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REVIEW ARTICLE

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Sustainable use of termite activity in agro-ecosystems with reference to earthworms. A review

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Abstract
Sustainable agriculture and agro-ecology justify the need to study and understand the role played by ecological processes, and soil biodiversity in particular, in agro-ecosystem functioning. A large number of studies have focused on earthworms in temperate and humid tropical ecosystems and have demonstrated their importance for improving soil biological, physical, and chemical properties in agro-ecosystems. Their "success" is so essential that earthworms are widely considered key species and relevant indicators of soil health in temperate ecosystems. In arid and sub-arid ecosystems, the role of "soil engineer" is usually attributed to termites, and especially fungus-growing termites in Africa and Asia. However, despite this recognition, significant effort is spent eradicating them in plantations because of their pest status. In this review, we discuss the status of termites ("pests" vs. "soil engineers") and question whether termites play similar roles to earthworms in arid- and sub-arid agroecosystems, with a focus on their influence on nutrient cycling and water dynamics. We argue that the dream of controlling natural interactions and ridding plantations of termites remains a costly legacy of the green revolution. We review the agricultural practices that have been used to reduce termite damage in plantations by restoring refuges to predators or by reorienting termite foraging activity towards organic amendments. Then, we show that the stimulation of termite activity can be used to improve key ecological functions in agro-ecosystems, such as increasing water availability to plants or producing fertility hot-spots. Finally, we suggest that more research on how termites can be used for improving ecosystem services, as is actually done with earthworms in temperate and humid tropical countries, could lead to a paradigm shift in our understanding of the impact of termites in tropical agro-ecosytems.

Keywords Agro-ecology · Sustainability · Dryland · Heterogeneity · Pests · Ecosystem services · Ecosystem disservices

Contents

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1 Introduction

The green revolution in the 1940s and blue revolution in the 2000s, which led to the intensive use of fertilizers, pesticides, irrigation, and high-yield crop varieties, have undoubtedly increased crop production and reduced the number of chronically undernourished people. Unfortunately, these gains in production have come at high environmental costs with the degradation and over-exploitation of terrestrial and aquatic ecosystems, hence threatening their sustainability and the services they provide to society (Tilman et al. 2002). It is in this context that the concepts of sustainable agriculture and agro-ecology have emerged as paradigm shifts, justifying the need to study and understand the roles played by ecological processes, and soil biodiversity in particular, in (agro)ecosystem functioning (Altieri 1995, 2002; Tilman et al. 2002; Wezel et al. 2009; Wilkinson et al. 2009).

Regarding their importance in soil functioning as key decomposers and soil bioturbators, a large number of studies have demonstrated the positive impacts of earthworms on numerous soil biological, physical, and chemical properties in agro-ecosystems (Lavelle 1997; Brown et al. 1999; Laossi et al. 2010; Jouquet et al. 2014; Bertrand et al. 2015; Kanianska et al. 2016). Their "success" is understood to be so important that earthworms are commonly considered emblems, key species, ecosystem engineers, and relevant indicators of soil health in temperate and humid tropical ecosystems (e.g., Lavelle 1997; Rochfort et al. 2009; Bertrand et al. 2015). In tropical arid and sub-arid ecosystems, soils are usually fragile, highly susceptible to erosion and compaction, and characterized by low clay and nutrient contents, low water infiltration rates, and low water holding capacities. In these environments, litter decomposition and soil bioturbation are mainly carried out by termites, which are therefore considered the "soil engineers" or "ecosystem services providers" of dry tropical soils (e.g., Smeathman 1781; Harris 1956; Lee and Wood 1971; Black and Okwakol 1997; Lavelle 1997; Bignell and Eggleton, 2000; Holt and Lepage 2000; Jouquet et al. 2011, 2016; Bottinelli et al. 2015). The influence of termites on ecosystem functioning can be considered across a range of spatial scales, from the modification of local soil properties and water infiltration rates to the creation of patches that influence the distribution of nutrients, water dynamics, plant growth, and diversity at the landscape scale (Collins 1983; Dangerfield et al. 1998; Yamada et al. 2005a, b; Pringle et al. 2010; Bonachela et al. 2015; Bottinelli et al. 2015; Jouquet et al. 2016) (Fig. 1).

Theoretically, biodiversity contributes to enhanced ecosystems services (Balvanera et al. 2006; Lavelle et al. 2006; Barrios 2007), such as ecosystem stability and productivity, and improved nutrition and human health (Baidu-Forson et al. 2012; Wall et al. 2015). However, soil organisms can also perform "disservices" (Dunn 2010). For instance, although termites are excellent decomposers and have a positive impact on numerous ecological functions, they become serious issues when they attack crops and constructions. Consequently, the positive roles played by termites are often overshadowed by their status as pests threatening agriculture in the tropics where billions of US$ are annually spent on their prevention and extermination (Su and Scheffrahn 2000; Verma et al. 2009; Tilahun et al. 2012: Shanbhag and Sundararaj 2013). A rapid and non-exhaustive survey assessing the number of articles on termites as either pests or ecosystem engineers (key words = "termites" and either "pest" and "control" or "ecosystem engineers") reveals very clear differences, with approximately 2077 versus 154 articles for termites as "pests" and "ecosystem engineers," respectively (source: Web of Science, carried out in March 2017) (Figs. 2 and 3). This clearly shows that more effort has been spent on eradicating termites than on understanding their environmental impacts, and/or how to use their impacts for improving specific ecological functions in agro-ecosystems. Hence, it appears that the role of termites, as ecosystem service providers (sensu Lavelle et al. 2006; Jouquet et al. 2011), is clearly under-appreciated and that more research is needed to better evaluate the importance of termite activity and diversity in tropical agro-ecosystems.

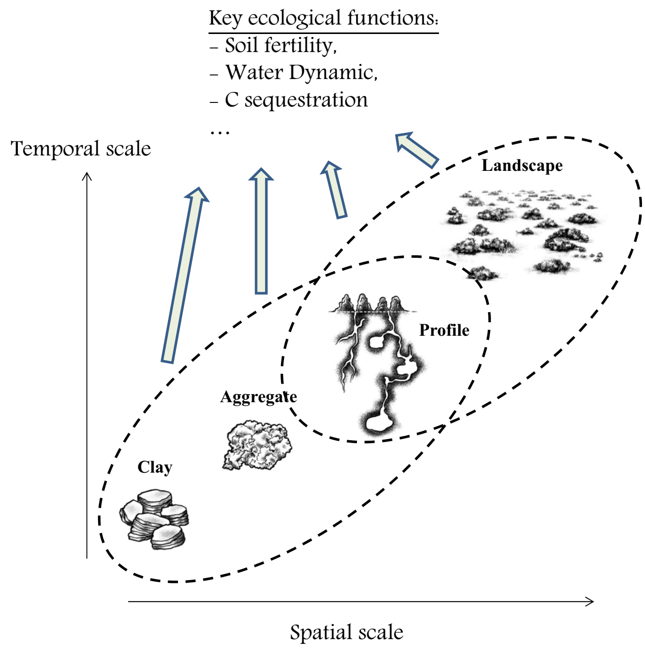

Fig. 1 Impact of termites on ecosystem functioning at different spatial and temporal scales. At the smallest scale, termites influence clay mineralogy and soil aggregation. The production of tunnels in soil and the construction of below- and aboveground nests are important at the soil profile scale. The concentrations of C and nutrients within termite nests maintain heterogeneity at the landscape scale. At these different scales of observation, termites influence several key ecological functions in agrosystems such as C sequestration, soil fertility, water dynamics, and nutrient distribution. Figure modified from Jouquet et al. (2016)

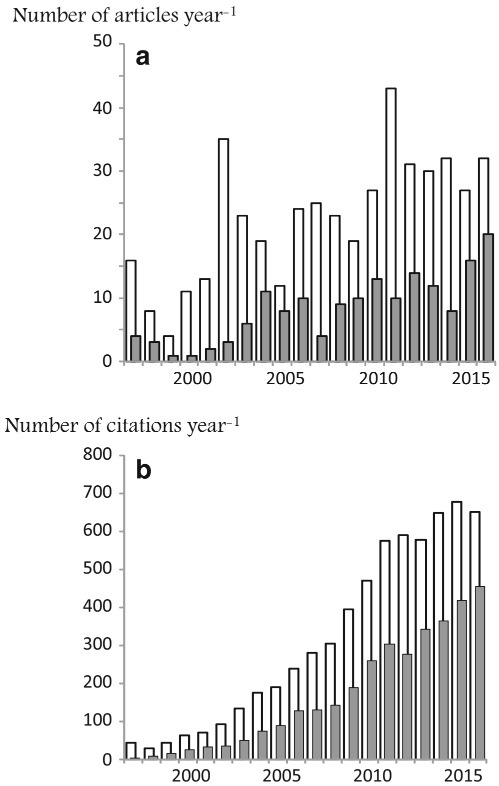

Fig. 2 Number of articles (**a**) and citations (**b**) referenced since 1997 in the Web of Science. Keywords are "termites" and either "pests" (in white) or "engineers" (in gray). This figure highlights that termites are perceived more through their negative than positive effects as "pests" and "engineers," respectively

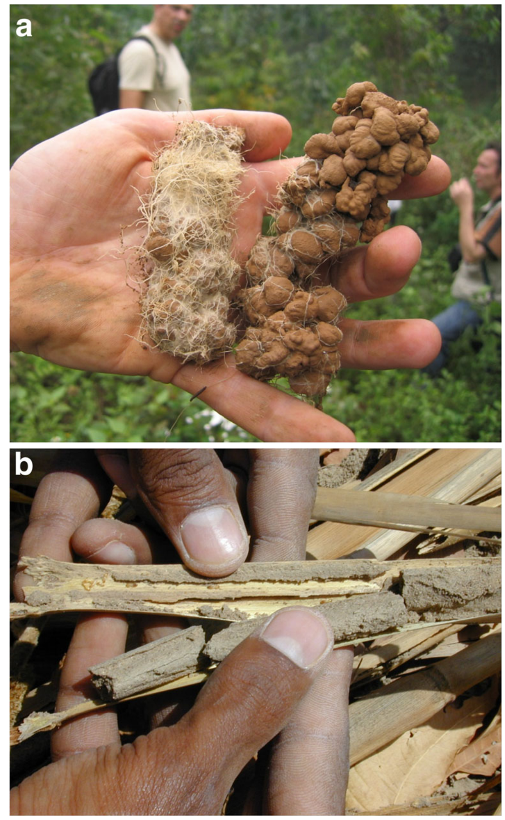

Fig. 3 Earthworms are generally considered to have a positive impact on plant growth and soil fertility. As an example, **a** shows a proliferation of roots within earthworm casts in Northern Vietnam (photograph by P. Jouquet). In contrast, termites are seen as pests in agro-ecosystems. A proliferation of termites and soil sheetings within plant stems is shown in **b** (photograph by C. Rouland-Lefevre)

The aim of this article is to review the value of termites ("pests" vs. "key decomposers and soil engineers") in the context of sustainable development and agro-ecology concepts. We discuss the use of termite bioturbation to improve agro-ecosystem services, as is actually done with earthworms, and thus "ask whether termites have the right" to request a similar status to that of earthworms in arid and sub-arid tropical ecosystems.

2 Termites as pests

2.1 Damage resulting from termite activity

To date, between 2300 and 3000 termite species have been identified (Kambhampati and Eggleton 2000; Engel et al. 2009). Among them, between 180 and 300 termite species are pests in homes and crops (Verma et al. 2009). All of these species belong to the wood-feeding and litter harvester groups. The fungus-growing Macrotermitinae species (Termitidae, especially from the genera *Macrotermes*, *Odontotermes*, *Ancistrotermes*, and *Microtermes*) and the Rhinotermitidae species (especially *Reticulitermes* spp. and *Coptotermes* spp.) contain most of the pest species (Pearce 1997). For example, fungus-growing termites are responsible for the majority of crop damage and 90% of tree mortality in South African forests (Mitchell 2002). In India, the total number of species drops to approximately 300 and only 35 have been reported to damage agricultural crops and wood constructions (Chhotani 1980; Verma et al. 2009; Shanbhag and Sundararaj 2013). In this country, the annual loss caused by termites has been estimated to reach several hundred million rupees (> 1.5 million US$) (Potineni 1986). In the USA, termites are the most important structural pests and about 2–5 billion US$ are spent annually on their prevention and extermination (Jeffery et al. 2010; Suiter et al. 2012). Termites can cause damage to crops, human constructions, pastures and forestry as well as to non-cellulosic materials such as electrical cables (Su and Scheffrahn 2000; Rouland-Lefèvre 2000; Mugerwa et al. 2011c; Mugerwa 2015a, b). The impact of termites is, however, highly variable. For instance, records on crop yield losses vary from 3 to 100% in Africa and Asia (Umeh and Ivbijaro 1999; Mitchell 2002; Sekamatte et al. 2003; Joshi et al. 2005; Verma et al. 2009). In a sub-humid tropical environment, Paul et al. (2015) found that a reduction in termite abundance was associated with a 22% increase in crop yield. Termite activity can also affect crop quality. For example, the scarification of crop tubers by termites can reduce their market value and may increase the toxin contents in groundnuts (Black and Okwakol 1997). However, termite attack may not necessarily result in yield loss and their attacks are usually more significant in weak plants suffering from drought or inappropriate soil properties (Potineni 1986). Indeed, in a rainforest in central Amazonia, Apolinário and Martius (2004) found that around 15% of living trees contained termites whereas 70% of trees with rotten cores contained the wood-feeder *Coptotermes* spp. termites. In this specific environment, the existence of termites in internal cavities of living trees did not have a negative impact on the trees, although it could constitute a serious issue for the wood industry. Finally, aboveground termite mounds can also interfere with plowing and grazing and reduce the surface of land used by farmers to grow cash crops (Choosai 2010; Mugerwa 2015a, b). Mugerwa et al. (2011a, b) reported that termite mounds can cover between 25 and 75% of the total soil surface area in African savannas. For instance, the giant earth mounds formed by the Southern harvester termite *Microhodotermes viator* occupy 14 to 25% of the land surface in South-western parts of Southern Africa (Lovegrove and Siegfried 1986, 1989; Picker et al. 2007). In this case, the area occupied by termite mounds is a non-exploitable environment for the production of fodder and thus reduces the amount of food available for livestock. When termite mounds are bare of vegetation, these structures also facilitate high rates of water runoff and soil erosion in rangeland ecosystems (Janeau and Valentin 1987; Zziwa et al. 2012) (Fig. 4).

2.2 Why do termites become pests?

Termites have been considered as our "enemies" for decades, if not centuries (Snyder 1935). Energy and significant budgets have been spent to identify and improve methods for controlling or eradicating termite populations in human-impacted environments (i.e., cities and agro-ecosystems). The control of termite pests relies mainly on chemical insecticides, although the use of biological control methods (e.g., based on the utilization of the entomo-pathogenic fungus *Metarhizium anisopliae*, or through the stimulation of ant predators) has also been reported (Cowie et al. 1989; Logan et al. 1990; Maniania et al. 2001; Sekamatte et al. 2001; Verma et al. 2009; Mugerwa 2015a, b). These methods are mostly ineffective and often not environmentally friendly (Cowie et al. 1989). As highlighted by Mugerwa (2015a, b), such methods do not address the root cause of termite infestation and thus only provide temporary relief to the problem. More research is therefore needed to understand why termites are still considered our "enemies" in agro-ecosystems even though it is recognized that they perform important services in cultivated and non-cultivated ecosystems. The main factors which lead to termites becoming pests are summarized in Table 1. Farmers usually rank overgrazing and deforestation among the most important factors leading to destructive behavior by termites (Mugerwa et al. 2011a, b). Sharma et al. (2004) studied the influence of termites on rice and wheat yields for 2 years in India and concluded that an approximate inverse relationship exists between termite incidence and rainfall or wet soil conditions, with a higher incidence of termites attributed to dry conditions. Overhunting activities can also lead to destructive behavior (Mugerwa 2015a, b). Finally, a shift in biodiversity can result in the predominance of pests in agro-ecosystems due to the disappearance and/or reduction of certain feeding groups from the ecosystems which often give way to other feeding groups that increase in abundance (Dawes 2010).

Fig. 4 This photo shows a mound produced by *Odontotermes obesus* (Macrotermitinae) in a pasture in Southern India. The degradation of termite mounds by the rain or predators leads to an accumulation of soil in the vicinity of the mounds. The erosion of particles then forms a soil crust that impedes plant growth (Photograph by P. Jouquet)

3 Termites as key decomposers and engineers in agro-ecosystems

Statements from soil ecologists such as "although termites pose potentially negative effects, their positive effects may be the overriding factors" are common (Lamoureux and

Table 1 Agricultural practices that lead to termites becoming pests in agro-ecosystems

Agricultural practice	Mechanism leading to termites gaining pest status
Deforestation and overgrazing	Reduction in food (less litter, lower diversity) leading to a reduction in termite diversity, lower inter-specific competition, and proliferation of resistant or invasive species
Ecosystem simplification and hunting	Less predators (arthropods, mainly ants, and mega-fauna such as bears, aardvark, pangolins, chimpanzees) leading to a lower control of termite populations
Drought	Plants are less resistant

O'Kane 2012). Hence, an abundant literature presents termites as ecosystem services providers. In agro-ecosystems, termites have an impact on three major ecological functions: (i) litter decomposition and nutrient recycling, (ii) water dynamics in soil, and (iii) ecosystem complexity and the distribution of nutrients at the landscape scale.

3.1 Influence of termites on C and nutrient cycling

In agro-ecosystems, termites can feed on plant material and/or soil humus and they are of the greatest importance in recycling C and nutrients from wood, other plant materials, and herbivore dung (e.g., Yamada et al. 2005a, b; Freymann et al. 2008; Noble et al. 2009; Veldhuis et al. 2017). If their impact on litter decomposition can be considered positive in fire-prone ecosystems where C and nutrients can be lost by fire (Konaté et al. 2003), termite foraging activity appears as a drawback when C and nutrients from the litter could have participated in the formation of humus without the action of termites (Potineni 1986). This is typically observed in dry tropical forests where most of the aboveground litter can be consumed by termites before it enters the soil layer (Yamada et al. 2005a). This is also true in agro-ecosystems where organic amendments (e.g., mulch, farmyard manure, or compost) are consumed by litter-feeder termites before being incorporated into the soil. In this case, nutrients become temporarily immobilized in the termite biomass and their symbiotic fungus (in the case of the fungus-growing termite species), thus limiting the positive outcomes of conservation farming practices in terms of soil chemical fertility and C sequestration (Potineni 1986). Organic matter can also be temporarily incorporated in termite sheetings and mounds. However, the low stability of termite-worked soil aggregates (Jouquet et al. 2004b, 2015a) suggests a rapid mineralization of this soil organic matter pool but a non-significant impact on nitrate and phosphate contents in soil (Harit et al. 2017). Since termites prefer some organic substrates to others, low palatable organic matter (e.g., compost) can be preferred to fresh residues (e.g., manure or straw) if the aims are to reduce the exportation of C from the field by termites and to increase the C content of soils. Finally, although less abundant in agro-ecosystems, the impact of soil-feeding termites on C sequestration and nutrient dynamics can also be considered as a drawback when they consume the C stock and nutrients from soil, thus hampering C sequestration in soils (Dahlsjö et al. 2014) (e.g., the 4p1000 initiative, see: http://4p1000.org/ and Minasny et al. 2017).

3.2 Influence of termites on soil water dynamics

The beneficial impact of termites on water dynamics in soil appears to be more important than their impact on nutrient cycling at the field scale (Kaiser et al. 2017). Indeed, termite foraging activity is often associated with the production of belowground galleries which increase soil macroporosity, create "preferential flow paths" and increase water infiltration in soil (Elkins et al. 1986; Mando et al. 1996, 1999; Mando and Miedema 1997; Léonard et al. 2001, 2004; Evans et al. 2011; Kaiser et al. 2017). The influence of termites on water infiltration is obviously influenced by the number of tunnels, their depths, size, etc. On average, it is considered that termites increase water infiltration above the natural rate by a factor of 1 to 4, depending on termite activity, soil type, and rainfall intensity (Lamoureux and O'Kane 2012; Kaiser et al. 2017). However, this effect is only significant in soils with low hydraulic conductivity. In the Chihuahuan desert, USA, termite foraging activity increases water infiltration from 51.3 to 88.4 mm h^{-1} (Elkins et al. 1986). However, to be significant at the plot scale, a large number of foraging holes is sometimes needed (e.g., > 30 m^{-2} in Sub-Sahelian ecosystems, Léonard and Rajot 2001). Termite foraging activity can be associated with the production of large amounts of sheetings which are usually enriched in clay, silt, and organic matter compared to the surrounding top-soil (Harit et al. 2017). Especially in compacted and gravelly soils in semi-arid regions, sheetings can locally improve soil physical and chemical properties. On the other hand, in sloping land in a humid tropical climate, Jouquet et al. (2012) observed that sheeting degradation might also be related to crust formation, higher water runoff, and soil detachment.

3.3 Influence of termites on ecosystem complexity

At the landscape scale, termites also act as heterogeneity drivers when they produce aboveground mounds that appear like nutrient "hot-spots" or "fertility islands" in which primary productivity is locally increased and water flow improved. Although termite mounds usually represent a small proportion of the landscape, they might constitute a mosaic of comparatively more productive areas in an ecosystem (e.g., Lamoureux and O'Kane 2012). In contrast to the surrounding savanna soil, these constructions are usually enriched in cations (magnesium, potassium, calcium…) and clay (Arshad 1981; Coventry et al. 1988; Mills et al. 2009; Jouquet et al. 2004a, 2015b; Brossard et al. 2007; Lopez-Hernandez et al. 2004; Sileshi et al. 2010; Seymour et al. 2014). Depending on the feeding group (e.g., soil feeding termites vs. fungus-growers) and the pedoclimatic properties of the environment, these mounds can also have higher C and N contents compared to the surrounding soil. The higher clay content along with the higher proportion of swelling clay in termite mounds also explain their higher water retention (Konaté et al. 1999). As shown in African savanna ecosystems, these aboveground constructions also provide refuges for plants and soil biodiversity, offer a better resistance of plants to fire, represent foraging hot-spots for herbivores, and increase the robustness of dryland ecosystems to climatic change (Mobaek et al. 2005;

Traoré et al. 2008, 2015; Choosai et al. 2009; Moe et al. 2009; Brody et al. 2010; Erpenbach et al. 2013, Erpenbach et al. 2017; Davies et al. 2014, 2016; Seymour et al. 2014; Tobella et al. 2014; Bonachela et al. 2015).

4 Towards the sustainable application of termite activity in agro-ecosystems

Two main types of agricultural practices have been proposed for improving the services termites provide in agro-ecosytems while reducing their negative impacts. The first focuses on the provision of refuges for predators, which control termite populations, and of food for stimulating termite foraging activity and improving soil properties. The second relies on taking advantage of the heterogeneity created by termites at the landscape scale.

4.1 Less intensive agricultural practices providing litter, predators, and pathogens

Reduced food availability (litter) and the loss of termites' natural predators (e.g., ants, bears, aardvark, pangolins), parasites, and pathogens (e.g., nematodes, fungi) are reported to be among the major factors explaining why termites are destructive in grasslands and for crops (Snyder 1929; Mugerwa 2015a, b). Hence, one promising strategy is the development of practices that provide other food besides crops for termites and which stimulate predators and/or entomopathogens for controlling termite populations. For example, studies carried out in Africa and Asia showed that termite infestation and crop damage could be reduced by inter-cropping with legumes, mulching in crop plantations, or by keeping leaf litter on the ground in tree plantations (Pong 1974; Sands 1977; Shivashankar et al. 1991; Sekamatte et al. 2001, 2003; Girma et al. 2009; Kihara et al. 2015). Less damage to crops and tree attacks result from ants nesting and feeding on termites (e.g., *Leptogenys processionalis* in India, which live in temporary nests and always forage under low-intensity sunlight conditions (Rajagopal and Ali 1984); or *Pheidole megacephala* and *Megaponera foetens* in Africa (Sheppe 1970; Longhurst et al. 1978; Lepage 1981)), as well as the fact that termites prefer feeding on mulch and litter, a more palatable food resource for termites than crops and trees (Shivashankar et al. 1991; Mugerwa 2015a, b). The above examples are important because they show that termite attacks on crops and trees can be reduced to a level acceptable for farmers if termite populations are limited (but not eradicated) by stimulating predators or entomopathogens, such as fungi, ants, spiders, beetles and lizards, and/or if more palatable food is given to them (mulch and litter in these cases). Interestingly, several studies also showed that the application of mulch or different organic amendments (e.g., cattle or goat dung, urine, or a mixture) increases termite foraging activity which in turn enhances soil porosity, water infiltration, and water holding capacity in soil (Mando et al. 1996, 1999; Roose et al. 1999; Léonard and Rajot 2001; Dawes 2010; Kaiser et al. 2017), while reducing termite damage on crops (Mugerwa 2015a, b), and increasing plant growth and yield. For example, in the case of the agricultural and forestry Zaï systems, the application of organic matter into the soil triggers termite activity which then create burrows through the crusted soil surface, thus improving the productivity of the ecosystems from 0.5 to 5.3 tons ha^{-1} for straw and from 0.15 to 1.7 tons ha^{-1} for *Sorghum* (Roose et al. 1999). The main obstacle to the widespread uptake of this technique is, however, that it is labor intensive (300 h ha^{-1} of work), requires a huge amount of organic substrates (3 tons ha^{-1}), and is limited to semi-arid environments receiving between 300 and 800 mm water (Roose et al. 1999). These results are also likely to be context dependent, and perhaps species dependent. Indeed, no significant influence on soil aggregate stability and C content was measured in sub-humid tropical ecosystems by Paul et al. (2015), who even measured an increase in crop yield (+ 34% for maize and 22% for soybean) after the eradication of termites in the field.

Tillage has a negative impact on termites and ants (Sanabria et al. 2016). The influence of zero or low tillage on termites has also been investigated in wheat and maize plantations in India (Reddy et al. 1994; Sharma et al. 2004). These practices were associated with lower termite damage compared to rotary and conventional tillage, probably because of the higher soil moisture that could favor pathogenic fungi (e.g., *Metarhizium anisopliae*, Grace 1997; Wright et al. 2005) or predators (e.g., ants) throughout the crop growth period. However, it is worth mentioning that zero and low tillage were also associated with weed development, potentially more herbicides for their control, and lower yield (Reddy et al. 1994; Sharma et al. 2004), thereby highlighting the limits of this approach.

4.2 Considering agro-ecosystems as heterogeneous and complex environments.

Aboveground termite mounds, especially those built by fungus-growing termites, create hot-spots of nutrients in ecosystems (Sileshi et al. 2010; Jouquet et al. 2016). Termite mounds are usually enriched in clay, exchangeable cations, and macronutrients compared with the surrounding top-soil layers (Holt and Lepage 2000; Jouquet et al. 2011). Their positive influence on plant growth and diversity, hydrology, and ecosystem resistance to drought was mainly found in non-cultivated environments (Collins 1983; Dangerfield et al. 1998; Yamada et al. 2005a; Pringle et al. 2010; Bonachela et al. 2015; Bottinelli et al. 2015; Jouquet et al. 2016). However, studies carried out in Africa highlight that these structures can also help farmers to reduce the risks of crop failure (Brouwer et al. 1993; Harris et al. 1994, cited by Tilahun et al. 2012). Subsistence farmers in Africa and Asia commonly destroy and spread termite mound soils in their fields to improve soil fertility (Fairhead and Scoones 2005; Verlinden et al. 2006). Termite mounds can also be associated with fruit trees, as shown in Namibia by Verlinden et al. (2006). They provide numerous ecosystem services in paddy fields in Thailand such as shade for cattle and for growing vegetables, proteins from insects, mushrooms, medicines from the diversity of trees growing on mounds, or even refuges for predators such as ants (Choosai et al. 2009; Choosai 2010). In Africa, traditional soil classification is also based on the abundance of termite mounds (Adamou et al. 2007, Tilahun et al. 2012). Fairhead and Scoones (2005) mentioned that traditional farming practices in Africa consist in selecting lands with many large termite mounds, which can be used for gardening. These authors also report direct and indirect methods for triggering termite activity in the fields, for example through the maintenance of trees that offer a beneficial environment to termites (Fairhead and Scoones 2005).

5 Conclusion and implications

The relationship between termites and humans can be seen as another example of the numerous conflicts between humans and wildlife, such as those that exist between men and elephants, leopards, or tigers in India. As we learn to share our environment with large herbivores and predators, a new challenge for agronomists is to develop agricultural practices that get the best from termites (e.g., their abilities to improve water dynamics in soil and to improve soil fertility close to their nests) while making their negative impacts on plant growth and yield acceptable to farmers.

The green revolution led to a simplification and homogenization of agro-ecosystems and to an overuse of chemicals, thereby precluding termites from our cultivated lands. In retrospect, we know that the utilization of these chemicals is of concern as they create problems for our health and the environment. The dream of ridding termites from plantations thus appears today as a costly legacy from the green revolution. In contrast, the development in agroecology highlights the importance of considering the soil as a living system (e.g., Okwakol and Sekamatte 2007; Gobat et al. 2010), and of the enhanced use of biodiversity as an essential element of agroecological approaches (Altieri 1995). New, environmentally friendly and more ecological approaches have also to emerge to give termites a status similar to that of earthworms in arid and sub-arid ecosystems. It is stated in the Biodiversity Atlas (Jeffery et al. 2010) that "termites and ants appear to have a similar role to earthworms and enchytraeids in more temperate and tropical organic soils (…)". This review highlights that termites are obviously not playing the same roles as earthworms in arid- and sub-arid cultivated ecosystems, and that they provide both ecosystem services and disservices. However, the examples given in this article emphasize that (i) not all termite species are harmful in plantations and that a first step towards a more sustainable use of biodiversity is perhaps to teach farmers to recognize the different species and/or functional groups that occupy their lands and to adapt their management accordingly, (ii) termite damage can be reduced by restoring refuges to predators or by reorienting termite foraging activity towards organic amendments (litter and dung or compost materials), and (iii) the stimulation of termite activity improves key ecological functions in agro-ecosystems (water availability to plants and the creation of fertility hotspots in the examples given above). This review also stresses the need for a better understanding of the services that termite mounds can provide in agro-ecosystems. We believe that one of the challenges for sustainable agriculture is to consider drylands as complex and heterogeneous systems where termite mounds can provide numerous services and contribute to ensure food security and improve the resistance to environmental change.

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References

Adamou I, Pierre NJ, Pogenet P, Tchimbi B, Gonlaina G (2007) Soil degradation in the Sudano-Guinea savannas of Mbe Cameroon: farmers' perception, indicators and soil fertility management strategies. Res J Agric Biol Sci 3:907–916

Altieri MA (1995) Agroecology: the science of sustainable agriculture. Westview Press, 433 pp

Altieri MA (2002) Agroecology: the science of natural resource management for poor farmers in marginal environments. Agric Ecosyst Environ 93:1–24. https://doi.org/10.1016/S0167-8809(02)00085-3

Apolinário FE, Martius C (2004) Ecological role of termites (Insecta, Isoptera) in tree trunks in central Amazonian rain forests. For Ecol Manag 194(1-3):23–28. https://doi.org/10.1016/j.foreco.2004.01.052

Arshad MA (1981) Physical and chemical properties of termite mounds of two species of *Macrotermes* (Isoptera, termitidae) and the surrounding soils of the semiarid savanna of Kenya. Soil Sci 132(2):161–174. https://doi.org/10.1097/00010694-198108000-00006

Baidu-Forson JJ, Hodgkin T, Jones M (2012) Introduction to special issue on agricultural biodiversity, ecosystems and environment linkages in Africa. Agric Ecosyst Environ 157:1–4. https://doi.org/10.1016/j.agee.2012.04.011

Balvanera P, Pfisterer AB, Buchmann N, He J-S, Nakashizuka T, Raffaelli D, Schmid B (2006) Quantifying the evidence for biodiversity effects on ecosystem functioning and services. Ecol Lett 9(10):1146–1156. https://doi.org/10.1111/j.1461-0248.2006.00963.x

Barrios E (2007) Soil biota, ecosystem services and land productivity. Ecol Econ 64(2):269–285. https://doi.org/10.1016/j.ecolecon.2007.03.004

Bertrand M, Barot S, Blouin M, Whalen J, Oliveira T, Roger-Estrade J (2015) Earthworm services for cropping systems. A review. Agron Sustain Dev 35(2):553–567. https://doi.org/10.1007/s13593-014-0269-7

Bignell DE, Eggleton P (2000) Termites in ecosystems. In: Abe T, Bignell DE, Higashi M (eds) Termites: evolution, sociality, symbiosis, ecology. Kluwer Academic Publishers, Dordrecht. https://doi.org/10.1007/978-94-017-3223-9_17

Black HIJ, Okwakol MJN (1997) Agricultural intensification, soil biodiversity and agroecosystem function in the tropics: the role of termites. Appl Soil Ecol 6(1):37–53. https://doi.org/10.1016/S0929-1393(96)00153-9

Bonachela JA, Pringle RM, Sheffer E, Coverdale TC, Guyton JA, Caylor KK, Levin SA, Tarnita CE (2015) Termite mounds can increase the robustness of dryland ecosystems to climatic change. Science 347(6222):651–655. https://doi.org/10.1126/science.1261487

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 Tillage Res 146:118–124. https://doi.org/10.1016/j.still.2014.01.007

Brody AK, Palmer TM, Fox-Dobbs K, Doak DF (2010) Termites, vertebrate herbivores, and the fruiting success of *Acacia drepanolobium*. Ecology 91(2):399–407. https://doi.org/10.1890/09-0004.1

Brossard M, Lopez-Hernandez D, Lepage M, Leprun J-C (2007) Nutrient storage in soils and nests of mound-building *Trinervitermes* termites in Central Burkina Faso: consequences for soil fertility. Biol Fertil Soils 43(4):437–447. https://doi.org/10.1007/s00374-006-0121-6

Brouwer J, Fussell LK, Hermann L (1993) Soil and crop growth microvariability in the West African semiarid tropics—a possible risk-reducing factor for subsistence farmers. Agric Ecosyst Environ 45(3-4):229–238. https://doi.org/10.1016/0167-8809(93)90073-X

Brown G, Pashanasi B, Villenave C, Patron JC, Senapati BK, Giri S, Barois I, Lavelle P, Blanchart E, Blakemore RJ, Spain AV, Boyer J (1999) Effects of earthworms on plant production in the tropics. In: Lavelle P, Brussaard L, Hendrix P (eds) Earthworm management in tropical agroecosystems. CAB International, Wallingford, pp 87–147

Chhotani OB (1980) Termite pests of agriculture in the Indian region and their control. Tech. Mongr. No. 4, zoological survey of India Calcutta, 94 pp

Choosai C (2010) Biological activity in paddy fields: the role of soil engineers in ecosystem functioning. Paris VI. 126pp

Choosai C, Mathieu J, Hanboonsong Y, Jouquet P (2009) Termite mounds and dykes are biodiversity refuges in paddy fields in north-eastern Thailand. Environ Conserv 36(1):71–79. https://doi.org/10.1017/S0376892909005475

Collins NM (1983) The utilization of nitrogen resources by termites (Isoptera). In: MS LJA, Rorison IH (eds) Nitrogen as an ecological factor. The 22nd Symposium of the British Ecological Society, Oxford. Blackwell Scientific Publications, Oxford, pp 381–412

Coventry R, Holt J, Sinclair D (1988) Nutrient cycling by mound building termites in low fertility soils of semi-arid tropical Australia. Soil Res 26(2):375–390. https://doi.org/10.1071/SR9880375

Cowie RH, Logan JW, Wood T (1989) Termite (Isoptera) damage and control in tropical forestry with special reference to Africa and Indo-Malaysia: a review. Bull Entomol Res 79(02):173–184. https://doi.org/10.1017/S0007485300018150

Dahlsjö CAL, Parr CL, Malhi Y, Rahman H, Meir P, Jones DT, Eggleton P (2014) First comparison of quantitative estimates of termite biomass and abundance reveals strong intercontinental differences. J Trop Ecol 30(02):143–152. https://doi.org/10.1017/S0266467413000898

Dangerfield JM, Mc Carthy TS, Ellery WN (1998) The mound-building termites *Macrotermes michaelseni* as an ecosystem engineer. J Trop Ecol 14(4):507–520. https://doi.org/10.1017/S0266467498000364

Davies AB, Levick SR, Asner GP, Robertson MP, van Rensburg BJ, Parr CL (2014) Spatial variability and abiotic determinants of termite mounds throughout a savanna catchment. Ecography 37(9):852–862. https://doi.org/10.1111/ecog.00532

Davies AB, Levick SR, Robertson MP, van Rensburg BJ, Asner GP, Parr CL (2016) Termite mounds differ in their importance for herbivores across savanna types, seasons and spatial scales. Oikos 125(5):726–734. https://doi.org/10.1111/oik.02742

Dawes TZ (2010) Reestablishment of ecological functioning by mulching and termite invasion in a degraded soil in an Australian savanna. Soil Biol Biochem 42(10):1825–1834. https://doi.org/10.1016/j.soilbio.2010.06.023

Dunn RR (2010) Global mapping of ecosystem disservices: the unspoken reality that nature sometimes kills us. Biotropica 42(5):555–557. https://doi.org/10.1111/j.1744-7429.2010.00698.x

Elkins NZ, Sabol GV, Ward TJ, Whitford WG (1986) The influence of subterranean termites on the hydrological characteristics of a Chihuahuan desert ecosystem. Oecologia 68(4):521–528. https://doi.org/10.1007/BF00378766

Engel MS, Grimaldi DA, Kumar K (2009) Termites (Isoptera): their phylogeny, classification, and rise to ecological dominance. Am Mus Novit 3650:1–27. https://doi.org/10.1206/651.1

Erpenbach A, Bernhardt-Römermann M, Wittig R, Thiombiano A, Hahn K (2013) The influence of termite-induced heterogeneity on savanna vegetation along a climatic gradient in West Africa. J Trop Ecol 29(01):11–23. https://doi.org/10.1017/S0266467412000703

Erpenbach A, Bernhardt-Römermann M, Wittig R, Hahn K (2017) The contribution of termite mounds to landscape-scale variation in vegetation in a West African national park. J Veg Sci 28(1):105–116. https://doi.org/10.1111/jvs.12463

Evans TA, Dawes TZ, Ward PR, Lo NT (2011) Ants and termites increase crop yield in a dry climate. Nat Commun 2:262. https://doi.org/10.1038/ncomms1257

Fairhead J, Scoones I (2005) Local knowledge and the social shaping of soil investments: critical perspectives on the assessment of soil degradation in Africa. Land Use Policy 22(1):33–41. https://doi.org/10.1016/j.landusepol.2003.08.004

Freymann BP, Buitenwerf R, Desouza O, Olff H (2008) The importance of termites (Isoptera) for the recycling of herbivore dung in tropical ecosystems: a review. Eur J Entomol 105(2):165–173. https://doi.org/10.14411/eje.2008.025

Girma D, Addis T, Tadele T (2009) Effect of mulching and intercropping on termite damage to maize at Bako, Western Ethiopia. Pest Manag J Ethiop 13:38–43

Gobat J-M, Aragno M, Matthey W (2010) Le sol vivant: bases de pédologie, biologie des sols: PPUR Presses polytechniques

Grace JK (1997) Biological control strategies for suppression of termites. J Agric Entomol 14:281–289

Harit A, Moger H, Duprey JL, 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 67(2):247–253. https://doi.org/10.1007/s00040-017-0541-3

Harris WV (1956) Termite mound building. Insect Soc 3(2):261–268. https://doi.org/10.1007/BF02224306

Harris D, Fry GJ, Miller ST (1994) Microtopography and agriculture in semi-arid Botswana 2. Moisture availability, fertility and crop performance. Agric Water Manag 26(1-2):133–148. https://doi.org/10.1016/0378-3774(94)90029-9

Holt AJ, Lepage M (2000) Termites and soil properties. In: Abe TB, Higashi M (eds) Termites: evolution, sociality, symbioses, ecology. Springer, Dordrecht, pp 389–407. https://doi.org/10.1007/978-94-017-3223-9_18

Janeau JL, Valentin C (1987) Relationships between termite mounds of *Trinervitermes* and soil surface—rearrangement, runoff and erosion. Rev Ecol Biol Sol 24:637–647

Jeffery S, Gardi C, Jones A, Montanarella L, Marmo L, Miko L, Ritz K, Peres G, Römbke J, van der Putten WH (2010) Atlas européen de la biodiversité du sol. Commission européenne, Bureau des publications de l'Union européenne, Luxembourg

Joshi PK, Singh NP, Singh NN, Gerpacio RV, Pingali PL (2005) Maize in India: production systems, constraints, and research priorities. D.F. CIMMYT, Mexico, p 22

Jouquet P, Boulain N, Gignoux J, Lepage M (2004a) Association between subterranean termites and grasses in a West African savanna: spatial pattern analysis shows a significant role for *Odontotermes* n. *pauperans*. Appl Soil Ecol 97(2):99–107. https://doi.org/10.1016/j.apsoil.2004.05.002

Jouquet P, Tessier D, Lepage M (2004b) The soil structural stability of termite nests: role of clays in *Macrotermes bellicosus* (Isoptera, Macrotermitinae) mound soils. Eur J Soil Biol 40(1):23–29. https://doi.org/10.1016/j.ejsobi.2004.01.006

Jouquet P, Traore S, Choosai C, Hartmann C, Bignell D (2011) Influence of termites on ecosystem functioning. Ecosystem services provided by termites. Eur J Soil Biol 47(4):215–222. https://doi.org/10.1016/j.ejsobi.2011.05.005

Jouquet P, Janeau J-L, Pisano A, Sy Tran H, Orange D, Luu Thi Nguyet M, 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. https://doi.org/10.1016/j.apsoil.2012.04.004

Jouquet P, Blanchart E, Capowiez Y (2014) Utilization of earthworms and termites for the restoration of ecosystem functioning. Appl Soil Ecol 73:34–40. https://doi.org/10.1016/j.apsoil.2013.08.004

Jouquet P, Guilleux N, Chintakunta S, Mendez M, Subramanian S, Shanbhag RR (2015a) The influence of termites on soil sheeting properties varies depending on the materials on which they feed. Eur J Soil Biol 69:74–78. https://doi.org/10.1016/j.ejsobi.2015.05.007

Jouquet P, Guilleux N, Shanbhag RR, Subramanian S (2015b) Influence of soil type on the properties of termite mound nests in Southern India. Appl Soil Ecol 96:282–287. https://doi.org/10.1016/j.apsoil.2015.08.010

Jouquet P, Bottinelli N, Shanbhag RR, Bourguignon T, Traoré S, Abbasi SA (2016) Termites: the neglected soil engineers of tropical soils. Soil Sci 181(3/4):157–165. https://doi.org/10.1097/SS.0000000000000119

Kaiser D, Lepage M, Konaté 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. https://doi.org/10.1016/lagee.2016.11.023

Kambhampati S, Eggleton P (2000) Phylogenetics and taxonomy. Termites: evolution, sociality, symbioses. Ecology:1–23

Kanianska R, Jauová J, Makovníková J, Kizeková M (2016) Assessment of relationships between earthworms and soil abiotic and biotic factors as a tool in sustainable agricultural. Sustainability 8(9):906. https://doi.org/10.3390/su8090906

Kihara J, Martius C, Bationo A (2015) Crop residue disappearance and macrofauna activity in sub-humid western Kenya. Nutr Cycl Agroecosyst 102(1):101–111. https://doi.org/10.1007/s10705-014-9649-2

Konaté S, Le Roux X, Verdier B, Lepage M (2003) Effect of underground fungus-growing termites on carbon dioxide emission at the point- and landscape-scales in an African savanna. Funct Ecol 17(3):305–314. https://doi.org/10.1046/j.1365-2435.2003.00727.x

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 and Soil 206(1):47–60

Lamoureux S, O'Kane M (2012) Effects of termites on soil cover system performance. Dalam Fourie dan Tibbet (eds) Mine Clossure, Perth, pp 433-446

Laossi K-R, Decaëns T, Jouquet P, Barot S (2010) Can we predict how earthworms effects on plant growth vary with soil properties? Appl Environ Soil Sci:6

Lavelle P (1997) Faunal activities and soil processes: adaptive strategies that determine ecosystem function. Adv Ecol Res 27:93–132. https://doi.org/10.1016/S0065-2504(08)60007-0

Lavelle P, Decaëns T, Aubert M, Barot S, Blouin M, Bureau F, Margerie P, Mora P, Rossi J-P (2006) Soil invertebrates and ecosystem services. Eur J Soil Biol 42:3–15. https://doi.org/10.1016/j.ejsobi.2006.10.002

Lee KE, Wood TG (1971) Termites and soils. Academic Press Inc, London

Léonard J, Rajot JL (2001) Influence of termites on runoff and infiltration: quantification and analysis. Geoderma 104(1-2):17–40. https://doi.org/10.1016/S0016-7061(01)00054-4

Léonard J, Perrier E, de Marsily G (2001) A model for simulating the influence of a spatial distribution of large circular macropores on surface runoff. Water Resour Res 37(12):3217–3225. https://doi.org/10.1029/2001WR000337

Léonard J, Perrier E, Rajot JL (2004) Biological macropores effect on runoff and infiltration: a combined experimental and modelling approach. Agric Ecosyst Environ 104(2):277–285. https://doi.org/10.1016/j.agee.2003.11.015

Lepage MG (1981) Étude de la prédation de *Megaponera foetens* (F.) sur les populations récoltantes de Macrotermitinae dans un ecosystème semi-aride (Kajiado-Kenya). Insect Soc 28(3):247–262. https://doi.org/10.1007/BF02223627

Logan JW, Cowie RH, Wood T (1990) Termite (Isoptera) control in agriculture and forestry by non-chemical methods: a review. Bull Entomol Res 80(03):309–330. https://doi.org/10.1017/S0007485300050513

Longhurst C, Johnson RA, Wood TG (1978) Predation by *Megaponera foetens* (Fabr.) (Hymenoptera: Formicidae) on termites in the Nigerian southern Guinea savanna. Oecologia 32(1):101–107. https://doi.org/10.1007/BF00344694

Lopez-Hernandez D, Araujo Y, Lopez A, Hernandez-Valencia I, Hernandez C (2004) Changes in soil properties and earthworm populations induced by long-term organic fertilization of a sandy soil in the Venezuelan Amazonia. Soil Sci 169(3):188–194. https://doi.org/10.1097/01.ss.0000122524.03492.b7

Lovegrove BG, Siegfried WR (1986) Distribution and formation of Mima-like earth mounds in the western Cape Province of South Africa. S Afr J Sci 82:432–436

Lovegrove BG, Siegfried WR (1989) Spacing and origin(s) of Mima-like earth mounds in the Cape Province of South Africa. S Afr J Sci 85:108–112

Mando A, Miedema R (1997) Termite-induced change in soil structure after mulching degraded (crusted) soil in the Sahel. Appl Soil Ecol 6(3):241–249. https://doi.org/10.1016/S0929-1393(97)00012-7

Mando A, Stroosnijder L, Brussaard L (1996) Effects of termites on infiltration into crusted soil. Geoderma 74(1-2):107–113. https://doi.org/10.1016/S0016-7061(96)00058-4

Mando A, Brussaard L, Stroosnijder L (1999) Termite- and mulch-mediated rehabilitation of vegetation on crusted soil in West Africa. Restor Ecol 7(1):33–41. https://doi.org/10.1046/j.1526-100X.1999.07104.x

Maniania NK, Ekesi S, Songa JM (2001) Managing termites in maize with the entomopathogenic fungus *Metarhizium anisopliae*. Insect Sci Appl 21:237–242

Mills AJ, Milewski A, Fey MV, Gröngröft A, Petersen A (2009) Fungus culturing, nutrient mining and geophagy: a geochemical investigation of *Macrotermes* and *Trinervitermes* mounds in southern Africa.

J Zool 278(1):24–35. https://doi.org/10.1111/j.1469-7998.2008.00544.x

Minasny B, Malone BP, McBratney AB, Angers DA, Arrouays D, Chambers A, Chaplot V, Chen Z-S, Cheng K, Das BS, Field DJ, Gimona A, Hedley CB, Hong SY, Mandal B, Marchant BP, Martin M, McConkey BG, Mulder VL, O'Rourke S, Richer-de-Forges AC, Odeh I, Padarian J, Paustian K, Pan G, Poggio L, Savin I, Stolbovoy V, Stockmann U, Sulaeman Y, Tsui C-C, Vågen T-G, van Wesemael B, Winowiecki L (2017) Soil carbon 4 per mille. Geoderma 292:59–86. https://doi.org/10.1016/j.geoderma2017.01.002

Mitchell JD (2002) Termites as pests of crops, forestry, rangeland and structures in southern Africa and their control. Sociobiology 40:47–69

Mobaek R, Narmo AK, Moe SR (2005) Termitaria are focal feeding sites for large ungulates in Lake Mburo National Park, Uganda. J Zool (Lond) 267(01):97–102. https://doi.org/10.1017/S0952836905007272

Moe SR, Mobaek R, Narmo AK (2009) Mound building termites contribute to savanna vegetation heterogeneity. Plant Ecol 202(1):31–40. https://doi.org/10.1007/s11258-009-9575-6

Mugerwa S (2015a) Magnitude of the termite problem and its potential anthropogenic causes in Nakasongola district of Uganda. Grassl Sci 61(2):75–82. https://doi.org/10.1111/grs.12087

Mugerwa S (2015b) Infestation of African savanna ecosystems by subterranean termites. Ecol Complex 21:70–77. https://doi.org/10.1016/j.ecocom.2014.11.009

Mugerwa S, Nyangito M, Nderitu J, Bakuneta C, Mpairwe D, Zziwa E (2011a) Farmers ethno-ecological knowledge of the termite problem in semi-arid Nakasongola. Afr J Agric Res 6:3183–3191

Mugerwa S, Nyangito M, Mpairwe D, Nderitu J (2011b) Effect of biotic and abiotic factors on composition and foraging intensity of subterranean termites. Afr J Environ Sci Technol 5:579–588

Mugerwa S, Nyangito M, Mpairwe D, Bakuneeta C, Nderitu J, Zziwa E (2011c) Termite assemblage structure on grazing lands in semi-arid Nakasongola. Agric Biol J N Am 2(5):848–859. https://doi.org/10.5251/abjna.2011.2.5.848.859

Noble JC, Müller WJ, Whitford WG, Pfitzner GH (2009) The significance of termites as decomposers in contrasting grassland communities of semi-arid eastern Australia. J Arid Environ 73(1):113–119. https://doi.org/10.1016/j.jaridenv.2008.08.004

Okwakol MJN, Sekamatte MB (2007) Soil macrofauna research in ecosystems in Uganda. Afr J Ecol 45(s2):2–8. https://doi.org/10.1111/j.0141-6707.2007.00800.x

Paul BK, Vanlauwe B, Hoogmoed M, Hurisso TT, Ndabamenye T, Terano Y, Six J, Ayuke FO, Pulleman MM (2015) Exclusion of soil macrofauna did not affect soil quality but increased crop yields in a sub-humid tropical maize-based system. Agric Ecosyst Environ 208:75–85. https://doi.org/10.1016/j.agee.2015.12.018

Pearce MJ (1997) Termites: biology and pest management: Cab International

Picker MD, Hoffman MT, Leverton B (2007) Density of *Microhodotermes viator* (Hodotermitidae) mounds in southern Africa in relation to rainfall and vegetative productivity gradients. J Zool 271(1):37–44. https://doi.org/10.1111/j.1469-7998.2006.00189.x

Pong TY (1974) The termite problem in plantation forestry in Peninsular Malaysia. Malays Forester 37:278–283

Potineni K (1986) Studies on termites (*Odontotermes* spp.) with special reference to their role in the fertility of soil. Agricultural Entomology. University of Agricultural Sciences, Bangalore 150 pp

Pringle RM, Doak DF, Brody AK, Jocque R, Palmer TM (2010) Spatial pattern enhances ecosystem functioning in an African savanna. PLoS Biol 8(5):12. https://doi.org/10.1371/journal.pbio.1000377

Rajagopal D, Ali TMM (1984) Predatory ants of the mound building termite, *Odontotermes wallonensis* (Wasmann) with special reference to the predatory behaviour of *Leptogenys processionalis* (Jerdon). J Bombay Nat Hist Soc 81:721–725

Reddy MV, Cogle AL, Balashouri P, Kumar VPK, Rao KPC, Jangawad LS (1994) Soil-management and termite damage to maize (*Zea Mays* L.) in a semiarid tropical Alfisol. Int J Pest Manage 40(2):170–172. https://doi.org/10.1080/09670879409371877

Rochfort SJ, Ezernieks V, Yen AL (2009) NMR-based metabolomics using earthworms as potential indicators for soil health. Metabolomics 5(1):95–107. https://doi.org/10.1007/s11306-008-0140-4

Roose E, Kaboré V, Guenat C (1999) Zai practice: a West African traditional rehabilitation system for semiarid degraded lands, a case study in Burkina Faso. Arid Soil Res Rehabil 13(4):343–355. https://doi.org/10.1080/089030699263230

Rouland-Lefèvre C (2000) Symbiosis with fungi. Termites: evolution, sociality, symbioses, ecology. Springer, pp 289–306. https://doi.org/10.1007/978-94-017-3223-9_14

Sanabria C, Dubs F, Lavelle P, Fonte SJ, Barot S (2016) Influence of regions, land uses and soil properties on termite and ant communities in agricultural landscapes of the Colombian Llanos. Eur J Soil Biol 74:81–92. https://doi.org/10.1016/j.ejsobi.2016.03.008

Sands W (1977) Role of termites in tropical agriculture. Outlook Agric 9(3):136–143. https://doi.org/10.1177/003072707700900307

Sekamatte M, Latigo M, Smith A (2001) The effect of maize stover used as mulch on termite damage to maize and activity of predatory ants. Afr Crop Sci J 9:411–419

Sekamatte BM, Ogenga-Latigo M, Russell-Smith A (2003) Effects of maize–legume intercrops on termite damage to maize, activity of predatory ants and maize yields in Uganda. Crop Prot 22(1):87–93. https://doi.org/10.1016/S0261-2194(02)00115-1

Seymour CL, Milewski AV, Mills AJ, Joseph GS, Cumming GS, Cumming DHM, Mahlangu Z (2014) Do the large termite mounds of *Macrotermes* concentrate micronutrients in addition to macronutrients in nutrient-poor African savannas? Soil Biol Biochem 68:95–105. https://doi.org/10.1016/j.soilbio.2013.09.022

Shanbhag RR, Sundararaj R (2013) Host range, pest status and distribution of wood destroying termites of India. J Trop Asian Entomol 2:12–27

Sharma RK, Srinivasa Babu K, Chhokar RS, Sharma AK (2004) Effect of tillage on termites, weed incidence and productivity of spring wheat in rice–wheat system of North Western Indian plains. Crop Prot 23(11):1049–1054. https://doi.org/10.1016/j.cropro.2004.03.008

Sheppe W (1970) Invertebrate predation on termites of the African Savanna. Insect Soc 17(3):205–218. https://doi.org/10.1007/BF02226194

Shivashankar T, Rajagopal D, Veeresh GK (1991) Termites have their choice of food in the midst of plenty. In: Veeresh GK, Rajagopal D, Viraktamath CA (eds) Advances in management and conservation of soil fauna. Proceedings of the 10th international Soil Zoology Colloquium, Bangalore, August 7–13, 1988. Oxford and IBH Publishing Co. Pvt. Ltd., New Delhi, pp 127–135

Sileshi GW, Arshad MA, Konaté S, Nkunika POY (2010) Termite-induced heterogeneity in African savanna vegetation: mechanisms and patterns. J Veg Sci 21(5):923–937. https://doi.org/10.1111/j.1654-1103.2010.01197.x

Smeathman H (1781) Some account of the termites, which are found in Africa and other hot climates. In a letter from Mr. Henry Smeathman, of Clement's Inn, to Sir Joseph Banks, Bart P.R.S. Philos Trans R Soc Lond 71(0):139–192. https://doi.org/10.1098/rstl.1781.0033

Snyder T (1929) Termites and architecture. Sci Mon 28:143–151

Snyder STE (1935) Our enemy, the termite. Frontispiece, Comstock Publishing Company, 196pp

Su N-Y, Scheffrahn RH (2000) Termites as pests of buildings. Termites: evolution, sociality, symbioses, ecology. Springer, p 437–453

Suiter DR, Jones SC, Forschler BT (2012) Biology of subterranean termites in the Eastern United States. Bulletin 1209. University of Georgia, Athens, Georgia

Tilahun A, Kebede F, Yamoah C, Erens H, Mujinya BB, Verdoodt A, Van Ranst E (2012) Quantifying the masses of *Macrotermes subhyalinus* mounds and evaluating their use as a soil amendment. Agric Ecosyst Environ 157:54–59. https://doi.org/10.1016/j.agee.2011.11.013

Tilman D, Cassman KG, Matson PA, Naylor R, Polasky S (2002) Agricultural sustainability and intensive production practices. Nature 418(6898):671–677. https://doi.org/10.1038/nature01014

Tobella BA, Reese H, Almaw A, Bayala J, Malmer A, Laudon H, Ilstedt U (2014) The effect of trees on preferential flow and soil infiltrability in an agroforestry parkland in semiarid Burkina Faso. Water Resour Res 50(4):3342–3354. https://doi.org/10.1002/2013WR015197

Traoré S, Tigabu M, Ouédraogo SJ, Boussim JI, Guinko S, Lepage M (2008) *Macrotermes* mounds as sites for tree regeneration in a Sudanian woodland (Burkina Faso). Plant Ecol 198(2):285–295. https://doi.org/10.1007/s11258-008-9404-3

Traoré S, Ouédraogo SJ, Jouquet P, Nacro BH, Boussin JI, Guinko S, Lepage M (2015) Long-term effects of *Macrotermes* termites, herbivores and annual early fire on woody undergrowth community in Sudanian woodland, Burkina Faso. Flora 211:40–50. https://doi.org/10.1016/j.flora.2014.12.004

Umeh VC, Ivbijaro MF (1999) Effects of termite damage to maize of seed extracts of *Azadirachta indica* and *Piper guineense* in farmers fields. J Agric Sci 133(4):403–407. https://doi.org/10.1017/S002185969900670X

Veldhuis MP, Laso FJ, Olff H, Berg MP (2017) Termites promote resistance of decomposition to spatiotemporal variability in rainfall. Ecology 98(2):467–477. https://doi.org/10.1002/ecy.1658

Verlinden A, Seely MK, Hillyer A (2006) Settlement, trees and termites in Central North Namibia: a case of indigenous resource management. J Arid Environ 66(2):307–335. https://doi.org/10.1016/j.jaridenv.2005.11.012

Verma M, Sharma S, Prasad R (2009) Biological alternatives for termite control: a review. Int Biodeterior Biodegrad 63(8):959–972. https://doi.org/10.1016/j.ibiod.2009.05.009

Wall DH, Nielsen UN, Six J (2015) Soil biodiversity and human health. Nature 528:69–76. https://doi.org/10.1038/nature15744

Wezel A, Bellon S, Doré T, Francis C, Vallod D, David C (2009) Agroecology as a science, a movement and a practice. A review. Agron Sustain Dev 29(4):503–515. https://doi.org/10.1051/agro/2009004

Wilkinson MT, Richards PJ, Humphreys GS (2009) Breaking ground: pedological, geological, and ecological implications of soil bioturbation. Earth Sci Rev 97(1-4):257–272. https://doi.org/10.1016/j.earscirev.2009.09.005

Wright MS, Raina AK, Lax AR (2005) A strain of the fungus *Metarhizium anisopliae* for controlling subterranean termites. J Econ Entomol 98(5):1451–1458. https://doi.org/10.1093/jee/98.5.1451

Yamada A, Inoue T, Wiwatwitaya D, Ohkuma M, Kudo T, Abe T, Sugimoto A (2005a) Carbon mineralization by termites in tropical forests, with emphasis on fungus combs. Ecol Res 20(4):453–460. https://doi.org/10.1007/s11284-005-0062-9

Yamada A, Inoue T, Wiwatwitaya D, Ohkuma M, Kudo T, Sugimoto A (2005b) Nitrogen fixation by termites in tropical forests, Thailand. Ecosystems 8(1):1–9. https://doi.org/10.1007/s10021-005-0024-7

Zziwa E, Mugerwa S, Owoyesigire B, Mpairwe D (2012) Contribution of integrated catchment and surface water management to livestock water productivity in pastoral production systems. Int J Biosci 2: 52–60