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RESEARCH ARTICLE

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Termite footprints in restored versus degraded agrosystems in South West Niger

Abdourhimou Amadou Issoufou[1] | **Garba Maman[2]** | **Idrissa Soumana[2]** | **Dorkas Kaiser[3]** | **Souleymane Konate[1,4]** | **Sabiou Mahamane[2]** | **Ali Mahamane[5]**

[1] WASCAL Graduate Research Program on Climate Change and Biodiversity, Université Félix Houphouet Boigny, Abidjan, Côte d'Ivoire
[2] Department of Natural Resources Management, Institut National de la Recherche Agronomique du, Niger
[3] Animal Ecology and Tropical Biology, University of Rostock, Rostock, Germany
[4] Natural Sciences Training and Research Unit, Université Nangui Abrogoua, Côte d'Ivoire
[5] Department of Biology, Univesité de Diffa, Diffa, Niger

Correspondence
Abdourhimou Amadou Issoufou, WASCAL Graduate Research Program on Climate Change and Biodiversity, Université Félix Houphouet Boigny, Côte d'Ivoire.
Email: amadou_issoufou@ymail.com

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Abstract
One approach to achieving sustainable food security is to maintain or restore natural ecosystem services that diminish dependence on human inputs to agrosystems. More efficient use of agrosystem restoration practices can be achieved with the aid of termites' activities, which positively influence the physicochemical and hydraulic properties of soils in favor of productive soil. However, termites have a significant place in agrosystems, but it has remained under exploited and unrefined and needs to be restored to increase its yield. Here, we quantify the colonization rates of termites on marginal soils and in agrosystems with ongoing restoration efforts, as well as determine their footprints on soil characteristics over a 2-year period in semi-arid Niger. We used a rapid assessment protocol, a technic used to assess termites' population in semi-arid regions, adapted from an earlier studies. The results from various analyses showed that termite abundance, richness, and diversity were 15% to 45% higher in the restored agrosystems than in the degraded ones. The evenness did not augment in the restored habitats what might result from the changes in soil properties triggered by clearcutting. Moreover, organic compounds, particularly carbon, nitrogen, in some cases phosphorus, and exchangeable cations are more abundant in restored sites where termite activities are intense than in the controls. A higher termite diversity and abundance are important factors underlying positive changes in soil properties. This study provides evidence of the effectiveness of termite species in restoring degraded soil and in maintaining long-term soil fertility, thereby facilitating sustainable agriculture.

KEYWORDS
agrosystems restoration, bio indicators, soil properties, taxonomic richness, termites

1 | INTRODUCTION

Tropical soils have less than 10 g·kg^{-1} of organic matter because of climatic conditions and to land use (Lal, 2015). This is particularly true for the plinthosoils prevalent in South West Niger. The challenge is to restore soil organic matter (SOM) so as to improve and maintain the productivity of these soils. Enhancement of SOM is essential for crop growth as it activates the development of soil microorganisms important for decomposition and delivery of nutrients to soil (Govorushko, 2018; Lal, 2015). Several interventions can be applied to restore soil nutrients. In South West Niger, there is an increasing interest in the application of traditional soil restoration practices as a coping strategy of small scale farmers to high cost of inorganic fertilizer and agrochemicals. Among the practices used by farmers to sustainably produce in the changing climate is the traditional *zaï* technique combined with crop residue mulching. The litter used in this practice attracts termites (Isoptera), which colonize the substrate.

The role of termites is rarely considered in soil restoration although several studies revealed that the services provided by these ecosystem engineers may be critical for the restoration process (Lal, 2015; Cheik, Bottinelli, et al., 2019).

Termites are among the most influential ‘ecosystem engineers’ (Jones, Lawton, & Shachak, 1994) whose biogenic structures (e.g., nests, soil sheetings, and foraging holes) modify the availability of resources for other organisms. Their role in ecosystems has been reviewed by several authors (de Bruyn & Conacher, 1990; Sithole, Magwaza, Mafongoya, & Guy, 2018). In arid and semi-arid regions, termites are the key soil turbators all year round, strongly influencing SOM turnover and soil structure in agrosystems (Abe, Bignell, & Higashi, 2000; Lal, 2015; Cheik, Shanbhag et al., 2019). By constructing networks of foraging tunnels, they alter soil water infiltration and soil aeration (Colloff, Pullen, & Cunningham, 2010; Lal, 2015). Better soil aggregation may have significant impacts on soil quality. They influence the decomposition of litter by enhancing populations of bacteria and fungi, thereby affecting SOM turnover (Rakshiya, Verma, & Sindhu, 2016). In this regard, termites can be used to sustain nutrient accessibility to crop growth and recovery from drought. Such field studies have provided more information on soil processes (Bottinelli et al., 2014). But only a few quantitative data are available to evaluate the exploitation of termites on soil functioning, in particular to nutrient cycling, and their reaction on changing environmental parameters (Bottinelli et al., 2014). To our knowledge, few studies were conducted in the Sahel on the assessment of termites' communities.

The assessment of termite communities could indicate the state of the agrosystems regarding the restoration goals and the effectiveness of the restoration interventions. Our objective is to quantify the colonization rates of termites on marginal soils and in agrosystems with ongoing restoration efforts, as well as determine their footprints on soil characteristics and on environmental variables (soil temperature, soil water content, and water infiltration). Moreover, as a measure of the restoration success, termite communities (richness, diversity, and evenness) and soil properties were characterized. We therefore, hypothesized that the practice of *zaï* + millet stover mulching (MSM) can have important impacts on termite community indices and have complex effects on ecosystem process. Moreover, manipulation of termite abundances under *zaï* + mulching could be an optimistic approach to improve soil properties such as nutrient contents, which are indeed pre-eminent for the ecological restoration of marginal soils in arid and semi-arid areas.

2 | MATERIAL AND METHODS

2.1 | Site description

A climatic gradient was chosen in the South West of Niger. The study was carried out at three sites, namely, Simiri (14°07′60.00″ N 2°07′ 60.00″ E), Balleyara (13°47′ 07″ N 2° 56′ 50″ E), and Kollo (13°18′ 15.48″ N 2° 20′ 20.40″E), at 18 farm sites in 2 ha. All of them are located in the South West Sahelian agro-pastoral zone of Niger where pearl millet (*Pennisetum glaucum*) is the predominant annual crop. The climate is characterized by a long dry season from October to May and a short rain season from late June to September, hence allowing one harvesting period per year. The mean annual precipitation during the last decade was 380 ± 135 mm (Mahamane, Saadou, & Nonguierma, 2005). The mean annual temperature ranges from 31°C to 36.5°C. There was a trend towards decreasing length of rainy seasons and higher evapotranspiration rates (Mahamane et al., 2005). Increasingly, the climate becomes unforeseeable, with extreme droughts occurring during continuous years or even the complete loss of the rainy season (Mahamane et al., 2005). The vegetation in the region is mostly dominated by annual grasses and shrubs, and its dynamics are highly adapted to droughts (Tongway, Valentin, & Seghieri, 2001). The soils of the region are plinthosoils characterized by inherent low soil water holding capacity, a poorly developed soil structure, and limited organic matter contents (Gavaud, 2014). In the three selected sites, soil nutrient deficiency is a major limiting factor for agricultural productivity, particularly N and P. However, agriculture has an important role for the local people who are mostly (80%) small-scale subsistence farmers (Dan-badjo et al., 2017). Most farmers in the study area practice soil restoration (stones line, *zaï* + mulching, half-moon, livestock corralling, etc.) and have a long experience in the restoration of low fertility soils. The three survey sites were chosen to represent habitats that might be expected to differ in termite diversity.

2.2 | Experimental setup

At each site, a rapid assessment protocol based on the transect protocol of Jones and Eggleton (2000) for termites in tropical forests, which was recently modified to account for the conditions prevailing in semi-arid agrosystems (Kaiser, 2014), was used to characterize the termite communities of our study sites. In each of the three study sites (Kollo, Simiri, and Baleyara), we collected termites both in restored (*zaï* + MSM) and in adjacent control plot agrosystems. Depending on the direction of the slope, the belt transect was 50 or 100 m long and 2 m wide and consists of 10 or 20 contiguous sections of 5 × 2 m sections (Figure 1). In the three selected sites, we had 36 transects of 200 m^2 and 18 transects of 100 m^2.

2.3 | Soil characterization

A total of 90 soil samples (0–20 cm) were also taken in the sections of transects, conducted to collect termites. The soil samples were first labeled and transported to the pedological laboratory of iEES-Paris (Sorbonne University) where they were stored at laboratory conditions before analyses. All sampled were crushed and air dried. Once in the laboratory, they were homogenized, crushed, randomly subsampled, and sieved at 200 μm. These samples were analyzed using standard methods (Table 1) for pH, cation exchange capacity,

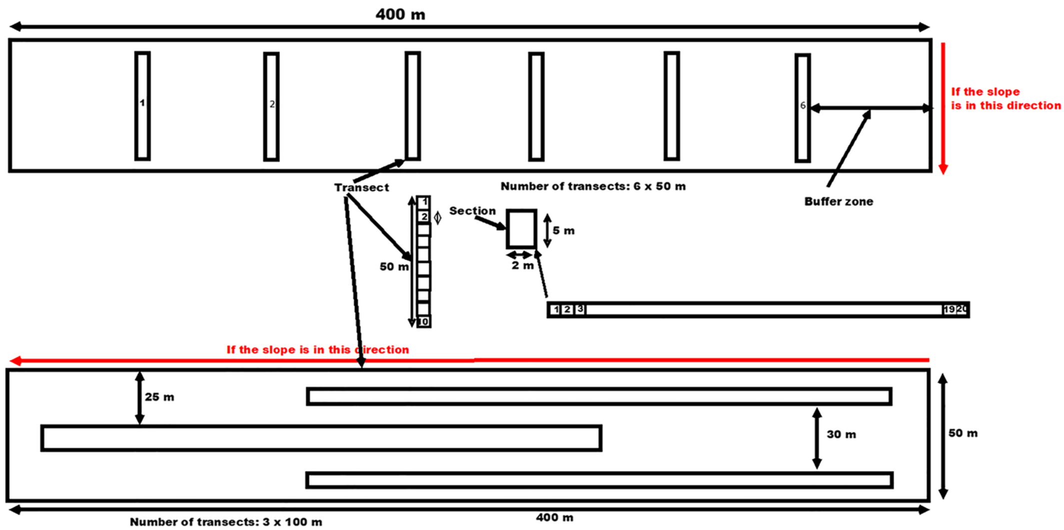

FIGURE 1 Relative position of sampling sites according to the combined and standardized rapid assessment protocol followed to assess termite communities [Colour figure can be viewed at wileyonlinelibrary.com]

TABLE 1 Physico-chemical parameters analyzed in the pedological laboratory (University of Paris 6, Sorbonne, France) including their abbreviations (short), units, and the methods used

Soil parameters	Short	Unit	Laboratory methods
Soil pH	pH_{KCL}	_	In suspension of deionized water and 0,1 n potassium chloride (KCl) pursuant DIN 19684–1
Soil organic carbon	SOC	g kg-1 or mg kg-1	LECO EC-12 for mineral soil; DIN ISO 10694 (1996)
Total soil nitrogen	Ntotal		Kjeldahl-method (Kjeldahl 1883) as described by (Anderson & Ingram 1993), DIN 19684–4
Total soil phosphorus	Ptotal		Inductively coupled plasma optical emission spectrometry (ICP-OES); DIN EN ISO 11885
Exchangeable cations	Na+, K+, Mg2 +,Ca2	mmolc kg-1	Mehlich-procedure set out in DIN 19684–8 and DIN ISO 13536 (1997); exchangeable cations: sodium (Na), potassium (K), magnesium (Mg), calcium (Ca)
Cation exchange capacity	CEC		
Grain size distribution, soil texture	clay%, silt%, sand%,	%	Köhn-method (Köhn 1928) set out in DIN 19683–1,2; Measured were the seven fractions clay, coarse- (gU), middle- (mU) and fine silt (fU), coarse- (gS), middle- (mS) and fine sand (fS); the totals of the three main fractions were used in the analysis

phosphorous (P), carbon (C), nitrogen (N), sodium (Na), and potassium (K) contents (Table 2).

2.4 | Termite communities' assessment

In each section of transects, we first searched for termites in as many different microhabitats as possible (such as accumulations of litter, inside and underneath dead logs and twigs, epigeal mounds, and runways on vegetation). Then, after removing the litter layer, we randomly took eight soil samples (soil scrapes), each 0.12 × 0.12 m and 0.15 m deep, which were searched throughout (Dorkas, Michel, Souleymane, & Karl, 2017). Priority was given to finding soldiers, as they are the easiest to identify, but workers were collected as well. The sampling time per section was one person-hour; stopping rules applied if less or no microhabitats could be found resulting in a shorter sampling time. The sampling was done during the early morning because termite activity decreases later during the day (Jones & Eggleton, 2000; Kaiser, Tra Bi, Yéo, Konaté, & Linsenmair, 2015). The sampling time per section was one man-hour; stopping rules was applied if no microhabitats can be found, resulting in a shorter sampling time.

2.5 | Other observations

In each section, soil moisture and soil temperature (0–0.01 m depth) were recorded in the soil scrapes at the time of sampling using a TDR 300 Probe (Spectrum Technologies, Inc., USA). At each site, three measurements of water infiltration rate were taken with a double-ring infiltrometer at the same time as termites were collected. The time took for water to pass into the soil surface was noted, and this value

TABLE 2 Soil characteristics of the study sites

Soil properties	Kollo		Simiri		Baleyara	
	Restored	Control	Restored	Control	Restored	Control
pH	6.16	5.68	6.01	5.57	6.33	5.72
C g kg^{-1}	8.1	5.5	7.8	5.2	10.7	3.7
Total N mg kg^{-1}	0.78	0.48	0.60	0.36	0.67	0.39
Olsen P mg kg^{-1}	1.77	1.64	1.77	1.61	1.74	1.69
Ca^{2+} cmol kg^{-1}	1.12	0.89	0.97	0.81	1.10	1.09
Mg^{2+} cmol kg^{-1}	0.42	0.29	0.38	0.3 [d]	0.46	0.33
K^{+} cmol kg^{-1}	0.21	0.11	0.18	0.16	0.2	0.18
Na^{+} cmol kg^{-1}	0.09	0.04	0.07	0.05	0.09	0.07
CEC cmol kg^{-1}	6.7	5.80	6.02	4.89	6.50	5.04
Clay (%)	21.3	15.1	20.6	18.7	23.4	17.5
Silt (%)	43.0	40.7	44.6	37.9	40.5	34.8
Sand (%)	35.7	44.2	34.8	43.4	36.1	47.7

Note. Within a column, means followed by the same letters showed significant differences (ANOVA followed by Tukey's honest significance test test $p > .05\%$).

was converted to infiltration rate on the basis of the quantity of water infiltrated into the soil (Matthews, 1986).

2.6 | Termites' species identification

All collected specimens were stored in labeled vials containing 90% ethanol and taken to the laboratory of the Nangui Abrogua University (Cote d'Ivoire) for species identification. The termites were identified to the level of species based on their morphological characteristics (mandible, form and size) and as described by (Bouillon & Mathot, 1965).

2.7 | Data analysis

The richness, the abundance, and diversity and evenness indices were calculated using vegan and ggplot2 packages in R 3.2.4 (Team, 2013). This software was used to characterize and compare the biological diversity of termite communities and the environmental variables between the degraded and restored habitats. We used Pearson correlation matrix to test the relationship between soil properties and termite community indices. The normality and homoscedasticity of the residuals of the models were respectively tested with Shapiro–Wilk and Bartlett tests. The significance threshold of all tests was set to $\alpha = 0.05$, and the significance is presented as follows: *** for $p < .001$; ** for $p < .01$; and * for $p < .05$.

3 | RESULTS

3.1 | Sites characteristics

The mean values of control sites showed that the soil texture was sandy loam with a low nitrogen and phosphorus contents, had very low organic carbon level, and was very acidic. As, expected the analysis of variance showed that the application of *zaï* + MSM significantly ($p < .05$) affected C, N, and P. No significant effects by the treatment were recorded on P, Ca^{2+}, Na^{+}, and pH (H_2O), soil particle size, available phosphorus, and pH (Table 2). From the parameters that were not influenced by the treatment were significantly higher in Kollo and Baleyara restored (Table 2). In the present study, the control agrosystems were characterized by limited soil nutrients with low termites' population.

Soil temperature determination after restoration of agrosystems was increased significantly approximately by 1.2°C under restored when compared with control sites (Figure 2a). While, applications of *zaï* + MSM resulted in a significant increase in soil moisture due to the presence of mulch, which conserves humidity (Figure 2b) when, similarly, rate water infiltration were significantly higher in the protected plots than in the control plots ($F = 60$; $p < .0001$).

Four hundred and sixty one specimens belonging to nine species were recorded in the three sites (Table 3). Six of the latter could be identified to the species level, the three other to the level of morphospecies. The fungus-growing *Odontotermes* sp1 (19.08%) was the most abundant in all sites, followed by the fungus-growing *Microtermes* sp1 and the wood-feeding species *Microcerotermes aff*. *Parvus* had the least abundance. The two most abundant species were widespread in all sites. The composition of the termite communities and their abundances differed significantly across the different study sites ($p < .05$; Figure 3a). We collected 184 specimens in Kollo representing eight species, 95 specimens from five species in Simiri, and 182 specimens from seven species in the Baleyara sites (Figure 3b). The number of species increased with gradient climatic impact (increasing of rainfall) from 17 species in the less rainfed sites to 25 in the degraded agrosystems.

Compared with the degraded habitats, a significant variation in richness was found in the restoration sites. The Shannon index indicated a higher termite diversity in Kollo than in Simiri and Baleyara. Biological

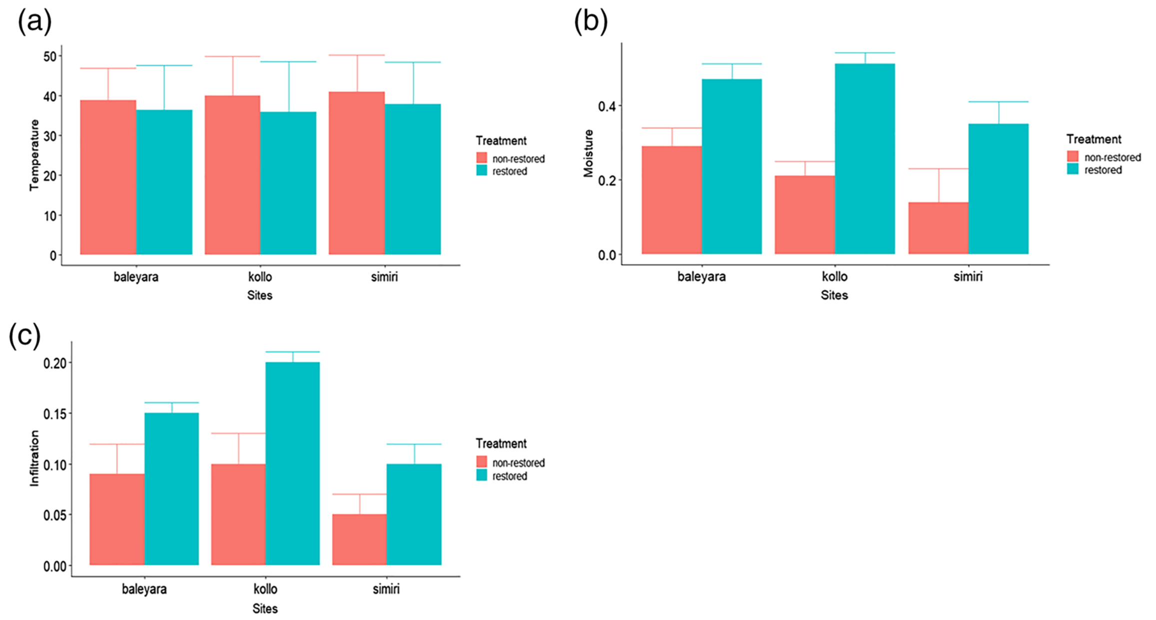

FIGURE 2 Average value (±standard error) of (a) soil temperature (°C), (b) moisture (%), and (c) infiltration (cm/mn) under restored and control sites [Colour figure can be viewed at wileyonlinelibrary.com]

TABLE 3 Number of specimens per termite species and relative frequency in restored (*zaï* + MSM) and degraded (control) ecosystems recorded from three sites in Niger

Species	Relative frequency	Simiri		Baleyara		Kollo	
		zaï + MSM	Control	*zaï* + MSM	Control	*zaï* + MSM	Control
Amitermes evuncifer	9.3	3	0	21	0	3	3
Amitermes aff. Guineensis	6	0	0	0	0	23	5
Microtermes sp	15.8	22	4	23	5	15	4
Microcerotermes aff. Parvus	1	0	0	0	0	4	0
Macrotermes bellicosus	14.9	21	5	14	3	24	2
Ondototermes sp 1	19.7	13	4	28	1	36	6
Ondototermes sp2	16.4	19	4	13	4	32	5
Trinervitermes geminatus	9.3	0	0	26	5	12	0
Ancistrotermes aff. Cavithorax	7.1	0	0	32	1	0	0
Total		78	17	163	19	149	35

Abbreviation: MSM, millet stover mulching.

diversity indices (abundance, richness, diversity, and evenness) were calculated in order to characterize the within diversity of termites in the study sites. The values of the Shannon–Weiner index ranged from 7.06 in Kollo to 0.33 in Simiri (Figure 3c). The highest value (Q = 0.56) was observed in the restored habitat in Kollo (kr), followed by the restored habitats in Baleyara (br; Q = 0.47) and in Simiri (sr).

The Pielou's evenness measure did not differ significantly between restored and degraded sites (Figure 3d), meaning that species evenness was not related with the restoration (χ^2 = 0.331, df = 4, R^2 = .0279, p = .565).

By doing a matrix model (Figure 4), Pearson correlation showed that termite compositional (abundance, richness, and diversity) shifts were significantly correlated with clay and silt content (r < 0.5; Figure 4). In addition, termites' abundance, richness, and diversity were clearly linked to the key soil properties (C, N, P, and K^+; R = 1). However, they were correlated with environmental variables (soil moisture and infiltration). In contrast, termite communities were negatively correlated to the concentrations of Mg^{2+}, Ca^{2+}, pH, cation exchange capacity, soil temperature, and sand particles.

Overall, changes in termites' activity and community composition significantly affected biochemical processes.

4 | DISCUSSION

The present study shows that termites' assemblages respond to soil restoration, both in functional and in taxonomic terms. Multiple

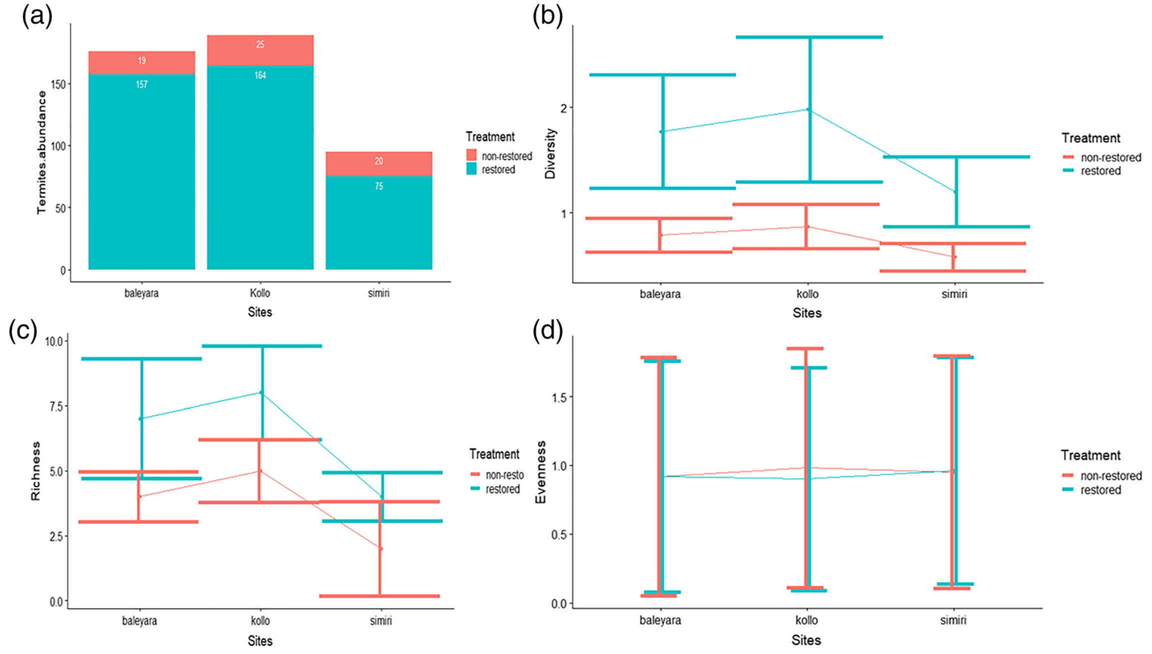

FIGURE 3 Average value (±standard error) of (a) total abundance, (b) diversity (Simpson), (c) richness, and (e) species evenness (Pielou) of termites in the two habitat types, degraded and restored at Kollo, Simiri, and Baleyara, Niger [Colour figure can be viewed at wileyonlinelibrary.com]

studies have documented how restored agrosystems promote soil fauna (Cheik et al., 2019). However, *zaï* + mulching will be a useful strategy for augmenting termites' communities in agrosystems where they are not present. This was mainly a consequence of the presence of litter, which is termites' food. Overall termite indices were high in the site of Kollo, an area with high pluviometry that enhanced termites' blooming. These findings support studies by Bottinelli et al. (2014) and Wildemeersch, Sabiou, Sleutel, and Cornelis (2015), where it was shown that termites were abundant,

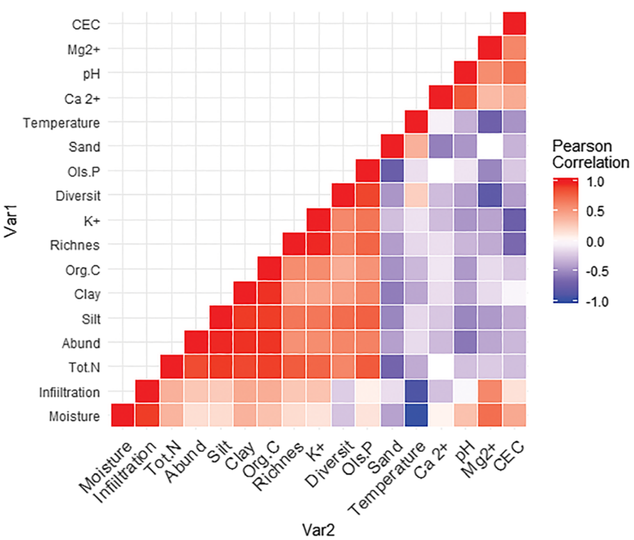

FIGURE 4 Relationships between termites' composition and soil properties across the restored sites (Kollo, Simiri, and Balayara, Niger) [Colour figure can be viewed at wileyonlinelibrary.com]

rich, and diverse in higher rainfall areas. It is important to note that these changes can be useful for evaluating changes related to soil properties (Dorkas et al., 2017).

The practice *zaï* + mulching affects soil water content partly by lowering soil temperature and increasing soil moisture; they act as stabilizers. Consequently, litter decomposition was higher in these restored sites than at the degraded ones. Although various aspects of the *zaï* + MSM effect on soil have been documented (Cheik et al., 2019), there is little information to establish to what extent each aspect of this practice is effective in improving soil microclimate. At the same time, with termite activities under this practice, pores in soil have been created as well asincreasing water infiltration, and this confirms and explains the results of Mando (1997) who measured better drainage in termite plots compared with non-termite plots.

A positive effect of *zaï* + MSM is reported in this study because the combined effect can have great increase the soil nutrient availability (C, N, P, Mg^{2+}, and K^{+}) to meet crop need (Cheik et al., 2019) during the short-term application. Interestingly, this effect was stronger when agrosystems are in high rainfall area. Soil pH was not affected by the treatment for the reason that soil pH was very acid.

In this study, termites' community was shown to be positively correlated with C, N, P, K, and Mg. Such enhanced nutrients contents might have offset crop chemical needs. In a study examining the impacts of termites on the incorporation of lime in soils, (Jouquet, Blanchart, & Capowiez, 2014) found C, N, and P to increase substantially in termites' casts, but to show relatively no change in soil pH. It can be explained by the fact that termites break down litter and incorporate it into the soil. Because of the enhanced rates of nutrient release and availability in the drilosphere, crops grown in the presence of termites often have more nutrients, particularly N and P (Frouz, 2018).

We also found a significant positive correlation between the particle size, especially clay content and termites. In general, soil clay is positively correlated with carbon content, which in turn could affect soil aggregation (Dorkas et al., 2017) and could physically protect organic from degradation (Jouquet et al., 2014). Furthermore, (Franco, Cherubin, Cerri, Guimarães, & Cerri, 2017) determined that soil with a high fauna has the best soil structure.

In this study, moisture and infiltration showed significant positive correlations with termites' community and soil nutrients. A similar result was obtained by Bottinelli et al. (2014), who found that the cumulative infiltration rate closely correlated with termites' richness. Moreover, (Colloff et al., 2010) demonstrated that the infiltration rate was also significantly related to soil nutrients. This indicated that soil physical properties and structure played important roles in soil infiltration in these study regions.

These results indicate that termites can enhance the efficacy of some soil fertility restoration, and that farmers may be able to improve resource use efficiency by fostering healthy termites' communities through improved restoration practices.

5 | CONCLUSIONS

Our results show that actively restored agrosystems have notable impact on the recovery of termites' species that provide ecosystem services and need consideration when working towards sustainability. Variations in the biomass and diversity of termites' community significantly influenced the soil physicochemical properties (e.g., pH, temperature, moisture, total organic carbon, total nitrogen, and percentage of clay). Based on this, we can conclude that any changes in termites' community composition are likely to have positive impacts on agrosystems, influencing a wide range of ecosystem processes.

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CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.

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ORCID

Abdourhimou Amadou Issoufou https://orcid.org/0000-0002-8444-3962

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