

Combined effects of termite activity and agricultural practices on soil physicochemical properties and aggregation in Southern India

Auteur : Lejoly, Justine

Promoteur(s) : Cornelis, Jean-Thomas

Faculté : Gembloux Agro-Bio Tech (GxABT)

Diplôme : Master en bioingénieur : sciences et technologies de l'environnement, à finalité spécialisée

Année académique : 2016-2017

URI/URL : <http://hdl.handle.net/2268.2/3053>

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**COMBINED EFFECTS OF TERMITE ACTIVITY AND
AGRICULTURAL PRACTICES ON SOIL
PHYSICOCHEMICAL PROPERTIES AND
AGGREGATION IN SOUTHERN INDIA**

JUSTINE LEJOLY

**MSC THESIS SUBMITTED FOR MASTER'S DEGREE IN BIO-ENGINEERING
SCIENCES AND TECHNOLOGIES OF THE ENVIRONMENT**

ACADEMIC YEAR: 2016-2017

PROMOTOR: PR. JEAN-THOMAS CORNELIS

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Acknowledgments

The achievement of my MSc thesis would not have been possible without the help of many stakeholders.

To start with, I would like to thank my supervisor, Pr. Jean-Thomas Cornelis, for his availability, trust and valuable advice. He gave me the opportunity to build this project with a great freedom while ensuring its feasibility.

Christian and Erik, from Auro-orchard, gave me the opportunity to work in the farm and our numerous talks helped me to build my research in a way that the outcome could benefit to their work. In the Environmental Monitoring Service laboratory, Igor, Tamil and Rathina welcomed me and helped me for chemical analyses.

I also want to thank all the members of BIOSE, Gembloux Agro-Bio Tech, for their help, especially Raphaël Tarantino, Françoise Toussaint, Jean-Charles Bergen, Kévin Lefébure and Sébastien Ligot.

Stéphane Becquevort supervised me for the retention curve analysis, from sampling to final data. I would like to thank him for his availability and his patience, without forgetting Daniel Baes. Pr. Aurore Degré gave me precious advice for data interpretation. Anne-Catherine Dalcq and Pr. Yves Brostaux answered all my questions about the statistical analyses of my data.

Pitchandikulam Bioresource Centre allowed me to borrow important material for the field. Pr. Yves Roisin, ULB, identified the termite samples with me and Pr. François Malaisse was very helpful for all the entomological aspects of my MSc thesis.

Sage Waters, Victor Burgeon, Julien Lejoly were careful rereaders. Jeppe Aa Kristensen from Lund University gave me another outlook on termite activity.

To continue, I would like to thank the Royal Academy for Overseas Sciences. By according me the Floribert Jurion fund, they allowed me to achieve this project and beyond the financial aspect, they gave significance to my study.

To all the MSc thesis students, thanks for the mutual support and motivation.

Of course, I want to thank my family for their support, and especially my mom for her help in the field.

I am closing the chapter of my life with emotion, but I cannot wait to see what is coming next.

List of Acronyms

AAS	Atomic absorbance spectrophotometer
B_{Exch}	Exchangeable bases
BS	Base saturation
C	Carbon
Ca_{av}	Available calcium
CEC	Cationic exchange capacity
DCB	Dithionite citrate bicarbonate
Fe_{DCB}	Iron extracted with DCB
Fe_{pyro}	Iron extracted with sodium pyrophosphate
K_{av}	Available potassium
Mg_{av}	Available magnesium
Mn_{pyro}	Manganese extracted with sodium pyrophosphate
OC	Organic carbon
OM	Organic matter
P_{av}	Available phosphorus
POC	Particulate organic carbon
RBAP	Rapid biodiversity assessment protocol
RUSLE	Revised universal soil loss equation
SOM	Soil organic matter
TN	Total nitrogen

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Abstract

The soils of different agrosystems are studied simultaneously with termite activity in the context of long-term restoration project. The aim is to highlight the positive impact of termites on soil physicochemical properties. Previous studies have mainly focused on permanent structures built by those insects such as mounds, punctually impacting the landscape. In order to study a more widespread impact of termites, the temporary structures built for food foraging are compared to the underlying soil. It is assumed that, after rainfall or watering, these structures will return to the soil surface. The three sites are a fallow land (permanent pasture), a tilled field and agroecological raised beds. Termites only show up where there is organic matter, irrespective of its type. In the three sites, clay content, available K, Mg and P, organic carbon, pH, cation exchange capacity (except in the fallow) and exchangeable bases are increased in the biogenic constructions. The increase is generally lower in the beds because the reference soil already has higher values. In the field and the fallow, the aggregation is improved in termite sheetings, as the macroaggregates in both sites and the protected microaggregates in the field increase whereas the free microaggregates decrease. In the beds, the reference soil already has a better physical stability, with more macroaggregates and protected microaggregates. Our results demonstrate that agricultural conservation practices are able to improve most of the soil properties in the same way that for ecosystem engineers such as termites.

Key words: Termitidae; SOM; Soil management; Soil chemico-physical properties

Résumé

Dans le contexte d'un projet de restauration à long terme, les sols de différents agrosystèmes sont comparés entre eux et en lien avec l'activité des termites. Le but de cette étude est de souligner l'impact positif des termites sur les propriétés physico-chimiques du sol en milieu agricole. Dans le passé, la majorité des études se sont concentrées sur les termitières, qui sont des structures permanentes, impactant ponctuellement le paysage. Afin d'étudier un impact plus large des termites, les structures temporaires, servant à recouvrir la matière organique avant son utilisation/ingestion, sont comparées avec le sol sous-jacent. Notre hypothèse de travail est que les structures se désagrègent pour former le sol de surface après une pluie. Les trois sites considérés sont une friche permanente, un champ labouré et des buttes agroécologiques. Les termites se déplacent dans les zones étudiées uniquement lorsqu'il y a de la matière organique, quel qu'en soit le type. Dans les trois sites, une augmentation du pourcentage d'argile, du potassium, magnésium et phosphore disponibles, du carbone organique, du pH, de la capacité d'échange cationique (sauf dans la friche) et des bases échangeables est observée dans les structures biogéniques des termites. L'accroissement est globalement plus faible dans le site agroécologique car le sol de référence a déjà une meilleure qualité chimique. Pour le champ et la friche, les structures termitiques ont une meilleure aggrégation que le sol sous-jacent, le pourcentage de macroagrégats et de microagrégats protégés (champ uniquement) augmentant alors que le pourcentage de microagrégats libres diminue. Dans le site agroécologique, les macroagrégats et les microagrégats protégés sont déjà présents en nombre dans le sol de référence, témoignant de sa stabilité physique, et la densité apparente est plus faible. Les résultats montrent que les pratiques agricoles de conservation peuvent améliorer la plupart des propriétés du sol, d'une manière similaire à l'action des ingénieurs écosystémiques tels que les termites.

Mots-clés: Termitidae; Matière organique du sol; Gestion du sol; Propriétés physico-chimiques du sol

Part I
Article

INTRODUCTION

The pool of soil organic matter (SOM) represents more carbon than vegetation and atmosphere combined (Batjes, 1996; Watson, 2000). In the actual context of climate change, understanding carbon fluxes and stocks is essential. Moreover, it has a major importance for soil functioning (Devine et al., 2014). Indeed, organic matter (OM) improves soil water-holding capacity as well as cation exchange capacity (CEC), promotes soil structure (Lehmann and Kleber, 2015) and is a source of nutrients for plant growth (Gao and Chang, 1996; Trumbore, 1997).

Most of the organic carbon (OC) is mineralized within months and only a small percentage can be stabilized on the millenia time scale. As SOM is the largest pool of OC on Earth, the stabilisation of this small percentage is crucial for global carbon cycle (Lehmann et al., 2007) and occurs as physical protection in aggregates (Devine et al., 2014). The relationship between SOM and aggregation is mutual: SOM improves soil aggregation, which enhances carbon stabilisation (Blanco-Canqui, 2013; Devine et al., 2014). Macroaggregates are primarily formed by temporary binding agents such as roots and hyphae. When those aggregates decompose, the fragments become encrusted with clays, forming microaggregates (Waters and Oades, 1991; Six et al., 2004).

Soil aggregation and SOM can be used as indicators of geosystem resilience (Cammaraat and Imeson, 1998). Soil resilience is defined by Blanco-Canqui and Lal (2010) as « *the capacity of the system to recover from a perturbation and return to a new equilibrium, or its ability to recover its functional and structural integrity* ». Soils with a high OC content and physically stable are highly resilient and resistant to erosion (Blanco-Canqui and Lal, 2010). SOM input is therefore a key for soil resilience (Cammaraat and Imeson, 1998).

On the one hand, microaggregates are the most stable soil C pool (Lehmann et al., 2007), protecting SOM in the long term (Six et al., 2004). On the other hand, macroaggregates

have a low inertia, responding quickly to perturbations (Cammaraat and Imeson, 1998). Therefore, their turnover is major for SOM stabilization (Six et al., 2004). The mechanical stability of soil aggregates is improved with OM content and clay content (Bronick and Lal, 2005).

Soil fauna is known to be a driving factor in soil resilience (Blanco-Canqui and Lal, 2010; Jouquet et al., 2011), impacting nutrients and C turnover, as well as soil aggregation. Termites are dominant animals in tropical soils (Dawes, 2010; Pardeshi and Prusty, 2010), where they act as ecosystem engineers (Decaëns et al., 2006), meaning that they « *directly or indirectly modulate the availability of resources to other species* » (Herrick, 2000). In India, they are considered as an alternative to expensive products to improve agriculture sustainability (Pardeshi and Prusty, 2010).

Even though termites are mainly seen as pests, only 185 over 2800 species actually are (Jouquet et al., 2011). They have a significant role in soil formation (Hole, 1981) and their activity creates favourable conditions for vegetation development (Jouquet et al., 2011). Some species are fungus-feeding, living in symbiosis with the fungus *Termitomyces*, which they feed in combs with OM (Mando and Brussaard, 1999).

The soil area influenced by termites is called termitosphere (Lavelle et al., 1992), one of the four principal biological regulation systems. Their impact can be seen on four different scales. At the landscape level, they are heterogeneity drivers (Lavelle et al., 1992; Donovan et al., 2001). At the soil profile scale, they are bioturbators. At the aggregates level, they reorganize the litter cover, by covering it with wet soil particles enriched with clay. At the clay mineral level, they are weathering agents (Jouquet et al., 2016b), fastening the soil weathering (Jouquet et al., 2002, 2007).

While foraging, termites cover OM with sheetings (Ferrari and Watson, 1970) made of fine soil particles cemented with saliva and/or faeces (Jouquet et al., 2002, 2015). Those temporary structures (Mora et al., 2003) have a higher OM content, as well as a higher

C/N, compared to the surrounding soil (Lavelle et al., 1992; Awadzi et al., 2004). Thus, termites impact SOM dynamics, which can be protected in biogenic structures (Lavelle et al., 2001). When these are degraded, clay and nutrients are redistributed and become available for plants (Lavelle et al., 1992; Bottinelli et al., 2015).

By collecting fine particles such as clay (Jouquet et al., 2002), termites create a stone free uppermost layer (Lavelle et al., 1992). Therefore, they lead to an enrichment in gravels and pebbles of the underlying horizons, a process called reverse illuviation (Awadzi et al., 2004).

Termites play a major role in bioturbation, which is always coupled with foraging (Malaisse, 1978; Kaiser et al., 2017). By building foraging tunnels and covering OM with soil sheetings, they create a temperature-controlled environment, which allows them to use dung during the dry season (Ferrari and Watson, 1970). Moreover, bioturbation regulates microbial activity (Lavelle et al., 2001).

Termite activity improves soil physical properties, such as infiltration (Lavelle et al., 1992; Mando et al., 1996; Léonard and Rajot, 2001), soil water balance (Donovan et al., 2001; Pardeshi and Prusty, 2010) and water movements (Lavelle et al., 1992). Moreover, the percentage of water stable aggregates is higher in termite modified soils (Lavelle et al., 1992).

They also improve soil chemical properties by releasing assimilable nutrients (Lavelle et al., 2001). Indeed, termite affected soils show higher pH, nutrient levels, cation exchange capacity (CEC), OM content (Nutting et al., 1987; Basappa and Rajagopal, 1990; Lavelle et al., 1992; Donovan et al., 2001).

Mulching is a way to enhance termite activity, to improve soil properties and to protect soil against extreme temperatures and drought (Dawes, 2010). In the case of crusted soils, the combination of termites and organic inputs helps to soften the soil (Pardeshi and Prusty, 2010), since termites burrow through the crust (Léonard and Rajot, 2001; Jouquet et al., 2014). In general, all the practices with return of plant residues are favourable for termite activity and for stabilisation of biogenic

structures (Lavelle et al., 2001).

Compared to earthworms, termites have been less studied (Six et al., 2004). Their impacts on soil properties have been explored mainly in Africa, whereas there are few studies about Southern India, especially in an agricultural context (Jouquet et al., 2015). Jouquet et al. (2016b) studied the influence of termites on soil aggregation by comparing termite mounds and reference soil. On the contrary, the impact of temporary buildings, that will return to the soil after rainfall or watering is not well documented so far (Jouquet et al., 2015).

To improve agricultural practices in the long term, it is important to understand the impact of termite activity on SOM and soil aggregation. In the context of a restoration project started in 1968 in Auroville, this study aims to highlight the sustainability of conservation agricultural practices, equal to ecosystem engineers such as termites. Firstly, the impact of conservation management is compared with conventional practices. Secondly, the impact of termites within each system is defined. Thirdly, the impact of termite activity is compared to agroecological practices.

MATERIALS AND METHODS

Study site

The experiment has been conducted in Auro-orchard, a 45 acres farm in Auroville, Tamil Nadu, Southern India. The climate is tropical wet and dry, classified as Aw by Köppen and Geiger (Peel et al., 2007). The average temperature is 28.1 °C and the average annual rainfall is 1385 mm (Appendix B.1.1). The indigenous vegetation is a tropical dry evergreen forest, which was cut down during colonial times to be replaced by cashew orchards (Baldwin and Declercq, 2011).

The parent material is a red sandstone, from charnockite erosion, dating from Tertiary (Middle Mio-Pliocene) (Selvaraj and Ramasamy, 1998). Soils are classified as Acrisol, according to WRB (World Soil Resources, 2015). A complete soil description is available in Appendix C.

Table 1: Site description. The number of each bed is specified by #.

Site	Description	Current culture	Watering	Soil preparation	Inputs
Beds	Agroecological practices since 2012 (raised beds)	Tapioca (#7), cabbage and radish (#12), taro (#14)	Drip irrigation	Manual	Compost, mulch, green manure
Field	Conventional tilled field	Pumpkins	Open channels	Disk-ripper and cultivator shanks	Compost, mulch, green manure
Fallow	Permanent pasture since 2012 Previously: conventional peanut culture	None (Soil cover: legumes and grass)	None	None	None

Experimental setup

The study is conducted on three sites, differing in agricultural practices (Table 1). The beds have a permanent soil cover and watering is done by drip irrigation. The field is tilled, bare, irrigated by open channels. The fallow land is a permanent pasture since 2012, with no added OM nor water. More details are available in Appendix B.1.2.

In each site, three modalities are considered and replicated three times, on a surface of $1 \times 1 \text{ m}^2$. In the first case, no OM is added to the zone in order to keep a reference soil. In the second case, a 2 cm compost layer is covered with 5 cm of mulch and the zone is watered daily (3–4 L). In the third case, a unique mulch layer (5 cm) is watered daily with a diluted solution of *Jiwamrita* (Pathak and Ram, 2013). It is made of 1 kg of cow dung, 1 L of cow urine and 50 g of jaggery, mixed together and fermented during at least three days. The 10 times diluted solution is used as watering water (3–4 L) every day for eight days as a booster (Appendix B.2, Fig. B.2).

Sampling

In each zone, composite soil samples are taken 0–15 cm deep.

The termite sheetings are sampled by taking most of what is available on the entire surface in maximum 15 minutes. The quantity sampled is then weighted.

The samples (termite sheetings and soil samples) are dried in the shades for five days, then sieved to collect the $< 2 \text{ mm}$ fraction.

Undisturbed soil samples of 100 cm^3 are taken in the field and the bed sites. In the

field, two samples from bare zones and two samples from zones covered with mulch are taken. In the bed site two samples are collected in covered zones, as there is no bare soil.

Termite identification and counting

In each zone, the Rapid Biodiversity Assessment Protocol (RBAP) (Jones and Eggleton, 2000) is applied to quantify termite activity in early morning (6–8:30 am). A $12 \times 12 \text{ cm}^2$ block, 5 cm deep, is sampled and the termite individuals are stored in 70% alcohol before identification and counting.

Termites are identified to genus-level according to Chhotani (1997), making the assumption of one species per sample.

Analyses

Soil chemical properties

The pH analyses (Water and CaCl_2) are conducted following the Potentiometrical Method. The temperature being out of range ($32 \text{ }^\circ\text{C}$), water pH is raised by 1.3 unit for the field (± 0.2) and the beds (± 0.1) and by 1.4 unit for the fallow land (± 0.4), thanks to a second analysis performed in the correct room temperature. After Neutral Normal Ammonium Acetate extraction at pH 7, available calcium (Ca_{av}), magnesium (Mg_{av}) and potassium (K_{av}) are analysed, by EDTA titration for Ca and Mg and using flame photometer for K (Tandon, 2005). OC is estimated with wet combustion method, by digesting soil sample with potassium dichromate and sulphuric acid before titration with ferrous ammonium sulfate (IS 2720-22, 1972). CEC

is analysed with the Silver Thiourea method (Pleysier and Juo, 1980), which consists of complex saturation with Ag before its quantification using Atomic Absorption Spectrophotometer (AAS). Available phosphorus (P_{av}) is extracted with HCl 0.025M and NH_4F 0.03M for acid soils ($pH < 6.5$) (Bray and Kurtz, 1945) and with sodium bicarbonate 0.5M pH 8.5 for neutral soil ($pH \geq 6.5$) (Olsen, 1954). A solution containing ammonium molybdate 12 g/L, $K_2Sb_2(C_4H_2O_6)_2$ 0.291 g/L, H_2SO_4 2.5N and ascorbic acid 5.3 g/L (and boric acid 1% for acid soils) is then added and P_{av} is quantified by measuring absorbance at 720 nm (Bray and Kurtz, 1945; Olsen, 1954). The base saturation percentage is determined using Metson's method, which determines exchangeable bases concentrations (Ca, Mg, K, Na) with AAS after ammonium acetate extraction (Metson, 1956). Total N is extracted following Micro Kjeldhal Method (Bremner and Mulvaney, 1996). Sodium pyrophosphate is used to extract organically complexed Fe and Mn oxides (Bascomb, 1968). And finally, DCB is used to extract crystalline oxo-hydroxides of Fe (Mehra and Jackson, 1958). More details about analyses are available in Appendix D.

For each chemical property, an average value is calculated for termite sheetings and soil samples of each site. There are nine replicates for the soil samples in the three sites, six replicates for the termite sheetings from the fallow land and five replicates for the termite sheetings from the field and the beds.

Soil physical properties

The grain size is determined, after drying and crushing, by sedimentation following the pipette method (NF-X 31-107). The average grain size distribution (clay, silt and sand) is calculated for termite sheetings and soil samples of each site. There are three replicates for the soil samples, two replicates for the termite sheetings from the beds and the fallow land and one replicate for the termite sheetings from the field.

The water retention curve is obtained by running bulk samples at different pressures and measuring weight in between, thanks to

pressure extractor (Richards, 1941) (cfr. Appendix D.13). According to the literature, macropores are comprised between pF 0 and 1.8 (>0.6 mm diameter), mesopores between 1.8 and 2.54 (0.1 – 0.6 mm diameter) and micropores over pF 2.54 (<0.1 mm diameter) (Ruiz-Colmenero et al., 2013).

Soil aggregates

The air-dried soil (<2 mm-fraction) is separated by wet sieving in macroaggregates (*macro-agg*: 250 μm –2 mm), free microaggregates (*f.micro-agg*: 50 – 250 μm) and free silts and clays (*f.SC*: <50 μm) (Six et al., 1998). The second step is to break up the macroaggregates using a device designed by Six et al. (2000a), in order to quantify the protected microaggregates (*p.micro-agg*). Each aggregate fraction is reduced by the corresponding sand fraction: coarse sand (200 μm –2 mm) for macroaggregates and fine sand (50–200 μm) for free microaggregates. This leads to an overestimation of microaggregates and an underestimation of macroaggregates, since a 250 μm -sieve is used for aggregate fractionation whereas a 200 μm -sieve is used for grain size distribution. The sand content of protected microaggregates is calculated separately, since it differs from the bulk soil (cfr. Appendix D.12).

Statistical analysis

A first analysis of variance is performed with comparisons between the soils of the three sites. The main factors are sample type (soil or termite sheetings) and zone (beds, field or fallow), since the modality does not impact the results. A second analysis of variance is performed within each site, with sample type as factor. For both of the analyses of variance, the significance level was $P < 0.05$. Tukey's HSD was used to differentiate means between the three sites and within each site, with a significance level of $P < 0.05$, $P < 0.01$ being highly significant and $P < 0.001$ very highly significant. Within each site, relationships between two variables are highlighted by linear regression using *lm* model in R Studio.

Table 2: Observations of termite activity.

Site	Modality	Genera	Number of termites	Collected soil [g]	Number of days with new constructions	Number of days with termite presence	First day of termite appearance
Bed	None	/	0	0	1	0	/
Bed	None	<i>Odontotermes</i>	8	375	9	6	3
Bed	None	<i>Odontotermes</i>	14	90	3	1	2
Bed	Mulch	<i>Macrotermes</i>	96	187	12	6	1
Bed	Mulch	/	0	0	1	1	/
Bed	Mulch	<i>Hypotermes</i>	18	548	13	3	1
Bed	Jiwamrita	<i>Odontotermes</i>	31	267	11	1	1
Bed	Jiwamrita	/	0	0	2	0	/
Bed	Jiwamrita	<i>Odontotermes</i>	95	299	12	1	2
Field	None	/	0	0	0	0	/
Field	None	/	0	0	0	0	/
Field	None	/	0	0	0	0	/
Field	Mulch	<i>Odontotermes</i>	208	428	7	2	3
Field	Mulch	<i>Odontotermes</i>	94	277	11	8	3
Field	Mulch	<i>Odontotermes</i>	163	184	10	2	4
Field	Jiwamrita	<i>Odontotermes</i>	27	143	9	3	5
Field	Jiwamrita	<i>Odontotermes</i>	40	158	9	0	3
Field	Jiwamrita	<i>Odontotermes</i>	152	56	6	1	7
Fallow land	None	/	0	13	1	0	2
Fallow land	None	/	0	39	5	3	2
Fallow land	None	/	0	98	4	1	2
Fallow land	Mulch	<i>Odontotermes</i>	17	543	12	6	2
Fallow land	Mulch	<i>Speculitermes</i>	83	380	12	7	2
Fallow land	Mulch	/	0	281	8	4	5
Fallow land	Jiwamrita	/	0	493	12	0	2
Fallow land	Jiwamrita	/	0	395	9	2	4
Fallow land	Jiwamrita	/	0	303	10	4	4

RESULTS

Termite activity



Figure 1: March 3, 2017: plot in the fallow land with fresh mulch. Photo credits: Lejoly 2017



Figure 2: April 18, 2017: same plot, covered by termite sheetings. Photo credits: Lejoly 2017

The first sampling day, only eight plots contained some individuals. In two days, termites have been found in 14 plots over 27 in total. 11 plots over 14 contained *Odontotermes*, one contained *Macrotermes*, one contained *Hypotermes*, all fungus growing species, and one contained *Speculitermes*, soil feeder species (Table 2). They all belong to Termitidae family.

During the entire experiment, some plots never showed termite activity: three plots from the same bed and the three plots with no OM in the field. Termite activity was visible in the other plots after one to three days in the beds, two to five days in the fallow land and three to seven days in the field. There is no difference in sheetings quantities between compost and *Jiwamrita* treatments.

After 43 days, the plot surface is almost completely covered with termite sheetings in the fallow land (Fig. 1 and 2).

Table 3: Synthesis of the chemical properties. The samples that do not share a letter are significantly different. For BS, the values over 100% have been capped to 100%.

Property	Beds		Fallow land		Field	
	Soil sample	Termite sheetings	Soil sample	Termite sheetings	Soil sample	Termite sheetings
Clay [%]	6.72 _d	8.88 _{cd}	10.54 _{bc}	12.86 _{ab}	6.61 _d	16.06 _a
Silt [%]	5.25 _b	5.00 _b	6.54 _a	7.72 _a	4.93 _b	4.38 _{bc}
Sand [%]	88.03 _a	86.12 _{ab}	82.92 _{bc}	79.43 _c	88.47 _a	79.57 _c
Water pH	7.6 _a	7.7 _a	6.2 _c	7.7 _a	6.7 _b	7.9 _a
CaCl ₂ pH	5.3 _b	5.7 _a	4.7 _c	5.9 _a	5.1 _b	5.9 _a
K _{av} [mg/100g]	6.83 _c	37.89 _b	5.45 _c	50.42 _a	5.68 _c	43.38 _{ab}
Ca _{av} [mg/100g]	107.33 _a	98.4 _{ab}	90.67 _{ab}	99.33 _{ab}	54.00 _c	63.60 _{bc}
Mg _{av} [mg/100g]	9.25 _{ab}	17.15 _a	9.11 _{ab}	16.36 _a	7.32 _b	12.67 _{ab}
P _{av} [mg/100g]	16.40 _a	19.27 _a	7.58 _b	18.90 _a	5.16 _b	13.01 _{ab}
OC [%]	1.01 _{bc}	1.52 _a	0.72 _{cd}	1.59 _a	0.31 _d	1.33 _{ab}
TN [%]	0.89 _a	0.49 _a	0.33 _a	0.49 _a	0.30 _a	0.36 _a
CEC [meq/100g]	2.89 _b	5.24 _a	4.54 _a	4.55 _a	2.69 _b	3.74 _{ab}
B _{Exch} [meq/100g]	6.11 _a	6.83 _a	4.09 _b	6.58 _a	2.16 _c	5.87 _a
BS [%]	100.0 _a	94.2 _{ab}	88.5 _{ab}	99.2 _a	79.7 _b	100.0 _a
Fe _{DCB} [g/kg]	4.81 _b	7.17 _{ab}	6.67 _{ab}	6.89 _{ab}	4.71 _b	8.91 _a
Fe _{pyro} [g/kg]	0.08 _a	0.09 _a	0.07 _a	0.11 _a	0.06 _a	0.10 _a
Mn _{pyro} [g/kg]	0.074 _a	0.098 _a	0.078 _a	0.091 _a	0.046 _a	0.076 _a

Soil physico-chemical properties

Comparison of the three sites

All the samples are rich in sand, from 77.7 to 89.5% of bulk soil (Table 3). The beds and the field contain 88% of sand, whereas the fallow land contains only 83% and is richer in clay: 10% against 7%. There is no significant difference between the modalities within a site. According to FAO (1990), beds and field are classified as sand whereas the fallow is a loamy sand.

The fallow land is slightly acidic, with an average water pH of 6.2, the field is very slightly acidic (6.7) and the beds are slightly alkaline (7.6)(Table 3). CaCl₂ pH is less variable between the sites, from 4.7 in the fallow to 5.3 in the beds, with an intermediate value of 5.1 in the field.

Concerning the available macro-nutrients, all the three sites have a similar concentration of K_{av} (5-6 mg/100g)(Table 3). Ca_{av} is similar in the bed and fallow (107.33 and 90.67 mg/100g, respectively) and significantly lower in the field (54 mg/100g). Mg_{av} concentration is similar for all the three sites, from 7.32 to 9.25 mg/100g on average. P_{av} is significantly higher in the bed (16.4 mg/100g) than in the fallow and the field (7.58 and 5.16 mg/100g, respectively). The OC content is the lowest in field (0.31%), two times higher in the fallow (0.72%) and three times higher

in the beds (1.01%). TN concentration is similar in all the three sites, except one sample in the bed with a value out of the average range, 42 mg/100g, corresponding to the modality *Ji-wamrita*.

CEC is higher in the fallow, 4.54 meq/100g, than in the beds and field soil, respectively 2.89 and 2.69 meq/100g. The B_{Exch} concentration in the beds is significantly the highest, the fallow is intermediate and the field soil is the lowest. The base saturation is close to 100% in the beds, equal to 88.5% in the fallow and to 79.7% in the field soil (Table 3).

Fe_{pyro}, Mn_{pyro} and Fe_{DCB} show no difference between the sites (Table 3).

The three sites are dominated by free silt and clay fraction, ranging from 54 to 67% of the sand-free soil weight (Table 4). The macroaggregates constitute 41% of the sand-free fraction in the beds, 4% in the field and 3% in the fallow, the last two zones being significantly lower (p-value<0.05). The free microaggregates tend to be lower in the beds than in the fallow and field. The microaggregates protected in the macroaggregates are respectively 3 and 6 times higher in the beds than in the fallow and field (p-value<0.05).

Except for the free silt and clay fraction, OC content in each fraction is following Beds > Fallow land > Field (Table 4). There is more carbon in the free silt and clay fraction from the beds, the field is intermediate and the fal-

low the lowest (Fig. 3). The latter contains less carbon in the protected microaggregates than in the fallow and beds.

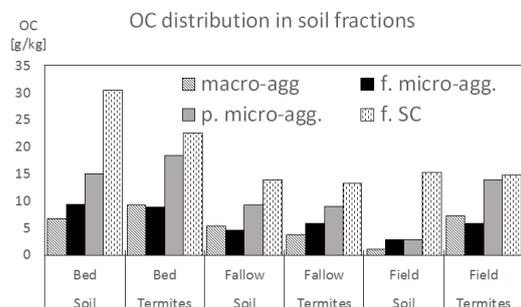


Figure 3: Organic carbon concentration in each fraction of the sand-free soil [g/kg]

Total porosity is 16% higher in the beds than the field (Fig. 4). On average, macro and microporosity are respectively 15 and 3% higher in the beds, whereas mesoporosity is similar in both sites. One sample from the beds contains a taro tuber and is therefore not taken into account, as its behaviour differs.

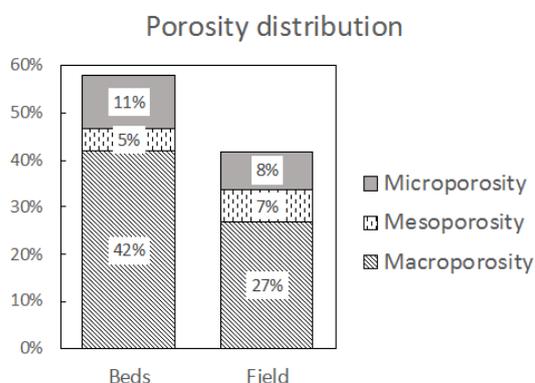


Figure 4: Porosity distribution calculated with retention curve, according to Ruiz-Colmenero et al. (2013)

Comparison between soil and termite sheetings within each site

In the beds and the field, there is a significant increase of clay content in termite sheetings (p-value<0.05), whereas in the fallow,

the silt content is significantly increased (p-value<0.05).

In the beds site, there is no significant difference in water pH between soil and termite sheetings; but CaCl₂ pH is significantly increased in termite sheetings (p-value<0.05). In the tilled field, water pH is 1.2 unit higher in termite sheetings on average (p-value<0.01) and 0.8 unit higher for CaCl₂ pH (p-value<0.05). In the fallow land, pH is also higher in termite sheetings, 1.5 unit for water pH (p-value<0.001) and 1.2 for CaCl₂ pH (p-value<0.001). The values reached by termite sheetings are similar for all the three sites, on average 7.7 to 7.9 for water pH and 5.7 to 5.9 for CaCl₂ pH (Table 3).

K_{av} is significantly increased in termite sheetings, five times in the bed (p-value<0.05), 10 times in the fallow land (p-value<0.001) and seven times in the field (p-value<0.001) on average, compared to soil. Ca_{av} and TN show no tendency in termite sheetings but Mg_{av} and P_{av} are increased (12.67 to 17.15 mg/100g and 13.01 to 19.27 mg/100g, respectively) in all the sites. (Table 3). Termite sheetings also have a higher OC content than the soil in all the three sites (p-value<0.05 for beds, <0.001 for fallow land and <0.01 for open field), reaching an average values of 1.52, 1.59 and 1.33% respectively (Table 3).

There is a significant increase of CEC in termite sheetings for the beds (p-value<0.05), reaching 5.24 meq/100g, and an increasing tendency in the field (3.74 meq/100g). B_{Exch} increases compared to the soil in the fallow land and the field, reaching values of 5-6 meq/100g, similar to beds soil. The base saturation is increased in the field termite sheetings (p-value<0.01), reaching 100% and there is a tendency of increase in the fallow land (Table 3).

Fe_{DCB} increases significantly in the field termite sheetings (Table 3). On the contrary, Fe_{Pyro} and Mn_{Pyro} do not show any trend.

The percentage of macroaggregates tends to increase in the field and fallow termite sheetings, as opposed to a decreasing trend in the beds (Table 4). The free microaggregates in-

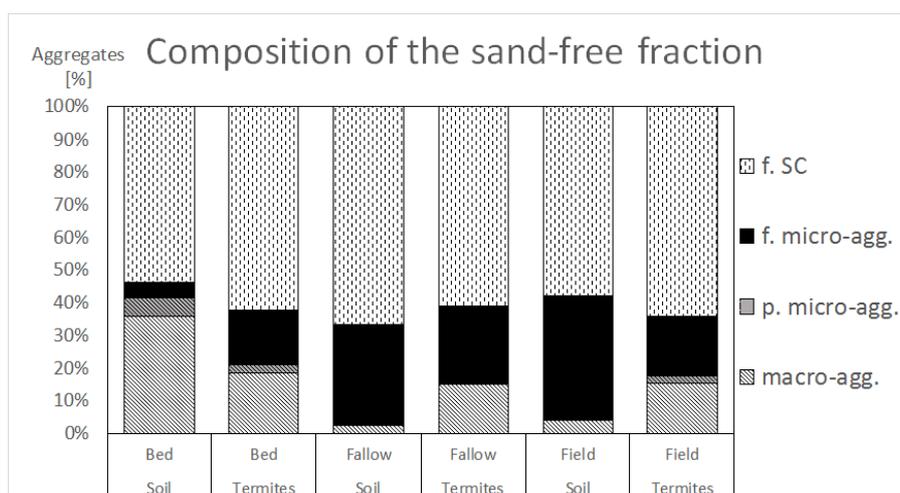


Figure 5: Composition of the sand-free fraction. The macroaggregates are represented by macro-agg and p. micro-agg.

crease non-significantly in the beds termite sheetings and tend to be lower in the fallow land and the field termite sheetings, compared to the soil in the same zone. There is no trend for the free silt and clay fraction. The protected micro-aggregates are six times higher in the termite sheetings from the field (p -value <0.05), whereas there is no tendency for the beds nor the fallow land. In terms of percentage of the total sand-free fraction, there is a decrease in the beds and the field termite sheetings, compared to the corresponding reference soil and a slight increase in the fallow land.

There is a tendency of increase in macroaggregates and protected microaggregates OC (p -value <0.01) in the field termite sheetings.

In the beds termite sheetings, the percentage of macroaggregates decreases while the OC content increases and there is less carbon in the free silt and clay fraction, although not statistically significant.

Table 4: Aggregate composition of the sand-free fraction. The fraction C corresponds to the microaggregates protected within the macroaggregates.

Fraction	Analysis	Beds		Fallow land		Field	
		Soil sample	Termite sheetings	Soil sample	Termite sheetings	Soil sample	Termite sheetings
A	% of macroaggregates	41 _a	21 _{ab}	3 _b	15 _{ab}	4 _b	18 _{ab}
	TOC [g/kg]	6.82 _a	9.29 _a	5.38 _a	3.73 _a	1.10 _a	7.26 _a
B	% of free microaggregates	5 _a	17 _a	30 _a	24 _a	38 _a	18 _a
	TOC [g/kg]	9.38 _a	8.87 _{ab}	4.52 _{bc}	5.82 _{abc}	2.87 _c	5.92 _{abc}
C	% of protected microaggregates	13 _a	12 _a	4 _b	2 _b	2 _b	13 _a
	TOC [g/kg]	15.14 _a	18.29 _a	9.33 _{ab}	9.01 _{ab}	2.91 _b	13.89 _{ab}
D	% of free silt and clay	54 _a	62 _a	67 _a	61 _a	58 _a	64 _a
	TOC [g/kg]	30.43 _a	22.5 _{ab}	13.92 _b	13.22 _b	15.36 _b	14.81 _{ab}

DISCUSSION

Effect of land use on soil properties

In this section, soil samples from the three zones are compared. Beds and field are similar in terms of grain size distribution, allowing a direct comparison between the zones. The fallow is richer in clay and therefore, its behaviour might differ from the other two.

The OC content, which is an indicator for soil quality (Herrick and Wander, 1997), is high in the beds thanks to an appropriate management with regular return of OM (Rasmussen et al., 1980), whereas it is the lowest in the field, due to the lack of OM and soil cover. Indeed, most of the plant biomass is removed while harvesting. Moreover, no till management, such as in the beds, allows an increase in SOM, both particulate and mineral associated (Bayer et al., 2001; Devine et al., 2014). In the fallow, the intermediate content of OC is explained by the absence of OM output compared to the field, typical when a permanent grassland is established (Post and Kwon, 2000).

The globally very low CEC is associated with soils that are rich in kaolinite, Fe and Al oxides, high sand content and that accumulate sand-size quartz grains, as residue of weathering (Sparks and Liebhardt, 1981; Sanchez and Logan, 1992; Parfitt et al., 1995; Ross et al., 2008). The higher CEC in the fallow is probably due to its higher clay content, compared to the field and the beds (Kaiser et al., 2017). The difference observed between the latter two is due to a difference in OC content and pH. OC has a high CEC compared to other colloids and therefore increases the total soil CEC (Sanchez and Logan, 1992; Zech et al., 1997).

The exchangeable bases are the highest in the beds, even though CEC is higher in the fallow, suggesting that the complex is supposedly much more saturated in the beds (100%) than in the fallow (80%). The apparent high base saturation is due to a saturation of the CEC by Ca. It might come from added OM, such as poultry manure, in both the field and the beds. Indeed, Steiner et al. (2007) found an increase

in Ca concentration for the surface soil when poultry manure is used. For the fallow land, the only explanation found so far is the uptake by plants.

Organically complexed Fe and Mn show low concentrations due to tropical climate. Indeed, SOM decomposition rate is five times higher than in a temperate climate (Sanchez and Logan, 1992). This rapid OM turnover leaves little time for complexation with metal ions to occur (von Lützow et al., 2006).

Globally, our soils do not follow the aggregate hierarchy theory (Oades and Waters, 1991), because the C concentration does not increase with aggregate size. The dominance of free silts and clays in the three sites is probably linked to the soil type, mainly containing sand. Indeed, quartz does not show affinities with OM (von Lützow et al., 2007) and thus does not take part in aggregate formation. Only 11 to 17% of bulk soil, corresponding to the silt and clay fractions, controls aggregation in this case.

Differences in porosity can usually be associated with clay content and OC content (Kay et al., 1997). Since the field and the beds have a similar grain composition, the observed difference is partially explained by the higher OC content of the beds. Moreover, it is linked to soil macrofauna activity, which can loosen the soil by creating galleries and burrows and thus improves soil infiltration (Lavelle, 1997). Indeed, *Odontotermes* creates 4-5 mm diameter galleries (Léonard and Rajot, 2001) and termites in general increase soil porosity, up to 7% (Mando et al., 1996).

The aggregation percentage is not significantly higher in the beds, but the aggregate size distribution varies depending on the site. There are very few macroaggregates in the field because of tillage, which breaks down aggregates and their two major binding agents, roots and fungal hyphae (Ball-Coelho et al., 2000; Verhulst et al., 2010). As a result, it shortens macroaggregate lifecycle and thus reduces the physical protection of C (Six et al., 2000a), the formation of protected microaggregates and the stabilization of new OM in free microaggregates (Six et al., 1999). In the

fallow land, even though there is no tillage any more, the effects of the agricultural practices before 2012, as a conventional peanut field, are still existent. Moreover, the soil is indurated and the vegetation is sparse. The low macroaggregates concentration is probably due to a lack of roots combined with low mycorrhizal activity. Therefore, the combination of no tillage and high biological activity explains the high percentage of macroaggregates in the beds.

While comparing the beds and the field, tillage increases the amount of C-poor microaggregates and decreases C-rich macroaggregates (Six et al., 2000b). Moreover, there are more microaggregates protected in macroaggregates in the beds than in the tilled field, as Six et al. (2000a) hypothesised when comparing tillage and no tillage. These also contain five times more C on average. This is explained by the slower turnover of macroaggregates with conservation management and the higher OM input. As a result, new OM can be included into aggregates more easily. Compared to temperate climate, the percentages are however low, since Six et al. (2000a) found 27% of microaggregates protected in macroaggregates for conventional tillage and 47% for no tillage.

To summarise this part of the discussion, conservation management, in the beds, clearly improves soil properties such as aggregate stability, nutrients availability and OC content and stabilisation. The key practices are no tillage and an increase OM input, leading to an improved soil fauna activity.

Effect of land use on termite activity

The few individuals found during the first sampling day might be due to the low relative humidity. Indeed, the night temperature did not drop below +26 °C and the vegetation was completely dry at 6:30 am. As termites are susceptible to desiccation (Wood, 1988), they need to keep their environment moist and thus to avoid leaving the nest in dry conditions.

Broadly speaking, OM attracts termites. Indeed, none is found in the bare plots of the field. On the contrary, the reference plots from

the beds and the fallow, with no added OM, are not totally bare, and thus, some termites are found. Adding OM or maintaining a soil cover are possible ways to keep active communities of ecosystem engineers, as stated by Lavelle et al. (2001). The presence of compost and *Jiwamrita* does not change termite behaviour whereas external factors might play a role in termite presence, such as their spatial heterogeneity. Indeed, they concentrate their activity in hotspots (Jouquet et al., 2006). This might explain the absence of termites in some bed plots, even with OM presence.

In the beds, the surrounding environment is attractive to termites, which is attested by their rapid presence. As shown in the results, there is 30 to 70% more OM available as a food source (Brune, 1998) and its stabilisation in higher within macroaggregates (37% more) and protected microaggregates (8% more). Moreover, the higher total and micro-porosity in the beds (16% and 3% more than the field, respectively) means that water is better retained, protecting termites from desiccation (Wood, 1988). In the fallow land, it is intermediate, since there is a soil cover but no water (Table 1). In the field, the lack of OM (only 0.3%), the absence of continuous watering system (Table 1) and the lower porosity (Fig. 4) make of it the worse environment for termites. All the genera in presence, except *Speculitermes*, belong to the Macrotermitinae sub-family, which is the most resistant to disturbance according to Collins (1980). The diversity is the highest in the beds, with three genera, while there are only *Odontotermes* in the field (Table 2).

There is a positive relationship between the number of days with visible new termite sheetings and the final quantity collected from those constructions (Fig. 6). It shows that average termite activity can be estimated by weighting the produced sheetings. On the contrary, the daily termite observation is not a reliable proxy, since the time window is short and, depending on the weather, their activity at the same moment of the day may vary a lot. However, daily observations are important to understand the temporal pattern of those insects, which is

clearly heterogeneous.

To conclude, termites prefer an environment with high moisture and high OC. They are very active in the beds, but can reach other sites in a few days if the environmental conditions are improved.

a stone-free horizon and the underlying horizons are enriched in coarse particles. The increased clay content positively impacts CEC as seen in fig. 7, confirming what Ross et al. (2008) found.

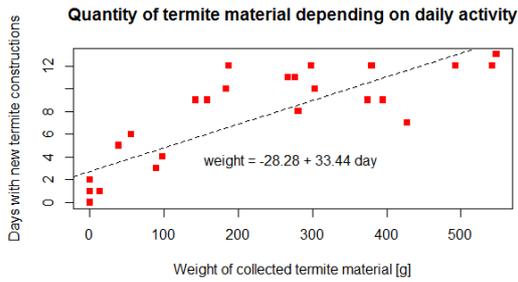


Figure 6: The weight of final termite material increases with the number of days with new constructions.

Effect of termite activity on soil properties

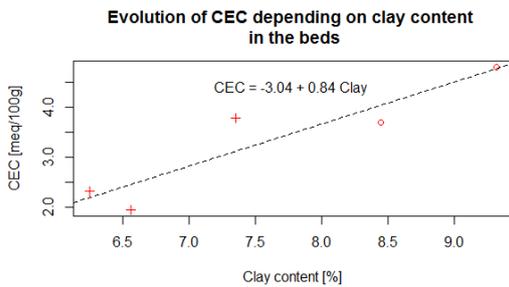


Figure 7: *P*-value for the slope is 0.0267 (Adjusted $R^2=0.80$). Crosses correspond to soil samples and circles to termite sheetings.

In this part, termite sheetings are compared to soil samples within each site.

The presence of a stoneline in the profile (Fig. 8), 150 cm deep, might be attributed to termite activity (Nye, 1955). Indeed, termites seem to collect preferentially clay particles in the lower horizons (Table 3), as stated by Jouquet et al. (2002). Therefore, they create



Figure 8: Stoneline at a depth of 150 cm. Photo credits: Lejoly 2017

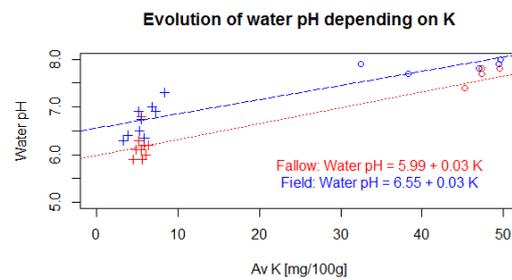


Figure 9: Field (blue): *p*-value= 7.83×10^{-6} for the slope and 3.39×10^{-15} for the independent term (Adjusted $R^2=0.81$). Fallow (red): *p*-value= 4.55×10^{-8} for the slope and 4.72×10^{-16} for the independent term (Adjusted $R^2=0.90$). Crosses correspond to soil samples and circles to termite sheetings.

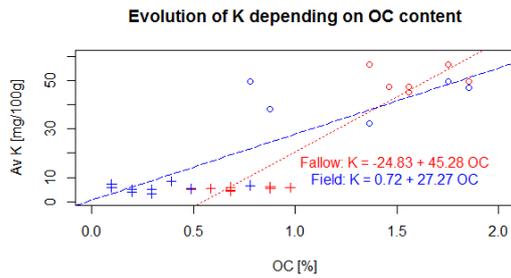


Figure 10: Field (blue): p -value= 1.44×10^{-4} for the slope (Adjusted $R^2=0.69$). Fallow land (red): p -value= 3.72×10^{-7} for the slope and 4.2×10^{-7} for the independent term (Adjusted $R^2=0.86$). Crosses correspond to soil samples and circles to termite sheetings.

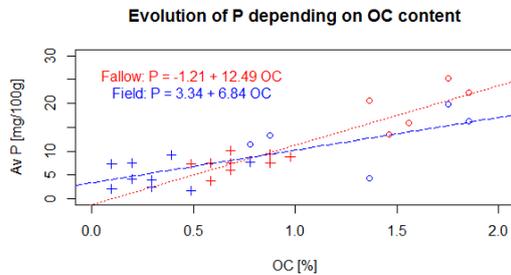


Figure 11: Field (blue): p -value= 2.67×10^{-3} for the slope (Adjusted $R^2=0.50$). Fallow land (red): p -value= 2.13×10^{-6} for the slope and 0.0392 for the independent term (Adjusted $R^2=0.82$). Crosses correspond to soil samples and circles to termite sheetings.

The higher pH in termite sheetings does not fit most of the studies about termite-modified soils reviewed by Lobry de Bruyn and Conacher (1990). However, an increased pH for termite sheetings was also found by Kaiser et al. (2017) and especially for low initial pH (4–5) (Donovan et al., 2001). The observed difference is probably due to the passage of soil particles in termite gut, where pH can reach 12.5, the highest value known in biological systems (Brune, 1998). As suggested by Donovan et al. (2001), termites might act as a buffer, since the values reached in all the three sites sheetings are very close (7.7 for the beds and the fallow, 7.9 for the field), even though the reference soil pH is different. Therefore,

pH increase might be considered as a proxy for termite activity. In the field and the fallow, water pH positively impacts K_{av} , both sites having the same slope (Fig. 9).

The increased concentrations of available Mg, K and P and OC in termite sheetings are probably due to added saliva and faeces (Bagine, 1984; Nutting et al., 1987; Lobry de Bruyn and Conacher, 1990; Mora et al., 2003), pH being considered as a proxy for termite activity. Moreover, basic cations and OM can originate from plant remains (Bagine, 1984). Indeed, K_{av} and P_{av} show both a positive relationship with OC content in the field and the fallow (Fig. 10 and 11). An increase of OC was found by Kaiser et al. (2017) during the dry season, whereas Jouquet et al. (2015) found an impoverishment in carbon positively correlated with structure expected lifetime. In this study, the increase in OC and available nutrients except Ca coupled with an increase in clay content explain the higher CEC observed in the beds (Fig. 7) and the field sheetings (Fig. 12 and 13). The higher the pH, the more the increase in CEC due to OC content (Helling et al., 1964). Indeed, pH is originally higher in the beds and the slope of the relationship between CEC and OC is steeper (Fig. 12).

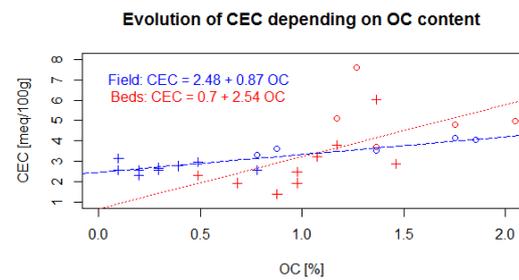


Figure 12: Beds (red): p -value=0.0109 for the slope (Adjusted $R^2=0.28$). Field (blue): p -value= 5.26×10^{-4} for the slope and 1.11×10^{-4} for the independent term (Adjusted $R^2=0.76$). Crosses correspond to soil samples and circles to termite sheetings.

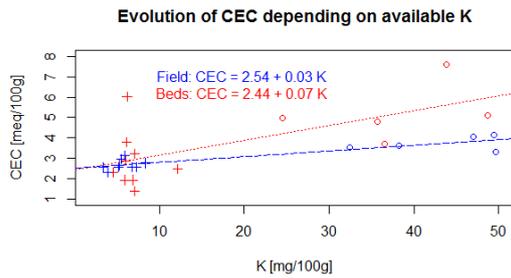


Figure 13: Beds (red): p -value= 9.83×10^{-3} for the slope and 9.6×10^{-4} (Adjusted $R^2=0.39$). Field (blue): p -value= 1.53×10^{-5} for the slope and 1.45×10^{-11} for the independent term (Adjusted $R^2=0.78$). Crosses correspond to soil samples and circles to termite sheetings.

Termite mounds tend to have lower OC content and lower stability than the surrounding soil, in the case of Ferrasol (Jouquet et al., 2016b). Therefore, it is plausible that their buildings are made differently depending on their function. Indeed, temporary sheetings are on the contrary enriched in OM in this study.

As opposed to what is commonly found in the literature, no change in exchangeable Ca was found (Bagine, 1984; Kaiser et al., 2017). This might be explained by the little wood content of the mulch. Indeed, wood is rich in Ca (Bagine, 1984) and could have been a potential source for termites.

The increase in Fe_{DCB} observed in both the field and the beds corresponds to what was found by Abe and Wakatsuki (2010). Indeed, they observed in the termite mound a decrease of active non-crystalline forms of iron and an increase in non-active crystalline forms. This is due to a change in redox conditions. On the contrary, Mujinya et al. (2013) found a loss of crystalline iron oxides in epigeous mounds, compared to the surrounding soil. In our case, there is an enrichment in crystalline oxi-hydroxides of iron, that can come from the preferential removal of clay particles.

In the three sites, termite sheetings aggregates tend to be similar. Indeed, macroaggregates, originally high in the beds, are reduced to 21% whereas in the fallow and the field they

are raised to 15 and 18% respectively. The process is reversed for free microaggregates. Protected microaggregates also tend to represent the same fraction of macroaggregates in both the field and the beds. In the conventional sites (field and fallow), termite sheetings show an improved physical stability, whereas in the conservation site (beds), it is reduced. According to Eschenbrenner (1986), termites are able to produce aggregates of a diameter from 50 to 1000 μm . It is verified here, since termites impact both micro and macroaggregates, ranging from 50 to 2000 μm . The observed pattern seems to show that termites have a ability to produce a determined amount of each type of aggregates. It must be mentioned that the process for aggregate fractionation is a way to imitate the effect of rainfall on termite sheetings.

From a general point of view, the OC content tends to increase in most of the aggregates, which shows an enhancement of SOM protection.

To summarise, termites act as soil ecosystem engineers by improving most of its physico-chemical properties. Their impact can be compared to conservation agricultural practices as in the beds. A hierarchical clustering with all the available parameters of the 43 samples highlighted four main groups (Fig. 14). The first division occurs between soil and termite sheetings, except for two soil samples from the beds. This might be explained by the similarity previously shown between termite sheetings and bed soil. Next, the bed soils are separated from the fallow and the field soils. One bed sample is isolated, mainly because of its high TN concentration. One sample of field soil is included in the *Bed soil* group. Finally, field and fallow soils are separated. This repartition brings out the action of termite activity. With three originally different sites, their action tends to homogenise the soils. Indeed, even though most of the analysed properties are not significantly higher in beds sheetings compared to underlying soil, there is a tendency of improvement even in conservation agriculture, visible through the hierarchical clustering.

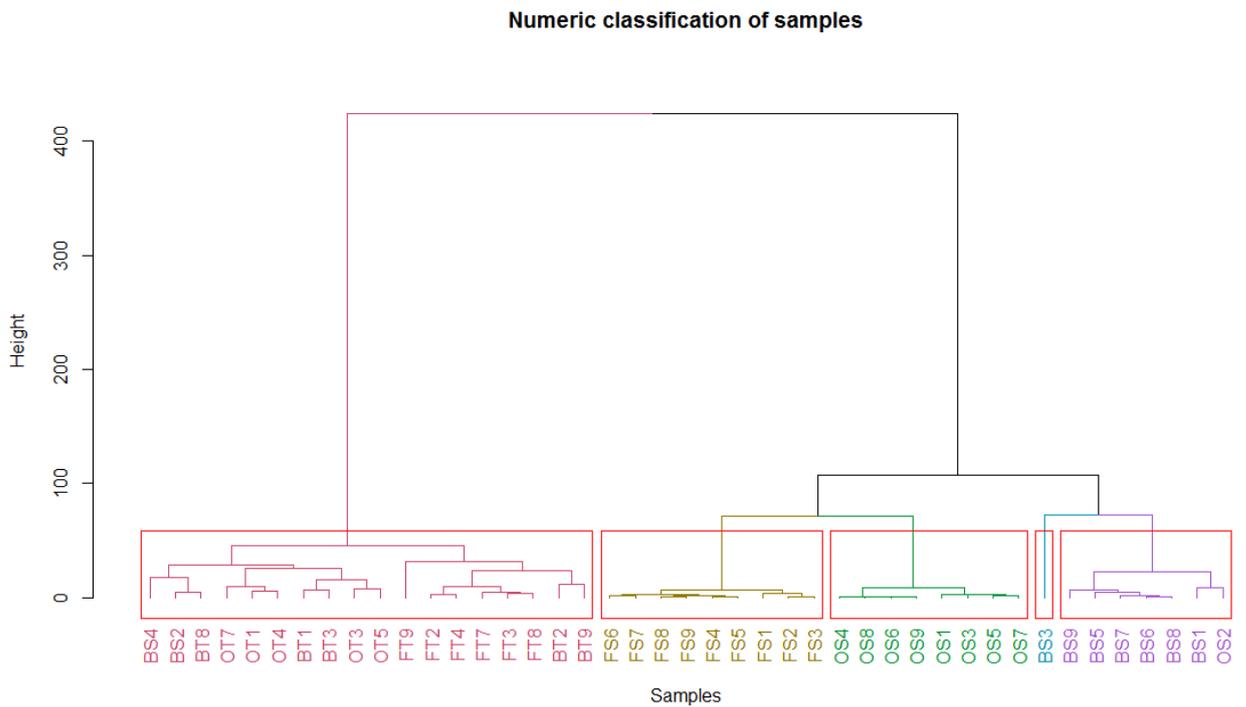


Figure 14: Hierarchical clustering of the samples. The first letter corresponds to the site: O for open field, B for beds, F for fallow land. The second letter corresponds to the sample type: S for soil, T for termite sheetings. The number corresponds to the plot number.

CONCLUSION

This study provides new conclusions concerning the properties of termite sheetings, whereas most of the previous studies focused on permanent buildings.

Termites are an important potential help to restore and/or keep suitable soil properties for agriculture, by bringing to the surface soil of better global physical and chemical quality. The improvement is more important in conventional sites. The combination of OM input and termite activity is an agricultural practice that should be widely used in the tropics. Termite sheetings could also be moved by farmers to the fields for an enhanced effect.

Moreover, conservation management set up by farmers has as comparable an impact as termites. This outcome clearly strengthens the importance of adapted agricultural practices, even for short-term results.

PERSPECTIVES

In this study, it was not possible to isolate some plots from termites. It is therefore hard to quantify their impact on soil proper-

ties, since it is the combination of OM input and termite activity that improves soil properties. Moreover, the experiment was short (two weeks) and the impact on soil itself was therefore not visible yet. Moreover, termite activity and soil translocation might vary depending on the season. A long-term experiment would allow a better understanding of the processes occurring in termite sheetings after their disaggregation. By marking the original level of soil, it would also be possible to quantify the rate of soil formation by termites.

OSL dating can be used to quantify termite bioturbation and could be an interesting approach for termite activity quantification in no-till patches.

To make further progress, available nutrients should be quantified within each aggregate type, in order to better understand the action of termites. Indeed, even though it is clear that they improve soil nutrient levels, the nutrients location and thus stability is not known. Moreover, carbon dating would help to determine if termites reorganize existing aggregates or create new ones with fresh OC.

NB: the bibliography is available at the end of the appendixes.

Part II

Appendixes

Appendix A

State of art

Soil organic matter

The pool of soil organic matter (SOM) represents more carbon than vegetation and atmosphere combined (Batjes, 1996; Watson, 2000). In the actual context of climate change, understanding carbon fluxes and stocks is primordial. Moreover, it has a major importance for soil functioning (Devine et al., 2014). Indeed, organic matter (OM) improves soil fertility by retaining water and nutrients and promoting soil structure (Lehmann and Kleber, 2015).

Most of the organic carbon (OC) is mineralized within months and only a small percentage can be stabilized for up to thousands of years. As SOM is the largest pool of OC on Earth, the stabilisation of this small percentage is crucial for global carbon cycle (Lehmann et al., 2007). This part is physically protected in aggregates, leading to a mechanism of stabilisation, especially for particulate organic carbon (POC) and fine C protection in macroaggregates (Devine et al., 2014).

For a long time, the concept of humification has dominated the study of SOM, which is based on an alkaline extraction method. According to this model, OM is transformed into stable molecules, called humic substances, protected from mineralisation. Humic substances include humic acids, fulvic acids, both ex-

tracted from soil with a base, and humin, which is insoluble (IHSS, 2007). With the modern technics, it appears that those three fractions only correspond to a specific procedure and do not represent different physical components of the SOM (Lehmann and Kleber, 2015). Moreover, there is no consensus in the scientific community for describing those fractions (Piccolo, 2001; Lehmann and Kleber, 2015). Later on, the concept of selective preservation has been developed, presenting OM as a combination of labile and recalcitrant compounds (von Lützow et al., 2006). However, it is known that the presumed recalcitrant compounds, such as lignin can be decomposed quickly in suitable conditions, including high carbon bioavailability (Klotzbücher et al., 2017). The third concept is the progressive decomposition (Lehmann and Kleber, 2015), which describes SOM as three pools: the first is rapidly decomposed, the second is persistent OC in the soil and the third is intermediate (Trumbore, 1997). Lehmann and Kleber (2015) presented a new concept: the Soil Continuum Model. According to them, SOM is made of a continuum of fragments from different sizes and thus having a different solubility in water and a different accessibility to microorganisms.

Aggregates

Soil aggregation depends on five main factors: soil fauna, soil microorganisms, roots, inorganic binding agents and environmental variables; but little has been done before 1950 to understand interactions between those factors (Six et al., 2004). Emerson (1959) presented a model for soil crumb, made of domains of orientated clay and quartz particles. Later, Edwards and Bremner (1967) developed the microaggregate theory, where microaggregate formation is defined as « *a reaction between organic matter, polyvalent metals and electrically neutral clays* », forming complexes. This theory discredits Emerson's theory, where aggregates are primarily made of sand grains (Emerson, 1959).

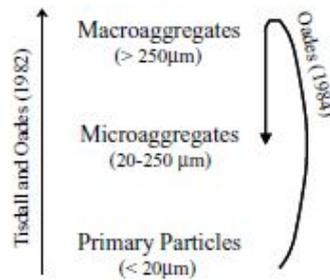


Figure A.1: Differences between the original article of Tisdall and Oades (1982) and the modification by Oades (1984), according to Six et al. (2004).

Edwards and Bremner (1967) stated that organic matter contained in microaggregates ($< 250 \mu\text{m}$) is physically protected from microorganisms.

Tisdall and Oades (1982) introduced a new concept of aggregate hierarchy, in which different types of binding agents play a role at different steps in aggregate architecture. Binding agents are grouped in three different classes: transient, such as polysaccharides, temporary with roots and fungal hyphae and persistent, as aromatic components combined with metal cations and polymers (Tisdall and Oades, 1982). Microaggregates are formed by 2-20 μm diameter particles, bound together by persistent and transient agents. They can be combined to form macroaggregates, which have a diameter $> 250 \mu\text{m}$ (Edwards and Bremner, 1967), with temporary binding agents (Tisdall and Oades, 1982). As a result, microaggregates are more stable than macroaggregates. A small adjustment of this theory has been made by Oades (1984) (Fig. A.1). Indeed, unlike it is presented, macroaggregates are first formed by temporary binding agents. Then, when they are decomposed, microaggregates are formed by the fragments cemented with mucilage, which are incrustated with clay particles (Oades, 1984).

During the first stages of decomposition, carbon content firstly increases rapidly in macroaggregates, before being transferred to microaggregates (Angers et al., 1997). This redistribution of carbon through time means that carbon is *in*

fine protected in stable aggregates.

Soil aggregation can be used as an indicator of geosystem resilience (Cammeraat and Imeson, 1998). While microaggregates are the most stable soil C pool (Lehmann et al., 2007), macroaggregates have a low inertia, responding quickly to perturbations (Cammeraat and Imeson, 1998). Indeed, a soil biological degradation leads to a decrease of SOC and C biomass (Lal, 1997). And in case of restoration including the maintenance of SOC content (Lal, 1997), the recovery of water-stable macroaggregates can be rapid (Devine et al., 2014). Therefore, SOM input seems to be a key for soil resilience (Cammeraat and Imeson, 1998).

Soil resilience

Soil resilience is a concept coming from ecology. It is defined as « *the capacity of the system to recover from a perturbation and return to a new equilibrium, or its ability to recover its functional and structural integrity* » (Blanco-Canqui and Lal, 2010). Actually, the soils considered to be stable or resilient usually do not resist to a perturbation, but find a new equilibrium (Lal, 1997).

Depending on physical, biological and chemical properties, soils have different responses to perturbation (Blanco-Canqui and Lal, 2010). The resilience of a soil ecosystem depends on several factors, mainly soil type and vegetation, climate, scale, land use and disturbance regime (Seybold et al., 1999; Blanco-Canqui and Lal, 2010). The parental material has an influence, a sandy soil being more permeable and thus less resistant. The climate also has an impact: the drier the climate, the lower the resilience. Moreover, seasonal disturbance impacts soil biota and weathering intensity. From a biochemical point of view, reactions are doubled every 10 °C increase. The fauna itself influences the resilience, being higher when there is a vegetation cover, and humans also have an influence, by altering soil formation. And finally, topography has an impact, a

gentle slope being easier to restore (Blanco-Canqui and Lal, 2010).

Land management impacts the aggregate stability, which is a key factor for SOC levels. Devine et al. (2014) showed that no tillage increases SOC in the uppermost 5 cm, compared to tillage. Moreover, the aggregate stability is, in the long run, the highest in a forest succession, intermediate with no tillage and the lowest with conventional tillage (Devine et al., 2014). In a bare land, the stability is even lower (Cammeraat and Imeson, 1998).

Soil fauna is known to be a driving factor in soil resilience (Blanco-Canqui and Lal, 2010; Jouquet et al., 2011), impacting nutrients and carbon turnover, as well as soil aggregation. Most of the studies concerning soil fauna have focused on earthworms and the interest in termite impact on soil structure is recent (Six et al., 2004). As shown in fig. A.2, there are fewer studies discussing the impact of termites on soil restoration than earthworms, plants being far ahead. However, they tend to be recognized as important actors in agro-ecosystems (Pardeshi and Prusty, 2010). Soil organisms have different activities in soil: mounding, mixing, forming voids, forming and destroying peds, regulating soil erosion, plant and animal litter, promoting the movement of air and water and regulating nutrients cycling (Jouquet et al., 2011). Soil organism assessment and species richness are used as proxies for soil health, which is a way to quantify agriculture sustainability (Doran and Zeiss, 2000).

In the actual context of climate change and soil loss threats, resilience is important to understand the capacity of soil « *to recover from continuous and persistent anthropogenic stresses* » (Blanco-Canqui and Lal, 2010).

In India, agriculture is being intensified to follow the sharp population increase, accelerating the soil degradation process. In the state of Tamil Nadu, soil losses have been estimated to 6 t/ha/yr by RUSLE equation (Balasubramani et al., 2015). In this context of increasing environmental pressure, focusing on soil resilience and finding affordable ways to restore ecosystem are main goals to

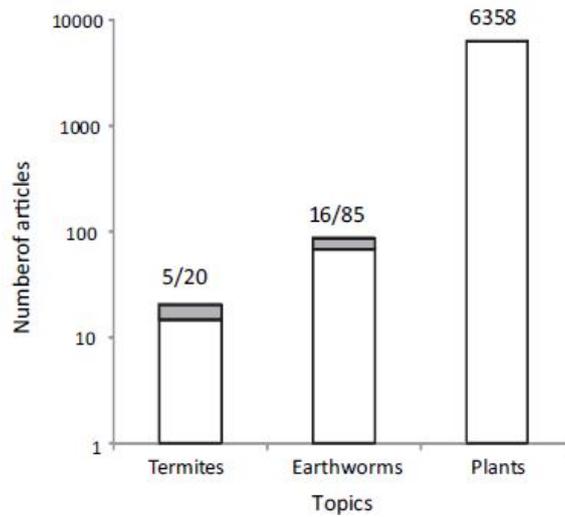


Figure A.2: Comparison of the number of articles found in Web of Science with the keywords « Soils », « Rehabilitation » and either « Termites », « Earthworms » or « Plants ». The articles discussing the impact of soil engineers on soil restoration are in grey, according to Jouquet et al. (2014).

be achieved.

Termites

Termites are part of the order Blattodea, infraorder Isoptera (Evans and Iqbal, 2015). They are social insects, living in colony (Higashi et al., 2000). The queen produces eggs for both the sexual and the neuter lines (Watson et al., 1987). The latter is composed of soldiers, protecting the colony thanks to their hyper-developed mandibles (Chinery, 2012), and workers, foraging and nursing (Higashi et al., 2000). After the egg stage, the sterile individuals are only passing through larvae stages, whereas the sexual individuals develop from larvae to nymphs before becoming alates (Watson et al., 1987). They are present mainly in the tropics (Bignell and Eggleton, 2000), where the average density is 2000 to 7000 individuals per m^2 (Jouquet et al., 2011). Their heterogenous repartition leads to activity hotspots at nest location (Jouquet et al., 2016a). The vertical impact of termites on landscape cannot be neglected either, since the mounds of *Macrotermes* sp. can reach a height of 10 m, with a diameter up

to 15 m (Erens et al., 2015). In savannah and semi-arid environments, 25% of termite abundance can be found below 1 m depth and 7% below 1.75 m (Bignell and Eggleton, 2000). Macrotermitinae are the least affected sub-family by environmental disturbance (Collins, 1980).

In India, 337 species are known and 239 of them belong to the family Termitidae (Chhotani, 1997), called « “higher termites” » (Rouland-Lefèvre and Bignell, 2004). In the region of Auroville, 2 sub-families are represented: Macrotermitinae and Amitermitinae (Chhotani, 1997). Macrotermitinae contains the genera *Macrotermes* Holmgren, *Odontotermes* Holmgren and *Hypotermes* Holmgren, among others, whereas Amitermitinae includes *Speculitermes* Wasmann. *Odontotermes* Holmgren is the predominant genera in India (Chhotani, 1997).

Termites are able to digest resistant OM including lignocellulose, hemicellulose and humus (Rouland-Lefèvre and Bignell, 2004) thanks to mutualism with a complex microflora (Brune, 1998), such as archaea, eubacteria and eukaryotes (Rouland-Lefèvre and Bignell, 2004). Attractive OM usually having a high C/N, they need to add nitrogen or remove carbon to be able to decompose it (Higashi et al., 2000). Thanks to steep gradients in the lumen, the ingested organic matter is incubated at different pH and oxygen levels in termite gut (Brune, 1998). They are known to produce methane in their guts and contribute to 3-19% of the global emissions (Bignell and Eggleton, 2000).

Termites are divided in three or five major feeding groups, depending on the authors. Bignell and Eggleton (2000) identified the soil-feeders, soil/wood interface-feeders, wood-feeders, litter-foragers and grass-feeders, whereas Jouquet et al. (2016a) differentiates the soil feeders, the grass/litter feeders and the fungus-growing termites. Some species fit in more than one group. Macrotermitinae are particularly difficult to classify, since workers from different ages feed on different materials (Bignell and Eggleton, 2000).

The Macrotermitinae are fungus-growing species (Chhotani, 1997; Jouquet

et al., 2004). They live in symbiosis with a basidiomycete fungus *Termitomyces* which they feed in combs with OM (Mando and Brussaard, 1999). Those combs are therefore made of both the growth substrate and the fungus. Depending on the species, they are dispersed in the soil or included in mound nests (Rouland-Lefèvre and Bignell, 2004). The fresh OM, such as leaves and grass, is first ingested by Macrotermitinae and move rapidly through the gut to be incorporated to the comb containing *Termitomyces*. After several days, there is a production of clusters of conidia on the surface, which are eaten by termites (Rouland-Lefèvre and Bignell, 2004). *Termitomyces* is able to digest polyphenols, which make Macrotermitinae less sensitive to poor quality food (Mando and Brussaard, 1999).

The low competitiveness of *Termitomyces* with other microorganisms is overcome by an optimal microenvironment and secretions from the termites to inhibit competitors and stimulate fungus growth (Rouland-Lefèvre and Bignell, 2004).

Despite the fact that they are mainly seen as pests, only 185 over 2800 species actually are (Jouquet et al., 2011). Termites are part of the soil macrofauna (Lavelle et al., 1992), having a significant role in soil formation (Hole, 1981). Their activity creates favourable conditions for vegetation development: return of OM to the soil through faeces, soil loosening, bioturbation and weathering development (Jouquet et al., 2011). Even after the death of the colony, the positive impacts last for long (Lavelle et al., 2001), as abandoned termite mounds may be 2400 years old (Erens et al., 2015).

Termites build two types of structures: permanent, such as the termite mound, and, for food foraging, temporary constructions (Mora et al., 2003). These ephemeral biogenic structures are made of topsoil particles, collected as close as possible to the food source and mixed with saliva and/or faeces (Villenave et al., 2009; Jouquet et al., 2015). In contrast, the permanent structures are mainly made of neighbouring subsoil (Abe and Wakatsuki, 2010). All those biogenic

structures contain OM which is protected from mineralization (Mora et al., 2003).

The enrichment in OM and exchangeable cations, through saliva and faeces, have a positive influence on structural stability of soil (Six et al., 2004). They first take basic aggregates (0.62 mm diameter) in the profile, pill them up to create compound aggregates (1 mm diameter) and bring them to the surface for cementation with faeces and/or saliva, covering OM with sheetings (Ferrar and Watson, 1970). The compound aggregates are less stable than the basic ones and thus can be disintegrated by runoff and splash (Jungerius et al., 1999). These constructions consist of the first step in food foraging, creating a favourable environment. Indeed, termites need a high relative humidity, close to saturation, as it is in the nest (Wrey, 2012). In a second time, OM is removed through galleries (Ferrar and Watson, 1970).

Those insects are considered as ecosystem engineers (Decaëns et al., 2006) in tropical zones, which means that they « *directly or indirectly modulate the availability of resources to other species* » (Herrick and Lal, 1996). They are dominant animals in the tropical soils (Dawes, 2010; Pardeshi and Prusty, 2010) and impact SOM dynamics, which is sequestered in nests, mounds and galleries for a long time (Lavelle et al., 1992). They are considered as carbon sinks, as they protect organic matter from « normal » mineralization pathway (Whitford et al., 1992). Therefore, termites are a valuable resource for soil restoration (Dawes, 2010).

Their impact can be divided in four different scales. At the landscape level, they are heterogeneity drivers. At the soil profile scale, they are bioturbators. At the aggregates level, they reorganize the litter cover, by covering it with wet soil particles enriched with clay. And at the clay mineral level, they are weathering agents (Jouquet et al., 2016a), fastening the soil weathering (Jouquet et al., 2002, 2007).

The area influenced by termites is called termitosphere (Lavelle et al., 1992),

one of the four principal biological system regulations. It is characterized by interactions between OM, decomposing and soil regulating organisms (Lavelle and Kohlmann, 1984).

Termite activity can be highlighted by the presence of microgranular structures from biological origin. Moreover, bioturbation by termites leads to highly stable sand-size aggregates, often named *pseudosand* (Jungerius et al., 1999; Jouquet et al., 2016b). They can even participate to soil formation and modify soil structure in the long term, as shown by (Reatto et al., 2009) for a Brazilian Latosol. By digging tunnels for food foraging, termites create soil macropores, and thus increase water infiltration (Evans et al., 2011), even though they might be destroyed by raindrops (Mando et al., 1996). Moreover, they improve soil water balance (Pardeshi and Prusty, 2010) and water movements, increasing infiltration five times in earthworms and termite presence in West Africa (Lavelle et al., 1992).

Termite affected soils show a higher percentage of water stable aggregates (Lavelle et al., 1992). Jouquet et al. (2016a) yet found various results, depending on termite type: the soil-feeding termites improve the stability of aggregates > 2 mm, whereas the fungus-feeding termites diminish it.

Termites cannot transport particles > 1000 μm . Below this limit, there is no consensus. Some studies showed that they do not seem to have any preference for a specific particle size (Nye, 1954; Awadzi et al., 2004). However, Jouquet et al. (2002) showed that they prefer finer particles if available. And Nutting et al. (1987) estimated an increase in clay content of surface soil by 21 kg/ha/year. Therefore, they lead to an enrichment in gravels and pebbles of the underlying horizons, a process called reverse illuviation (Awadzi et al., 2004).

Some species play a role in the recycling of herbivore dung, like beetles, but with a higher removal activity during the dry season, reaching 31% in tropical ecosystem (Freymann et al., 2008). Indeed, they are the only organisms able

to forage thanks to a temperature-controlled environment (Ferrar and Watson, 1970) and they do not need a highly moisturized food (Freyman et al., 2008). One gram of dry dung decomposed by termites is estimated to lead to two grams of soil accumulated (Herrick and Lal, 1996). These social insects also contribute to litter removal, up to 70% under Sahelian conditions (Mando and Brussaard, 1999), 24% in a Nigerian savannah (Collins, 1981). Their preferences for different types of dung, litter, grass or wood depend on the species (Freyman et al., 2008). Foraging is always coupled with bioturbation, by digging tunnels and producing soil particle sheets (Kaiser et al., 2017). They translocate soil on food surfaces at a rate of 1059 kg/ha/year in Northern Kenya (Bagine, 1984) and 744 kg/ha/year in Sonoran Desert grassland (Nutting et al., 1987). Moreover, they seem to be the connexion between herbivores and microbial decomposers in nutrient cycles (Freyman et al., 2008).

In case of soil crust, the combination of termites and organic inputs is the solution (Pardeshi and Prusty, 2010), since termites burrow through the crust (Léonard and Rajot, 2001; Jouquet et al., 2014). Mulching is a way to enhance termite activity, leading to an improvement of soil properties (Dawes, 2010). In degraded Australian tropical savannah, macroporosity, plant cover, litter decomposition and soil water storage have increased while soil strength has decreased thanks to termites. Moreover, mulch can reduce soil temperature in hot climate (Tian et al., 1993), being an efficient protection for soil against extreme temperatures and drought (Dawes, 2010). It also improves soil moisture (Tian et al., 1993). From a more general point of view, all the practices with return of plant residues are favourable for termite activity (Lavelle et al., 2001).

They also improve soil chemical properties. Indeed, termite affected soils show higher pH, nutrient levels, CEC and OM content (Nutting et al., 1987; Lavelle et al., 1992; Donovan et al., 2001). If the nutrient level is low in the surrounding soil, termites enrich it, by adding faeces and/or saliva (Lobry de Bruyn

and Conacher, 1990). Termite sheeting also have a higher carbon and nitrogen content than the surrounding soil (Jouquet et al., 2002). However, some studies did not show any improved chemical properties (Mora et al., 2003; Awadzi et al., 2004).

The main impact is the raise of local microsite soil quality, being a source of heterogeneity (Donovan et al., 2001). Indeed, their activity is concentrated in nests and galleries, leading to an irregular nutrient repartition, which is positive for ecological diversity (Lavelle et al., 1992). Those biogenic structures are microcosms regulating the organic matter turnover (Bagine, 1984).

In agriculture, the positive impact of termites has been highlighted by Evans et al. (2011), among others. Indeed, there was an increase of 36% in wheat yield thanks to their action. They increase nitrogen-fixing capacity, which reduces fertilizer costs. In summary, they improve agriculture sustainability.

The effect of tillage is controversial. Evans et al. (2011) found that a shallow tillage, for weed control, does not affect soil insects nor crop yields, whereas Kaiser et al. (2017) showed that when the anthropogenic impact increases, the buildings by termites decrease.

Macrotermitinae have been studied mainly in Africa, even though they also are present in Asia (Jouquet et al., 2015). Moreover, most of the studies compare mound material to surrounding soil, but little is known on foraging galleries, which are temporary. After rainfall or watering, these biogenic structures are disintegrated and return to the soil surface (Jouquet et al., 2015). According to Jouquet et al. (2011), few researches have focused on termite use for soil rehabilitation and fertility management.

In India, termites are considered as an important alternative to expensive products in agriculture. It is cheap, affordable and accessible (Pardeshi and Prusty, 2010).

Appendix B

Experimental protocol

B.1 Site description

B.1.1 Climate and vegetation

The experiment has been conducted in a farm of Auroville, Tamil Nadu, South India. The climate is tropical wet, classified as Aw by Köppen and Geiger. The average annual temperature is 28.1 °C (Climate Data) and rainfall is 1384.6 mm (Fig. B.1).

The indigenous vegetation is a tropical dry evergreen forest, which has been cut down during colonial time to be replaced by cashew orchards (Baldwin and Declercq, 2011).

B.1.2 Farm

Auro-orchard, a 45 acres farm of Auroville, started in 1969 and the organic conversion happened in 2012. It mainly produces vegetables and fruits for Auroville, with the aim of being a « *balanced organic farm providing high quality food while being financially sustainable* » (Baldwin and Declercq, 2011).

The study is conducted in three sites, corresponding to different types of agri-

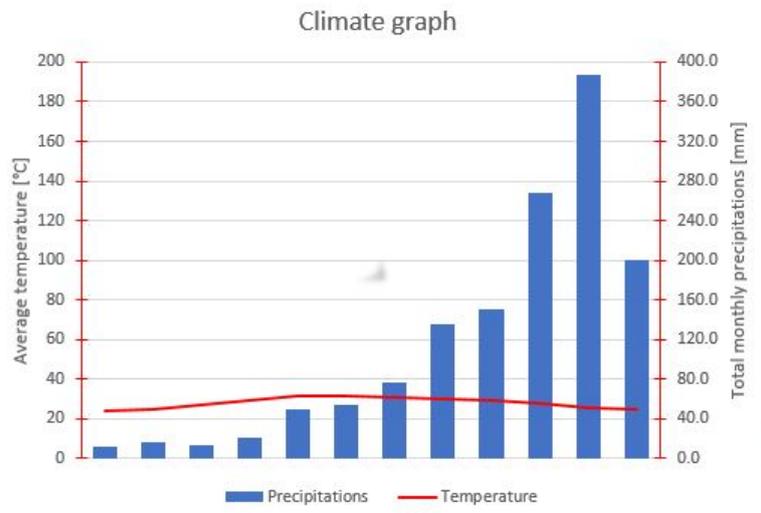


Figure B.1: The average monthly temperatures are based on Climate Data, whereas the average monthly precipitations are based on CSR data for the period 1977-2015.

cultural fields:

1. *BEDS*

The soil cover is permanent in the beds, either culture, green manure or mulch and the soil preparation is only manual, such as weeding. The bed #7 was neglected for a long time before being covered by compost and mulch for a resting period. During the experient, tapioca was growing. In bed #12, there is cabbage and radish. In bed #14, there is taro. There is a drip irrigation system, giving about 4 L of water per day per m². Compost and ligneous OM are the only fertilizers.

2. *FALLOW LAND*

Being a permanent pasture for over six years, this zone used to be a conventional peanut culture. There is no fertilization, irrigation system nor tillage in this zone. The soil cover is made of legumes and grass.

3. *TILLED FIELD*

In this zone, the soil is tilled by disk-ripper and cultivator shanks before the culture starts. Irrigation is assured by open channels and fertilizers

are compost and green manure. The study was conducted in the zones situated between pumpkin plants, soil being bare.

B.2 Experimental setup

In each site, three modalities are considered and replicated three times, on a surface of $1 \times 1 \text{ m}^2$ (Fig. B.2). These modalities are « no OM added », as a reference soil, « compost+mulch », compost covered with mulch and « mulch+Jiwamrita », mulch watered with *Jiwamrita*. Every day, pictures and notes are taken for every site, in order to check termite activity.

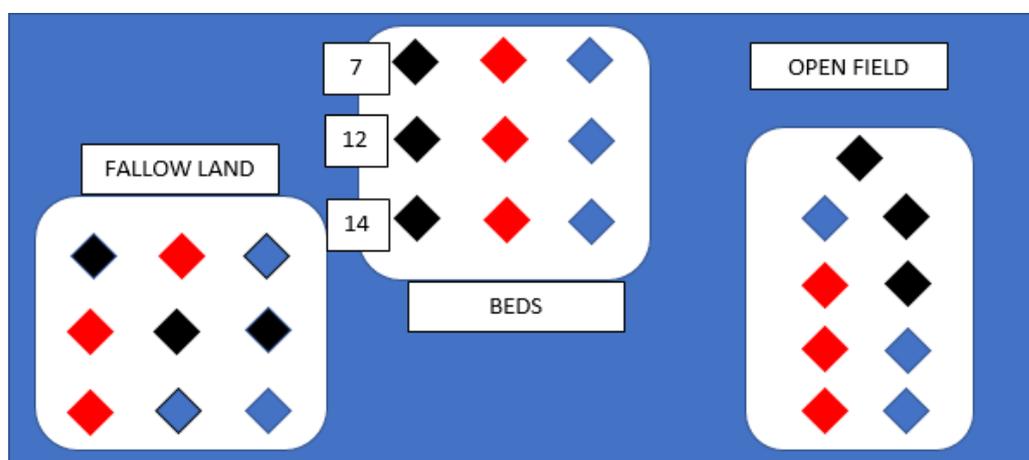


Figure B.2: Experimental setup. The black squares correspond to "no OM added", the red squares correspond to "compost+mulch" and the blue squares correspond to "mulch+Jiwamrita". The numbers 7, 12 and 14 correspond to the three beds used for this experiment.

Table B.1: Water calendar during the 2 weeks experiment. W corresponds to water, J corresponds to *Jiwamrita*.

Days	1	2	3	4	5	6	7	8	9	10	11	12	13	14
None	/	/	/	/	/	/	/	/	/	/	/	/	/	/
Compost	W	W	W	W	W	W	W	W	W	/	W	/	W	W
Jiwamrita	J	J	J	J	J	J	J	J	W	/	W	/	W	W

Appendix C

Soil profile description

The climate is tropical wet and dry (Aw) (Fig. B.1). The soil climate is isohyperthermic (the mean annual soil temperature is above 22 °C and the variation between summer and winter does not exceed 6 °C) and has an aridic (torric) moisture regime (dry in all parts for more than half of the year and moist in some or all parts for less than 90 consecutive days). The site is situated on a plateau with a NW slope of 1-2%, in a cashew orchard with extensive grazing. The original vegetation is a dry evergreen forest and the parent material is a red sandstone, from charnockite erosion, dating from Tertiary (Middle Mio-Pliocene) (Selvaraj and Ramasamy, 1998). The profile is described in fig. C.4.



Figure C.1: *Fine quartz gravels*



Figure C.2: *Coarse quartz gravels*



Figure C.3: *Mottling*



Horizon	Depth [m]	Description
O	0-2	Homogeneous red (5YR4/6) matrix of sandy clay texture with few very fine distinct red (2.5YR5/6) dots. Weak fine granular structure, many coarse channels (pedofauna), fine and medium roots common, medium porosity.
A	2-15	Transition with the previous horizon abrupt. Homogeneous red (5YR5/8) matrix of coarse sandy loam texture, very few fine gravels of angular, slightly weathered quartz (Fig. C.1). Weak very fine blocky subangular structure, few coarse channels (pedofauna), fine and medium roots common, low porosity.
B	15-50	Transition with the previous horizon clear. Heterogeneous red (2.5YR4/6) matrix of coarse sandy loam texture with medium distinct yellow (10R4/4) and violet (10YR7/8) mottles (Fig. C.3), the abundance increasing with depth. Fine gravels of angular, slightly weathered quartz (Fig. C.1) and coarse gravels of subrounded, slightly weathered quartz (Fig. C.2), abundance increasing with depth. Weak fine blocky subangular structure, few coarse channels (pedofauna), few fine and medium roots, low porosity.
C	50-150	Transition with the previous horizon gradual. Heterogeneous red (2.5YR4/6) matrix of sandy clay loam texture with many medium distinct yellow (10R4/4) and violet (10YR7/8) mottles (Fig. C.3). Many coarse subrounded, slightly weathered gravels of quartz. Strong fine blocky structure, very few coarse channels (pedofauna) up to 1m, very few fine and medium roots, low porosity.
•	150	Transition with the previous horizon abrupt. Stone line: dominant coarse subrounded gravels of quartz (cfr. Article, Fig. 8).

Figure C.4: Profile IN/TN/AV-001 described by Justine Lejoly on April 18th 2017, site located in Auro-orchard, South-East of the junction between Chennai-Nagapattinam Highway and Edayanchavady Main Road (11°59'6.7" N 79°47'18.2" E), 55 m above sea-level, in sunny conditions with no rain in the previous month.

Appendix D

Analyses

D.1 pH

Method

Potentiometrical Method (ISO 10390): the pH of the soil is potentiometrically measured in the supernatant suspension. The liquid is made up of a 0.01M solution of calcium chloride in water (pH-CaCl₂) or water (pH-H₂O). The standard deviation and precision of the method is available in table D.1.

Reagents

- Calcium chloride (CaCl₂) 0.01M: dissolve 1.47 g CaCl₂·2H₂O in one L of distilled water.
- pH buffer solutions.

Procedure

- pH water
 1. Weigh 10 g soil (< 2 mm fraction)
 2. Place the sample in the 50 mL beaker and add 20 mL of distilled water;
 3. Mix the suspension vigorously three times in half an hour using the manual agitator. Wait 10 minutes;
 4. Adjust the pH-meter and check that the temperatures of the buffer solution and the soil suspension do not differ by more than 1 °C;
 5. Measure the pH in the settling suspension. Read the pH after stabilization (one decimal).
- pH CaCl₂
 1. Weigh 5 g soil (< 2 mm fraction);
 2. Place the sample in the 50 mL beaker and add 25 mL of CaCl₂ 0.01M;
 3. Mix the suspension vigorously three times in half an hour using the manual agitator. Wait 10 minutes;

4. Adjust the pH-meter and check that the temperatures of the buffer solution and the soil suspension do not differ by more than 1 °C;
5. Measure the pH in the settling suspension. Read the pH after stabilization (one decimal).

D.2 CEC

Method

Silver Thiourea Method (Pleysier and Juo, 1980). The standard deviation and precision of the method is available in table D.1.

Reagents

- Silver nitrate AgNO₃ solution 0.4M: Dissolve 1.7 g of AgNO₃ in 250 mL of water and store in an amber bottle.
- Thiourea 0.2M: Dissolve 7.5 g of Thiourea in 500 mL of water. Handle Thiourea carefully with gloves and spectacles, in fume hood.
- AgTU extractant: To 500 mL Thiourea solution add 250 mL of water and mix well under fume hood. Add slowly 250 mL AgNO₃ 0.4M with thorough mixing, do not reverse this operation.
- HNO₃ 1N : Take 6.3 mL of concentrated HNO₃ in 100 mL flask and make it to 100 mL with distilled water. Keep the solution in a dark place.

Procedure

1. Weigh 1 g soil (< 0.5 mm fraction) in a dry 100 mL conical flask;
2. Include one control and one blank sample;
3. Add 40 mL of AgTU extractant to the flasks and close it properly with rubber stopper, if it needed seal it with bottle sealer;
4. Shake it for four hours in fume hood;
5. Centrifuge the sample and filter through Whatman No. 5 filter paper;
6. Take 50 mL flask and add 2.5 mL 1N HNO₃ and 1 mL extract. Add distilled water up to 50 mL and mix it well;
7. Take 5 mL of this solution and add 25 mL of distilled water (5× dilution);
8. Analyse the samples with AAS (Atomic Absorption Spectrophotometer) after calibration with blank, 1, 5 and 10 ppm.

Calculation

For 1.0 g soil

$$CEC[\text{meq}/100\text{g}] = (B - S) \times 1.85 \times 5$$

where *B* = Blank; *S* = Sample

D.3 Available potassium

Method

Neutral Normal Ammonium Acetate Extraction Method
Methods of Analysis of Soil, Plants, Waters, Fertilizers & Organic Manures (Tandon, 2005).

Remarks

Interference in the internal - standard method occurs at $\text{Na}/\text{K} \geq 5$.

Ca may interfere if $\text{Ca}/\text{K} \geq 10$.

Mg begins to interfere when $\text{Mg}/\text{K} \geq 100$.

Minimum detectable concentration: 0.1 mg/L.

The standard deviation and precision of the method is available in table D.1.

Reagents

- Ammonium acetate solution 1N (Soil extracting reagent): Dilute 57 mL of glacial acetic acid to 800 mL and then neutralize to pH 7.0 with concentrated NH_4OH . Make up final volume to 1 L. OR dissolve 73.1 g of ammonium acetate in 200 mL of H_2O and dilute to 1 L.

Procedure

1. Weigh 5 g soil (< 2 mm fraction) and add 25 mL extracting reagent (ammonium acetate) in a conical flask;
2. Shake the mixture vigorously for about 20 minutes and filter it through Whatman No.5 filter paper;
3. Switch on the flame photometer;
4. Calibrate the instrument with the extracting reagent for zero reading and with the standard solutions 10, 50 and 100 ppm;
5. Analyse the soil extracts.

Calculation

$$K[\text{ mg}/100\text{g}] = A \times 0.5$$

where A = value from the photometer

D.4 Available calcium and magnesium

Method

Neutral Normal Ammonium Acetate Extraction Method
Methods of Analysis of Soil, Plants, Waters, Fertilizers & Organic Manures (Tandon, 2005).

Remarks

Not suitable for calcareous soils.

Minimum reporting limit (MRL): 1 mg/kg

Deduction limit (DL): 0.1 mg

Interference: Extract should be colourless and CO₂ bubbles should be removed before analysis. The standard deviation and precision of the method is available in table D.1.

Reagents

- Ammonium acetate solution 1N (soil extracting reagent): Dilute 57 mL of glacial acetic acid to 800 mL and then neutralize to pH 7.0 with concentrated NH₄OH. Make up final volume to 1 L. OR dissolve 73.1 g of ammonium acetate in 200 mL of H₂O and dilute to 1 L.
- Total hardness (TH), buffer for Mg: 1.179 g EDTA and 780 mg MgSO₄·7H₂O OR 644 mg MgCl₂·6H₂O in 50 mL water and 16.9 g NH₄Cl in 143 mL concentrated NH₄O, diluted to 250 mL with distilled water.
- Erichrome Black T, indicator for Mg: 1 g in 100 mL triethanolamine (TEA).
- Standard 0.01M EDTA solution: 3.723 g EDTA in 1000 mL water store in polyethylene bottle.
- 1M NaOH for Ca: 10 g NaOH in 250 mL water.
- Indicator Ca: 100 mg calcon in 100 mL isopropyl alcohol.

Procedure

1. Weigh 5 g soil (< 2 mm fraction) and add 25 mL extracting reagent in a conical flask;
2. Shake the mixture vigorously for about 30 minutes and filter it through Whatman No. 5 filter paper;
3. Take 5 mL of aliquot in two different conical flask and add 20 mL of distilled water in both;
4. Add 5.0 mL of TH buffer to one flask to get the pH to 10 and 5 mL of NaOH 1M to the second flask to get the pH to 12-13;
5. Add 2 drops of Erichrome Black T indicators for TH (Mg) and a few drops (10) of calcon for Ca;
6. After addition of buffers and indicators titration should be done within two minutes;
7. Add EDTA titrant slowly, with continuous stirring, the endpoint is appearance of sky blue colour for both the cases.

Calculation

For 5 mL extract from 5 g soil in 25 mL

$$Ca [\text{mg}/100\text{g}] = TV_{Ca} \times 400$$

$$Mg [\text{mg}/100\text{g}] = (TV_{Mg} - TV_{Ca}) \times 248.5$$

where *TV* = titration value

Table D.1: Complementary information about analyses

Element	Standard deviation [mg/100g]	Precision [%]
pH	0.09	1.79
CEC	0.67	8.6
K	0.18	5.73
Ca	0.11	0.09
Mg	0.13	0.13

D.5 Available phosphorus for acidic soils

Method

Bray and Kurtz (1945), for soils with pH \leq 6.5

Reagents

- Ammonium fluoride 1M: Dissolve 3.7 g NH_4F in 100 mL of distilled water and store in polyethylene bottle.
- Hydrochloric acid 0.5M: Take 4.3 mL of concentrated HCl and add distilled water to 100 mL.
- Extraction solution Bray I: Add 15 mL of NH_4F 1M, 25 mL of HCl 0.5M in 400 mL and dilute to 500 mL with distilled water.
- Boric acid 1%: Dissolve 1 g H_3BO_3 in 100 mL distilled water.
- Reagent A: Dissolve 12 g of ammonium molybdate in 250 mL distilled water and also dissolve 0.291 g of antimony potassium tartrate in 100 mL of water. Both these solutions are added to 1000 mL of approximately 5N Sulphuric acid (140 mL sulphuric acid). This solution is mixed thoroughly and made up to 2 L with distilled water.
- Reagent B: Dissolve 530 mg of ascorbic acid in 100 mL of reagent A. This Solution must be freshly prepared.

Procedure

1. Weigh 2.5 g of soil (< 2 mm fraction) and pour it into a 100 mL flask. Include blank and control sample;
2. Add 14.0 mL of extraction solution Bray I;
3. Shake one min by hand and then immediately filter through Whatman No.1 filter paper;
4. The filtrate should be clear and colorless;
5. Pipette in 50 mL beaker 2 mL of filtrate or 2 mL of the blank - and add 4 mL boric acid and 6 mL reagent B;
6. Allow the solution to stand for at least 15 min;
7. Measure absorbance in 1 cm cuvette with a wave length of 882 or 720 nm.

Calculation

$$P[\text{ mg/100g}] = A \times 4.2$$

where A = absorbance

D.6 Available phosphorus for neutral and alkaline soils

Method

Olsen (1954), for soils with pH > 6.5

Remarks

Extract should be colourless and CO₂ bubbles should be removed before analysis.

Reagents

- Sodium bicarbonate 0.5M, pH 8.5 (Extracting solution): Dissolve 84 g sodium bicarbonate in water and make up to 2 L with distilled water. Adjust the pH to 8.5 with 10% Sodium hydroxide, mix and dilute to 2000 mL.
Note: Check and re-adjust pH after storage.
- Olsen reagent:
 - Reagent A: Dissolve 12 g of ammonium molybdate in 250 mL distilled water, dissolve 0.291 g of antimony potassium tartrate in 100 mL of water. Both these solutions are added to 1000 mL of approximately 5N sulphuric acid (140 mL concentrated sulphuric acid diluted to 1000 mL with water). This solution is mixed thoroughly and made up to 2 L with distilled water.
 - Reagent B: Dissolve 530 mg of ascorbic acid in 100 mL of reagent A. This solution must be prepared daily.

Procedure

1. Weigh 2.5 g of soil (< 2 mm fraction) in a 100 mL flask and add 50 mL of sodium bicarbonate 0.5M;
2. Add a pinch of charcoal to it;
3. Close with the rubber cork and place in the shaker for 30 minutes;
4. Filter through Whatman No.5 filter paper in a 50 mL beaker, the filtrate should be clear and colorless;
5. Pipette 6 mL of filtrate or 6 mL from the blank to 50 mL beaker, add 6 mL of Olsen reagent B and swirl.
6. Allow solution to stay for 15 min. Measure optical density with 1 cm cuvette at a wavelength of 882 or 720 nm.

Calculation

$$P[\text{mg}/100\text{g}] = A \times 3.98$$

where A = absorbance

D.7 Organic carbon

Method

Wet Combustion Method (IS 2720-22, 1972).

Three main sources of error arise with chromic acid digestion:

1. Interfering - inorganic constituents,
2. Differences in digestion conditions and reagent composition,
3. Variable composition of the organic matter itself.

Chlorides, if present, reduce Cr_2O_7 and lead to higher results. They can be rendered ineffective by precipitation with Ag_2SO_4 added to the digestion acid or by leaching with water prior to digestion. The presence of Fe^{2+} also leads to high results, but drying soils containing Fe^{2+} during preparation of the soil sample for analysis normally oxidizes Fe^{2+} to Fe^{3+} and thus minimizes the amount of Fe^{2+} present. Higher oxides of Mn compete with Cr_2O_7 for oxidation of organic matter, leading to lower results. Usually this is not a serious error. Carbonates and elemental C do not introduce any significant error.

Detection limit: 0.1%

Reagents

- Potassium dichromate 1N: Dissolve 24.52 g $\text{K}_2\text{Cr}_2\text{O}_7$ in H_2O and make up to 500 mL with distilled water.
- Concentrated H_2SO_4 .
- Ferrous ammonium sulfate 0.5N: Dissolve 98.04 g $\text{Fe}(\text{NH}_4)_2(\text{SO}_4)_2 \cdot 6\text{H}_2\text{O}$ in distilled water, add 10 mL H_2SO_4 and add distilled water up to 500 mL.
- Sulphuric acid.
- Ferrion indicator.

Procedure

1. Weigh 0.2 g soil (< 0.5 mm fraction) and place it in a dry COD digestion tube;
2. Pipette 5 mL $\text{K}_2\text{Cr}_2\text{O}_7$, swirl beaker gently to mix the reagent well with the soil;
3. Add carefully 5 mL concentrated H_2SO_4 , swirl again and do not close the tube;
4. Switch on the COD digester 10 minutes before installing the sample tubes for digestion;
5. Keep the tubes for digestion at 155 °C for about 30 min and shake the tube two times carefully (every 10 min);
6. Cool it down to room temperature, pour it to 50 mL beaker and wash the tubes carefully with distilled water into the beaker;
7. Add 10 mL of distilled water;
8. All the 7 steps should be done in the fume hood;
9. Titrate the contents with ferrous ammonium sulfate 0.5N based on auto titrator procedure, in presence of ferrion indicator. The appearance of a red colour indicates the end of the titration;
10. Run a blank without the soil.

Calculation

1 mL of 1 N $\text{K}_2\text{Cr}_2\text{O}_7$ corresponds to 3 mg of carbon.

$$OC[\%] = (TV_B - TV_S) \times 0.975$$

where TV_B = blank titration value; TV_S = sample titration value

$$OM[\%] = OC \times 2$$

for Organic Matter

D.8 Total nitrogen

Method

Micro Kjeldahl Method (Bremner and Mulvaney, 1996).

Detection limit: 0.1 mg/100g

Reagents

- Hydrogen peroxide.
- Concentrated H₂SO₄.
- Selenium powder.
- Lithium sulfate.
- Digestion mixture for:
 - 2 samples: 5.2 mg selenium powder, 17.5 mg Li₂SO₄, 4.4 mL 30% H₂O₂ and 5.6 mL concentrated H₂SO₄
 - 4 samples – 10.4 mg Selenium powder, 35 mg Li₂SO₄, 8.8 mL 30% H₂O₂ and 11.2 mL concentrated H₂SO₄
 - 10 samples - 26 mg Selenium powder, 87.5 mg Li₂SO₄, 22 mL 30% H₂O₂ and 28 mL concentrated H₂SO₄
 - NB: concentrated H₂SO₄ added slowly with care. It can be stored for 4 weeks at 2 °C (Ice bath).
- Boric acid 2%: dissolve 20 g boric acid in distilled water and dilute to 1000 mL.
- Sodium Hydroxide 40%: dissolve 40 g NaOH in distilled water and dilute to 100 mL.
- Sulfuric acid 0.02N.
- Indicator: 0.066 g methyl red and 0.099 g Bromo cresol green in 100 mL of isopropyl alcohol.
- Phenolphthalein indicator: 100 mg in 100 mL isopropyl alcohol

Procedure

1. Weigh 0.2 g soil (< 0.5 mm fraction) in 100 mL flask;
2. Add 5 mL of digestion mixture to the flask carefully;
3. Put in digester for one hour until the solution is clear, make up the digested solution to 50 mL in volumetric flask and take aliquot for analysis;
4. All the steps above should be done in the fume hood with self protection.
5. Nitrogen estimation is done by taking well mixed 25 mL aliquot from 50 mL in Kjeldhal flask;
6. Add 150 mL distilled water and rise the pH to at least 8.5 by adding 40% NaOH with phenolphthalein indicator and connect immediately to the condenser to avoid ammonia loss;
7. Collect the distillate in 20 mL 2.5 % boric acid. Keep the circuit working until there is 70 mL in the flask.
8. Titrate with 0.02N H₂SO₄ until the colour changes from green to violet.

Calculation

For 25 mL extract of 0.2 g soil from 50 mL

$$TN[\text{ mg/100g}] = TV \times 350$$

where $TV = \text{titration value}$

D.9 Exchangeable bases

Method

Metson (1956)

Reagents

- Ammonium acetate 77.08 g/L
- HNO_3 7M

Procedure

1. Weigh 5 g soil (< 2 mm fraction) in a plastic tube;
2. Add 30 mL of ammonium acetate to each sample and shake it for two hours;
3. Centrifuge it 10 min - 3000 T/min;
4. Collect the supernatant in a 100 mL flask;
5. Add 22 mL of ammonium acetate in each tube and unstick the pellet. Rinse gently the lid and the sides;
6. Centrifuge 10 min - 3000 T/min and collect the supernatant in the same 100 mL flask;
7. Repeat steps 5 and 6;
8. Fill up the 100 mL to the trait with ammonium acetate;
9. Filter through Whatman 602 H 1/2 filter paper;
10. Add 0.100 mL of HNO_3 if the samples are stored for more than 48 hours;
11. Prepare a blank;
12. Determine the exchangeable bases concentrations:
 - Mg
 - (a) 10x (25x) dilution: In a 25 mL flask, add 2.5 mL (1 mL) of extract, 5 mL $\text{SrCl}_2 \cdot 6\text{H}_2\text{O}$ (30.34 g/L, 10 000 ppm) and fill up to the trait with distilled water.
 - (b) Calibration curve (0 - 0.1 - 0.3 - 0.5 ppm): In a 25 mL flask, add 0 – 0.025 – 0.075 – 0.125 mL of 100 ppm Mg solution, 5 mL $\text{SrCl}_2 \cdot 6\text{H}_2\text{O}$ (30.34 g/L, 10 000 ppm), 2.5 mL (1 mL) ammonium acetate and fill up to the trait with distilled water.
 - (c) Calculation: Lecture $[\text{ mg/L}] \times 20 (50) = [\text{ mg/100g}] (*1/12 = \text{ meq/100g})$
 - K
 - (a) 5 x dilution (or direct analysis): In a 25 mL flask, add 5 mL of extract and fill up to the trait with distilled water (or analyse directly in the cove).
 - (b) Calibration curve (0 - 1 - 2 - 6 ppm): In a 25 mL flask, add 0 – 0.25 – 0.50 – 1.50 mL of 100 ppm K solution, 5 mL ammonium acetate and fill up to the trait with distilled water (or ammonium acetate if direct analysis).
 - (c) Calculation: Calculation: Lecture $[\text{ mg/L}] \times 10 (2) = [\text{ mg/100g}] (*1/39 = \text{ meq/100g})$

— Na

(a) 2.5x (10x) dilution: In a 25 mL flask, add 10 mL (2.5 mL) of extract, 5 mL KCl (19.1 g/L, 10 000 ppm) and fill up to the trait with distilled water.

(b) Calibration curve (0 – 0.5 – 1.0 – 2.0 ppm): In a 25 mL flask, add 0 – 0.125 – 0.25 – 0.5 mL of 100 ppm Na solution, 5 mL KCl (19.1 g/L, 10 000 ppm), 10 mL (2.5 mL) ammonium acetate and fill up to the trait with distilled water.

(c) Calculation: Lecture [mg/L] * 5 (20) = [mg/100g] (*1/23= meq/100g)

— Ca

(a) 100x (25x) dilution: In a 25 mL flask, add 0.25 mL (1 mL) of extract, 5 mL KCl (19.1 g/L, 10 000 ppm) and fill up to the trait with distilled water.

(b) Calibration curve (0 – 0.5 – 1.0 – 2.0 – 3.0 ppm): In a 25 mL flask, add 0 – 0.125 – 0.25 – 0.5 – 0.75 mL of 100 ppm Ca solution, 5 mL KCl (19.1 g/L, 10 000 ppm), 0.25 mL (1 mL) ammonium acetate and fill up to the trait with distilled water.

(c) Calculation Lecture [mg/L] * 200 (50) = [mg/100g] (*1/20= meq/100g)

Calculation

$$\% \text{Saturation} = \left(\sum (\text{Exchangeable bases} [\text{meq}/100\text{g}] \times 100) / \text{CEC} [\text{meq}/100\text{g}] \right)$$

D.10 Fe extraction (DCB)

Method

Mehra and Jackson (1958)

Reagents

— Extraction solution: dissolve 176 g of $\text{C}_6\text{H}_5\text{Na}_3\text{O}_7 \cdot 2\text{H}_2\text{O}$ (sodium citrate) and 21 g of NaHCO_3 in distilled water and make the volume up to 2 L.

— NaCl 1M: dissolve 58.44 g of NaCl in 1 L of distilled water.

Procedure

1. Weigh 1 g soil (< 2 mm fraction) in a plastic tube;
2. Add 40 mL of extraction solution;
3. Put in a 75 °C water bath;
4. Add 1 g $\text{Na}_2\text{S}_2\text{O}_4$, shake it and wait a few minutes;
5. Repeat step 4 twice and let the samples cool down;
6. Centrifuge them 10 min - 3000T/min;
7. Collect the supernatant in a 250 mL flask;
8. Rinse the tube with 25 mL NaCl 1M, centrifuge and collect the supernatant in the same 250 mL flask;
9. Repeat step 8 twice;
10. If the pellet is still red or brown coloured, repeat the procedure from step 2;

11. Fill up to 250 mL with distilled water;
12. Filter the solution through Whatman 602 H 1/2 filter paper;
13. Prepare a calibration curve for Fe estimation.
 - Small scale (0 – 0.5 – 3.0 ppm): In a 25 mL flask, add 0 – 0.125 – 0.750 mL of 100 ppm Fe solution, 4 mL (8 mL if double extraction) of solution A, 7.5 mL (15 mL if double extraction) of NaCl 1M and fill up to 25 mL with distilled water.
 - Big scale (0 - 15.0 – 50 – 100 – 200 ppm): In a 25 mL flask, add 0 – 0.375 – 1.250 – 2.500 – 5.000 mL of 1000 ppm Fe solution, 4 mL (8 mL if double extraction) of solution A, 7.5 mL (15 mL if double extraction) of NaCl 1M and fill up to 25 mL with distilled water.
14. Depending on sample concentration, the wave length must be adapted:
 - 0→15 ppm : 248.3 nm
 - 0→100 ppm : 372.0 nm
 - 0→200 ppm : 386.0 nm
15. Measure Fe concentration with AAS, do not wait for too long.

Calculation

$$C_{Fe}[\text{mg}/100\text{g}] = C_{AAS}[\text{mg}/\text{L}] \times 0.025$$

where C_{AAS} = Concentration obtained with AAS

D.11 Al, Fe and Mn extraction (Pyrophosphate)

Method

Mehra and Jackson (1958)

Reagents

- Extraction solution: dissolve 44.61 g of Na pyrophosphate per L of distilled water.
- Solution A: dissolve 44.61 g of Na pyrophosphate and 36 g of Na_2SO_4 per L of distilled water.

Procedure

1. Weigh 0.5 g soil (< 2 mm fraction) in a plastic tube;
2. Add 50 mL of extraction solution;
3. Shake the samples for 16 hours;
4. Add 1.8 g Na_2SO_4 and shake it;
5. Filter the solution through Whatman 602 H 1/2 filter paper;
6. Prepare a calibration curve for Fe, Al and Mn estimation.
 - Fe
 - Small scale (0 – 0.5 – 3.0 ppm): In a 25 mL flask, add 0 – 0.125 – 0.750 mL of 100 ppm Fe solution and fill up to 25 mL with solution A.
 - Big scale (0 - 15.0 – 50 – 100 – 200 ppm): In a 25 mL flask, add 0 – 0.375 – 1.250 – 2.500 – 5.000 mL of 1000 ppm Fe solution and fill up to 25 mL with solution A.

- Depending on sample concentration, the wave length must be adapted:
 - 0→15 ppm : 248.3 nm
 - 0→100 ppm : 372.0 nm
 - 0→200 ppm : 386.0 nm
- Al
 - Small scale (0 – 0.5 – 3.0 ppm): In a 25 mL flask, add 0 – 0.125 – 0.750 mL of 100 ppm Al solution and fill up to 25 mL with solution A.
 - Big scale (0 - 20 – 100 – 250 ppm): In a 25 mL flask, add 0 – 0.5 – 2.50 – 6.25 mL of 1000 ppm Al solution and fill up to 25 mL with solution A.
 - Wave length: 309.3 nm
- Mn
 - Small scale (0 – 0.5 – 3.0 - 5.0 ppm): In a 25 mL flask, add 0 – 0.125 – 0.750 - 1.250 mL of 100 ppm Mn solution and fill up to 25 mL with solution A.
 - Big scale (0 - 25 – 60 ppm): In a 25 mL flask, add 0 – 0.625 - 1.500 mL of 1000 ppm Mn solution and fill up to 25 mL with solution A.
 - Depending on sample concentration, the wave length must be adapted:
 - 0→5 ppm : 279.5 nm
 - 0→60 ppm : 403.1 nm

7. Measure Fe, Al and Mn concentrations with AAS, do not wait for too long.

Calculation

$$C_x [\text{mg}/100\text{g}] = C_{AAS} [\text{mg}/\text{L}] \times 0.01$$

where C_{AAS} = Concentration obtained with AAS

D.12 Aggregate separation

Method

Wet sieving (Six et al., 1998)

Macroaggregate separation (Six et al., 2000a).

Wet sieving

1. Weigh 80 g of air-dried soil (< 8 mm fraction);
2. Submerge the sample in water for five minutes, on top of a 2 mm-sieve and place a collecting bowl underneath;
3. Move the sieve up and down 50 times in two minutes, to allow water to come and go;
4. Rinse (bottom, walls, upper and lower side);
5. This part is not considered as SOM and therefore is not kept.
6. Transfer entirely water and particles from the first collecting bowl to a 250 μm -sieve;
7. Repeat step 3 and 4 with a new collecting bowl underneath;
8. Transfer what is remaining in the sieve to a new container of known weight and rinse thoughtfully the sieve in it. This part is made of macroaggregates.
9. Transfer entirely water and particles from the second collecting bowl to a 50 μm -sieve;

10. Repeat step 3 and 4 with a new collecting bowl underneath;
11. Transfer what is remaining in the sieve to a new container of known weight and rinse thoughtfully the sieve in it. This part is made of free microaggregates.
12. The particles remaining in the collecting bowl correspond to free silts and clays.
13. Dry the different fractions (macroaggregates, free microaggregates and free silts and clays) in an oven at 60 °C.
14. Weigh each fraction after drying.

Macroaggregate separation

1. Weigh 10 g of macroaggregate fraction, add 50 mL water and wait for 20 minutes;
2. In the meanwhile, prepare the circuit designed by Six et al. (2000a) and adapted by Joachim Tullii for Gembloux Agro-Bio Tech (Tullii, 2016):
 - Attach the column to the agitator;
 - Put the 50 μm -sieve in the sink;
 - Fix the tube to the funnel and to the sieve;
 - Introduce the smaller tube in the column, to bring water.
3. Open the tap and fill the column up to 2 cm (the tube should be filled with water and the water level constant);
4. Add 50 glass beads in the column and transfer the soil sample;
5. Thoughtfully rinse the sides, so all the soil is sieved;
6. Start the horizontal agitator and open the tap;
7. Keep the circuit working until water is clear in the tube (3-20 minutes), then stop the agitator and the water circuit;
8. Rinse the sides of the column;
9. Empty and rinse the tube on the 50 μm -sieve;
10. Sieve the rest of the soil on the 50 μm -sieve (50 movements up and down in 2 minutes);
11. Transfer what is remaining on the sieve in a container of known weight and thoughtfully rinse. This part corresponds to the protected microaggregates.
12. Transfer what is in the column (50-250 μm) in a container of known weight and thoughtfully rinse. This part is composed of sands and organic matter.
13. Dry the different fractions in an oven at 60 °C.
14. Weigh each fraction after drying.

Sodium hexametaphosphate dispersion

1. Weigh 1 g of protected microaggregates (or the quantity you have, minimum 0.5 g) in a pH tube and note the weight;
2. Add 15 mL sodium hexametaphosphate 0.5% (5 g/L) and 10 glass beads and place the tubes on a horizontal agitator for 18 hours;
3. Transfer the samples on the 50 μm -sieve;
4. Rinse the sieve thoughtfully with water and transfer the sands (the part which remains on the sieve) to a container of known weight.
5. Dry the containers in an oven at 60 °C
6. Weight the container after drying

Calculation

In order to calculate the percentages of different aggregate sizes, the sand particles from the same diameter have to be removed:

$$\text{Aggregates}[\%] = \frac{\text{Fraction}[\text{g}] - \text{Sand of the same size}[\text{g}]}{\text{Sum of the fractions without sand}[\text{g}]}$$

This equation is valid for both macroaggregates and free microaggregates. The sand particle weights are obtained by grain size distribution. This leads to an overestimation of microaggregates and an underestimation of macroaggregates, since a 250 μm -sieve is used for aggregate fractionation whereas a 200 μm -sieve is used for grain size distribution.

Sodium hexametaphosphate dispersion gives composition of protected microaggregates. Indeed, their sand percentage differs from bulk soil. The following equation is used to calculate protected microaggregates percentage:

$$\text{Protected microaggregates}[\%] = \frac{\text{Protected microaggregates}[\text{g}] - (50 - 250 \mu\text{m}) \text{ sands}[\text{g}]}{\text{Macroaggregates}[\text{g}] - (250 - 2000 \mu\text{m}) \text{ sands}[\text{g}]}$$

D.13 Retention curve

Sampling

Undisturbed soil samples of 100 cm^3 are taken in the field and the bed sites. In the field, two samples from bare zones and two samples from zones covered with mulch are taken. In the bed site, two samples are collected in covered zones, as there is no bare soil.

The first 3 cm of soil are removed before putting the metallic ring in the soil. After having removed the ring containing the soil sample, its volume is adjusted to 100 cm^3 . The samples are conserved in plastic bags until analysis.

Pressure extractor

After saturation, soil samples are placed in a pressure plate extractor. The pressure is gradually increased and the weight of the sample is measured between two pressure levels (Table D.2). After the highest pressure, the samples are dried in an oven at 120 $^{\circ}\text{C}$ for 24 hours before weighting.

Table D.2: Calendar of pressure extractor

Date	May 9	May 12	May 15	May 18	May 21	May 24	May 29	June 5	June 15
Pressure [cm]	10	40	70	100	300	700	1000	5000	15000
Number of days	3	3	3	3	3	5	7	10	21

Calculation

Bulk density (ρ_b) is calculated by:

$$\rho_b = M_d/V_t \quad (\text{D.1})$$

where M_d is the dry mass of the sample and V_t is the total volume of the sample (100 cm^3). For each pressure lever, volumetric water content (WC) is calculated by:

$$\text{WC} = (M - M_d) \times \rho_w/V_t \quad (\text{D.2})$$

where M is the mass at the considered pressure and ρ_w water density. The retention curve is obtained by plotting water content depending on pressure as logarithm ($pF = \log_{10}(P[cm])$). According to Ruiz-Colmenero et al. (2013), macropores are comprised between pF 0 and 1.8, mesopores between 1.8 and 2.54 and micropores over 2.54.

Appendix E

Retention curve results

One sample from the beds could not be used because it contained a taro tuber, and thus had a different behaviour. The retention curve of the other samples (one from the beds, four from the field) has been adjusted using RETC program. Van Genuchten gave the best results for the field samples, whereas Brooks and Corey was preferred for bed sample (Table E.1). Moisture conditions were not optimal, since the last rainfall occurred more than a month before the sampling. There are no significant differences between the sites. A longer experiment could have lead to different results.

Table E.1: Adjustment parameters. RWC is the residual water content, SWC the water content at saturation, α a parameter corresponding to the air entry point and n a shape parameter. The second shape parameter, m , is estimated by $m = 1 - 1/n$

Sample	RWC (θ_r)	SWC (θ_s)	α	n
Bed	0.08 (0.06-0.10)	0.58 (0.55-0.61)	0.21 (0.15-0.26)	0.68 (0.51-0.86)
Field (bare 1)	0.05 (0.04-0.06)	0.43 (0.41-0.44)	0.14 (0.11-0.18)	1.54 (1.46-1.63)
Field (bare 2)	0.03 (0.00-0.05)	0.42 (0.41-0.44)	0.27 (0.14-0.39)	1.37 (1.27-1.47)
Field (mulch 1)	0.06 (0.04-0.08)	0.43 (0.40-0.46)	0.08 (0.04-0.11)	1.87 (1.57-2.18)
Field (mulch 2)	0.06 (0.05-0.07)	0.43 (0.41-0.44)	0.13 (0.10-0.16)	1.75 (1.62-1.88)

Appendix F

Raw data

XXXX

Code	Site	Modality	Crop	Sampling date	Sampling depth [cm]	GPS Coordinates	Volume [cm ³]	Soil dry weight [g]	Weight at a pressure [cm] of								
									10	40	70	100	300	700	1000	5000	15000
O1	Field	Compost	Pumpkins	25-04-17	5	11°59'06.7" N 79°47'18.2" E	100	153.4	184.7	173.4	168.9	166.2	163.1	161.6	160.5	159.3	158.5
O4	Field	Jiwamrita	Pumpkins	26-04-17	5	11°59'06.7" N 79°47'18.2" E	100	159.4	187.4	179.4	175.8	173.5	169.6	167.2	166.3	165	164.5
O6	Field	None	Pumpkins	27-04-17	5	11°59'06.7" N 79°47'18.2" E	100	147.1	183.5	164.3	161.9	159.9	157.2	155	154.1	152.8	152.3
O9	Field	None	Pumpkins	28-04-17	5	11°59'06.7" N 79°47'18.2" E	100	158.1	188.4	173.4	170.6	169.3	167.1	165.5	164.9	163.8	163.4
B7	Beds	Compost	Tapioca	29-04-17	3	11°59'06.7" N 79°47'18.2" E	100	111.3	150.2	130.2	127.5	125.7	124.5	122.6	121	119.5	118.5
B14	Beds	Compost	Taro	30-04-17	3	11°59'06.7" N 79°47'18.2" E	100	115.4	169.9	155.6	154	152.8	151	149.7	148.7	147.4	145.3

Figure F.1: Retention data

Composite	Site	Material	Modality	Fe (DCB) g/kg	Fe (pyro) g/kg	Mn (pyro) g/kg	Macroaggregates % of sand-free fraction	Free microaggregates % of sand-free fraction	Free silt and clay % of sand-free fraction	Protected microaggregates % of macroaggregates
1	Bed	Soil	None	4.9	0.07	0.07	45.8%	0.0%	54.2%	11.6%
2	Bed	Soil	Compost	4.9	0.10	0.09	30.4%	14.5%	55.1%	14.8%
3	Bed	Soil	Jimwarita	4.6	0.08	0.06	48.0%	0.0%	52.0%	13.5%
4	Bed	Termites	None	5.1	0.08	0.11	35.3%	10.5%	54.2%	9.9%
5	Bed	Termites	Compost	7.4	0.09	0.09	1.0%	28.3%	70.7%	10.6%
6	Bed	Termites	Jimwarita	8.9	0.10	0.09	26.4%	11.5%	62.1%	14.4%
7	Open field	Soil	None	4.6	0.05	0.04	8.0%	30.8%	61.2%	2.3%
8	Open field	Soil	Compost	4.4	0.06	0.05	0.0%	56.5%	43.5%	2.3%
9	Open field	Soil	Jimwarita	5.2	0.06	0.05	4.3%	26.9%	68.8%	2.3%
10	Open field	Termites	Compost	10.4	0.11	0.08	6.6%	23.2%	70.2%	9.8%
11	Open field	Termites	Jimwarita	7.4	0.09	0.07	28.7%	13.2%	58.2%	15.2%
12	Fallow land	Soil	None	7.1	0.09	0.07	0.0%	33.2%	66.8%	3.1%
13	Fallow land	Soil	Compost	6.5	0.01	0.05	0.0%	37.9%	62.1%	3.5%
14	Fallow land	Soil	Jimwarita	6.4	0.11	0.12	8.1%	19.8%	72.1%	6.0%
15	Fallow land	Termites	Compost	6.2	0.11	0.07	0.0%	40.5%	59.5%	1.3%
16	Fallow land	Termites	Jimwarita	7.6	0.11	0.11	30.6%	7.3%	62.1%	2.4%

Figure F.2: Composite data

	Code	Zone	Material	Modality	Replicate	water-pH	CaCl2-pH	Av K	Av Ca	Av Mg	OC	CEC	P dis	TN	Mg éch	Exch K	Exch Na	Exch Ca	Exch. Bases	TSB
								mg/100g	mg/100g	mg/100g	%	meq/100g	mg/100g	%	mg/100g	mg/100g	mg/100g	mg/100g	meq/100g	%
1	BS1	Bed	Soil	None	1	6.3	4.7	4.5	116	9.9	0.49	2.31	14.5	0.98	13.1	5.7	8.0	85.9	5.88	100
2	BS2	Bed	Soil	Compost	1	6.4	5.2	6.1	96	14.9	1.17	3.79	9.5	0.49	15.7	26.2	8.2	81.9	6.43	100
3	BS3	Bed	Soil	Jiwamrita	1	6.1	5.2	5.9	78	13.7	0.68	1.94	8.4	4.20	9.3	7.8	8.5	54.9	4.09	100
4	BS4	Bed	Soil	None	2	6.4	5.3	6.2	136	7.5	1.37	6.01	15.1	0.56	13.5	74.8	7.6	125.2	9.64	100
5	BS5	Bed	Soil	Compost	2	6.2	5.3	6.0	118	11.2	1.46	2.87	17.6	0.28	13.8	7.1	7.8	101.1	6.73	100
6	BS6	Bed	Soil	Jiwamrita	2	6.2	5.4	7.0	108	7.5	1.07	3.24	19.1	0.49	8.2	7.2	8.7	82.5	5.37	100
7	BS7	Bed	Soil	None	3	6.2	5.5	6.8	110	9.9	0.98	1.94	25.6	0.35	8.2	5.3	8.8	96.7	6.04	100
8	BS8	Bed	Soil	Compost	3	6.3	5.5	12.2	104	8.7	0.98	2.50	21.4	0.35	7.3	11.5	8.7	87.9	5.67	100
9	BS9	Bed	Soil	Jiwamrita	3	6.2	5.4	7.0	100	0.0	0.88	1.39	16.4	0.35	8.8	7.1	8.4	77.9	5.18	100
10	BT1	Bed	Termites	None	1	6.2	5.7	24.6	104	19.9	2.05	5.00	18.9	0.56	13.0	68.1	9.7	95.9	8.05	100
11	BT2	Bed	Termites	Compost	1	6.2	5.6	43.9	96	19.9	1.27	7.59	24.1	0.49	10.3	11.1	9.3	76.4	5.37	71
12	BT3	Bed	Termites	Jiwamrita	1	6.5	5.8	48.8	84	22.4	1.17	5.09	10.9	0.49	9.5	72.4	9.4	68.5	6.48	100
13	BT8	Bed	Termites	Compost	3	6.7	5.7	36.6	96	12.4	1.37	3.70	11.8	0.42	19.4	9.0	8.9	86.9	6.58	100
14	BT9	Bed	Termites	Jiwamrita	3	6.4	5.8	35.7	112	11.2	1.76	4.81	30.7	0.49	19.6	8.5	8.8	108.9	7.68	100
15	OS1	Field	Soil	Compost	1	6.0	5.6	8.3	50	2.5	0.39	2.78	9.2	0.14	5.1	11.1	7.2	32.3	2.64	95
16	OS2	Field	Soil	Jiwamrita	1	5.5	4.8	5.5	140	8.7	0.49	2.96	1.7	0.91	4.9	6.7	6.2	19.9	1.85	62
17	OS3	Field	Soil	Compost	2	5.7	5.1	6.8	40	7.5	0.78	2.59	7.8	0.28	5.3	9.3	6.5	31.8	2.55	99
18	OS4	Field	Soil	Jiwamrita	2	5.2	4.9	5.3	34	11.2	0.29	2.68	4.0	0.21	4.3	6.2	7.0	18.3	1.74	65
19	OS5	Field	Soil	Compost	3	5.6	5.2	7.2	60	8.7	0.10	2.59	7.4	0.14	5.4	9.8	7.3	37.0	2.87	100
20	OS6	Field	Soil	None	1	5.1	5.0	3.9	40	8.7	0.19	2.31	4.2	0.21	4.8	4.3	5.5	21.3	1.81	78
21	OS7	Field	Soil	Jiwamrita	3	5.6	5.2	5.2	44	5.0	0.19	2.59	7.6	0.28	5.1	6.3	5.9	30.9	2.39	92
22	OS8	Field	Soil	None	2	5.1	4.9	5.9	40	6.2	0.10	3.15	2.1	0.21	4.7	7.0	6.6	19.2	1.82	58
23	OS9	Field	Soil	None	3	5.0	4.9	3.3	38	7.5	0.29	2.59	2.5	0.35	4.5	4.1	6.3	19.9	1.75	68
24	OT1	Field	Termites	Compost	1	6.4	5.7	38.3	56	17.4	0.88	3.61	13.2	0.42	14.3	47.0	13.8	39.3	4.96	100
25	OT3	Field	Termites	Compost	2	6.5	5.9	47.1	74	16.2	1.85	4.07	16.2	0.14	20.2	68.2	5.4	49.1	6.12	100
26	OT4	Field	Termites	Jiwamrita	2	6.7	6.0	49.7	52	12.4	0.78	3.33	11.4	0.42	20.4	84.2	11.8	30.5	5.90	100
27	OT5	Field	Termites	Compost	3	6.6	5.9	49.5	80	11.2	1.76	4.16	19.9	0.49	26.7	90.1	10.5	55.9	7.79	100
28	OT7	Field	Termites	Jiwamrita	3	6.6	5.8	32.5	56	6.2	1.37	3.52	4.3	0.35	14.4	46.8	10.0	34.8	4.57	100
29	FS1	Fallow	Soil	None	1	5.4	5.1	5.5	80	9.9	0.59	4.72	3.8	0.42	11.7	7.9	6.3	50.2	3.96	84
30	FS2	Fallow	Soil	Compost	1	4.9	4.5	5.2	76	9.9	0.49	4.53	7.4	0.35	11.8	8.3	7.3	51.3	4.08	90
31	FS3	Fallow	Soil	Jiwamrita	1	4.7	4.6	4.9	68	12.4	0.68	4.44	7.6	0.28	9.5	3.4	6.6	51.0	3.72	84
32	FS4	Fallow	Soil	Compost	2	4.6	4.7	6.0	84	8.7	0.68	4.63	10.1	0.28	10.3	4.9	5.8	56.3	4.05	88
33	FS5	Fallow	Soil	None	2	4.8	4.7	6.3	90	5.0	0.88	4.63	7.6	0.35	10.0	4.4	5.2	55.3	3.94	85
34	FS6	Fallow	Soil	None	3	4.8	4.7	5.8	108	9.9	0.98	4.90	8.8	0.35	12.5	3.9	5.5	61.3	4.44	91
35	FS7	Fallow	Soil	Jiwamrita	2	4.7	4.7	5.5	96	12.4	0.88	3.98	9.5	0.35	9.3	4.1	6.3	47.3	3.52	88
36	FS8	Fallow	Soil	Jiwamrita	3	4.5	4.6	4.5	104	7.5	0.68	4.63	6.1	0.28	9.8	3.1	6.2	56.9	4.02	87
37	FS9	Fallow	Soil	Compost	3	4.5	4.6	5.6	110	6.2	0.59	4.44	7.6	0.35	12.6	4.6	6.3	73.3	5.10	100
38	FT2	Fallow	Termites	Compost	1	6.1	6.0	56.4	102	13.7	1.37	3.05	20.6	0.56	21.0	38.1	14.1	68.2	6.75	100
39	FT3	Fallow	Termites	Jiwamrita	1	6.0	5.9	45.3	86	11.2	1.56	4.63	16.0	0.42	15.8	30.7	10.3	53.5	5.23	100
40	FT4	Fallow	Termites	Compost	2	6.4	6.0	49.6	116	13.7	1.85	3.89	22.3	0.56	23.3	41.5	13.1	73.4	7.24	100
41	FT7	Fallow	Termites	Jiwamrita	2	6.4	5.9	47.4	88	9.9	1.56	5.92	16.0	0.42	17.4	32.8	14.1	54.6	5.64	95
42	FT8	Fallow	Termites	Jiwamrita	3	6.3	5.9	47.3	114	13.7	1.46	5.00	13.4	0.49	24.0	34.3	11.8	65.4	6.66	100
43	FT9	Fallow	Termites	Compost	3	6.5	6.0	56.6	90	36.0	1.76	4.81	25.2	0.49	26.0	38.0	9.8	88.4	7.99	100

Figure F.3: Lab data

	Site	Modality	Material	Clay	Fine silt	Coarse silt	Total silt	Fine sand	Coarse sand	Total sand
BS1	Bed	None	Soil	6.25	2.21	2.94	5.15	22.93	65.68	88.60
BS2	Bed	Compost	Soil	7.35	2.57	2.94	5.51	19.27	67.86	87.14
BS3	Bed	Jiwamrita	Soil	6.56	2.19	2.91	5.10	23.37	64.97	88.34
BT8	Bed	Compost	Termites	8.44	1.84	2.57	4.41	21.04	66.11	87.15
BT9	Bed	Jiwamrita	Termites	9.32	2.61	2.98	5.59	19.14	65.95	85.09
OS1	Field	Compost	Soil	5.80	2.54	2.18	4.71	20.58	68.90	89.48
OS2	Field	Jiwamrita	Soil	6.47	1.80	3.24	5.03	27.49	61.00	88.49
OS9	Field	None	Soil	7.55	1.80	3.23	5.03	24.65	62.77	87.42
OT1	Field	Compost	Termites	16.06	1.82	2.55	4.38	19.28	60.28	79.57
FS1	Fallow land	None	Soil	10.20	2.55	4.01	6.56	24.48	58.76	83.24
FS4	Fallow land	Compost	Soil	10.87	2.54	3.99	6.52	21.79	60.82	82.61
FS7	Fallow land	Jiwamrita	Soil	10.55	2.91	3.64	6.55	23.00	59.90	82.90
FT4	Fallow land	Compost	Termites	11.43	3.69	3.69	7.38	21.94	59.25	81.19
FT7	Fallow land	Jiwamrita	Termites	14.28	4.03	4.03	8.06	25.27	52.39	77.66

Figure F.4: Grain size data

Bibliography

- Abe, S. S. and Wakatsuki, T. (2010). Possible influence of termites (*Macrotermes bellicosus*) on forms and composition of free sesquioxides in tropical soils. *Pedobiologia*, 53(5):301–306.
- Angers, D., Recous, S., and Aita, C. (1997). Fate of carbon and nitrogen in water-stable aggregates during decomposition of ¹³C¹⁵N-labelled wheat straw in situ. *European Journal of Soil Science*, 48(2):295–300.
- Awadzi, T. W., Cobblah, M. A., and Breuning-Madsen, H. (2004). The Role of Termites in Soil Formation in the Tropical Semi-Deciduous Forest Zone, Ghana. *Geografisk Tidsskrift*, 104(2):27–34.
- Bagine, R. K. (1984). Soil translocation by termites of the genus *Odontotermes* (Holmgren) (Isoptera: Macrotermitinae) in an arid area of Northern Kenya. *Oecologia*, 64(64):263–266.
- Balasubramani, K., Veena, M., Kumaraswamy, K., and Saravanabavan, V. (2015). Estimation of soil erosion in a semi-arid watershed of Tamil Nadu (India) using revised universal soil loss equation (rusle) model through GIS. *Modeling Earth Systems and Environment*, 1(3):10.
- Baldwin, G. and Declercq, B. (2011). *Auroville Farms, Forests and Botanical Gardens | Auroville*. Prisma, Auroville.
- Ball-Coelho, B. R., Roy, R. C., and Swanton, C. J. (2000). Tillage and cover crop impacts on aggregation of a sandy soil. *Canadian Journal of Soil Science*, 80(2):363–366.
- Basappa, H. and Rajagopal, D. (1990). Physico-chemical properties of termite modified soils due to foraging on dung in comparison with surrounding soils. *Sociobiology*, 16(3):275–284.
- Bascomb, C. L. (1968). Distribution of pyrophosphate-extractable iron and organic carbon in soils of various groups. *European Journal of Soil Science*, 19(2):251–268.
- Batjes, N. H. (1996). Total carbon and nitrogen in the soils of the world. *European Journal of Soil Science*, 47:151–163.
- Bayer, C., Martin-Neto, L., Mielniczuk, J., Pillon, C., and Sangoi, L. (2001). Changes in soil organic matter fractions under subtropical no-till cropping systems. *Soil Science Society of America Journal*, 65:1473–1478.
- Bignell, D. E. and Eggleton, P. (2000). Termites in ecosystems. In *Termites: Evolution, Sociality, Symbioses, Ecology*, chapter 17, pages 363–387. Kluwer Academic Publishers.
- Blanco-Canqui, H. (2013). Crop Residue Removal for Bioenergy Reduces Soil Carbon Pools: How Can We Offset Carbon Losses? *BioEnergy Research*, 6(1):358–371.
- Blanco-Canqui, H. and Lal, R. (2010). Soil resilience and conservation. In *Principles of soil conservation and management*, chapter 16, pages 425–447. Blanco-Canqui, H Lal, R., springer edition.
- Bottinelli, N., Jouquet, P., Capowiez, Y., Podwojewski, P., Grimaldi, M., and Peng, X. (2015). Why is the influence of soil macrofauna on soil structure only considered by soil ecologists? *Soil and Tillage Research*, 146:118–124.
- Bray, R. H. and Kurtz, L. T. (1945). Determination of total, organic and available forms of phosphorus. *Soil Science*, 59(1):39–46.
- Bremner, J. and Mulvaney, C. (1996). Nitrogen-total. Methods of soil analysis. Part 2, chemical and microbiological. *The Soil Science Society of America*, 9(2):595–624.
- Bronick, C. J. and Lal, R. (2005). Soil structure and management: A review. *Geoderma*, 124(1-2):3–22.
- Brune, A. (1998). Termite guts: The world's smallest bioreactors. *Trends in Biotechnology*, 16(1):16–21.

- Cammeraat, L. H. and Imeson, A. C. (1998). Deriving indicators of soil degradation from soil aggregation studies in southeastern Spain and southern France. *Geomorphology*, 23(2-4):307–321.
- Chhotani, O. (1997). *Fauna of India: Isoptera (Termites) Volume II*. Zoological Survey of India, Calcutta.
- Chinery, M. (2012). *Insectes de France et d'Europe occidentale*. Flammarion edition.
- Collins, N. M. (1980). The effect of logging on termite (Isoptera) diversity and decomposition processes in lowland tropical forests. In Furtado, J. I., editor, *Tropical ecology and development.*, pages 113–121. International Society of Tropical Ecology, Kuala Lumpur, Malaysia.
- Collins, N. M. (1981). The role of termites in the decomposition of wood and leaf litter in the Southern Guinea savanna of Nigeria. *Oecologia*, 51(3):389–399.
- Dawes, T. Z. (2010). Reestablishment of ecological functioning by mulching and termite invasion in a degraded soil in an Australian savanna. *Soil Biology and Biochemistry*, 42(10):1825–1834.
- Decaëns, T., Jiménez, J., Gioia, C., Measey, G., and Lavelle, P. (2006). The values of soil animals for conservation biology. *European Journal of Soil Biology*, 42:S23–S38.
- Devine, S., Markewitz, D., Hendrix, P., and Coleman, D. (2014). Soil aggregates and associated organic matter under conventional tillage, no-tillage, and forest succession after three decades. *Plos One*, 9(1).
- Donovan, S. E., Eggleton, P., Dubbin, W. E., Batchelder, M., and Dibog, L. (2001). The effect of a soil-feeding termite, *Cubitermes fungifaber* (Isoptera: Termitidae) on soil properties: termites may be an important source of soil microhabitat heterogeneity in tropical forests. *Pedobiologia*, 45:1–11.
- Doran, J. W. and Zeiss, M. R. (2000). Soil health and sustainability: managing the biotic component of soil quality. *Applied Soil Ecology*, 15:3–11.
- Edwards, A. P. and Bremner, J. M. (1967). Microaggregates in soil. *Journal of Soil Science*, 18(1):64–73.
- Emerson, W. W. (1959). The structure of soil crumbs. *Journal of Soil Science*, 10(2):235–244.
- Erens, H., Mujinya, B. B., Mees, F., Baert, G., Boeckx, P., Malaisse, F., and Van Ranst, E. (2015). The origin and implications of variations in soil-related properties within *Macrotermes falciger* mounds. *Geoderma*, 249-250:40–50.
- Eschenbrenner, V. (1986). Contribution des termites à la microagrégation des sols tropicaux. *Cahiers ORSTOM.Série Pédologie*, 22(4):397–408.
- Evans, T. A., Dawes, T. Z., Ward, P. R., and Lo, N. (2011). Ants and termites increase crop yield in a dry climate. *Nature Communications*, 2:262.
- Evans, T. A. and Iqbal, N. (2015). Termite (order Blattodea, infraorder Isoptera) baiting 20 years after commercial release. *Pest Management Science*, 71(7):897–906.
- FAO (1990). Guidelines for Soil Profile Description (3d edition). Technical report, Food and Agriculture Organisation of the United Nations, Rome.
- Ferrar, P. and Watson, J. A. L. (1970). Termites (Isoptera) Associated With Dung in Australia. *Australian Journal of Entomology*, 9(2):100–102.
- Freyman, B. P., Buitenwerf, R., Desouza, O., and Olf, H. (2008). The importance of termites (isoptera) for the recycling of herbivore dung in tropical ecosystems: A review. *European Journal of Entomology*, 105(2):165–173.
- Gao, G. and Chang, C. (1996). Changes in CEC and particle size distribution of soils associated with long-term annual applications of cattle feedlot manure. *Soil Science*, 161(2):115–120.
- Helling, C. S., Chesters, G., and Corey, R. B. (1964). Contribution of Organic Matter and Clay to Soil Cation-Exchange Capacity as Affected by the pH of the Saturating Solution. *Soil Science Society of America Journal*, 28(4):517.
- Herrick, J. and Wander, M. (1997). Relationships between soil organic carbon and soil quality in cropped and rangeland soils: the importance of distribution, composition, and soil biological activity. In Lal, R., Kimble, J. M., Follett, R. F., and Stewart, B. A., editors, *Soil Processes and the Carbon Cycle*, chapter 28. Advances in Soil Science, crc press edition.
- Herrick, J. E. (2000). Soil quality: An indicator of sustainable land management? *Applied Soil Ecology*, 15(1):75–83.
- Herrick, J. E. and Lal, R. (1996). Dung decomposition and pedoturbation in a seasonally dry tropical pasture. *Biology and Fertility of Soils*, 23(2):177–181.

- Higashi, M., Yamamura, N., and Abe, T. (2000). Theories on the Sociality of Termites. In *Termites: Evolution, Sociality, Symbioses, Ecology*, pages 169–187. Springer Netherlands, Dordrecht.
- Hole, F. D. (1981). Effects of animals on soil. *Geoderma*, 25(1-2):75–112.
- IHSS (2007). What are humic substances.
- IS 2720-22 (1972). *Methods of test for soils, Part 22: Determination of Organic Matter*. Indian Standard, New Dehli.
- Jones, D. T. and Eggleton, P. (2000). Sampling termite assemblages in tropical forests: Testing a rapid biodiversity assessment protocol. *Journal of Applied Ecology*, 37(1):191–203.
- Jouquet, P., Blanchart, E., and Capowiez, Y. (2014). Utilization of earthworms and termites for the restoration of ecosystem functioning. *Applied Soil Ecology*, 73:34–40.
- Jouquet, P., Bottinelli, N., Lata, J. C., Mora, P., and 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(1-2):127–133.
- Jouquet, P., Bottinelli, N., Shanbhag, R. R., Bourguignon, T., Traoré, S., and Abbasi, S. A. (2016a). Termites: The Neglected Soil Engineers of Tropical Soils. *Soil Science*, 181(3/4):157–165.
- Jouquet, P., Chintakunta, S., Bottinelli, N., Subramanian, S., and Caner, L. (2016b). The influence of fungus-growing termites on soil macro and micro-aggregates stability varies with soil type. *Applied Soil Ecology*, 101:117–123.
- Jouquet, P., Dauber, J., Lagerlöf, J., Lavelle, P., and Lepage, M. (2006). Soil invertebrates as ecosystem engineers: Intended and accidental effects on soil and feedback loops. *Applied Soil Ecology*, 32(2):153–164.
- Jouquet, P., Guilleux, N., Chintakunta, S., Mendez, M., Subramanian, S., and Shanbhag, R. R. (2015). The influence of termites on soil sheeting properties varies depending on the materials on which they feed. *European Journal of Soil Biology*, 69:74–78.
- Jouquet, P., Lepage, M., and Velde, B. (2002). Termite soil preferences and particle selections: Strategies related to ecological requirements. *Insectes Sociaux*, 49(1):1–7.
- Jouquet, P., Tessier, D., and Lepage, M. (2004). The soil structural stability of termite nests: Role of clays in *Macrotermes bellicosus* (Isoptera, Macrotermitinae) mound soils. *European Journal of Soil Biology*, 40(1):23–29.
- Jouquet, P., Traoré, S., Choosai, C., Hartmann, C., and Bignell, D. (2011). Influence of termites on ecosystem functioning. Ecosystem services provided by termites. *European Journal of Soil Biology*, 47(4):215–222.
- Jungerius, P. D., Van Den Ancker, J. A. M., and Múcher, H. J. (1999). The contribution of termites to the microgranular structure of soils on the Uasin Gishu Plateau, Kenya. *Catena*, 34(3-4):349–363.
- Kaiser, D., Lepage, M., Konate, S., and Linsenmair, K. E. (2017). Ecosystem services of termites (Blattoidea: Termitoidea) in the traditional soil restoration and cropping system Zai in northern Burkina Faso (West Africa). *Agriculture, Ecosystems and Environment*, 236:198–211.
- Kay, B. D., da Silva, A. P., and Baldock, J. A. (1997). Sensitivity of soil structure to changes in organic carbon content: Predictions using pedotransfer functions. *Canadian Journal of Soil Science*, 77(4):655–667.
- Klotzbücher, T., Kaiser, K., Guggenberger, G., Gatzek, C., and Kalbitz, K. (2017). A new conceptual model for the fate of lignin in decomposing plant litter. *Ecology*, 92(5):1052–1062.
- Lal, R. (1997). Degradation and resilience of soils. *Philosophical Transactions of the Royal Society B: Biological Sciences*, 352(1356):997–1010.
- Lavelle, P. (1997). Faunal Activities and Soil Processes: Adaptive Strategies That Determine Ecosystem Function. *Advances in Ecological Research*, 27(C):93–132.
- Lavelle, P., Barros, E., Blanchart, E., Brown, G., Desjardins, T., Mariani, L., and Rossi, J. P. (2001). SOM management in the tropics: Why feeding the soil macrofauna? *Nutrient Cycling in Agroecosystems*, 61(1-2):53–61.
- Lavelle, P., Blanchart, E., Martin, A., Spain, A. V., and Martin, S. (1992). Impact of Soil Fauna on the Properties of Soils in the Humid Tropics. In *Myths and Science of Soils of the Tropics*, chapter 9, pages 157–185. Soil Science Society of American and American Society of Agronomy, Madison.
- Lavelle, P. and Kohlmann, B. (1984). Etude quantitative de la macrofaune du sol dans une forêt tropicale humide du Mexique (Bonampak, Chiapas). *Pedobiologia*, 27:377–393.

- Lehmann, J., Kinyangi, J., and Solomon, D. (2007). Organic matter stabilization in soil microaggregates: Implications from spatial heterogeneity of organic carbon contents and carbon forms. *Biogeochemistry*, 85(1):45–57.
- Lehmann, J. and Kleber, M. (2015). The contentious nature of soil organic matter. *Nature*, 528:60–8.
- Léonard, J. and Rajot, J. L. (2001). Influence of termites on runoff and infiltration: Quantification and analysis. *Geoderma*, 104:17–40.
- Lobry de Bruyn, A. L. and Conacher, A. J. (1990). The role of termites and ants in soil modification: A review. *Australian Journal of Soil Research*, 28(1):55–93.
- Malaisse, F. (1978). High termitaria. In Werger, M. J. A., editor, *Monographiae Biologicae 31*, pages 1279–1300. Springer, Dordrecht.
- Mando, A. and Brussaard, L. (1999). Contribution of termites to the breakdown of straw under Sahelian conditions. *Biology and Fertility of Soils*, 29(3):332–334.
- Mando, A., Stroosnijder, L., and Brussaard, L. (1996). Effects of termites on infiltration into crusted soil. *Geoderma*, 74:107–113.
- Mehra, O. and Jackson, M. (1958). Iron oxide removal from soils and clays by a dithionite-citrate system buffered with sodium bicarbonate. In Swineford, A., editor, *National conference on clays and clay minerals*, pages 317–327, Washington DC. Pergamon Press.
- Metson, A. (1956). Methods of chemical analysis for soil survey samples Bull NZ Dept. *Scient. Md Res. Soil Bur*, 12.
- Mora, P., Seuge, C., Chotte, J., and Rouland, C. (2003). Physico-chemical typology of the biogenic structures of termites and earthworms: a comparative analysis. *Biology and Fertility of Soils*, 37:245–249.
- Mujinya, B. B., Mees, F., Erens, H., Dumon, M., Baert, G., Boeckx, P., Ngongo, M., and Van Ranst, E. (2013). Clay composition and properties in termite mounds of the lubumbashi area, D.R. congo. *Geoderma*, 192(1):304–315.
- Nutting, W., Haverty, M., and LaFage, J. (1987). Physical and chemical alteration of soil by two subterranean termite species in Sonoran Desert grassland. *Journal of Arid Environments*, 12:233–239.
- Nye, P. H. (1954). Some soil-forming processes in the humid tropics I. A field study of a catena in the West African forest. *Journal of Soil Science*, 5(1).
- Nye, P. H. (1955). Some soil-forming processes in the humid tropics: IV. The action of the soil fauna. *Journal of Soil Science*, 6(1):73–83.
- Oades, J. and Waters, A. (1991). Aggregate hierarchy in soils. *Australian Journal of Soil Research*, 29(6):815.
- Oades, J. M. (1984). Soil organic matter and structural stability: mechanisms and implications for management. In *Biological Processes and Soil Fertility*, pages 319–337. Springer Netherlands, Dordrecht.
- Olsen, S. (1954). Estimation of available phosphorus in soils by extraction with sodium bicarbonate. *Circular US department of agriculture*, 939.
- Pardeshi, M. and Prusty, B. A. K. (2010). Termites as ecosystem engineers and potentials for soil restoration. *Current Science*, 99(1):11.
- Parfitt, R., Giltrap, D., and Whitton, J. (1995). Contribution of organic matter and clay minerals to the cation exchange capacity of soils. *Communications in Soil Science and Plant Analysis*, 26(9-10):1343–1355.
- Pathak, R. K. and Ram, R. (2013). Bio-enhancers: A potential tool to improve soil fertility, plant health in organic production of horticultural crops. *Progressive Horticulture*, 45(2):237–254.
- Peel, M. C., Finlayson, B. L., and McMahon, T. A. (2007). Updated world map of the Köppen-Geiger climate classification. *HESSD Earth Syst. Sci. Discuss*, 4(4):439–473.
- Piccolo, A. (2001). the Supramolecular Structure of Humic Substances. *Soil Science*, 166(11):810–832.
- Pleysier, J. and Juo, A. (1980). A single-extraction method using silver-thiourea for measuring exchangeable cations and effective CEC in soils with variable charges. *Soil Science*.
- Post, W. and Kwon, K. (2000). Soil carbon sequestration and land-use change: processes and potential. *Global Change Biology*, 6:317–327.
- Rasmussen, P. E., Allmaras, R. R., Rohde, C. R., and Roager, N. C. (1980). Crop Residue Influences on Soil Carbon and Nitrogen in a Wheat-Fallow System. *Soil Science Society of America Journal*, 44(3):596.

- Reatto, A., Bruand, A., de Souza Martins, E., Muller, F., da Silva, E. M., de Carvalho, O. A., Brossard, M., and Richard, G. (2009). Development and origin of the microgranular structure in latosols of the Brazilian Central Plateau: Significance of texture, mineralogy, and biological activity. *Catena*, 76(2):122–134.
- Richards, L. A. (1941). A Pressure-Membrane Extraction Apparatus for Soil Solution. *Soil Science*, 51(5):377–386.
- Ross, D. S., Matschonat, G., and Skjellberg, U. (2008). Cation exchange in forest soils: The need for a new perspective. *European Journal of Soil Science*, 59(6):1141–1159.
- Rouland-Lefèvre, C. and Bignell, D. E. (2004). Cultivation of symbiotic fungi by the termites of the subfamily Macrotermitinae. *Symbiosis: Mechanisms and Model Systems*, pages 733–756.
- Ruiz-Colmenero, M., Bienes, R., Eldridge, D. J., and Marques, M. J. (2013). Vegetation cover reduces erosion and enhances soil organic carbon in a vineyard in the central Spain. *Catena*, 104:153–160.
- Sanchez, P. A. and Logan, T. J. (1992). Myths and Science about the Chemistry and Fertility of Soils in the Tropics. In *Myths and Science of Soils of the Tropics*, number 29, chapter 3, pages 35–46. Soil Science Society of American and American Society of Agronomy, Madison.
- Selvaraj, K. and Ramasamy, S. (1998). Depositional Environment Of Cuddalore Sandstone Formation, Tamil Nadu. *Journal Of the Geological Society Of India*, 51(June):803–812.
- Seybold, C., Herrick, J., and Brejda, J. (1999). Soil resilience: a fundamental component of soil quality. *Soil Science*, 164(4):224–234.
- Six, J., Bossuyt, H., Degryze, S., and Deneff, K. (2004). A history of research on the link between (micro) aggregates , soil biota , and soil organic matter dynamics. *Soil and Tillage Research*, 79:7–31.
- Six, J., Elliott, E., and Paustian, K. (1999). Aggregate and Soil Organic Matter Dynamics under Conventional and No-Tillage Systems. *Soil Science Society of America Journal*, 63(5):1350.
- Six, J., Elliott, E., Paustian, K., and Doran, J. W. (1998). Aggregation and Soil Organic Matter Accumulation in Cultivated and Native Grassland Soils. *Soil Science Society of America Journal*, 62(5):1367–1377.
- Six, J., Elliott, E. T., and Paustian, K. (2000a). Soil macroaggregate turnover and microaggregate formation: A mechanism for C sequestration under no-tillage agriculture. *Soil Biology and Biochemistry*, 32(14):2099–2103.
- Six, J., Paustian, K., Elliott, E., and Combrink, C. (2000b). Soil Structure and Organic Matter. *Soil Science Society of America Journal*, 64(2):681–688.
- Sparks, D. L. and Liebhart, W. C. (1981). Effect of Long-term Lime and Potassium Applications on Quantity-Intensity (Q/I) Relationships in Sandy Soil. *Soil Sci. Soc. Am. J.*, 45:786 – 790.
- Steiner, C., Teixeira, W. G., Lehmann, J., Nehls, T., De MacÊdo, J. L. V., Blum, W. E. H., and Zech, W. (2007). Long term effects of manure, charcoal and mineral fertilization on crop production and fertility on a highly weathered Central Amazonian upland soil. *Plant and Soil*, 291(1-2):275–290.
- Tandon, H. L. S. (2005). *Methods of analysis of soils, plants, waters, fertilisers & organic manures*. Fertiliser Development and Consultation Organisation, New Delhi.
- Tian, G., Kang, B. T., and Brussaard, L. (1993). Mulching effect of plant residues with chemically contrasting compositions on maize growth and nutrients accumulation. *Plant and Soil*, 153(2):179–187.
- Tisdall, J. M. and Oades, J. M. (1982). Organic matter and water stable aggregates in soils. *Journal of Soil Science*, 33(2):141–163.
- Trumbore, S. E. (1997). Potential responses of soil organic carbon to global environmental change. *Proc. Natl. Acad. Sci.*, 94(August):8284–8291.
- Tullii, J. (2016). Etude de l'influence des pratiques culturales de conservation sur la dynamique des matières organiques dans des contextes pédologiques contrastés. Technical report, Liège.
- Verhulst, N., François, I., and Govaerts, B. (2010). Conservation agriculture, improving soil quality for sustainable production systems? Technical report, International Maize and Wheat Improvement Center.
- Villénave, C., Djigal, D., Brauman, A., and Rouland-Lefevre, C. (2009). Nematodes, indicators of the origin of the soil used by termites to construct biostructures. *Pedobiologia*, 52(5):301–307.

- von Lützw, M., Kögel-Knabner, I., Ekschmitt, K., Flessa, H., Guggenberger, G., Matzner, E., and Marschner, B. (2007). SOM fractionation methods: Relevance to functional pools and to stabilization mechanisms. *Soil Biology and Biochemistry*, 39(9):2183–2207.
- von Lützw, M., Kögel-Knabner, I., Ekschmitt, K., Matzner, E., Guggenberger, G., Marschner, B., and Flessa, H. (2006). Stabilization of organic matter in temperate soils: Mechanisms and their relevance under different soil conditions - A review. *European Journal of Soil Science*, 57(4):426–445.
- Waters, A. and Oades, J. (1991). Organic matter in water stable aggregates. In Wilson, W. S., editor, *Advances in Soil Organic Matter Research: The impact on agriculture and the environment*, pages 163–174. Woodhead Publishing.
- Watson, J. A. L., B. M., O.-K., and C., N. (1987). *Caste Differentiation in Social Insects*, volume 43.
- Watson, R. T. (2000). *Land Use, Land-Use Change, and Forestry: a special report of the IPCC*. Cambridge, Cambridge edition.
- Whitford, W. G., Ludwig, J. A., and Noble, J. C. (1992). *The importance of subterranean termites in semi-arid ecosystems in south-eastern Australia*, volume 22. Elsevier Ltd.
- Wood, T. G. (1988). Termites and the soil environment. *Biology and Fertility of Soils*, 6(3):228–236.
- World Soil Resources (2015). World reference base for soil resources 2014 International soil classification system for naming soils and creating legends for soil maps. Technical report, Food and Agriculture Organization of the United Nations, Rome.
- Wrey, T. (2012). *Footsteps through the salad - Wildlife profiles and natural phenomena of Auroville*. Prisma & SAIER, Auroville.
- Zech, W., Senesi, N., Guggenberger, G., Kaiser, K., Lehmann, J., Miano, T. M., Miltner, A., and Schroth, G. (1997). Factors controlling humification and mineralization of soil organic matter in the tropics. *Geoderma*, 79:116–161.