibrary.com]

in the high-RW treatments may be partly due to increased nutrient input by high RW (0.08 Mg N·ha$^{-1}$; low RW was 0.02 Mg N·ha$^{-1}$). The fact that buried RW in some cases outperformed the effect of mulched RW deserves a closer look by taking into account decomposition dynamics of RW (i.e., by termites), in light of modifications to soil water dynamics due to RW.

## 4.1 | From local innovation to experimental agronomy

Studies in native agroforestry systems of Central America highlight the significant potential of slash-and-mulch practices on soil C storage (Fonte, Barrios, & Six, 2010). In SWA, mulching with small branches is a common technique to rehabilitate physically degraded soils by broadcasting branches and leaves on specific sectors of a field (CSFD, 2015). On low-fertility soils in farmer fields of Niger, 1–2 Mg DM·ha$^{-1}$ shrub material application (*Guiera senegalensis* J.F. Gmel.) had no significant effect on millet yield due to high variability of observed effects between farmer fields (Wezel & Böcker, 1999). On-station experimental studies using *Piliostigma*-based leaf material as soil amendment in Saria, Burkina Faso, showed that rates of 2.4 Mg DM·ha$^{-1}$ in addition to NPK and urea, as compared with application, almost duplicated yields (Yélémou, Yaméogo, Koala, Bationo, & Hien, 2014). In Gampéla, Burkina Faso, mixed branches and leaves at rates of 1.5 Mg DM·ha$^{-1}$ as soil amendments, as compared with no application, showed only small (and not statistically significant) increases in sorghum grain yields and soil C (Barthès et al., 2015).

Our results over a 7-year trial at Gampéla, Burkina Faso, support the fact that RW applications, as compared with no-RW application, at rates of 1.5 Mg DM·ha$^{-1}$ (3t) do not allow to increase the sorghum yield. Higher rates of 6 Mg DM·ha$^{-1}$ (12t) allowed grain yield achievements of 0.4 Mg·ha$^{-1}$, as compared with 0.2 Mg·ha$^{-1}$ in the control, which is an average two-fold increase during the last 4 years of the study.

In addition to crop yields, our study revealed treatment effects on soil stocks of C, N, and P. Soil C ($C_{tot}$) content decreased over time despite yearly input of low-RW application (3 Mg FM·ha$^{-1}$·y$^{-1}$) of woody shrub material, either mulch or buried. For the high-RW treatments (12 Mg FM·ha$^{-1}$·y$^{-1}$), $C_{tot}$ was maintained over the 4-year period of application, especially when buried. Indeed, burying or mulching RW led to differences in soil C decline over time: Burying high-RW rates quasicompensated C losses, with a decline of 0.7%·y$^{-1}$, whereas mulching the same amount of RW still led to a decline of 3–5%·yr$^{-1}$ in soil C content. Even though soil total N ($N_{tot}$) content was systematically higher with RW application rate, $N_{tot}$ contents decreased for all treatments and at both studied depths (0–5 and 5–15 cm), at an average 5%·y$^{-1}$. Soil mineral N ($N_{min}$) was not affected by treatments, rather by rainfall, but the general trend was towards decline in time. Soil total P ($P_{tot}$) decreased over time for low-RW and control treatments but was maintained at depth of 0–5 cm and slightly increased at depth of 5–15 cm for the high-RW treatments. Available P ($P_{av}$) decreased in time for all treatments.

In terms of nutrients, *Piliostigma* is a non-N-fixing legume shrub with low N, P, and K content (Table 2); thus, low soil nutrient content and declining yield data are expected under sole-RW input application. The limited capacity of *Piliostigma*-based RW input to replenish nutrient exports is a call for further field research with different sources of RW, as locally found in the regions (Table 1), and combination with other nutrient supply sources. Treatment effects on yields may also be linked to modifications in soil water dynamics—a known limiting

**TABLE 4** Contributions to the variance and $R^2$ (%) explained in the multiple regression analysis for crop productivity parameters as affected by block, year, treatment, rainfall effects, and soil attributes (total C, total N, mineral N, total P, and available P) at depths of 0–5 and 5–15 cm, and year quadratic and year-to-treatment effects

| Factors | Grain yield | Aboveground biomass |
|---|---|---|
| 2007–2012: Treatments with low amendment applications (Ctrl, WoMu3t, WoBu3t, WoBu3t+N) | | |
| Block | 0.07* | 0.05** |
| Year (Y) | 0.34*** | 0.55*** |
| Treatment (T) | 0.05 | 0.05* |
| $Y^2$ | | |
| Y:T | | |
| Rainfall | | 0.013 . |
| $C_{tot}$ 0–5 cm | | |
| $C_{tot}$ 5–15 cm | | |
| $N_{tot}$ 0–5 cm | | |
| $N_{tot}$ 5–15 cm | 0.009* | 0.005** |
| $N_{min}$ 0–5 cm | 0.004 . | 0.004* |
| $N_{min}$ 5–15 cm | | |
| $P_{tot}$ 0–5 cm | 0.009* | 0.003 . |
| $P_{tot}$ 5–15 cm | 0.015** | 0.009*** |
| $P_{av}$ 0–5 cm | 0.009* | 0.005** |
| $P_{av}$ 5–15 cm | 0.006* | |
| Total ($R^2_{adj}$) | 0.50 | 0.69 |
| 2010–2012: RW treatments (i.e., with high amendment applications WoMu12t and WoBu12t) | | |
| Block | | 0.05* |
| Year (Y) | 0.32*** | 0.46*** |
| Treatment (T) | 0.15*** | 0.17*** |
| $Y^2$ | | |
| Y:T | | |
| Rainfall | 0.19*** | |
| $C_{tot}$ 0–5 cm | | |
| $C_{tot}$ 5–15 cm | | |
| $N_{tot}$ 0–5 cm | | |
| $N_{tot}$ 5–15 cm | | |
| $N_{min}$ 0–5 cm | | 0.02 . |
| $N_{min}$ 5–15 cm | | |
| $P_{tot}$ 0–5 cm | 0.02* | |
| $P_{tot}$ 5–15 cm | | 0.015 . |
| $P_{av}$ 0–5 cm | | 0.015 . |
| $P_{av}$ 5–15 cm | | |
| Total ($R^2_{adj}$) | 0.68 | 0.73 |

*Note*. Treatments with low amendment applications (2007 through 2013): control (Ctrl), ramial wood (RW) mulched 3 $\mathrm{Mg\cdot ha^{-1}}$ (WoMu3t), RW buried 3 $\mathrm{Mg\cdot ha^{-1}}$ (WoBu3t), and RW buried 3 $\mathrm{Mg\cdot ha^{-1}}$ with synthetic fertilizer (WoBu3t+N). Treatments featuring high amendment applications (from 2010 through 3013): RW mulched 12 $\mathrm{Mg\cdot ha^{-1}}$ (WoMu12t) and RW buried 12 $\mathrm{Mg\cdot ha^{-1}}$ (WoBu12t).

***$p < 0.001$. **$p < 0.01$. *$p < 0.05$, . $p < 0.1$.

factor for crop growth in the Sahelian region. Additional research with RW should include farmer knowledge through participatory techniques that have proven useful in better understanding soil dynamics while targeting for more efficient resource-allocation strategies (Barrios, Coutinho, & Medeiros, 2012).

## 4.2 | Where did the carbon input go?

Added carbon could come from both the RW amendment and extra biomass production in the high-RW treatments, but the effect of treatments on belowground growth was limited (root estimation on the basis of 15% aboveground biomass, see Sher, Barbanti, Ansar, & Azim, 2013). A comprehensive study for the Sahel showed that 0.8 $\mathrm{Mg\ C\cdot ha^{-1}\cdot yr^{-1}}$ is sufficient to maintain soil C stocks at approximately 5 $\mathrm{Mg\ C\cdot ha^{-1}}$ (Nakamura et al., 2012). Accordingly, the $C_{leftover}/C_{input}$ ratio would be of 26% in the agroecosystems described by Nakamura et al. (2012). A similar line of reasoning leads to a ratio of 15% in our study, underlining low soil C stocks at Gampéla.

In our experiment, the estimated decline rate in the control treatment was higher (0.42 $\mathrm{Mg\cdot ha^{-1}\cdot yr^{-1}}$) and the leftover carbon of amendments was lower (15.2% of buried RW), so that a larger amount of 2.8 $\mathrm{Mg\ C\cdot ha^{-1}\cdot yr^{-1}}$ input required for balancing degradation. This is an unexpected outcome because lignin-rich RW inputs should be prone to slower C mineralization rates than the crop residues and the manure considered in the study by Nakamura et al. (2012). This leaves us with the question: "Where did the carbon input go?" The most probable hypothesis to explain the high degradation rates in this experiment is that C was mostly exported in the form of organic particles via termite foraging (Orgiazzi et al., 2016). This hypothesis is coherent with results that show increased termite activity when organic matter inputs are applied and modelling studies that show termite activity as a nonnegligible source of error in soil C prediction models (e.g., Shirato et al., 2005). This also highlights the link between termite activity, organic matter inputs, and soil physical properties, including water dynamics.

Termite casts were monitored only during 2 years in our study, but there was a clear treatment effect, with significantly higher termite activity as RW application rates increased (12t > 3t > Ctrl). At Gampéla, Barthès et al. (2015) found that RW attracted more termite activity than did sorghum crop residues in 2008, possibly due to the nature of organic matter (e.g., cellulose in sorghum stalks and lignin in RW). When this experimental set-up shifted from crop residue application to higher doses of RW, we observed enhanced termite activity, along with enhanced crop productivity, an element often described in SWA (Sileshi et al., 2009). Whereas termites increase crop growth conditions via enhanced soil physical structure (e.g., increased porosity leading to enhanced water infiltration, upper soil fertilization by nutrient-rich casts), an additional effect of RW could be attributed to organic amendment effects on water dynamics, more likely for high RW application (Barthès, Manlay, & Porte, 2010): higher infiltration and lower evaporation (especially when mulched) and higher soil water content retention (especially when buried). Interpretation of our data may, however, be limited by lack of soil water content data. Future studies should consider isotopic techniques to trace the magnitude of movement of organic input by termites from experimental plots, jointly with soil water studies.

## 4.3 | Woody resource availability—Bottleneck and opportunity

Aboveground standing woody biomass estimates in semiarid Burkina Faso are low and highly variable, ranging from 5 to 7 $\mathrm{Mg\ DM\cdot ha^{-1}}$

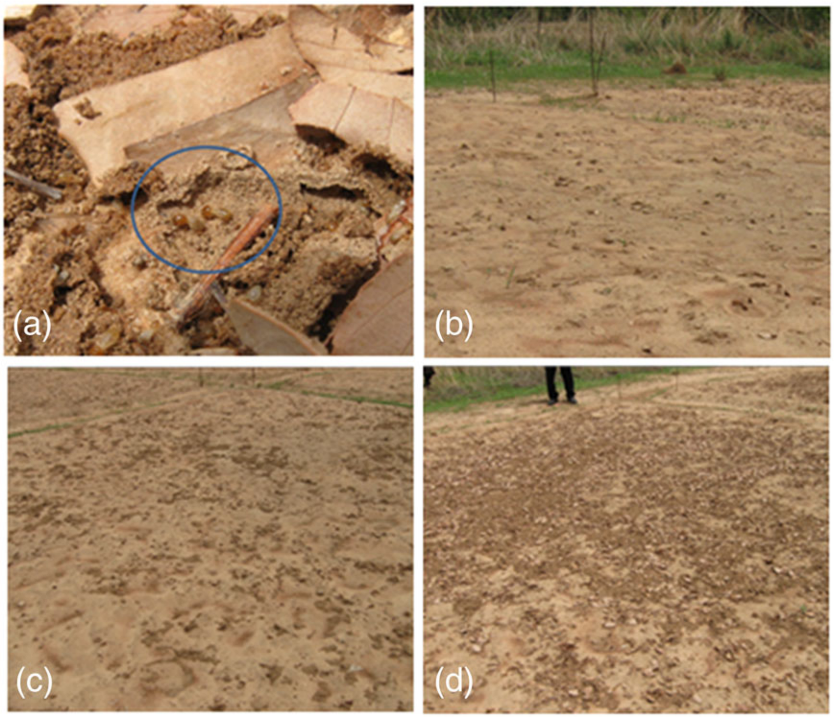

**FIGURE 5** Termite cast abundance at Gampéla experimental station at the onset of planting season in 2010. A close-up on termites while foraging on ramial woody and leafy amendments (a) will allow the naked eye to observe low termite cast abundance when no RW mulch is applied (b), medium cast abundance with 3 Mg FM·ha$^{-1}$·yr$^{-1}$ (c), and high abundance of termite casts with 12 Mg FM·ha$^{-1}$·yr$^{-1}$ (d). Photo credits: Aurélien Penche [Colour figure can be viewed at wileyonlinelibrary.com]

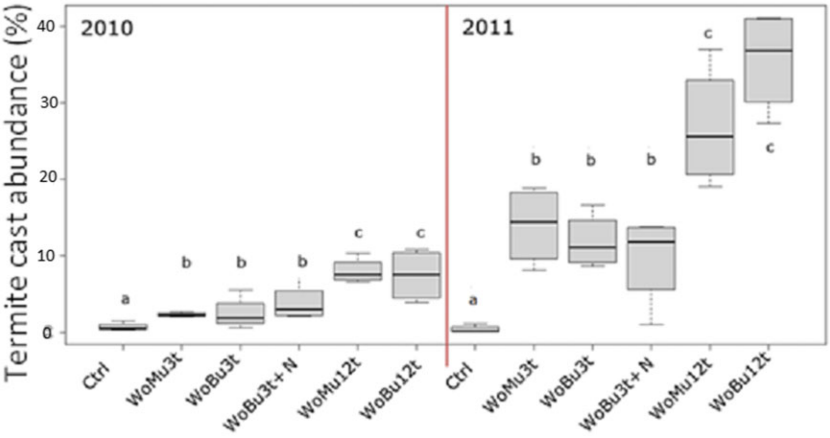

**FIGURE 6** Termite cast abundance in percent per treatment and per year measured (2010 and 2011), with different letters depicting statistical significant differences at $p < 0.05$ [Colour figure can be viewed at wileyonlinelibrary.com]

(Fischer, Kleinn, Fehrmann, Fuchs, & Panferov, 2011) but rarely exceeding 10 Mg DM·ha$^{-1}$ (Cabral, 2011; Feur, 2014). On the one hand, *Vitellaria paradoxa* C.F. Gaertn. constitutes an important share of this biomass, but its use is highly regulated by local and national laws (Elias, 2012; Gallagher, Dueppen, & Walsh, 2016), and it is therefore usually inaccessible for farmers as a viable source of RW. On the other hand, shrub species such as *P. reticulatum* and *G. senegalensis* are more abundant in SWA landscapes and accessible as RW but represent less than 1 Mg DM·ha$^{-1}$ (Kabré, 2010; Lufafa et al., 2008) and are, in theory, also subject to national forest regulation. Nevertheless, applying 12 Mg·ha$^{-1}$ of fresh wood and leaf material as soil amendment seems unrealistic or would require considerable concentration of nutrients from larger areas. Alternative ways of increasing the resource should be explored.

Increasingly, the effect of woody shrubs and trees is studied and documented, especially in light of ecosystems services provision in SWA (Bayala et al., 2015; Dossa et al., 2013). More rarely studied is the effect of in situ production of agroforestry mulches on crop productivity and soil quality. Farmers from across semiarid Africa (Figure 1a) can rely on a variety of services from surrounding vegetation by combining soil amendments from a diversity of sources, including trees and shrubs (Table 1), and provided little or no trade-offs exist between possible uses (e.g., amendment vs. fuelwood or medicine needs). The agronomic minimum crop requirement in light of the landscape constraints on the availability of RW is an issue fairly unexplored in the context of SWA.

Farmer-managed natural regeneration could be a feasible and low-investment strategy to increase woody resources locally and has already been implemented in many drylands of Africa with impressive results (Bayen, Lykke, & Thiombiano, 2015; Dia, 2012; Haglund, Ndjeunga, Snook, & Pasternak, 2011). Even though soil and water conservation systems such as stone bunds, *zaï*, half-moons, grass strips, mulching, manuring, and hedgerows are widely accepted in Burkina Faso, planting trees still remains a source of possible conflict between landowners and land users (Ouédraogo & Sorgho Millogo, 2007). When the regreening occurred in the South of Niger, partly due to a recovery of rainfall after the dry episodes of the 1970s and 1980s, it is important to highlight that restrictions on use of tree products were lifted (Reij, Tappan, & Belemvire, 2005). In other areas, national forest regulations can be a serious limitation to the motivation of farmers to plant or protect native species. Design options at the plot level should probably be explored at plot and community levels. The adequacy of woody resource availability to attain the desired agronomic effect needs to be tackled from an integrated perspective where RW is not just an input but also valued for other services rendered by shrub woody perennials. This would additionally support processes such as capture of wind-driven particles (Leenders, van Boxel, & Sterk, 2007), hydraulic and nutrient uplift from deeper soil layers (Kizito et al., 2012), and securing of forage provision during the dry season (Schlecht, Hiernaux, Kadaouré, Hülsebusch, & Mahler, 2006; Zampaligré, Dossa, & Schlecht, 2013).

## 5 | CONCLUSION

Soil carbon (C), soil nutrients ($N_{tot}$, $N_{mineral}$, $P_{tot}$, and $P_{av}$), and sorghum yields declined throughout the duration of the experiment. Sorghum productivity was low in all treatments. Nevertheless, yields were stimulated by treatments featuring buried high-RW rates and to some extent by mulched high RW without fertilization and by buried low-RW rates combined with N fertilization. These findings highlight the fact that RW amendments may mitigate tropical soil degradation but cannot replenish soil nutrient exports. In fact, a technique that is interesting from a certain point of view might not be so performant from another point of view. Our study analysed various crop performance criteria during several years, allowing for an assessment of trade-offs at the plot level of RW technology (i.e., soil C stocks vs. yield improvements). Enhancing the technology of RW application should take into account these performance criteria and be reasoned in terms of trade-offs and opportunities. Future research efforts should also focus on the effects of RW on water use efficiency by crops. This criterion is likely to be important in a context of climate change, where decreases are foreseen in the periodicity and intensity of rainfall events in SWA.

Our results also show that buried high-RW application rates of 12 Mg FM·$ha^{-1}$·$yr^{-1}$ of *Piliostigma* shrub-based material allowed to sustain topsoil C in Acrisols of Burkina Faso, whereas lower RW application rates resulted in decline of C content throughout the 7-year period of study. We noticed that C leftover in the soil was much lower than expected with high-RW annual rates of C input. The limited capacity of high-RW treatments to increase soil C stocks may be linked to enhanced degradation of C input through termite foraging activity. Employing isotopic techniques to trace the magnitude of movement of organic input by termites from experimental plots, jointly with soil water studies, would greatly contribute in better understanding C dynamics in the region.

From a farmer's perspective, the amount of shrub material needed to sustain crop yields with RW seems unrealistic given current biomass availability in the landscape. Reforestation strategies with woody perennials, including shrubs and trees, could however represent opportunities for farming families to further support development of RW technology in SWA, in light of local needs and labour allocation possibilities.

## ACKNOWLEDGEMENTS

This research is part of a collaborative effort funded by the European Union Seventh Framework Programme through the WASSA project (*Woody Amendments for Sudano-Sahelian Agriculture*; ERA-ARD-II; www.wassa-eu.org) and the ConneSSA project (*Connecting knowledge, scales and actors: an integrated framework for adaptive organic resource management, targeting soil aggradation and agro-ecosystems' resilience in Sub Saharan Africa*; ERAfrica; https://connessa.uni-hohenheim.de/112332). Additional funding was provided by AgroParisTech. Authors are grateful to university students who collected and analysed data and to IRD technicians in Burkina Faso, Prosper Sawadogo and Moussa Barry, for their invaluable contribution to data collection. The authors are thankful to the three anonymous reviewers for their critical comments and suggestions that improved the manuscript.

## ORCID

*Georges F. Félix* http://orcid.org/0000-0001-7342-6545
*Cathy Clermont-Dauphin* http://orcid.org/0000-0001-6500-9194
*Jeroen C.J. Groot* http://orcid.org/0000-0001-6516-5170
*Bernard G. Barthès* http://orcid.org/0000-0002-5074-9306
*Raphaël J. Manlay* http://orcid.org/0000-0003-0482-8457
*Pablo Tittonell* http://orcid.org/0000-0002-0284-2514
*Laurent Cournac* http://orcid.org/0000-0003-0371-938X

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**How to cite this article:** Félix GF, Clermont-Dauphin C, Hien E, et al. Ramial wood amendments (*Piliostigma reticulatum*) mitigate degradation of tropical soils but do not replenish nutrient exports. *Land Degrad Dev*. 2018;29:2694–2706. https://doi.org/10.1002/ldr.3033