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REVIEW

Properties and functional impact of termite sheetings

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Abstract Termites are considered soil engineers and key bioturbators in tropical and subtropical soils. A large number of studies have described the specific properties of the aboveground mounds that termites construct to protect their colonies from environmental hazards. However, there is a paucity of information on properties of soil sheetings; more temporary but often extensive structures are covering over or inserted within substrates on the ground such as leaves and woody materials or components of arboreal runways. Such sheetings are conspicuously produced not only by the Macrotermitinae but also by many other unrelated taxa. Here, we review the available literature and discuss (i) the relationship between rainfall and soil sheeting production and (ii) how termites affect the clay and C contents in soil sheetings. This reveals that sheeting production is highly variable and site specific. We also found that soil sheetings are always enriched in clay, but their impacts on soil C content are variable and related to the C content of the parent soil and to the quality of the substrates consumed by termites.

Keywords Termites · Soil sheeting · Soil engineers · Bioturbation · Carbon and clay

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Introduction

Soil bioturbation is the process in which soil aggregates are modified and/or displaced in the soil profile by soil fauna (Wilkinson et al. 2009; Bottinelli et al. 2015). This process is of primary importance in the soil system (sensu Ponge 2015) because it regulates key ecological functions such as nutrient cycling, infiltration and diffusion of water in soil, resistance of soil to erosion, and quality of runoff water (Jones et al. 2006; Ali et al. 2013). In many tropical soils, bioturbation is mainly carried out by termites and, to a lesser extent, by earthworms, ants, or beetles (Lavelle 1997; Bignell 2006; Jouquet et al. 2016c).

As bioturbators, termites mediate soil properties at different spatial and temporal scales, which range from modifying clay mineralogy, driving aggregate dynamics, and inducing physical stability to enhancing and sustaining porosity at the profile scale and generating nutrient-rich patches at landscape level (e.g., Hedde et al. 2005; Jouquet et al. 2011, 2016b; Bonachela et al. 2015). Most termite activity occurs below ground and involves the creation of subterranean nests and galleries (Holt and Lepage 2000). At the soil surface, termite activity leads to the production or epigeal structures such as mounds, and soil sheetings covering prospective substrates for consumption. But, while there is abundant bibliography describing the specific biological, physical, and chemical properties of termite mound soils compared to the surrounding environment (e.g. Holt and Lepage 2000; Jouquet et al. 2011, 2016a), much less information is available on the properties of soil sheetings. For instance, the number of articles identified by ISI Web of Science on 09 May 2017 was 731 for termite mounds as a keyword, 137 for termitaria and just 24 for soil sheetings. Sheetings are soil aggregates which have been partially or extensively reconstituted by termites and have different physical, chemical, and microbial properties compared to the surrounding environments (Lamoureux and O'kane 2012). The sheetings cover the organic materials the termites are consuming, and recent studies also suggest that their properties vary with the type of substrates being eaten (Diouf et al. 2005, 2006a, b; Jouquet et al. 2015; Harit et al. 2017). Regarding the ecological importance of soil sheetings for termites and their potential impact on soil dynamics, a contemporary dedicated review describing the influence of termites on the properties of soil sheetings and the impact of these biogenic structures (sensu Bullock et al. 1985) on ecosystem functioning is now therefore appropriate. Using the literature available from various sources such as the Web of Science, Scopus, and unpublished data from several PhD theses from the University of Agricultural Science (UAS GKVK, Bangalore, India), the aim of this article was therefore to review the impact of termites on soil surface properties when they produce soil sheetings. We also discuss the potential impact of these structures on soil and ecosystem functioning.

Soil sheeting production: why, where and who?

The ecological needs of termites and their impact on soil functioning are two closely related concepts (Jouquet et al. 2016c). This close dependence between termite fitness and soil properties is stressed by the "extended phenotype engineering" concept (Jones et al. 1994) which states that termites are "intended engineers" (in contrast to "accidental engineers") that modify the soil properties with purpose according to their ecological needs (Turner 2004; Jouquet et al. 2006). Although understanding how and why termites produce soil sheetings seems to be a simple question, it is however far from trivial. From an ecological point of view, the translocation of soil and the formation of sheetings by termites can be seen as a huge investment in terms of energy. In this context, why should termites spend so much energy producing soil sheetings? To date, three different scenarios have been suggested. First, termites are weak and relatively fragile invertebrates and sheetings are used for protection against predators and desiccation (Bagine 1984; Jouquet et al. 2002, 2015; Oberst et al. 2016; Kaiser et al. 2017). Second, termites produce sheetings when they excavate soil to construct belowground galleries and nest chambers (Harit et al. 2017). Finally, filling stems or logs with soil is a way to support the weight of plants, and thus avoid that they collapse while being eaten (Oberst et al. 2016).

In total, 29 articles were found which specifically studied termite sheetings (Table 1). Most of these studies were carried out in Africa (13), followed by Asia (6) and America and Australia (2 for each), whereas only one reported study was from Europe. Sheetings are generally constructed on dry grass, leaf litter, wooden logs and twigs, bark on living trees, and also on animal dung pads. Since termite sheetings are, by definition, covering organic substrates on the ground, it is unsurprising to see that most studies on sheetings have

Table 1 List of studies on soil sheetings and referenced in the Web of science, Scopus, and unpublished data from several PhD theses from the University of Agricultural Science (UAS GKVK, Bangalore, India)

References	Termite species (functional group)	Location	Habitat
Kaiser et al. (2017)	*Odontotermes* sp[a], *Macrotermes* sp[a], *Trinervitermes* sp[b] (FGT)	Burkina Faso, Africa	Sub-sahel zone
Harit et al. (2017)	*Hypotermes obescuriceps*[a] (FGT)	India	Laboratory
Oberst et al. (2016)	*Coptotermes acinaciformis*[c] (WFT)	Canberra, Australia	Laboratory
Jouquet et al. (2015)	*Odontotermes feae*[a] and *Odontotermes obesus*[a] (FGT)	India	Natural forest
Kihara et al. (2015)	–	Nyabeda, Kenya, Africa	Subhumid
Vlieghe et al. (2015)	*Psammotermes allocerus*[d] (GFT)	Namibia, Africa	Nature desert
Jouquet et al. (2012)	Unknown sp. (FGT)	Vietnam	Grassland
Killgore et al. (2009)	Unknown sp.	Mexico, USA	Chihuahuan Desert, Grassland
Villenave et al. (2009)	*Ancistrotermes guineensis*[a], *Odontotermes nilensis*[a], *Macrotermes subhyalinus*[a] (FGT)	Senegal, Africa	Savanna
Jouquet et al. (2007)	*Pseudacanthotermes spiniger*[a] (FGT)	France	Laboratory
Diouf et al. (2006a)	*Macrotermes subhyalinus*[a], *Odontotermes nilensis*[a], *Ancistrotermes guineensis*[a] (FGT)	Senegal, Africa	Sahelian savannah
Mora et al. (2006)	*Odontotermes nilensis*[a], *Ancistrotermes guineensis*[a] (FGT)	Senegal, Africa	Mango orchard
Mora et al. (2005)	*Spinitermes sp*[e], *Ruptitermes sp*[f]. (SFT)	Colombia, South America	Savanna
Diouf et al. (2005)	*Ancistrotennes guineensis*[a], *Macrotermes subhyalinus*[a], *Odontotermes nilensis*[a] (FGT)	Senegal, Africa	Savanna
Ndiaye et al. (2004)	*Macrotermes subhyalinus*[a], *Odontotermes nilensis*[a] (FGT)	Senegal, Africa	Semi-arid savanna
Rouland et al. (2003)	*Macrotermes subhyalinus*[a], *Odontotermes nilensis*[a],	Senegal, Africa	Semi-arid savanna

Table 1 (continued)

References	Termite species (functional group)	Location	Habitat
	Ancistrotermes guineensis^{a}, *Microtermes* sp^{a} (FGT)		
Mora et al. (2003)	*Odontotermes nilensis*^{a}, *Ancistrotermes guineensis*^{a} (FGT)	Senegal, Africa	Mango orchard
Mando and Brussaard (1999)	*Odontotermes smeathmani*^{a}, *Microtermes lepidus*^{a} (FGT)	Burkina Faso, Africa	Sahelian-Sudanian
Mando and Miedema (1997)	*Odontotermes smeathmani*^{a}, *Microtermes lepidus*^{a} (FGT)	Burkina Faso, Africa	Sahelian-Sudanian
Debruyn and Conacher (1995)	*Amitermes neogermanus*^{e}, *Tumultitermes* sp^{b}. (WFT)	Australia	Durokoppin Reserve and Farmland
Kumar (1991)	*Odontotermes* spp^{a} (FGT)	India	Green house
Kalidash (1986)	*Odontotermes* spp^{a} (FGT)	India	Farmland
Basappa (1984)	*Odontotermes* spp^{a} (FGT)	India	Farmland
Bagine (1984)	*Odontotermes latericius*^{a}, *O. boranicus*^{a} (FGT)	Northern Kenya, Africa	Arid shrub land area

FGT fungus-growing termites, *WFT* wood feeding termites, *SFT* soil feeding termite and *GFT* grass feeding termite

[a] Termitidae, Macrotermitinae

[b] Termitidae, Nasutitermitinae

[c] Rhinotermitidae, Coptotermitinae

[d] Rhinotermitinae, Psammotermitinae

[e] Termitidae, Termitinae

[f] Termitidae, Apicotermitinae

focussed on litter-feeding termites (Table 1). Indeed, from the 21 species identified, most belonged to the fungus-growing termite subfamily (Termitinae, Macrotermitinae). Only two studies have focused on lower termites, *Coptotermes acinaciformis* and *Psammotermes allocerus* (Rhinotermitidae, see Table 1). Thus, there is clearly a lack of information on how the other termite families influence soil dynamics when they produce soil sheetings.

Soil sheeting production and properties

Sheetings are temporary structures, removed by rain and the activities of other animals, including potential predators of termites. Consequently, and despite the fact that the sheetings contain much less soil than termite-nest structures, their turnover is quicker and their impact on ecosystem functioning can be considered to be more important in terms of soil and nutrient dynamics. The rate of soil translocation obviously varies from species to species and according to the soil type and climatic conditions. For example, several studies suggest that termites produce more sheetings during the dry season than during the rainy season (Mora et al. 2006; Kaiser et al. 2017). Similarly, Bagine (1984) stated that soil sheeting production decreased with increasing rainfall amounts or, in other words, that termites have a more pronounced effect on soil dynamics in drier and hotter habitats than in more humid environments because termite activity does not depend on soil moisture, which is not the case of earthworms and microbes (Lavelle 1997). However, this assumption is contradicted by the absence of a linear relationship ($R^2 = 0.18$, $P = 0.285$) between rainfall level and sheeting production obtained from the limited number of articles ($n = 8$) which measured the annual soil sheeting production rate (Fig. 1). Conversely, this distribution rather suggests a peak of production in environments with ~ 500 mm year^{-1} and a rather low production before and after. Although our conclusion should be considered carefully due to the low number of data points, Fig. 1 shows that the amount of soil translocated in the form of soil sheeting is highly variable and site specific, in addition to be highly seasonal. In Africa, 300 to 4000 kg soil ha^{-1} year^{-1} are translocated on the ground in the form of sheetings (Lepage 1974; Wood and Sands 1978; Aloni et al. 1983; Bagine 1984; Kooyman and Onck 1987). In Senegal, Rouland et al. (2003) reported a quantity of soil sheetings of nearly 47,000 kg ha^{-1} after 5 months, while Mando (1997) measured 3900 kg soil ha^{-1} in Burkina Faso within 2 weeks. In the Chihuahua desert (North America), Mackay and Whitford (1988) reported up to 2600 kg ha^{-1} year^{-1}.

The source of soil that termites use to produce sheetings appears to be the top centimeter of the profile, where foraging galleries are also most commonly found (Diouf et al. 2006a; Jouquet et al. 2015; Harit et al. 2017). The properties of soil sheetings vary depending on the species, type of feed, and soil type (Lee and Wood 1971; Konaté et al. 1999; Grohmann 2010). The C and clay content are the two variables most commonly used to characterize sheetings, but these are very variable, even within the same termite species. For example, although some studies found higher clay and C contents in termite sheeting than in the control surrounding soil (Bagine 1984; Basappa 1984; Kalidash 1986; Nutting et al. 1987; Ndiaye et al. 2004; Harit et al. 2017), others reported less C in sheetings than the control soil (Kumar 1991; Mora et al. 2003; Jouquet et al. 2007, 2015). Figure 2 shows that these contrasting findings can be explained by a logarithmic relationship between the C content in the sheetings and the surrounding soil ($y = 0.27 \log(x) + 0.95$, $n = 23$, $R^2 = 0.23$, $P = 0.022$). Indeed, Fig. 2 shows that, in soil with a low C content, termite sheetings are slightly enriched in C whereas they are impoverished in C in soil with a higher C content. The logarithmic regression suggests that this threshold value is

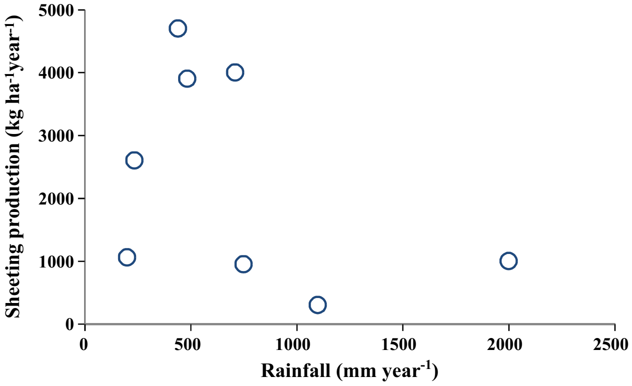

Fig. 1 Termite sheeting production (in kg ha^{-1} year^{-1}) according to the annual rainfall amount (mm year^{-1}) ($n = 8$)

reached for soils with approximately 1% C. A significant enrichment in clay content was also measured in termite sheetings compared to the surrounding soil environment (Fig. 3). The enrichment in clay followed a linear regression with values always above the bisecting line ($y = 1.41\ x + 4.07$, $n = 16$, $R^2 = 0.80$, $P < 0.001$). Consequently, although more data is clearly needed to confirm these results, they suggest that termites have a different impact on the clay and C contents in their constructions depending on the soil. While in poor soils termites tend to enrich their sheetings in C and decrease their C content in soil with C content > 1%, they are always enriched in clay compared to the surrounding surface soil.

The ratio of C or clay contents in soil sheetings to the C or clay contents in the surrounding soil provides information about the strategy termites use to cover their food (Fig. 4). In this example, *Odontotermes nilensis*, *O. wallonensis*, *O. horni*, *O. obesus*, and *Hypotermes obescuriceps* (all fungus-growing termite species) have a direct impact on these ratios (data obtained from Basappa 1984; Kalidash 1986; Kumar 1991; Mora et al. 2003; Ndiaye et al. 2004; Harit et al. 2017). Interestingly, a linear relationship was obtained from *O. nilensis*, which increases the C content the most in soil (highest $C_{sheeting}$:C_{soil}) and has the smallest impact on the soil clay content ($Clay_{sheeting}$:$Clay_{soil}$ ~ 1). On the contrary, *O. obesus* reduces the soil C content but enriches the soil the most with clay (highest $Clay_{sheeting}$:$Clay_{soil}$ value). Therefore, these results suggest a gradient from species enriching soil sheetings with clay particles to species that do not modify soil texture but incorporate organic matter in the form of saliva and/or organic residues, most likely for ensuring their stability and resistance to environmental hazards.

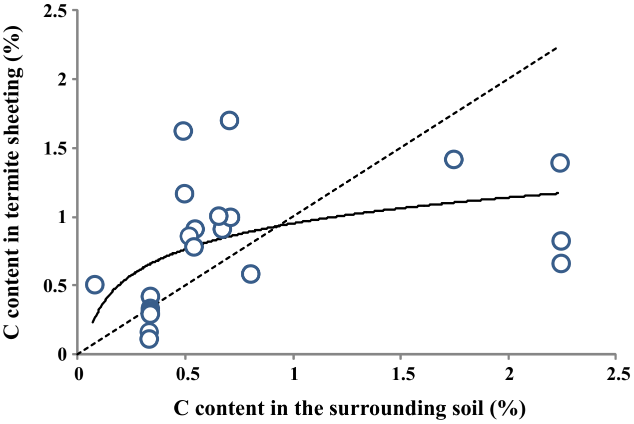

Fig. 2 C content (%) in termite sheetings and the surrounding soil environment. The logarithmic regression is shown ($n = 32$). The *dashed line* corresponds to the bisecting line ($y = x$)

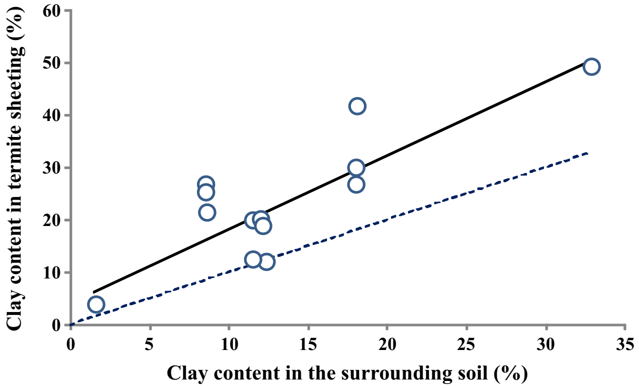

Fig. 3 Clay content (%) in termite sheetings and the surrounding soil environment. The linear regression is shown ($n = 16$). The *dashed line* corresponds to the bisecting line ($y = x$)

Similarly, the influence of the substrate quality on sheeting properties was reviewed from 16 articles. Organic substrates were grouped into five categories, namely manure, straw, fallen log on the ground, bark, and wood from living trees (Fig. 5). Non-parametric statistical analysis (pairwise comparisons using a Wilcoxon rank sum test) failed to show an influence of the substrate quality on clay enrichment in termite sheetings (ratio of clay content in sheeting to the clay content in soil, $P > 0.05$). In contrast, a significant impact of the substrate

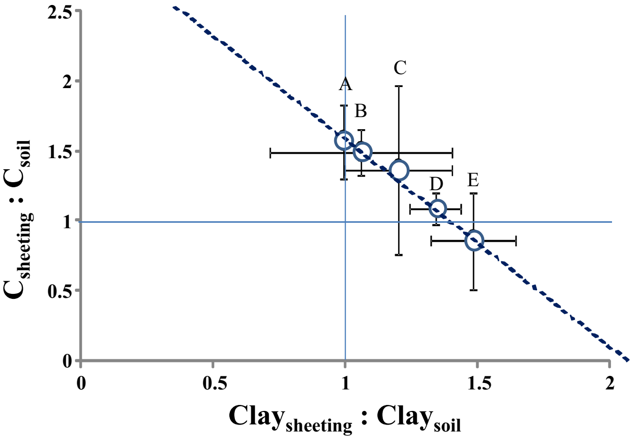

Fig. 4 Relationship between the ratios of the C and clay contents in termite sheetings and the control surrounding environments ($C_{sheeting}$:C_{soil} and $Clay_{sheeting}$:$Clay_{soil}$) for different fungus-growing termite species: *Odontotermes nilensis* (*A*), *Hypotermes obescuriceps* (*B*), *O. wallonensis* (*C*), *O. horni* (*D*), and *O. obesus* (*E*). The linear regression is shown

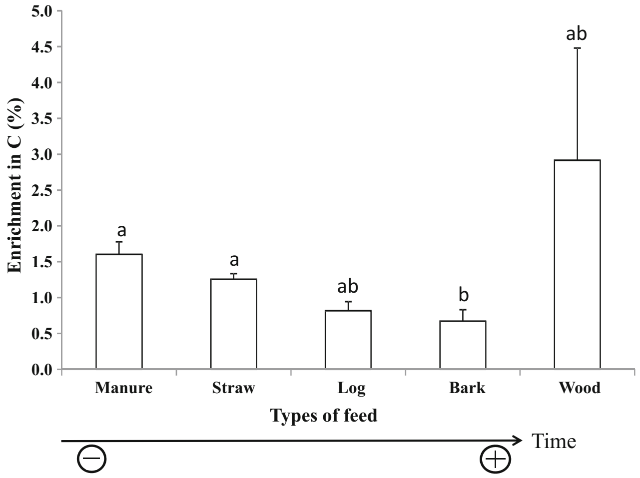

Fig. 5 Enrichment in C (percentage of the C content in the surrounding soil to the C content in the termite sheeting) for different types of food resources (manure, straw, log, bark, and wood). The arrow represents the time needed for termites to consume the different substrates, from rapidly consumed manure substrates to slowly consumed bark and wood substrates
Histograms with similar letters are not significantly different at $P = 0.05$.

quality on C enrichment was observed in sheetings (ratio of C content in sheeting to the C content in soil, $P = 0.009$). The higher enrichment in C was measured in the sheetings that covered the manure and straw substrates ($P > 0.05$ between both), and the lowest values were measured in sheetings covering the bark ($P < 0.05$). Intermediate values were measured for sheetings that covered the log substrates ($P > 0.05$ in all cases). Although it is possible that foreign particles from the substrates were glued with the termite saliva during the molding of sheetings, especially in the case of dung and straw materials, these results suggest that termites incorporate more C within their sheetings when they cover more fibrous and less compact substrates (dung > straw > log > bark). Finally, the C content in the wood was very high but it varied considerably making it difficult to distinguish this substrate from the others ($P > 0.05$ in all cases). Unfortunately, further information about the tree species and their properties (e.g., wood density and C:N ratio) are not available and we could not test whether this high variability is due to the diversity of trees and the quality of their wood.

The redistribution of termite sheetings on the ground is likely to influence the properties of the soil surface, such as their resistance to erosion and water infiltration rate (Jouquet et al. 2012). The higher clay and C content in sheetings may also contribute to improve soil fertility, especially in sandy soils with low C and nutrient contents, while their erosion can be associated with a significant loss of nutrients in water runoff (Mando 1997; Mando and Stroosnijder 1999; Léonard and Rajot 2001; Kaschuk et al. 2006; Jouquet et al. 2012; Harit et al. 2017). As evidenced by several authors, the accumulation of sheetings over time can also contribute to the formation of stone lines in Africa and Australia (Nye 1955; Watson 1960; Williams 1968; Lee and Wood 1971). However, as yet, the importance of termites in stone line formation has never been specifically investigated and more research is therefore clearly needed for determining how the rain and animal trampling impact soil sheetings lifetime and then soil functioning.

Conclusion

The importance of soil sheetings in soil dynamics is highly variable but this review showed that there are both general patterns as well as key questions that remain to be studied. Termite sheetings clearly have different C and clay contents in comparison with the surrounding topsoil. However, more research is clearly needed to determine if a relationship exists between sheeting production and pedoclimatic conditions. We also showed that the clay content in sheetings is directly related to the clay content in the surrounding topsoil. On the other hand, the C content follows a logarithmic regression, leading to either an enrichment or impoverishment in C compared to the surrounding environment.

The influence of sheetings on soil functioning remains also poorly studied, especially compared to termite mounds which have received a lot of attention. For example, the lifetime and fate of termite sheetings, as well as the fate of their specific microbial populations and how they impact soil nutrient cycling, soil erosion, and soil profile, are unknown and should be the subject of further research.

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References

Ali IG, Sheridan G, French JRJ (2013) Ecological benefits of termite soil interaction and microbial symbiosis in the soil ecosystem. J Earth Sci Geotech Eng 3:63–85

Aloni K, Malaisse F, Kapinga I (1983) The role of termites in the decomposition of wood and the transfer of soil in a Zambezian forest. In: Lebrun H, Andre A, de Medts C, Gregoire W, Wauthy G (eds) New trends in soil biology. Dieu-Brichart, Louvain-la-Neuve, pp 600–602

Bagine RK (1984) Soil translocation by termites of the genus *Odontotermes* (Holmgren) (Isoptera: Macrotermitinae) in an arid area of Northern Kenya. Oecol 64:263–266

Basappa H (1984) Studies on the dung feeding termites and their role in removal of dung under dry land conditions. M. Sc (Agri) thesis, University of Agricultural Sciences, Bangalore, India

Bignell DE (2006) Termites as soil engineers and soil processors. In: König H, Varma A (eds) Intestinal microorganisms of termites and other invertebrates, vol 6. Springer Science & Business Media, Berlin, pp 183–220

Bonachela JA, Pringle RM, Sheffer E, Coverdale TC, Guyton JA, Caylor KK, Levin SA, Tarnita CE (2015) Termite mounds can increase the robustness of dry land ecosystems to climatic change. Science 347: 651–655

Bottinelli N, Jouquet P, Capowiez Y, Podwojewski P, Grimaldi M, Peng X (2015) Why is the influence of soil macrofauna on soil structure only considered by soil ecologists? Soil Till Res 146:118–124

Bullock P, Fedoroff N, Jongerius A, Stoops G, Tursina T (1985) Handbook for soil thin section description. Waine Research Publisher, Wolverhampton, p 150

Debruyn LAL, Conacher AJ (1995) Soil modification by termites in the central wheat-belt of western-Australia. Aust J Soil Res 33:179–193

Diouf M, Brauman A, Miambi E, Rouland C (2005) Fungal communities of the foraging soil sheeting built by several fungus-growing termite species (Isoptera, Termitidae: Macrotermitinae) in a dry savanna (Thies, Senegal). Sociobiology 45:899–914

Diouf M, Miambi E, Mora P, Delgarde S, Rouland C (2006a) The impact of termite sheetings age on their fungal communities. Eur J Soil Biol 4:S85–S91

Diouf M, Brauman A, Mora P, Miambi E, Rouland-Lefevre C (2006b) Modification of soil fungal communities in crop sheetings of fungus-growing termites and its effects on soil functioning (Isoptera: Termitidae). Sociobiology 47:353–371

Grohmann C (2010) Termite mediated heterogeneity of soil and vegetation patterns in a semi-arid savanna ecosystem in Namibia. Dissertation, Der Julius-Maximilians-Universität, Würzburg, Germany

Harit A, Moger H, Duprey JL, Gajalakshmi S, Abbasi SA, Subramanian S, Jouquet P (2017) Termites can have greater influence on soil properties through the construction of soil sheetings than the production of above-ground mounds. Insect Soc 64:247–253. doi:10.1007/s00040-017-0541-3

Hedde M, Lavelle P, Joffre R, Jiménez JJ, Decaëns T (2005) Specific functional signature in soil macro-invertebrate biostructures. Funct Ecol 19:785–793

Holt AJ, Lepage M (2000) Termites and soil properties. In: Abe T, Bignell DE, Higashi M (eds) Termites: evolution, sociality, symbioses, ecology, vol 18. Kluwer Academic Publishers, Dordrecht, pp 389–407

Jones CG, Lawton JH, Shachak M (1994) Organisms as ecosystem engineers. Oikos 69:373–386

Jones CG, Gutiérrez JL, Groffman PM, Shachak M (2006) Linking ecosystem engineers to soil processes: a framework using the Jenny State Factor Equation. Eur J Soil Biol 42:S39–S53

Jouquet P, Lepage M, Velde B (2002) Termite soil preferences and particle selections: strategies related to ecological requirements. Insect Soc 49:1–7

Jouquet P, Dauber J, Lagerlöf J, Lavelle P, Lepage M (2006) Soil invertebrates as ecosystem engineers: intended and accidental effects on soil and feedback loops. Appl Soil Ecol 32:153–164

Jouquet P, Bottinelli N, Lata JC, Mora P, Caquineau S (2007) Role of the fungus-growing termite *Pseudacanthotermes spiniger* (Isoptera, Macrotermitinae) in the dynamic of clay and soil organic matter content. An experimental analysis. Geoderma 139:127–133

Jouquet P, Traoré S, Choosai C, Hartmann C, Bignell D (2011) Influence of termites on ecosystem functioning. Ecosystem services provided by termites. Eur J Soil Biol 47:215–222

Jouquet P, Janeau JL, Pisano A, Sy HT, Orange D, Minh LTN, Valentin C (2012) Influence of earthworms and termites on runoff and erosion in a tropical steep slope fallow in Vietnam: a rainfall simulation experiment. Appl Soil Ecol 61:161–168

Jouquet P, Guilleux N, Chintakunta S, Mendez M, Subramanian S, Shanbhag RR (2015) The influence of termites on soil sheeting properties varies depending on the materials on which they feed. Eur J Soil Biol 69:74–78

Jouquet P, Airola E, Guilleux N, Harit A, Chaudhary E, Grellier S, Riotte J (2016a) Abundance and impact on soil properties of cathedral and lenticular termite mounds in Southern Indian woodlands. Ecosystems 20:769–780

Jouquet P, Chintakunta S, Bottinelli N, Subramanian S, Caner L (2016b) The influence of termites on soil macro- and micro-aggregates varies with soil properties. Appl Soil Ecol 101:117–123

Jouquet P, Bottinelli N, Shanbhag RR, Bourguignon T, Traoré S, Abbasi SA (2016c) Termites: the neglected soil engineers of tropical soils. Soil Sci 181:157–165

Kaiser D, Lepage M, Konate S, Linsenmair KE (2017) Ecosystem services of termites (Blattoidea: Termitoidae) in the traditional soil restoration and cropping system Zaï in northern Burkina Faso (West Africa). Agric Ecosyst Environ 236:198–211

Kalidash P (1986) Studies on termite (*Odontotermes spp.*) with special reference to their role in the fertility of soil. PhD Thesis, University of Agricultural Sciences, Bangalore, India

Kaschuk G, Santos JCP, Almeida JA, Sinhorati DC, Berton-Junior JF (2006) Termite activity in relation to natural grassland soil attributes. Sci Agric 63:583–588

Kihara J, Martius C, Bationo A (2015) Crop residue disappearance and macrofauna activity in sub-humid western Kenya. Nutr Cycl Agroecosyst 102:101–111

Killgore A, Jackson E, Whitford WG (2009) Fire in Chihuahuan Desert grassland: short-term effects on vegetation, small mammal populations, and faunal pedoturbation. J Arid Environ 73:1029–1034

Konaté S, Le Roux X, Tessier D, Lepage M (1999) Influence of large termitaria on soil characteristics, soil water regime, and tree leaf shedding pattern in a West African savanna. Plant Soil 206:47–60

Kooyman C, Onck RFM (1987) Distribution of termite (Isoptera) species in southwestern Kenya in relation to land use and the morphology of their galleries. Biol Fertil Soils 3:69–73

Kumar NG (1991) Studies on the ecology of the subterranean *Odontotermes horni* (Wasmann**)** (Isoptera:Termitidae) and its foraging effects on the soil nutrient status, PhD Thesis. University of Agricultural Sciences, Bangalore, India

Lamoureux S, O'Kane MA (2012) Effects of termites on soil cover system performance. Mine clossure. Australian Centre for Geomechanics, Perth, pp 433–446

Lavelle P (1997) Faunal activities and soil processes: adaptive strategies that determine ecosystem function. Adv Ecol Res 27:93–132

Lee KE, Wood TG (1971) Physical and chemical effects on soils of some Australian termites and their pedological significance. Pedobiologia 11:376–409

Léonard J, Rajot JL (2001) Influence of termites on runoff and infiltration: quantification and analysis. Geoderma 104:17–40

Lepage M (1974) The termites of a Sahelian savanna (Northern Ferlo, Senegal): population, populations, consumption, role in the ecosystem. Thesis, University of Dijon, Dijon, France

MacKay WP, Whitford WG (1988) Spatial variability of termite gallery production in chihuahuan desert plant communities. Sociobiology 14:281–289

Mando A (1997) The role of termites and mulch in the rehabilitation of crusted Sahelian soils. Thesis, Wageningen Agricultural University, Wageningen

Mando A, Brussaard L (1999) Contribution of termites to the breakdown of straw under Sahelian conditions. Biol Fertil Soils 29:332–334

Mando A, Miedema R (1997) Termite-induced change in soil structure after mulching degraded (crusted) soil in the Sahel. Appl Soil Ecol 6: 241–249

Mando A, Stroosnijder L (1999) The biological and physical role of mulch in the rehabilitation of crusted soil in the Sahel. Soil Use Manag 15:123–127

Mora P, Seugé C, Chotte JL, Rouland C (2003) Physico-chemical typology of the biogenic structures of termites and earthworms: a comparative analysis. Biol Fertil Soils 37:245–249

Mora P, Miambi E, Jiménez JJ, Decaëns T, Rouland C (2005) Functional complement of biogenic structures produced by earthworms, termites and ants in the neotropical savannas. Soil Biol Biochem 37(6):1043–1048

Mora P, Seuge C, Rossi JP, Rouland C (2006) Abundance of biogenic structures of earthworms and termites in a mango orchard. Eur J Soil Biol 42:S250–S253

Ndiaye D, Lensi R, Lepage M, Brauman A (2004) The effect of the soil-feeding termite Cubitermes niokoloensis on soil microbial activity in a semi-arid savanna in West Africa. Plant Soil 259:277–286

Nutting WL, Haverty MI, LaFage JP (1987) Physical and chemical alteration of soil by two subterranean termite species in Sonoran Desert grassland. J Arid Environ 12:233–239

Nye PH (1955) Some soil-forming processes in the humid tropics. Eur J Soil Sci 6:51–62

Oberst S, Lai JC, Evans TA (2016) Termites utilise clay to build structural supports and so increase foraging resources. Sci Rep 6

Rouland C, Lepage M, Chotte JL, Diouf M, Ndiaye D, Ndiay S, Seuge C, Brauman A (2003) Experimental manipulation of termites (Isoptera, Macrotermitinae) foraging patterns in a Sahelo-Sudanese savanna: effect of litter quality. Insect Soc 50:309–316

Ponge JF (2015) The soil as an ecosystem. Biol Fertil Soils 51:645–648

Turner JS (2004) Extended phenotypes and extended organisms. Biol Philos 19:327–352

Villenave C, Djigal D, Brauman A, Rouland-Lefevre C (2009) Nematodes, indicators of the origin of the soil used by termites to construct biostructures. Pedobiologia 52:301–307

Vlieghe K, Picker M, Ross-Gillespie VERE, Erni B (2015) Herbivory by subterranean termite colonies and the development of fairy circles in SW Namibia. Ecol Entomol 40:42–49

Watson JP (1960) Some observations on soil horizons and insect activity in granite soils. In: Proceedings 1st Federal Science Congress, Rhodesia, Nyasaland, pp 271–276

Wilkinson MT, Richards PJ, Humphreys GS (2009) Breaking ground: pedological, geological, and ecological implications of soil bioturbation. Earth Sci Rev 97:257–272

Williams MAJ (1968) Termites and soil development near Brocks Creek, Northern Territory. Aust J Sci 31:153–154

Wood TG, Sands WA (1978) The role of termites in ecosystems. In: Brian MV (ed) Production ecology of ants and termites. Cambridge Univ Press, Cambridge, pp 245–292