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Use of Soil and Litter Arthropods as Biological Indicators of Soil Quality in Southern Rwanda

Venuste NSENGIMANA

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Promotor: Professor Frédéric FRANCIS

Co-promotor: Associate Professor Donat NSABIMANA

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To my mum Drocella KANKUYO

To my wife Justa UWIMBABAZI

To my daughters Joy Arlette SANGWA and Angel Ora SHIMWA

To my late father, brother and sister

Is dedicated this thesis

Abstract - Nsengimana Venuste (2018). Use of soil and litter arthropods as biological indicators of soil quality in Southern Rwanda. University of Liège, Gembloux Agro Biotech. Pages: 121, tables: 13, figures: 3

To assess soil quality under different land uses by the use of soil and litter arthropods as biological indicators, a research was conducted in the Arboretum of Ruhande and the Rubona agricultural research station in southern Rwanda. Soil and litter arthropods were collected by pitfall sampling technique and identified to the family level. Ants (Hymenoptera: Formicidae) were identified to species level. Soil cores were collected and analysed for soil organic carbon, total nitrogen, available phosphorus, pH, aggregate stability, cation exchange capacity, electrical conductivity, silt, and clay and sand soil textures. C:N ratios were calculated from the mass of carbon to the mass of nitrogen. Higher levels of total nitrogen, soil organic carbon, and clay and silt soil texture were found in native and exotic tree species. Higher levels of cation exchange capacity, pH, and electrical conductivity were found in native tree species and banana plantations, while higher levels of available phosphorus, aggregate stability and sand soil texture were found in coffee and banana plantations. The analysis of the abundance of collected soil and litter arthropods indicated higher abundance of the most of identified families in native and exotic tree species than in the varieties of coffee and banana plantations. Families of Scolopendridae, Trombiculidae, Eosentomidae, Formicidae and Staphylinidae showed strong correlation with soil physicochemical properties. Formicidae highly occurred in all land uses and discriminated between clay, sand, aggregate stability, pH, available phosphorus, electrical conductivity and cation exchange capacity. The ecological functions of identified families contribute to the soil quality through predation, decomposition, bioturbation and phytophagous that increase soil organic matter and facilitate water retention and soil aeration. The taxonomy of ants to species level indicated 30 species belonging to 14 genera, and four subfamilies, the Formicinae, Dorylinae, Myrmicinae and Ponerinae. These species correlated with soil properties in different ways, but their ecological functions that contribute to soil quality are not yet well documented. We recommend further studies to be replicated in other land uses and ecological zones of Rwanda, to include the impact of climate variability, altitudinal variation, functional diversity, metal and soil microbiology and the taxonomy of the entire community composition of collected soil and litter arthropods to species level in order to generalize these findings.

Key words:

Community composition, Doryllinae, Formicinae, Myrmicinae, Ponerinae, land use, physicochemical parameters

Résumé - Nsengimana Venuste (2018). Utilisation des arthropodes du sol et de la litière comme indicateur de la qualité du sol au sud du Rwanda. Université de Liège, Gembloux Agro Bio-Tech, Belgique. Pages: 121, tableaux: 13, figures: 3

Pour évaluer la qualité du sol sous différentes utilisations des terres en utilisant des arthropodes du sol et de la litière comme indicateurs biologiques, une recherche a été menée à l'Arboretum de Ruhande et à la station de recherche agricole de Rubona au sud du Rwanda. Les arthropodes du sol et de la litière ont été recueillis au moyen d'une technique d'échantillonnage par piégeage et identifiés jusqu'au niveau de la famille. Les fourmis ont été identifiées jusqu'au niveau de l'espèce. Le sol a été collecté et analysé pour le carbone organique, l'azote total, le phosphore disponible, le pH, agrégat stable, la capacité d'échange de cations, la conductivité électrique, le sol limoneux, argileux et sableux. La relation C :N a été calculée par les masses du carbone sur la masse de l'azote. Des niveaux plus élevés d'azote total, du carbone organique, du sol argileux et limoneux ont été observés dans les plantations des espèces d'arbres indigènes et exotiques. Des niveaux plus élevés de capacité d'échange cationique, de pH et de conductivité électrique ont été observés dans les plantations d'arbres indigènes et de bananeraie, tandis que des niveaux plus élevés de phosphore, stabilité globale et du sol sableux ont été trouvés dans les plantations de café et de bananeraie. L'analyse de l'abondance des arthropodes du sol et de la litière recueillis indique une plus forte abondance de la plupart des familles dans les plantations des espèces d'arbres indigènes et exotiques. Les familles de Scolopendridae, Trombiculidae, Eosentomidae, Formicidae et Staphylinidae ont montré une forte corrélation avec les propriétés physicochimiques du sol. Les Formicidae apparaissent dans tous les milieux d'études et séparent les sols argileux, et sableux, ainsi que la stabilité des agrégats du sol, pH, phosphore disponible, conductivité électrique et capacité d'échange de cations. Les fonctions écologiques des familles identifiées contribuent à la qualité du sol par la prédation, la décomposition, la bioturbation et phytophages qui augmentent les matières organiques dans le sol, facilitent la rétention de l'eau et l'aération du sol. La taxonomie des fourmis au niveau des espèces indiquait 30 espèces appartenant à 14 genres et à quatre sous-familles, les Formicinae, les Dorylinae, les Myrmicinae et les Ponerinae. Ces espèces étaient en corrélation avec les propriétés du sol de différentes manières, mais leurs fonctions écologiques qui contribuent à la qualité du sol ne sont pas encore bien connues. Nous recommandons que d'autres études soient reproduites dans d'autres zones d'utilisation des terres et dans des zones écologiques du Rwanda, afin d'inclure l'impact de la variabilité climatique, la variation altitudinale, la diversité fonctionnelle, la microbiologie des métaux et des sols et la taxonomie de la composition de la communauté entière au niveau de l'espèce afin de généraliser ces résultats.

Mots clés:

Composition de la communautée, Doryllinae, Formicinae, Myrmicinae, Ponerinae, utilisation de la terre, paramètres physicochimiques

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Abbreviations

FHIA17	Variety of banana plantations used as banana fruit
MPOROGOMA	Variety of banana plantations used as banana vegetables
INJAGI	Variety of banana plantations used as banana vegetables
HARRAR	Variety of coffee plantations
JACKSON	Variety of coffee plantations
RBC15	Variety of coffee plantations

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General introduction and objectives

1. Introduction

Soil is a dynamic and living entity that is vital to the function of terrestrial ecosystems (Doran and Safley, 1997). Soil provides habitat for animals, in particular arthropods comprising as much as 85% of the species richness of soil fauna (Culliney, 2013). In soil and litter fauna, arthropods function as plant litter decomposers and ecosystem engineers that contribute to the availability of soil nutrients and to the improvement of soil structures (Culliney, 2013; Bagyaraj et al., 2016). This introduction includes a brief literature review of current research on soil quality, soil biodiversity, effects of land use on soil quality and soil biodiversity, and techniques applied in the assessment of soil quality in forest plantations and agricultural lands. It ends with the statement of the problem, the structure of the thesis, general and specific research objectives and hypothesis.

1.1. Soil quality and soil biodiversity

By definition, soil quality is the capacity of a specific kind of soil to function, within natural or managed ecosystem boundaries, to sustain animal and plant productivity, maintain or enhance water and air quality, and support human health (Doran and Parkin, 1994). Actually, soil functions as the medium for plant growth, habitat for soil organisms, biochemical and nutrient reactor, hydrological buffer and the foundation for the physical support of the structures of the earth (Rao et al., 2008).

Soil plays an important role in sustaining biological productivity, maintaining environmental quality, plants, animal communities and human health (MEA, 2005). Soil contributes to economic activities including food and fibre production, forestry and industry resources (Bone et al., 2010). Soil is at the basis of agricultural activities (Manimegalai and Sukanya, 2014), and protects ecosystems from adverse effects of environmental pollutants (Sumithra et al., 2013).

Soil represents a favourable habitat for many organisms (Koehler, 1992). Most of the species living in soil are microorganisms such as bacteria, fungi, and protozoan, which are the chemical engineers, responsible for the decomposition of plant organic matter into nutrients readily available for plants, animals and humans (Jeffrey et al., 2010). Soil also is the habitat of earthworms, springtails, mites and some small mammals, which act as predators (Suift and Anderson, 1979; Culliney, 2013). Earthworms, beetles, ants and termites, as well as other organisms are soil ecosystem engineers, litter transformers and macropredators (Fatima et al., 2008) that contribute to the formation of channels, pores, and soil aggregates that facilitate the movement of water and oxygen at different levels of soil horizons (Manhães et al., 2013).

In soil ecosystems, the activities and diversity of soil organisms are regulated by species interactions as well as the environmental factors including climate, temperature, texture, nutrients and soil pH (Bagyaraj et al., 2016). A conceptual model showing various factors mediated by soil biota that affect the supply of essential nutrients to plants (Figure 1) indicates the contribution of soil biota to the formation of aggregate stability, soil structures and organic matter leading to the availability of essential nutrients for plant growth (Roper and Gupta, 1995). In addition, ecosystem processes (evolution, habitat interactions, food web dynamics, ecosystem function) and ecosystem properties (gene, species, functional group, community) are linked in a hierarchical way so that the response variable at one level may be the driving variable for the next level (Niles and Freckman, 1996).

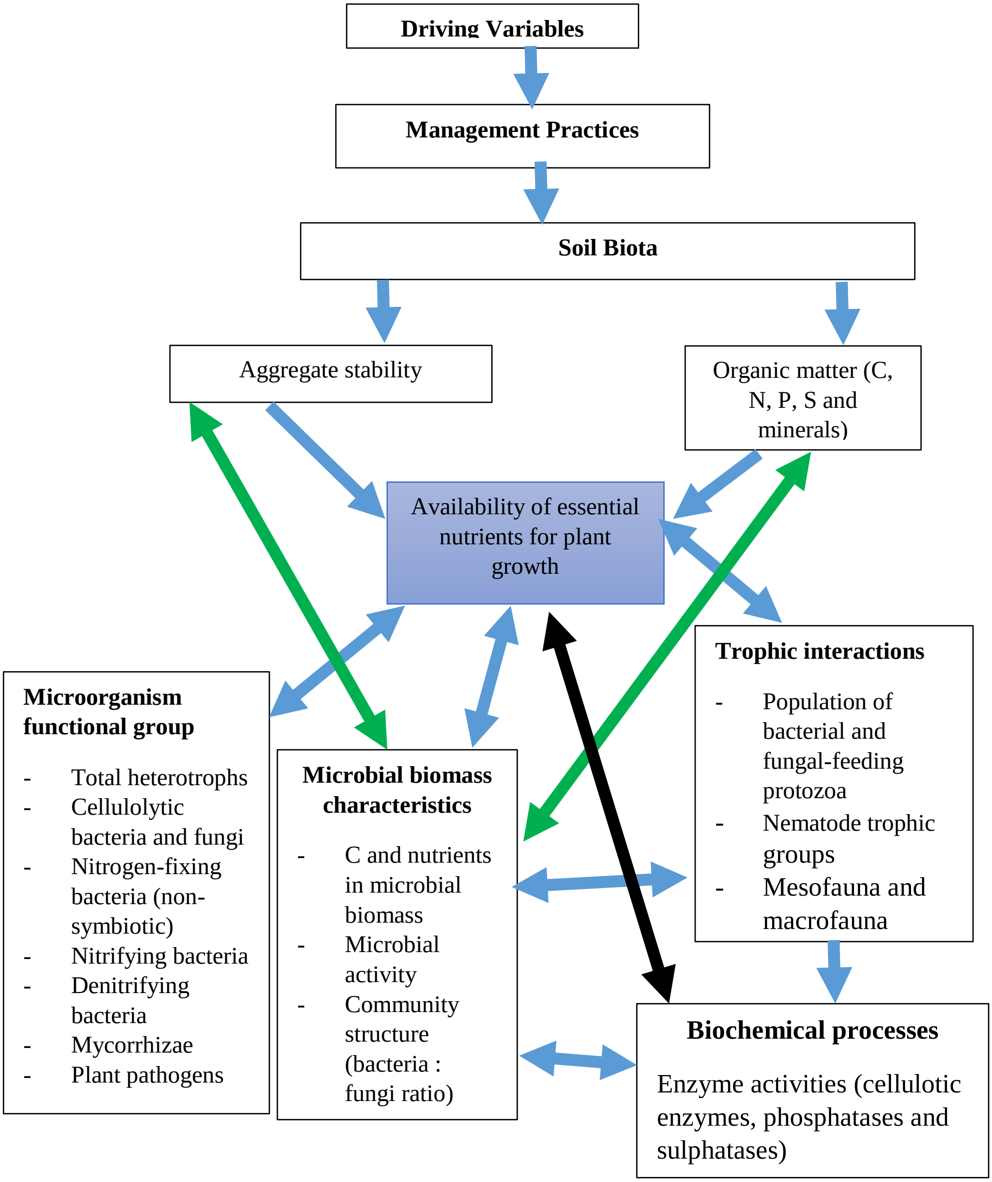

Figure 1. Conceptual model showing the various factors mediated by the soil biota that affect the supply of essential nutrients to plants (Adapted from Roper and Gupta, 1995)

1.2. Soil and land use changes

Currently, a large proportion of land cover has been transformed into agricultural lands. Statistics indicated that around 11% (1.5 billion of hectares) of the globe's land surface (13.4 billion of hectares) is used for crop production (Max and Ritchie, 2018). Due to the increase of human population, agricultural practices have shifted from traditional ways to the modern agriculture using modern technologies, fertilizers and pesticides with the main purpose to increase food and revenue production (Lavelle et al., 2001).

Another considerable part of the global land is used for forest plantations. Statistics indicated that planted forests increased about 7% of the total global forest area between 1990 and 2010, from 178 million of hectare to 264 million of hectare (Jürgensen et al., 2014). Planted forests provide benefits to humans including timber, food, fuel wood, fodder, medicinal resources and opportunities for recreation (Campos et al., 2005). They also serve ecological and environmental roles including climate regulation, soil and water protection, biodiversity preservation, and carbon sequestration (Dyck, 2003; Mishra et al., 2003).

1.3. Assessment of soil quality in forests and agricultural lands

Soil status can be assessed using indicators of disturbance by anthropogenic and/or natural activities. Soil indicator is a measurable soil property that influence the capacity of soil to perform crop production or environmental function and indicates changes in soil quality (Acton and Padbury, 1993). Scientific relevance of an indicator of soil quality depends on its sensitivity to variations in soil management, good correlation with soil functions and other variables, which are difficult to measure, helpfulness in revealing ecosystem processes, compensability and utility for land managers, cheap and easy to measure (Parisi et al., 2005).

From its inception, physicochemical and biological indicators (Lobry de Bruyn, 1997) have measured soil quality. Most common indicators used in soil quality assessment under different land uses include soil organic carbon (SOC), total nitrogen, soil pH, electrical conductivity (EC), available nutrients, cation exchange capacity (CEC), bulk density (BD), aggregate stability (AS), soluble carbon and nitrogen, heavy metals, organic pollutants, particle size, water holding capacity, porosity, root penetration resistance, carbon and nitrogen mineralization, microbial biomass carbon and nitrogen, microbial communities, enzyme activities, fungal mycelium, community of invertebrates and pathogens (Zornoza et al., 2015).

Recently, members of soil fauna were studied and qualified as biological indicators of soil quality (Oliveira Filho et al., 2016; Vasconcellos et al., 2013; Santarufo et al., 2012). By definition, a bioindicator is any species whose function, population or status can reveal the qualitative status of the environment in which they inhabit (Brown et al., 2017). The diversity, abundance, biomass, ecomorphology indices and density of soil fauna are used as indicators of natural or anthropogenic impacts on terrestrial ecosystems (Eggleton et al., 2005).

Faunal activity affects soil structure due to the aggregation of soil particles, in addition to the microbial effects (Belnap, 2003). Their actions mix soil particles and produces galleries, pores, tunnels, and other biological compartments that make the air and water flow in the soil (Lavelle et al., 2006). Soil with low faunal activity shows more compaction, which constrains the penetration of water, oxygen and plant roots (Drewry et al., 2008).

Some groups of arthropods are recognized for their active role in organic matter decomposition, nutrient cycling, agricultural productivity, plant growth and improving physicochemical and biological conditions of soil (Vasconcellos et al., 2013). By their digestive action, soil arthropods can form stabilized aggregates, and decompose resisting chemical substances, thereby improving nutrients availability for plants and microorganisms (Lavelle, 1997). Saprophagous arthropods affect the decomposition through feeding on litter and adhering microflora, thus converting the energy contained therein into production of biomass and respiration, and through mixing litter with soil and regulation of microflora (Suift and Anderson, 1979).

The class Insecta is the most dominant of all arthropods. It is very diverse and highly susceptible to changes in soil characteristics, making it a good biological indicator of soil status. The most used orders include Diptera, Termites, Hymenoptera (ants), and Coleoptera. Beside insects, other group of arthropods used as biological indicators of soil quality include springtails (Collembola), Crustaceans (Isopoda), Protura, Diplura, ticks and mites (Acari), myriapods including Pauropoda, centipedes (Chilopoda), millipedes (Diplopoda) and Symphyla. Use of arthropods as indicators of soil quality has commonly been done by measuring arthropod biomass, density, abundance, species richness, and biological indices (Foissner, 1994; Yeates and Bongers, 1997) of either single taxon groups (Santarufo et al., 2012), or of the entire community (Aspetti et al., 2010).

2. Statement of the problem

Although modern agriculture has increased food and revenue production for humans, it has also caused extensive environmental damage (Lal, 2015). In agricultural lands with monoculture intensification, the misuse of pesticides has led to contamination of land and water resources, affected non-targeted plant and animal species and may have favoured the emergence of pesticide-resistant pests (Bedano and Anahi, 2017). Frequent and deep tillage, inadequate soil cover and poor management of organic residues, physical degradation, and contamination by fertilizers and pollutants are some of other negative impacts of modern agriculture on soil quality (Lavelle et al., 2001).

Currently, the land surface affected by anthropogenic degradation is increasing and approximately 23% of arable land of the planet is degraded (Sérgio et al., 2013). Approximately 910 million of hectares are under moderate to extreme degradation (Sérgio et al., 2013). These land use changes affect soil carbon storage and cause changes in soil organic matter (SOM) and soil physicochemical characteristics that directly affect the soil fauna and soil properties (Culliney, 2013).

In addition, land use change affects nutrient cycling and availability of nutrients in soil. Annual and perennial crops, pastures and forests generate different residues whose dynamics and cycling differ due to differences in composition (Cardoso et al., 2013). Intense agricultural practices speed up the oxidation processes in soils and reduce the stable organic matter, and consequently the biological activity of soil fauna (Kennedy and Smith, 1995).

Continuous increase of human population, decreasing of natural resources, and social instability may continue to accelerate the environmental degradation and pose serious threats to the natural processes that sustain the global ecosphere and life on earth (Pearce and Warford, 1993). In relation to forest plantations, some tree species are often considered to play a great role in depleting soil nutrients, reducing soil water reserves, acidifying soil (FAO, 1985), and fail to provide food supplies and adequate habitat for soil wildlife (FAO, 1988).

In addition, few studies have combined physicochemical and biological indicators for the assessment of soil quality. The measurement of biomass, density, abundance, species richness, and biological indices either of single taxon groups, or of the entire community represent a snapshot in time due to the little information about the community structure (Anderson et al., 1985). Changes in biomass, density, abundance and species richness of arthropods used to assess the soil quality can be related to biotic factors such as predation, grazing and mutualistic relationships. They can also be related to abiotic factors (King et al., 1985) including climate variability and climate change, variations in temperature, soil salinity, soil pH, type of vegetation and land use management (Schils et al.., 2006).

Variations in biomass, density, abundance, and species richness of arthropods may also depend on the used sampling method (Ferrer-Paris et al., 2013) because less is known about the relative trapping efficiency of different sampling methods (Krell et al., 2005) and the knowledge of the taxa that are most likely collected by a given sampling method as well as the sampling method that is likely to collect the highest diversity of soil and litter arthropods (Sabu and Shiju, 2010). Furthermore, the taxonomy of arthropods to species level remains a challenging issue, and some other questions such as the correlation of species of soil and litter arthropods with variations in environmental factors remain a topic of interest for research.

3. Structure, objectives and hypothesis of the thesis

It is time to think about sustainable land use with the aim of meeting the needs of the present generation without compromising the production potential for the next generations. Rational use of soil must not only focus on socio-economic yield but also on the environmental sustainable yields, which will be reached with the maintenance of the soil quality and soil health (Cardoso et al., 2013). To achieve this objective using soil and litter arthropods as biological indicators, an understanding and theoretical framework of community composition and ecological functions of soil and litter arthropods in relation to soil properties has to be developed.

Factors including the relationship between biological parameters (species composition, life history diversity, feeding type and physiotype), environmental parameters (soil type, microbial populations, soil pH, temperature, nutrients, heavy metals and pesticide residues) and ecological functions of soil and litter arthropods have to be studied for the assessment of soil quality (van Straalen, 1998). In addition, the determination of suitable sampling methods for soil and litter arthropods and the taxonomy of identified soil and litter arthropods to species level needs to be developed.

This study contributes important information to help fill this gap. It focused on the use of soil and litter arthropods as biological indicators of soil quality in tree forest plantations and in varieties of coffee and banana plantations as dominant plantations in Rwanda. It is the first research in Rwanda dealing with the relationship between soil fauna and soil physicochemical properties and it is the first research in Rwanda identifying a given taxon to species level.

A literature review was done to illustrate how soil and litter arthropods are used as indicators of soil quality in forest plantations and agricultural land use (Paper 1). A pilot study was done in order to find out the trap wise differences in arthropods and the taxa that are most likely collected by pitfall traps, Berlese-Tullgren funnels and hand sorting sampling techniques for soil-litter arthropods (Paper 2). The community composition of soil and litter arthropods in relation to soil physicochemical parameters and ecological functions was studied (Paper 3). The taxonomy of dominant and diverse species taxon was done with the main purpose of documenting which species of soil and litter arthropods can serve as reference biological indicator of soil quality vis-à-vis soil physicochemical parameters (Paper 4).

The general objective of this study was to examine and compare the influence of different land uses on the diversity and abundance of soil and litter arthropods. Specifically, the research examined and compared the diversity, abundance and evenness of soil litter arthropods under dominant tree species at the Arboretum of Ruhande, coffee, and banana crop plantations at the Rubona agricultural research station in southern Rwanda. It examined the variation of soil physicochemical parameters in each land use and studied the correlation between abundance of soil and litter arthropods and soil physicochemical parameters including soil pH, total nitrogen, soil organic carbon, C:N ratio, cation exchange capacity, electrical conductivity, aggregate stability, available phosphorus and soil textures. The ecological functions of identified soil and litter arthropods was documented in the literature and were used to determine the contribution of soil and litter arthropods to soil properties. We hypothesized that positive correlation between soil and litter arthropods and soil physicochemical parameters is associated to the ecological functions that soil and litter arthropods exert on soil.

2

Literature review

General introduction to chapter 2

This chapter is in the form of a peer review paper (Paper 1). It consists of the review on the use of soil and litter arthropods as biological indicators of soil quality in forest plantations and agricultural lands. It presents the understanding of the relationship between soil quality and soil biodiversity, effects of land use change on soil quality and soil biodiversity, and the assessment of soil quality in forests and agricultural lands. It briefly indicated how modern agriculture has increased food production for humans on one hand, but it also contributed to extensive environmental damage on the other hand. It highlighted how some tree species are often considered to play a great role in depleting soil nutrients, reducing soil water resources, acidifying soils and fail to provide food supplies and adequate habitat for soil wildlife. It ended by inviting researchers to study the relationship between biological and environmental indicators of soil quality, and highlighted the need for conducting research in order to determine the suitable sampling methods for sampling a high diversity of soil and litter arthropods, and study the taxonomy of soil and litter arthropods to species level.

Use of soil and litter arthropods as biological indicators of soil quality in forest plantations and agricultural lands: A Review

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Abstract

This article reviewed published papers on the use of soil and litter arthropods as biological indicators of soil quality since the 1970s. Our review shows that soil and litter arthropods are litter transformers and ecosystem engineers. They contribute to the availability of organic matter. Their diversity, abundance, biomass, and density are suitable measures for the assessment of natural and/or anthropogenic effects on soil. However, their use is challenged by difficulties in sampling methods and the identification of soil and litter arthropod diversity up to species level, and few research projects combine both abiotic and biotic factors. We recommend further research to investigate the most suitable methods for sampling soil and litter arthropods, and create a classification of dominant groups up to species level, which, along with the use of integrative methodologies, will be valuable steps towards a generalized and accepted method for the assessment of soil quality.

Key words: Arthropods; soil quality; indicator; forest plantations; agricultural lands.

1. Introduction

Soil is an integral component of ecosystem processes and biogeochemical cycles, comprised of solid, liquid and gaseous components, which interact through a multitude of interrelated physicochemical and biological processes (Zornoza et al., 2015). Soil is a key resource for agriculture production and is a source of nutrients required for plant growth (Tsiafouli et al., 2015). Soil is also the foundation and the essence of all terrestrial life (Lal, 2015). In relation to biodiversity, soil is inhabited by a range of organisms including fungi, algae, bacteria, protozoa, and invertebrates (Koehler, 1992), with soil and litter arthropods representing as much as 85% of all soil fauna (Culliney, 2013).

Through history, soil has been essential to human well-being, and human dependence on soil is direct due to its contribution to food production and importance for economic development (Lal, 2015). However, intensive exploitation of soil can cause considerable decline in soil quality (Eswaran et al., 2016). Current estimations show that soil degradation affects around 33% of all soils in the world (FAO, 2017), and has strong consequences on soil ecosystem services and biodiversity conservation due to changes in the concentration of nutrients, loss of soil organic carbon, pollution, loss of soil biodiversity, wind and water erosions, desertification, acidification, salinization, increased greenhouse gas emissions, reduced water infiltration and purification, and perturbations of hydrological cycles (Zornoza et al., 2015).

Although some authors consider soil quality to refer to soil functions while soil health represents the finite non-renewable and dynamic living resource (Doran and Zeiss, 2000), soil quality and soil health are often used interchangeably and are defined as the ability of a specific soil to function within its capacity and within natural or managed ecosystem boundaries, to sustain productivity of plants and animals, maintain water and air quality, and support human health (Arshad and Martin, 2002). However, soil quality assessment has long been a challenging issue because soil presents high variability in properties and functions, and globally acceptable methodologies for assessing soil quality are not yet in place (Laishram et al., 2012).

The assessment of soil quality has long been based on various biological indicators (Vasconcellos et al., 2013), including indicators of biotic or abiotic conditions, indicators of various human activities (Basedow, 1990), or goal parameters deducted from nature conservation aims and translated into measurable factors such as species diversity (May, 1995). The use of the community of soil fauna as indicator of soil quality has received more attention in recent years and soil mesofauna are the most studied organisms in soil quality assessment (Lavelle and Spain, 2001). Currently, the focus is on soil and litter arthropods (Bagyaraj et al., 2016), although little is known about the advantages and challenges of using these organisms in assessing soil quality.

This paper reviews the use of soil and litter arthropods as biological indicators of the soil quality under forest plantations and agricultural lands. The focus on these land use is motivated by the fact that forest plantations become common landscapes across many parts of the world occupying around 264 million of hectares (7% of the total global forest area) (Jürgensen et al., 2014), while agricultural lands occupy around 1.6 billion of hectares (12% of global land area) (FAO, 2011). Planted forests serve to restore degraded lands, to control soil erosion (Mishra et al., 2003). Together with natural forests, they provide benefits to humans such as timber, food, fuel wood, medicinal resources, opportunities for recreation, climate regulation, soil and water protection, biodiversity preservation and carbon sequestration (Campos et al., 2005; Dyck, 2003). Agriculture is the main source of food and money for humans (FAO, 2011).

This review starts with a review of classical methods for soil quality assessment in forest plantations and agricultural lands, continues with a review of the dominant soil biodiversity of soil and litter arthropods, their role in maintaining soil quality, and types of measures of soil and litter arthropods indicating soil quality. It concludes with recommendations on how soil and litter arthropods can be effectively used as bio indicators of soil quality.

2. Literature

2.1. Measurements for soil quality assessment

Quality of an indicator must correlate well with ecosystem processes, integrate soil physicochemical and biological processes and serve as basic inputs needed for estimation of soil properties or soil functions, which are more difficult to measure directly (Doran and Safley, 1997). Furthermore, according to the same authors, an indicator must be relatively easy to use under field conditions and be assessable by both specialists and producers, be sensitive to variations in management and climate, and be components of existing soil databases where possible. The need for basic soil quality and health indicators is reflected in the question: what measurements should I make or what can I observe that will help me evaluate the effects of management on soil function now and in the future (Doran and Safley, 1997)?

Soil quality is assessed by considering soil properties that are sensitive to changes in land use (Andrews et al., 2004), and it has long been assessed by measuring physicochemical attributes (Table 1). The most commonly measured parameters include soil organic carbon and total nitrogen, soil pH, electrical conductivity, available nutrients, bulk density, and soil aggregation (Zornoza et al., 2015). In other studies, the choice of soil quality indicator considered land use and land management (Laishram et al., 2012) due to the interconnections of soil quality with other ecosystem components such as soil fertility, soil productivity and vegetation type (Doran, 2002).

In agricultural systems, soil organic carbon has been used as the most important indicator of soil quality (Arias et al., 2005), as well as soil pH, electrical conductivity, and nutrient availability (Rahmanipour et al., 2014). Physical indicators are the most commonly used with the measurement of aggregate stability and bulk density (Rouseau et al., 2013). Soil microbial activity and diversity (Table 2) are also often used (Li et al., 2014) because they are more susceptible and can therefore clearly indicate changes in the environment more responsively than physicochemical attributes (Masto et al., 2009). Due to agricultural economic development, soil quality in agricultural lands can also be assessed using measures of crop productivity (Zornoza et al., 2015) and direct or indirect impacts of soil degradation on human health (Deng, 2011).

Table 1: Soil physicochemical indicators for screening the condition and quality of soil (Adapted from: Doran and Parkin, 1994; Laishram et al., 2012; Cardoso et al., 2013).

Indicator of Soil Conditions	**Measured soil quality**
Physical indicators	
Soil texture	The capacity of retention and transport of water, minerals, and level of soil erosion.
Depth of soils or top soils	Potential productivity and level of soil erosion.
Infiltration and bulk density	The potential for leaching, productivity, and level of soil erosion.
Water holding capacity	The level of water retention, transport, and soil erosion.
Aggregation	Soil structure, erosion resistance, and soil management effects.
Chemical indicators	
Soil organic matter	Soil fertility, structure, stability, and extent of erosion.
Soil pH	Biological and chemical thresholds.
Electric conductivity	The threshold of plant and microbial activity, soil structure, and level of water infiltration.
Extractable nitrogen (N), phosphorus (P), and potassium (K)	Available plant nutrients and potential for nitrogen loss, productivity, and environmental quality indicators

Table 2*:* Microbial indicators of soil quality: soil cycles they are involved in, and methods for assessment (Adapted from: Doran and Parkin, 1994; Cardoso et al., 2013).

Indicator	**Soil Cycle**	**Measured indicator**
Microbial biomass nitrogen (N) and carbon (C)	C, N and P	Microbial catalytic potential, repository for C and N, and effects of organic matter on land management.
Soil respiration, water content, and temperature	C	Microbial activity, process modelling, and estimate of biomass activity.

Table 2 – cont

Indicator	**Soil Cycle**	**Measured indicator**
Metabolic quotient (qCO_2 index)	C	The metabolic quotient of soil microbial communities.
Microbial functional group	C, N and P	Levels of phosphate solubilizes and diazotrophic, nitrifying, denitrifying and ammonifying bacteria

Researchers have applied biochemical indicators to assess soil quality (Table 3). Simple ratio measures including C:N ratios, metabolic quotient, enzyme activities/microbial biomass ratios, fungal/bacteria biomass ratios, soil organic carbon and nitrogen stratification ratios were commonly used (D'Hose et al., 2014; Zhao et al., 2014). Ratios are considered more effective than physicochemical and microbiological indicators for the assessment of soil quality in forest plantations due to their high correlations with soil organic carbon and higher response to changes in soil use and soil management (Miralles et al., 2009).

Table 3*:* Enzyme indicators of soil quality and functions played in soil cycles (Adapted from: Cardoso et al., 2013).

Enzyme	**Soil Cycle**	**Enzyme function**	**Microorganisms**
Dehydrogenase	Carbon	Electron transfer	All aerobic microorganisms
ß-glucosidase	Carbon	Carbon oxidation	Several microorganisms
Cellulase, amylase	Carbon	Cellulose degradation	Mainly fungi, but also bacteria
Urease, glutamase, and asparaginase	Nitrogen	Organic N mineralization to ammonium salts and ammonia	Several microorganisms
Phosphatases (acid and alkaline)	Phosphorus	Organic phosphorus cycling	Microbial and several microorganisms
Aril-sulphatase	Sulfur	Organic sulphur cycling	Several microorganisms

Recently, more emphasis has been given to soil fauna as indicators of soil quality in forest and agricultural land use (Eggleton et al., 2005). Their diversity, abundance, biomass, and density have been proven to be suitable indicators of natural or anthropogenic impacts on terrestrial ecosystems due to their correlation with physicochemical and microbiological properties and ecological changes (Paula et al., 2010). Soil fauna produce galleries, pores, and tunnels in soil that facilitate the flow of air and water in soil (Lavelle et al., 2006). Soil fauna are good decomposers of organic matter and participate in nutrient cycling (Moore and De Ruiter, 1991). The aggregation of soil particles and litter feeding processes enhance soil structures and accelerate dynamic production of organic matter through mineralization processes (Barrios, 2007).

Protozoans, nematodes, and annelids are soil fauna of great importance in maintaining soil quality. Protozoans participate in the stimulation of mineralization of organic matter through microbial activities (Moore and De Ruiter, 1991). Nematodes including oligochaetes and enchytraeids are good litter transformers, and through their pellets, mineralization is enhanced in a short time, while annelids including earthworms are good ecosystem engineers, participating in the production of organomineral structures and formation of soil pores (Lavelle, 1996). The role of structures created by earthworms are essential to soil ecosystems as they offer the mineralization of C and N, denitrification, and facilitate water and air infiltration (Lavelle et al., 1997).

2.2. Soil arthropods and soil quality

Major groups of soil and litter arthropods including Acarina, Collembola, Myriapoda as well as various orders of the class Insecta are of significant importance in terrestrial ecosystems (Ogedegbe and Egwuonwu, 2014). They are recognized for their active role in organic matter decomposition, nutrient cycling, agricultural productivity, plant growth and improving physicochemical and biological soil conditions (Vasconcellos et al., 2013). By their digestive actions, soil and litter arthropods form stabilized aggregates and decompose resisting chemical substances, thereby improving nutrient availability for plants and microorganisms (Lavelle, 1997). Saprophagous arthropods affect decomposition through feeding on litter, mixing litter with soil and through the regulation of soil microflora (Suift and Underson, 1979).

The class Insecta is the most dominant of all soil and litter arthropods. It is very diverse and highly susceptible to changes in soil characteristics, making it a good indicator group. The order of Diptera is among these insects. The main natural environmental factors affecting the distribution of Diptera are the inputs of dead organic matter into soil, changes in litter depth and temperature as well as seasonal variation, and for agricultural systems, tillage, use of manure, fertilizers, and pesticide (Frouz, 1999). The community of soil-dwelling Diptera can serve as indicators of soil quality and environmental stress through an assessment of their distribution and abundance of their species in the community (Krebs, 1989). Lower taxonomic levels such from species to families are recommended to be used in this assessment (Frouz, 1999).

Soil termites also form a very important group of the class Insecta, used as indicators of soil quality due to their effects on soil profiles and soil texture, distribution of organic matter, and plant nutrients and their construction of subterranean galleries (Stork and Eggleton, 1992). Termites’ foraging and activities create conditions promoting microbial populations and the mineralization of organic compounds (Culliney, 2013). Soils modified by termites showed higher microbial activity and were significantly more concentrated in ammonium, calcium, magnesium, and potassium cations and inorganic phosphorus (Ndiaye et al., 2004), available phosphorus, total nitrogen, bicarbonates, chloride and sulphate anions (Badawi, et al., 1982). The reduction of C:N ratios by fungi provide organic matter enriched in nitrogen to termite colonies and, by feeding on fungi, nutrients from the litter are incorporated into the biomass of termites with highly efficient assimilation of nitrogen (Lee, 1983).

Hymenoptera, particularly ants, form another dominant group of the class Insecta in most terrestrial environments (Culliney, 2013). Mounds of ant species contain higher exchangeable cations including calcium, magnesium, potassium, sodium cations, and they are rich in trace elements including iron, manganese, and zinc (Wali and Kannowski, 1975). Ant mounds also contain higher concentrations of nitrate and ammonium salts (Amador and Görres, 2007), available phosphorus and potassium and showed higher levels of microbial activities than in uninhabited control soils (Czerwiński et al., 1971). The increase in soil nutrient and soil organic matter content in ant mounds are factors influencing the variation of soil pH (Frouz and Jilková, 2008).

In habitats with high anthropogenic activities, Coleoptera insects including carabid beetles are good indicators of changes in soil properties (Kromp, 1999), namely pH, sodium chloride levels and calcium content (Avgan and Luff, 2010). For sustainable agricultural systems, carabid beetles play the role of predators and prevent outbreaks of several pest insects (Luff, 1996). Scarabaeidae beetles are important in the breakdown of dung, carrion and leaf litter, and return nutrients to the soil (Greenslade, 1985). Communities of staphylinid can be used as bioindicators of human influence on soil ecosystems (Bohac, 1999), with species diversity indices, and individual relative abundance in the sample (Ruzicka and Bohac, 1994).

Besides insects, collembolans form another group of soil and litter arthropods used as indicators of soil quality. They contribute to the decomposition of plant residues, increase mineralization by selective feeding on fungi, and help in the formation of humus by mixing organic material and mineral soil particles (van Amelsvoort et al., 1988). They form water-stable aggregates in the soil and strong inter-particle cohesive forces within faecal pellets (Siddiky et al., 2012). Stimulatory effects of collembolans on fungal growth and respiration through grazing (Filser, 2002) results in mobilization of available nitrogen and calcium in soils (Ineson et al., 1982), and their faeces contain more nitrate ions, increasing their availability on the forest floor (Teuben and Verhoef, 1992).

Another group of soil and litter arthropods of interest in the assessment of the soil quality is Isopoda. They are sensitive to the application of pesticides and herbicides, which can cause a rapid decrease of these soil and litter arthropods in intensively managed agricultural and forest plantations (Fischer et al., 1997). Isopoda biomass contributes to the storage of potassium, sodium, phosphate ions, and nitrogen and calcium ions in soil (Teuben and Verhoef, 1992). They constitute an important nutrient pool, which immobilizes ions and prevents leaching from the soil (Zaady et al., 2003). Due to their tolerance to high-level metals, Isopoda indicate soil contamination by heavy metals especially copper (Hopkin et al., 1993), zinc, lead and cadmium (Prosi and Dallinger, 1988).

Soil quality assessment has been also done using mites, which are among the most species-rich and numerous soil and litter arthropods, having a positive influence on the decomposition rates of organic matter, bacterial and fungal colonizers. They produce faecal pellets, which enhance further decay and contribute to improved soil structures by assisting the distribution of bacterial and fungal propagules through the soil and leaf litter (Maraun et al., 1998). In agricultural lands, the processes of cultivations, rotations, monocultures, and application of pesticides are the activities with negative effects on the community of mites (Tomlin and Miller, 1987). Mites give good results of soil status once the cause of the change in soil properties is known in advance (Linden et al., 1994).

Diplopoda and Symphyla, the most important myriapods in soils, form another group of soil and litter arthropods used in the assessment of soil quality. They influence the distribution of microbial populations in soil (Szabó et al., 1983) and participate in the decomposition of plant material, which increases nutrients on the surface area and makes them available for bacteria and fungi (Paoletti et al., 2007). Diplopoda and Symphyla contribute to the decomposition of leaf litter by fragmentation and the addition of microflora through faecal pellets, and they release mineral nutrients into the soil by feeding and defecation which is essential for soil as this brings down C:N ratios. Furthermore, their faeces have a relatively high pH, which facilitates the growth and concentration of nitrogen-fixing bacteria (Bagyaraj et al., 2016).

2.3. Measures of arthropods indicating soil quality

Many soil and litter arthropods including collembolan, Oribatida, Isopoda and Diplopoda live a rather sedentary life and therefore reflect local conditions of a habitat (Van Straalen, 1998). These facts have been recognized for a long time, and relationships between soil types and soil and litter arthropods have been established in various studies (Rusek, 1989). Use of soil and litter arthropods as indicators of soil quality has commonly been done by measuring soil and litter arthropod biomass, density, abundance, species richness, and biological indices (Yeates and Bongers, 1997; Foissner, 1994) of either single taxon groups (Santarufo et al., 2012), or of the entire community (Aspetti et al., 2010).

Recently, a simplified ecomorphological index (EMI) based on the morphology of micro-arthropods has been introduced (Parisi and Menta, 2008). It is used to evaluate soil quality based on which groups are present in soil samples, where taxonomic groups receive an EMI score from 1 to 20 (Table 4), according to its adaptation to the soil environment. Deep soil living forms are given an EMI score of 20, intermediate forms are given a score proportional to their degree of specialization, while surface-living forms are scored with an EMI equal to 1 (Parisi et al., 2005). The Biological Quality of Soil Index (BQS) is calculated as the sum of EMI scores and soil quality correlates with the number of groups of arthropods with high EMI scores.

Table 4: Ecomorphological indices (EMIs) of edaphic microarthropod groups (Adapted from: Parisi et al., 2005).

Group	EMI Score	Group	EMI Score
Blattaria	5	Acari	20
Coleoptera	1-20	Araneae	1-5
Collembola	1-20	Opiliones	10
Diplura	20	Isopoda	10
Diptera (larvae)	10	Chilopoda	10-20
Embioptera	10	Palpigradi	20
Hemiptera	1-10	Diplopoda	10-20
Hymenoptera	1-5	Pauropoda	20
Orthoptera	1-20	Symphyla	20
Other holometabolous insects (adults)	1	Dermaptera	1
Other holometabolous insects (larvae)	10	Psocoptera	1
Protura	20	Microcoryphia	10
Thysanoptera	1	Zygentomata	10

Table 5: Classification of soil fauna according to their size and function (Adapted from: Schjønning et al., 2004; Faber, 1991). *Mites (Acari); springtails (Collembola); **Spiders (Arachnida), Millipedes (Diplopoda); Termites (Isoptera); Slater (Isopoda); Centipedes (Chilopoda); Ants (Hymenoptera; and Beetles (Coleoptera).

Function	Body size	
	Mesofauna (0.2 – 2.0mm)*	**Macrofauna (>2.0mm)****
Fragmentation of residues	+	+
Stimulation of microbial activity	-	+
Organic matter and nutrient redistribution	-	+
Soil aggregation (biopores)	+	+
Carbon sequestration	-	+
Nutrient cycling, mineralization, and immobilization	+	-
Humification	+	+
Feeding on fungal hyphae	+	
Opening channels and galleries	-	+
Regulation of bacterial and fungal populations	+	-
Mixing of organic and mineral particles	-	+

However, a true theory of community composition of soil and litter arthropods in relation with other environmental factors remains to be developed. Although diversity indices represent variables that can be measured independently of the difficulties involved in identification of soil and litter arthropods at species level, these measures represent a snapshot in time (Anderson et al., 1985). They give little information about the community structure, and changes in abundance can be related to other factors such as predation, grazing and mutualistic relationships. They can also be related to other abiotic and biotic factors (King et al., 1985), including climate variability and climate change, variations in temperature, soil salinity, soil pH, the type of vegetation, and land use (Schils et al., 2006).

These are the reasons why measuring abundance, biomass, density, diversity and evenness is not enough for assessing the status of soil arthropods and hence soil quality. Some other factors including the relationship between biological parameters (species composition, life history diversity, feeding type and physiotype) and environmental parameters (soil type, microbial populations, soil pH, temperature, nutrients, heavy metals and pesticide residues) have to be studied (Van Straalen, 1998). Functional significance including fragmentation, soil aggregation, organic matter and nutrient distribution, mineralization rate, and nutrient mobility (Table 5), as well as spatial and temporal scales, have to be considered (Bagyaraj et al., 2016).

Variations of soil and litter arthropods in samples may also depend on the sampling method used (Ferrer-Paris et al., 2013). Berlese-Tullgren funnels, pitfall traps, hand collection and Winkler extraction are the most used sampling methods for soil and litter arthropods (Tuf and Tvardik, 2003). However, less is known about the relative trapping efficiency of each of these sampling methods (Krell et al., 2005). The knowledge of the taxa that are most likely collected by each sampling method and the sampling method likely to collect the highest diversity of soil and litter arthropods remain the topic of interest, which has to be studied before generalization of any sampling-dependent findings (Sabu and Shiju, 2010).

3. Conclusions and recommendations

Even though community indicators meet most of the desired parameters to determine soil quality in the habitat under investigation, many other interesting criteria must be met, including soil physicochemical parameters, types of vegetation, soil microbial communities and enzymes (Van Straalen, 1998), soil ecological functions (Laishram et al., 2012) including availability of soil nutrients and soil structures (Culliney, 2013). Changes in these parameters may have varying effects on diversity and abundance of different species of soil and litter arthropods (Lavelle et al., 2006), so that the relationship between soil and litter arthropod biological parameters, and soil ecological functions played by soil and litter arthropods (Table 5) have to be studied (Cardoso et al., 2013) before making a general conclusion on soil status.

Further research should explore the effect of combinations of various sampling and measuring methods. If both species diversity and abundance have to be used for assessing soil quality in different land use, we recommend that they be used together with other physicochemical parameters of soil, microbiological communities and enzymes as well as environmental factors such as seasonal variability and altitudinal variations (Sicardi et al., 2004). These studies should focus on the identification, comparison and testing different sampling methods for sampling soil and litter arthropods and the development of a hierarchy classification system up to species level for dominant soil and litter arthropod species. From our review, we propose that these steps could lead to a generalized and accepted approach for soil quality assessment using soil and litter arthropods.

3

Methodology

General introduction to chapter 3

Chapter II focussed on the review on the use of soil and litter arthropods as biological indicators of soil quality under forest plantations and agricultural lands. It highlighted the classical and recent measures for soil quality assessments, the role of soil arthropods in maintaining soil quality, types of measures of soil and litter arthropods indicating soil quality and their challenges. It concluded that even though community indicators of soil and litter arthropods meet most of the desired parameters to assess soil quality, further research might explore the capture efficiency of sampling techniques for soil and litter arthropods with the aim of determining the sampling technique that can collect higher diversity and wide range of soil and litter arthropods.

Chapter III dealt with this purpose. It is a comparative study between Berlese – Tullgren funnel, hand sorting and pitfall traps sampling techniques for soil and litter arthropods. The goal of this study was to compare the trapping efficiency between hand sorting, pitfall traps and Berlese-Tullgren funnels sampling methods for collecting a wide range and diversity of soil and litter arthropods. It aimed at determining the species diversity of soil and litter arthropods from each sampling method, testing the trapping differences with which particular soil litter arthropods taxa were collected, and assess the trap-wise differences in the capture efficiency of individual taxa per each sampling technique.

A comparative study between sampling methods for soil-litter arthropods in conserved tree plots and banana crop plantations in Rwanda

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Abstract

The aim of this study was to compare trapping efficiency between Berlese-Tullgren funnels, pitfall traps and hand sorting sampling methods for soil litter arthropods. The study was carried out at the Arboretum of Ruhande and the Rubona agricultural research station, in southern Rwanda. Biological indices indicated that pitfall traps collect a wide range of soil litter arthropod diversity, and chi-square test indicated the dependence between Berlese-Tullgren funnels and pitfall traps, and between pitfall traps and hand sorting. Z-test and univariate comparison indicated differences in means between tested sampling methods. The analysis of variance revealed that pitfall traps are less time consuming. The family of Formicidae is likely to be collected by pitfall traps and Berlese-Tullgren funnels, while Julidae, Oniscidea and Geophilidae are likely to be collected by hand sorting. Research concluded that pitfall traps are more efficient than other studied sampling methods, but further studies should be conducted in other ecological zones, and different land uses in order to generate general information of these findings.

Key words: Efficiency, efficient, meantime, diversity, evenness

1. Introduction

The phylum Arthropoda is the largest in the animal kingdom and it includes more than one million species distributed in almost all habitats (Duelli et al., 1999). Soil litter arthropods control the stability and functioning of soil ecosystems (Bagyaraj et al., 2016), and participate in soil nutrient cycling through litter feeding and mineralization of nutrients, and contribute to the formation of soil structures through soil mixing, development of soil pores and formation of soil aggregates (Culliney, 2013). Soil litter arthropods are also ecosystem engineers that physically regulate the availability of resources for bacteria and fungi (Jones et al., 1994), thus minerals and nutrients of dead organisms become readily available in the soil for plant uptake (FAO, 2013).

Soil litter arthropods are frequently studied to understand their distribution for pest control, conservation purposes, understanding of the population dynamics, and to make predictions of future changes in abundance and diversity (Woodcock, 2005). In agricultural and forest systems, arthropods are studied in order to understand their economic benefits through pollination, seed dispersal (Isaac et al., 2009), predation (Wilson, 2005), and in the assessment of soil quality, soil health and environmental changes (Pankhurst et al., 1997). Recently, there is an increasing interest in studies by using arthropods, particularly insects in forensic and medical sciences (Bonebrake et al., 2010).

The species of soil litter arthropods captured during sampling is dependent on the sampling methods that were used (Ferrer-Paris et al., 2013), which are classified as either passive or active (Gullan and Cranston, 2005). The difference between active and passive methods is based on the intervention of the collector and the implication of the trap used (Yi et al., 2012). Simply, passive sampling methods are neutral and depend entirely on chance, while active sampling methods depend on the behaviour of the targeted taxa and take advantages of the behaviour and attractions by chemicals, baits or colours (Yi et al., 2012). Berlese-Tullgren funnels and pitfall traps are passive sampling methods, while hand sorting is an active sampling method (Tuf and Tvardik, 2003).

Each of these sampling methods has constraints to trapping efficiency. Hand sorting is appreciated to be suitable for sampling large and abundant soil litter arthropods, but it is more laborious and time-consuming (Tuf, 2015). Pitfall traps are time efficient in sampling ground-dwelling arthropods (Smith et al., 2008), while Berlese-Tullgren funnels are suitable for sampling soil and leaf litter microarthropods (Southwood and Henderson, 1997). Compared to pitfall traps and hand sorting, researchers indicated that Berlese-Tullgren funnels are easy to use and less time consuming (Basset et al., 1997), but soil samples have to be processed quickly to avoid mortality of specimens (Yi et al., 2012).

Few studies have been done to critically evaluate criticisms, and compare the trapping efficiency between Berlese-Tullgren funnels, pitfall traps and hand sorting sampling methods (Krell et al., 2005). The best approach to collect a wide range of soil litter arthropods remains a topic of interest (Yi et al., 2012), and the capture effectiveness of these sampling methods need to be studied (Sabu and Shiju, 2010) in order to solve other questions such as the knowledge of the taxa that are most likely collected by each sampling method and the taxa that are best collected by specific sampling methods between Berlese-Tullgren funnels, pitfall traps or hand sorting, as well as the mean time required for each sampling method (Sabu et al., 2012).

The goal of this study is to compare the trapping efficiency between hand sorting, pitfall traps and Berlese-Tullgren funnels sampling methods for collecting a wide range and diversity of soil litter arthropods. The research presented here aims at determining the species diversity of soil litter arthropods from each sampling method, testing the trapping differences with which particular soil litter arthropods taxa were collected, assess the trap-wise differences in the capture efficiency of individual taxa per each sampling method, and determine the mean time required for trap fixation, trap collection, and extraction of specimens in traps for each sampling method.

2. Material and sampling methods

This research was conducted in the Arboretum of Ruhande and Rubona agricultural research station, in southern Rwanda (Figure 2). The arboretum of Ruhande is located at 2˚36´ South and 29˚44´ East with a maximum elevation of 1737 meters (Nsabimana et al., 2009). The surface area is approximately 200 hectares, divided into 504 plots of 50mx50m each, and with 207 native and exotic trees species (Nsabimana et al., 2008). Rubona agricultural research station is located between 2˚35´ South and 29˚43´ East, at 1734 meters in elevation (Nabahungu et al., 2011). The station covers a surface area of around 675 hectares, dominated by tree plantations, a woodland zone dominated by *Hyparrhenia* and *Acacia* species, and agricultural research zone dominated by leguminous species, cereals, tubers, banana, coffee, and fruit plantations (ISAR, 1989).

2.1. Data Collection

Data on soil litter arthropods were collected three times separated by two weeks in-between, in March and April 2017, using Berlese-Tullgren funnels, pitfall traps, and hand sorting. At the Arboretum of Ruhande, data were collected in plots of *Eucalyptus maideni, Polyscias fulva, Cedrella serata* and *Grevillea robusta*; while at Rubona agricultural research station soil litter arthropod samples were collected in plots of four banana plantation varieties including *Mporogoma, Injagi, FHIA17*, and *FHIA25*. Three sampling points were selected randomly in each plot, and separated by at least 6m from another, by living five meters from the edge (Nsabimana, 2013). Each of the sampling points during the second and third sampling exercises was located at two meters ahead of the first sampling point to avoid the over sampling in the same sampling point (Sabu and Shiju, 2010). The time used for the trap fixation, trap collection, and extraction of specimens in the trap was recorded for each sampling method with a stopwatch.

2.1.1. Data collection by pitfall traps

Three pitfall traps placed randomly in each sampling site were used to collect soil litter arthropods. Each pitfall trap consisted of a transparent plastic bottle (6 cm diameter, 10 cm depth), buried in 20 x 20 cm soil up to its rim and partly filled with 20 ml of 75% ethanol after the removal of the leaf litter layer. Each trap was covered with cardboard fixed on nails in order to prevent the entry of rainwater, falling leaves, and debris, which may facilitate trapped fauna to escape (Sabu and Shiju, 2010). Each trap was maintained for 24 hours in order to avoid biases in captures, which could arise from diurnal activities of fauna (Mommertz et al., 1996). The content of each trap was emptied into sterile plastic bottles filled with 20ml of 75% ethanol, and analysed separately from others (Wang et al., 2014).

2.1.2. Data collection by hand sorting

Three sampling points selected randomly in each sampling site were sampled during this study by the use of the hand sorting sampling method. Soil litter arthropods were collected by using a meter square pick-up point sampling method (McGavin, 2007) in five centimetre soil depth after the removal of the leaf litter layer (Sayad et al., 2012). Targeted soil litter arthropods were pulled out the soil with 11cm sharp-pointed forceps and fingers (Martin, 1997). Each collected individual arthropod was conserved in a sterile plastic bottle filled with 20ml of 75% ethanol. Each bottle was stored in laboratory, and analysed separately from others (Wang et al., 2014).

2.1.3. Data collection by Berlese - Tullgren funnels

Three core soil samples (10cm x 10cm, 0 - 5cm depth) were taken randomly in each sampling site and bulked to give one representative sample, after the removal of the leaf litter layer and taken to the laboratory for the extraction of soil litter arthropods (Sakchoowong et al., 2008). Each representative soil sample was heated in Berlese-Tullgren funnels by a 60-watt bulb placed 10cm above the funnel for a period of 24 hours. The bottom of the apparatus was filled with 20ml of 75% ethanol and catches biota as they drop from the funnel (Moço et al., 2010). Collected arthropods were conserved in a sterile container, and analysed separately from others (Wang et al., 2014).

2.2. Data analysis

Samples of soil litter arthropods collected by each sampling method were taken to the laboratory for identification and classification to the family level using dichotomous keys in the literature (Mignon et al., 2016; Delvare and Aberlenc, 1989). Percentages, diversity and evenness indices were calculated to determine the abundance, diversity, and evenness of collected soil litter arthropods captured with each sampling method and to determine similarities or differences in Berlese-Tullgren funnels, pitfall traps and hand sorting sampling methods. Shannon diversity index (H´) was used to evaluate the diversity (Shannon and Wiener, 1946), Pielou's evenness index (P´) was used to calculate the evenness (Pielou, 1996), and the percentage of similarity (PS) was used to calculated the level of similarity between studied sampling methods (Henk, 1981).

The chi-square test was used to test for differences in the frequency with which particular soil litter arthropod taxa were collected by the three sampling methods (Sabu et al., 2012). The effect of sampling method on the proportion of arthropods captured was evaluated based on the significance of the chi-square test (Parasifka et al., 2007). Z-tests were used to assess the trap-wise differences in the capture efficiency of individual taxa among three sampling methods, while the univariate comparison was used to evaluate the significance level of differences among medians. When significant differences were found, the honestly significant test was used to determine which pairs of sampling methods differed significantly (Weiss, 2007).

3. Results

A total of 1768 individuals of soil litter arthropods distributed in five classes, eleven orders and fifteen families were collected. Classes with the highest number of individual were Insecta (49.3%), Diplopoda (32.9%), Chilopoda (9.8%), and Crustacea (7.9%). The class Arachnida had the lowest number of individuals (1.9%). The order Hymenoptera was abundant (38.9%) followed by Julida (25.3%), Coleoptera (9.5%), Isopoda (7.3%), Geophilida (6.6%), Isoptera (4.6%), Orthoptera (2.6%), Araneae (1.9%), Scolopendrida (1.1%), and Blattodea (1.7%). The families Formicidae (39.0%), Julidae (25.3%), and Oniscidea (7.4%) were abundant compared to other identified families (Table 6).

Variations in abundance of collected soil litter arthropods were observed within each land use (Table 7), where banana crop plantations had higher abundance (58.9%) of collected soil litter arthropods than conserved tree plantations (41.2%). Higher abundance was found in *Mporogoma* (17.2%) and *FHIA17* (16.8%) banana varieties, while higher abundance in conserved tree plantations was found in *Grevillea robusta* (12.9%) and *Cedrella serrata* (12.6%). Lower abundance was found in *Eucalyptus maideni* (5.7%) conserved trees and in *FHIA25* (11.9%) banana plantation.

Variations were also observed for each sampling method. The class Insecta was the most common class collected in pitfall traps (30.0%) and Berlese-Tullgren funnels (8.9%). The order Hymenoptera (Formicidae) comprised dominant species collected by pitfall traps (22.4%) and by Berlese-Tullgren funnels (6.3%). The most abundant class collected by hand sorting was Diplopoda (24.5%) and Julida (18.2%). Collembola, (0.8%) were collected by pitfall traps and not found in Berlese-Tullgren funnels and hand sorting (Table 6 and Table 7).

Results of diversity and abundance of collected soil litter arthropods indicated less diversity and evenness for Berlese-Tullgren funnels ($H' = 0.48$, $P'=0.15$), and hand sorting ($H' = 1.22$, $P'=0.163$) sampling methods. A higher diversity was found for pitfall traps ($H' = 1.37$, $P'=0.18$). Higher percentage (21.2%) was found between hand sorting and pitfall sapling technique, while less percentage of similarity was found between Berlese-Tullgren funnels and pitfall traps (PS = 12.6%), and between Berlese-Tullgren funnels and hand sorting (PS = 12.2%).

Table 6: Abundance (%) of arthropod families obtained by studied sampling methods (Sp: Number of individual species)

Family	**Berlese-Tullgren funnel**		**Pitfall traps**		**Hand Sorting**		**Total**	**%**
	Sp.	**%**	**Sp.**	**%**	**Sp.**	**%**		
Araneidae	1	0.1	16	9.6	17	1	34	1.9
Blattidae	0	-	13	0.7	17	1	30	1.7
Chrysomelidae	0	-	32	1.8	0	-	32	1.8
Staphylinidae	0	-	22	1.2	17	1	39	2.2
Tenebrionidae	9	0.5	28	1.6	61	3.5	98	5.5
Formicidae	112	6.3	396	22.4	181	10.2	689	39
Rhinotermitidae	10	0.6	0	-	0	-	10	0.6
Termitidae	25	1.4	39	2.2	8	0.5	72	4.1
Acrididae	0	-	2	0.1	2	0.1	4	0.2
Gryllidae	2	0.1	24	1.4	16	0.9	42	2.4
Geophilidae	5	0.3	23	1.3	78	4.4	106	6
Onicidea	10	0.6	9	0.5	111	6.3	130	7.4
Julidae	65	3.7	60	3.4	323	18.3	448	25.3
Sclopendridae	2	0.1	0	-	18	1	20	1.1
Isotomidae	0	-	14	0.8	0	-	14	0.8
Total	**241**	**13.6**	**678**	**38.3**	**849**	**48.0**	**1,768**	**100**

Table 7: Abundance of soil litter arthropods by land use and by sampling method (Sp: Number of individual species).

Land use	**Berlese-Tullgren funnels**		**Pitfall traps**		**Hand Sorting**		**Total**	**%**
	Sp.	**%**	**Sp.**	**%**	**Sp.**	**%**		
P. fulva	19	1.1	45	2.5	113	6.4	177	10
Mporogoma	35	2.0	117	6.6	152	8.6	304	17
Injagi	38	2.1	107	6.1	84	4.8	229	13
G. robusta	23	1.3	58	3.3	147	8.3	228	13
FHIA25	27	1.5	91	5.1	93	5.3	211	12
FHIA17	58	3.3	99	5.6	140	7.9	297	17
E. maideni	7	0.4	53	0.3	40	2.3	100	5.7
C. serrata	34	1.9	108	6.1	80	4.5	222	13
Total	**241**	**13.6**	**678**	**38**	**849**	**48**	**1768**	**100**

Statistical analysis indicated the independence between Berlese-Tullgren funnels and hand sorting (chi-square = 92.8, df = 72, P = 0.046, α = 0.05), while the dependence was found between Berlese-Tullgren funnels and pitfall traps (chi-square = 110.8, df = 88, P = 0.104, α = 0.05), and between pitfall traps and hand sorting (chi-square = 123.2, df = 99, P = 0.175, α = 0.05) sampling methods. The assessment of the trap - wise differences in capture efficiencies of individual species through Z-test indicated differences between means for Berlese-Tullgren funnels and hand sorting (P = 0.046, α = 0.05), Berlese-Tullgren funnels and pitfall traps (P = 0.038, α = 0.05), and between pitfall traps and hand sorting (P = 0.010, α = 0.05).

Honestly significant tests to verify if pairs of sampling methods differ significantly indicated that there is no difference between the pairs of pitfall traps and hand sorting (P =0.87, α = 0.05), and between Berlese-Tullgren funnels and pitfall traps (P = 0.06, α = 0.05). Significance differences were observed between Berlese-Tullgren funnels and hand sorting (P = 0.01, α = 0.05). The test for similarity between tested sampling methods indicated positive Pearson's correlation between hand sorting and Berlese-Tullgren funnels (ρ = 0.76), pitfall traps and hand sorting (ρ = 0.40), and between Berlese-Tullgren funnels and pitfall traps (ρ = 0.81).

4. Discussion

Results indicated that Berlese-Tullgren funnels collected less number as well as less diversity of soil litter arthropods compared to pitfall traps and hand sorting. Lower occurrence, less diversity of soil litter arthropods collected by Berlese-Tullgren funnels has been observed in other studies, and could be caused by the heat from the apparatus, especially when specimens are collected from the moist area (Bestelmeyer et al., 2000). Because soil litter arthropods have been collected during the rain period, some of the soil litter arthropods, especially those of small size were likely to die by desiccation before dropping into the collecting jar (Sabu et al., 2012).

Despite high differences in means between independent and paired samples, positive correlations between hand sorting, pitfall traps, and Berlese-Tullgren funnels may suggest that when different sampling methods are paired, they can yield good results and collect a wide range of soil litter arthropods. A combination of different sampling methods has been highly recommended in other studies, especially when focusing on specific taxa (Yi et al., 2012). Pairing hand sorting with litter sifting has been shown to yield good results for sampling centipedes (Sabu and Shiju, 2010), and pairing pitfall traps with leaf litter collection yielded good results for sampling ground-dwelling carabid beetles with small size (Olson, 1994), while pitfall and stocking traps were effective in sampling Elateridae commonly known as wireworms (Morales-Rodriguez et al., 2017).

The highest number and lower diversity of soil litter arthropod species collected by hand sorting might be due to the biases of this sampling method where observed and targeted arthropod species are collected, especially when they are big in size and abundant in the area of study (Woodcock, 2005). Similar findings were observed in savannah habitats (Druce et al., 2014), and in native forests, where hand sorting collected a large number of species in a high abundant species (Gaspar et al., 2014). As found in this study, hand sorting was criticized for being time-consuming (Tuf, 2015). Another disadvantage of hand sorting is that, variations in individual skills and experience in sampling create differences in sampling efficiencies that affect the results (Berthold et al., 1999).

Even though hand sorting sampling method has several disadvantages, other studies have identified benefits of this sampling method, including targeted extraction of soil litter arthropods, minimum disturbance to the habitat and shorter sampling periods for targeted taxa, as well as reduction of unnecessary mortality of unwanted invertebrates (Smith et al., 2008). In addition, field workers may gain a better understanding of the environmental factors influencing soil assemblages through direct observations of correlations between changes in soil texture and invertebrate abundances; so that such observations may inform future data collection or help develop new hypotheses (Smith et al., 2008).

Suitability of Berlese-Tullgren funnels and pitfall traps for collecting individual species of the family of Formicidae has been documented in other studies where these sampling methods were efficient for sampling the majority of litter and soil dwelling arthropods (Paoletti et al., 1991). However, differences have been observed in other studies, where pitfall traps yielded good results for sampling soil litter ants (Peck et al., 1998), while Berlese-Tullgren funnels collect a large number of the larvae of dipterans due to accelerated hatching of eggs laid by flies due to the lamps' light, allowing the larvae to emerge during extraction period (Smith et al., 2008). This was not the case for this study because funnels were covered during extraction to prevent such contamination.

Pitfall traps collected a higher diversity of soil litter arthropods dominated by the class Insecta (Hymenoptera: Formicidae). Efficacy of this sampling method for Formicidae has been documented in other research (Osbrink et al., 2017). High diversity and large numbers of soil arthropod groups including Scorpionida, Isopoda, Diplopoda, Chilopoda, Symphyla, Araneae, Acari, Collembola, Coleoptera, and Formicidae have been collected by this sampling method in other studies (Frank et al., 2012; Skavarla et al., 2014), and this method is recognized for its trapping efficiency (Spence and Niemelä, 1994). Other studies indicated that pitfall traps can have different designs in terms of materials used and in size (Jud and Schmidt-Entling, 2008), so that they are suitable for studying the occurrence and relative abundance of litter and soil dwelling arthropods of different sizes (Phillips and Cob, 2005; Buchholz et al., 2010), and can contribute to the collection of nocturnal soil litter arthropod species, and hence reduce biases (Work et al., 2002).

5. Conclusion and recommendations

Results obtained from this study illustrate that pitfall traps and Berlese-Tullgren funnels are suitable sampling methods for soil litter arthropods dominated by Formicidae. Hand sorting sampling method was suitable for sampling soil litter arthropods with a large size dominated by Julidae. Pitfall traps showed greater efficiency in terms of collecting a higher diversity of soil litter arthropods, and showed higher percentage of similarity with hand sorting. Further studies comparing the trapping efficiency between Berlese-Tullgren funnels, pitfall traps and hand sorting sampling methods for soil litter arthropods in other ecological zones, different land uses and different seasons have to be conducted to better understanding differences among these sampling methods.

6. Acknowledgement

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4

Use of soil and litter arthropods as biological indicators of soil quality

General introduction to chapter 4

Results of chapter III indicated that pitfall-sampling technique has greater efficiency in terms of collecting a higher diversity of soil and litter arthropods and higher percentage of similarity with hand sorting. These are the reasons why, this sampling technique was selected for sampling soil and litter arthropods in chapter IV and chapter V. Back to chapter II, one of the recommendation was to use species diversity and abundance together with other soil physicochemical parameters, microbiological communities, environmental factors such as seasonal variability and altitudinal variations and ecological functions of soil and litter arthropods when both species diversity and abundance have to be used for assessing soil quality in different land uses.

Chapter IV focused on the use of soil and litter arthropods as biological indicators of soil quality under different land uses in southern Rwanda. Its main purpose was to determine how the community composition of soil and litter arthropods correlated with physicochemical parameters under different land uses and how ecological functions of soil and litter arthropods justify the positive correlation. The study aimed at: (1) Identifying and testing for variations in diversity and abundance of individuals that compose the community of soil and litter arthropods, (2) Testing variations in soil physicochemical parameters under different land uses, and (3) Studying the relationship between the community composition of soil and litter arthropods and soil physicochemical parameters, and relate them to ecological functions of soil and litter arthropods.

Use of soil and litter arthropods as biological indicators of soil quality under conserved tree species, coffee and banana plantations in southern Rwanda

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Abstract

The community of soil and litter arthropods is highly diverse and provides a number of important ecosystem services including maintenance of soil structure, regulation of hydrological processes, nutrient cycling and leaf-litter decomposition. To assess soil quality of different land uses, we conducted a critical study of the potential implications of variations in soil physicochemical parameters on community composition of soil and litter arthropods in plots of tree species and varieties of coffee and banana plantations. Soil and litter arthropods were collected by pitfall sampling techniques. We collected and analysed soil cores for soil organic carbon, total nitrogen, available phosphorus, pH, aggregate stability, cation exchange capacity, electrical conductivity, silt, and clay and sand soil textures. C:N rations were calculated. Higher levels of total nitrogen, soil organic carbon, and humidity, clay and silt soil texture were found in plots of native and exotic tree species. Higher levels of cation exchange capacity, pH, and electrical conductivity were found in plots of native tree species and banana plantations, while higher levels of available phosphorus, aggregate stability and sand soil texture were found in plots of coffee and banana plantations. C:N ratios were higher in native and exotic tree species. Higher abundance of soil and litter arthropods was found in plots of native tree species. The families of Formicidae, Scolopendridae, Trombiculidae, Eosentomidae, and Staphylinidae showed strong correlations with soil physicochemical properties. Ecological functions that contribute to soil quality are more generalized to families and/or orders, and did not allow concluding about the family of litter arthropods that can serve as suitable bioindicator of soil quality. Studies that are more detailed should aim to identifying specific ecological functions for each family of soil and litter arthropods, and identify which species are the most closely associated with which soil physicochemical parameters in a given land use.

Key words: community composition, physicochemical parameter.

1. Introduction

Soil quality and soil health are used interchangeably and are defined as the fitness of a specific soil to function within its capacity and within natural or managed ecosystem boundaries, to sustain animal and plant productivity, to maintain water and air quality, and to support human health (Laishram et al., 2012). Soil quality is affected by land uses (Oliveira et al., 2016). Some tree species increase soil acidification and consume high quantities of water and soil nutrients, and this is magnified in mono-dominant stands (Jagger and Pender, 2003). In agricultural lands, tillage decreases soil organic matter (Kaschuk et al., 2010), and fertilizers and pesticides used to increase agricultural yields and to fight against pests cause variations in soil physicochemical properties (Gill and Garg, 2014) and soil fauna, including soil and litter arthropods (Nsabimana, 2013).

Relationships between land uses, soil properties and soil fauna have long been a topic of interest. Some soil and litter arthropods are litter decomposers (Lavelle, 1997) while others are efficient ecosystem engineers (Jones et al., 1994) that create networks of tunnels and galleries, thus improving soil porosity, aeration, and water holding capacity (Lobry de Bruyn, 1990). Some soil and litter arthropods improve soil structure and facilitate the movement of soil minerals and organic matters in soil horizons by mixing both kinds of mineral nutrients (Culliney, 2013). Faeces of soil and litter arthropods were found to facilitate soil aggregation, to contribute to humus stability and to improve the capacity of soils to store and maintain nutrients (Bagyaraj et al., 2016).

The use of soil fauna communities for assessing soil quality is a recent approach (Brown et al., 2009). Different studies focused on the effects of land use change on soil physicochemical parameters and soil fauna by investigating for example the relationship between physicochemical properties and individual species of soil and litter arthropods (Flieβbach et al., 2017). Studies of this kind were not yet done in Rwanda. There is a lack of information about arthropod biodiversity, and the ways that soil and litter arthropods correlated with soil physicochemical parameters under different tree species and croplands remains unanswered.

The research presented here fills the gap by investigating the structural diversity of soil and litter arthropods and explore possible application of their community composition as soil biological indicators in very different land use types, including monodominant stands of exotic and native tree species, and different varieties of coffee and banana plots, all located in southern Rwanda. Thus, we propose to assess the relationships between individuals of the families of soil and litter arthropods, land use systems, soil physicochemical parameters and ecological functions of identified soil and litter arthropods. We hypothesized that individuals of soil and litter arthropods respond differently to the land use and soil physicochemical parameters.

This study was guided by four research objectives: (1) Identify and test for variations in diversity and abundance of individuals that compose the community of soil and litter arthropods, (2) Test variations in soil physicochemical parameters under different land uses, (3) Study the correlation between soil and litter arthropods and soil physicochemical parameters, and (4) Document on the contribution of ecological functions of identified soil and litter arthropods on soil quality.

2. Materials and Methods

2.1. Area of study and data collection

Data were collected at the Arboretum of Ruhande and the Rubona agricultural research station. The Arboretum was used as human settlement and multiple crop lands until 1933. It is located at 2°36’S and 29°44’E, at the elevation of 1737- meter (Nsabimana et al., 2009), and covers an area of around 200 hectares, divided into 504 plots of 50 m x 50 m each. Each plot is numbered and has an historical database of growth measurement and management. The Arboretum hosts around 207 native, agroforestry and exotic tree species (Nsabimana et al., 2008). The Rubona station is located at 2°29´S and 29°46´E, at 1750 - meter elevation, with a distance of 15 kilometres from the Arboretum of Ruhande. Established in 1930, it is the first centre for agricultural research in Rwanda (Karangwa, 2007). It covers an area of around 675 hectares, including an agricultural research zone with varieties of coffee and banana plantations (ISAR, 1989).

Soil cores and soil and litter arthropods were sampled in mono-dominant stands of exotic and native tree species, and in varieties of coffee and banana plantations. In the Arboretum of Ruhande, three different exotic tree species including *Eucalyptus maideni*, *Cedrella serrata* and *Grevillea robusta* were sampled, while three native monodominant stands including *Entandrophragma excelsum*, *Polyscias fulva*, and *Podocarpus falcatus* were sampled. At Rubona station, samples were taken under three varieties of coffee plantations including *HARRAR*, *JACKSON*, and *RABC15*, and samples were taken in banana plantations including varieties of *FHIA17*, *INJAGI*, and *MPOROGOMA*.

Sample locations within each plantation type were selected randomly and three pseudo-replicates in each type of tree species, coffee and banana plantations were sampled. Each pseudo-replicate had the size of 50 m x 50 m, while the minimum distance of 10 meters between two stands was maintained. Figure 2 presents the location of the sites in Huye district, Rwanda.

Nine sampling points each of 1 m^2 in size were placed in each pseudo-replicate, by living five meters from the edge of the sample plot to avoid edge effects. To avoid autocorrelation, each point was separated from the other by a distance of 16 meters (Figure 3; Clark et al., 1996). When the placement of sampling point met an obstacle such as a tree, rocks, a nest or the marching columns of some soil and litter arthropods, a distance of 2 meters was maintained from the obstacle, nest or mulching column going inside the plot to avoid biases in results. In this case, the distance between two sampling points was reduced from 16 to 14 meters.

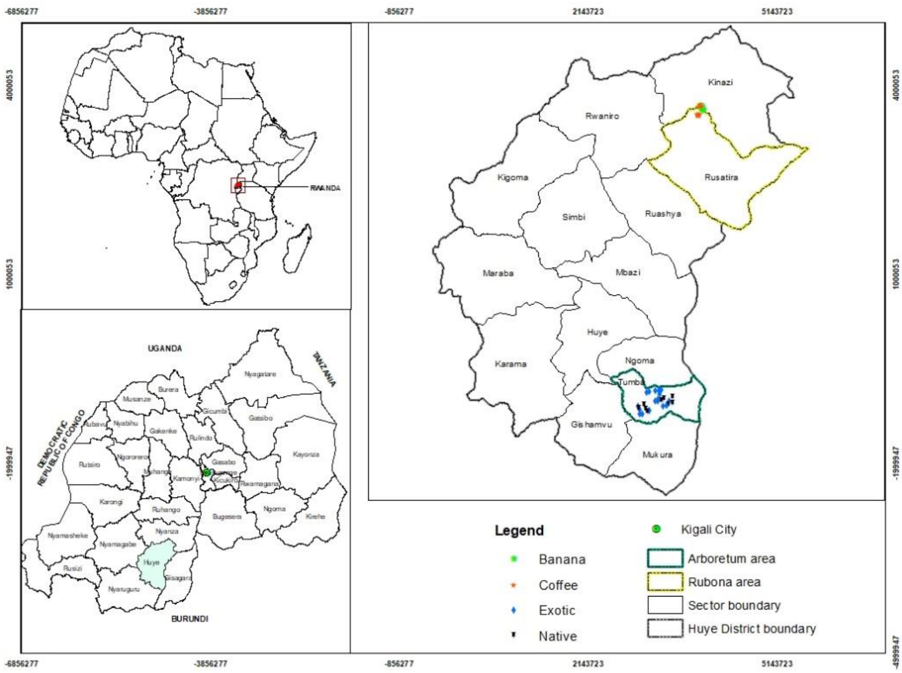

Figure 2. Area of study: Location of Rwanda in Africa, location of Huye in Rwanda and then, location of two sites in the sectors of Huye district (Adapted from data of the Centre for Geographic Information System – University of Rwanda)

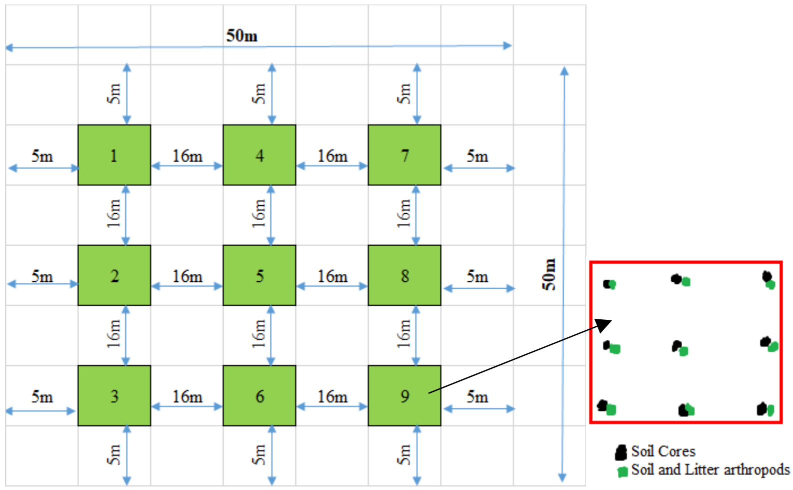

Figure 3. Sampling scheme for the collection of soil and litter arthropods and soil cores in each pseudo-replicate at the Arboretum of Ruhande and Rubona Agricultural Research station

Between April (end of the rain period) and July (starting of dry period) 2017, nine pitfall traps were placed around and in each sampling point for collecting soil and litter arthropods (Vasconcellos et al., 2013). Each trap consisted of a transparent plastic bottle (6 cm diameter, 10 cm depth), buried into the soil pit and partly filled with 20 ml of 75% of ethanol. To prevent rainwater, leaves and debris from entering the trap, each trap was covered with a piece of 10 cm x 10 cm cardboard. Each trap was placed in the site after the removal of the leaf litter layer (Sabu and Shiju, 2010), and they were maintained in place for 24 hours in order to avoid biases in captures which could arise from diurnal activities of fauna (Mommertz et al., 1996).

Thereafter, the content of each trap was emptied into individual plastic bottles filled with 20 millilitre of 75% ethanol, transferred to the laboratory of Biology, College of Education, at the University of Rwanda and analysed separately from other samples (Wang et al., 2014). Collected soil and litter arthropods were morphologically identified under microscope and classified to the family levels by the use of dichotomous keys in the literature (Delvare and Aberlenc, 1989; McGavin, 2002; Choate, 2010; Mignon et al., 2016). Names were confirmed after the consultation of specimens stored at the Royal Belgium Institute of Natural Sciences, Belgium.

In May 2017, nine soil cores (10 cm x 10 cm, 0-5 cm soil layer depth) were collected around and in each sampling point (Figure 2) in each pseudo-replicate and bulked to give one sample (Sayad et al., 2012). A distance of 5 meters from the edge of the sample plot was left out of the area of study to avoid edge effect, and a distance of 16 meters between sampling points was maintained to avoid autocorrelation. When the sampling point met an obstacle, it was displaced about two meters inside the plot, reducing the distance between two sampling points to 14 meters.

Samples for the analysis of soil pH, soil organic carbon, soil total nitrogen, available phosphorus, electrical conductivity, cation exchange capacity, and aggregate stability and soil textures were collected, bulked together, and put in a 1-kilogram (kg) plastic paper each. Then after, taken to the laboratory of soil and plant analyses, College of Agriculture, Animal Science and Veterinary Medicine, University of Rwanda, and analysed separately by specific laboratory techniques.

Prior to laboratory analysis, soil samples were sieved, and air-dried (Nsabimana et al., 2008). Soil texture was determined by hydrometer method (Bouyoucos, 1962), the electrical conductivity was calculated by electrical conductivity meter (Okalebo et al., 2002), the aggregate stability was calculated by wet sieving method (Kemper and Rosenau, 1986), while soil pH was measured by using pH meter in a soil-water suspension in the ratio of 1:1.25 (Watson and Brown, 1998). Further, total nitrogen was calculated by colorimetric method through ultraviolet visible spectrophotometer (Okalebo et al., 2002), available phosphorus was calculated by spectrophotometry at 884 nm wavelength (Bray and Kurtz, 1945), soil organic carbon was calculated by wet oxidation method (Nelson and Sommers, 1982), while cation exchange capacity was calculated by Kjeldahl distillation method (Chapman, 1965). The C:N ratio was also calculated from the data of soil organic carbon and soil total nitrogen.

2.2. Data analysis

One-way ANOVA tests were used to test for significant differences in soil and litter arthropods, and soil physicochemical parameters under different land uses (Sayad et al., 2012). Diversity indices and the abundance of soil and litter arthropods were used to compare soil and litter taxa in each land use (Wang et al., 2014). Treatment effects on arthropod community composition were analysed with non-metric multidimensional scaling (NMDS), while the analysis of similarity (ANOSIM) was done based on Bray-Curtis similarity (Ashford et al., 2013).

Only the most abundantly caught species were used for statistical analysis (Dekoninck et al. 2007) and rare species were down weighted by the use of the parallel discrimination rates calculated by taking the homogenized canonical coefficients times correlation coefficients (PDR = HCC x r). The greater the positive PDR value (Borcard et al., 1992), the more effective the variable is at discriminating between plots of native and exotic tree species and between coffee and banana plantations (ter Braak and Smilauer, 1998). The ecological functions of identified soil and litter arthropods was documented in the literature and they were used to justify the correlation between soil and litter arthropods and soil physicochemical parameters.

3. Results

A total of 3922 individuals of soil and litter arthropods distributed in eleven classes, fifteen orders and twenty-four families were collected. Myriapods identified in this study include centipedes (Chilopoda), Pauropoda, Symphyla and millipedes (Diplopoda). Other arthropods including Isopods (Oniscidea), spiders (Araneae), mites (Acari), springtails (Collembola), proturans, diplurans and insects represented by the orders of Hymenoptera, Isoptera, Coleoptera and Orthoptera were also identified in this study. Diplopoda (Julida: Julidae), springtails (Collembola: Isotomidae and Entomobryidae), and Hymenoptera (Formicidae) occurred in all land uses, and Formicidae showed higher abundance than other families (Table 9).

Higher abundance (total number of the mean individual of collected soil and litter arthropods) was found in plots of native tree species (17.8 ± 6.9) than in the plots of exotic tree species (12.0 ± 4.5), coffee (7.3 ± 4.9) and banana (3.16 ± 1.58) plantations. Higher diversity was found in plots of exotic tree species (H' = 2.10 ± 0.11) and native tree species (H' = 2.46 ± 0.17) compared to plots of banana (H' = 2.07 ± 0.13) and coffee plantations (H' = 1.44 ± 0.37), while higher evenness was found in plots of exotic tree species (E' = 0.47 ± 0.19) and banana plantations (E' = 0.37 ± 0.14) compared to plots of exotic tree species (E' = 0.34± 0.18) and coffee plantations (E' = 0.2 ± 0.45). The average species diversity was higher (H' = 2.1 ± 0.80) and the average evenness was low (E = 0.17±0.13) in plots of native and exotic tree species, compared to the plots of coffee and banana plantations (H' = 0.16 ± 0.38 and E = 0.19 ± 0.0.16), but these differences were not statistically significant ($F = 2.06$, $P > 0.05$).

Variations were also found in soil physicochemical parameters (Table 8). Higher levels of soil total nitrogen, soil organic carbon, and clay and silt soil texture were found in plots of native and exotic tree species. Higher levels of cation exchange capacity, soil pH, and electrical conductivity were found in plots of native tree species and banana plantations, while higher levels of available phosphorus, aggregate stability and sand soil texture were found in plots of coffee and banana plantations because of frequent and continuous land use. C:N ratios were higher in plots of native and exotic tree species than the plots of coffee and banana plantations (Table 8).

Statistical significant differences were found in plots of exotic tree species ($F = 2.6$, $df = 11$, $P < 0.05$), native tree species ($F = 2.8$, $df = 11$, $P < 0.05$), coffee ($F = 1.2$, $df = 11$, $P < 0.05$) and banana ($F = 2.0$, $df = 11$, $P < 0.05$) plantations. The test for treatment effects on soil physicochemical parameters indicated less conformity between samples (stress = 0.086), while the composition in soil physicochemical parameters differed significantly among plots of exotic and native tree species and plots of coffee and banana plantations ($R = 42.89\%$, $p < 0.05$).

Table 8: Variation (mean ± st.dev) of soil physicochemical properties in different land uses in southern Rwanda (SOC: Soil Organic Carbon, Tot. N: Total Nitrogen, Av. P: Available phosphorus, EC: Electrical Conductivity, CEC: Cation exchange capacity, AS: Aggregate Stability)

		Soil pH	**SOC (%)**	**Tot. N (%)**	**C:N ratios**	**Av. P (mg/kg)**	**EC (mS/cm)**	**CEC (Meq)**	**AS (%)**	**Clay (%)**	**Silt (%)**	**Sand (%)**
Exotic tree species	Mean	5.3	7.6	0.6	12.7	4	0.3	7.3	0.5	14.6	17.5	68
	st.dev	0.3	2.9	0.3	9.7	1.4	0	0.3	0.1	4.4	2.8	7
Native tree species	Mean	5.8	6.4	0.5	12.8	3.7	0.4	7.7	0.6	13.7	16.4	69.9
	st.dev	0.4	0.4	0.1	4.0	0.9	0.1	0.5	0.1	2.2	2.1	3.9
Coffee plantations	Mean	5.8	3.3	0.3	11.0	15.5	0.3	7.7	0.7	12.7	11.0	76.3
	st.dev	0.4	1.3	0.2	6.5	10.3	0.2	0.4	0.1	2	3.0	3.2
Banana plantations	Mean	6.1	2.6	0.4	6.5	13.7	0.4	8	0.7	12.7	11.7	75.7
	st.dev	0.5	0.7	0.1	7.0	8	0.2	0.4	0.1	1.5	1.5	2.5

Table 9: Abundance (mean ± standard deviation) of identified soil and litter arthropods in the litter of exotic and native tree species and coffee and banana plantations in southern Rwanda

Order	Family	Exotic tree species	Native tree species	Banana plantations	Coffee plantations
Acari	Trombiculidae	4.8 ± 1.8	6.7 ± 3.1	1.3 ± 1.5	3.0 ± 1.0
Acari	Trombidiidae	25.8 ± 8.6	5.0 ± 3.6	1.0 ±1.0	2.0 ± 1.0
Araneae	Theridiidae	21.0 ± 18.5	9.3 ± 2.1	2.3 ± 2.5	1.7 ± 0.6
Chilopoda	Geophilidae	0	7.7 ± 3.5	2.0 ± 0.0	0.7 ± 0.6
Coleoptera	Carabidae	9.2 ± 10.1	11.7 ± 1.1	2.3 ± 1.5	1.0 ± 1.0
Coleoptera	Chrysomelidae	10.3 ± 3.3	0	0.3 ± 0.6	1.0 ± 1.0
Coleoptera	Elateridae	2.0 ± 2.1	6.7 ± 2.5	1.0 ± 1.0	1.3 ± 0.6
Coleoptera	Histeridae	3.5 ±1.8	5.7 ± 0.6	0.7 ± 0.6	2.0 ± 1.0
Coleoptera	Staphylinidae	3.7 ± 1.5	7.7 ± 2.1	1.3 ± 1.5	2.7 ± 2.0
Coleoptera	Scarabaeidae	2.2 ± 3.5	0.3 ± 0.6	0	0
Collembola	Entomobryidae	36.0 ± 10.7	18.7 ± 1.5	6.0 ± 3.6	11.0 ± 8.7
Collembola	Isotomidae	3.8 ± 2.4	34.0 ± 9.5	2.7 ± 2.0	6.7 ± 5.0
Diplopoda	Julidae	6.0 ± 7.4	24.0 ± 5.0	10.3 ± 2.0	9.7 ± 2.3
Diplura	Cambodeidae	4.0 ± 1.5	4.7 ± 3.2	0.7 ± 0.6	1.0 ± 0.0
Diplura	Japigydae	3.7 ± 2.2	5.3 ± 2.5	1.3 ± 1.5	1.3 ±0.6
Hymenoptera	Formicidae	102.3 ± 80.4	224.7 ± 91.6	37.3 ± 32.0	123.3 ± 116.6
Isopoda	Porcellionidae	4.5 ± 2.0	4.7 ± 2.0	1.3 ± 1.5	2.3 ± 2.3
Isoptera	Rhinotermitidae	1.3 ± 18.7	17.3 ± 11.6	0	0
Isoptera	Termitidae	16.5 ± 13.6	7.7 ± 3.5	2.3 ± 0.4	7.3 ± 10.2
Orthoptera	Gryllidae	2.7 ± 2.8	16.7 ± 9.6	1.3 ± 0.6	1.7 ± 0.6
Pauropoda	Pauropodidae	1.3 ± 0.9	4.3 ± 3.9	1.7 ± 1.5	3.3 ± 1.5
Protura	Eosentomidae	3.3 ± 2.6	7.7 ± 7.2	1.0 ± 1.0	0.3 ± 0.6
Scolopendrida	Scolopendridae	5.2 ± 2.2	6.3 ± 3.2	0.7 ± 1.1	0
Symphyla	Scutigerellidae	5.0 ± 1.5	5.7 ± 3.2	0	0

Table 10: Pearson's correlation between soil – litter arthropods and soil physicochemical parameters (positive correlations r ≥ 0.5 are in bold)

Family	pHw	SOC	Tot.N	C:N	Av. P	EC	CEC	AS	Clay	Silt	Sand
Cambodeidae	0.2	**0.5**	0.5	**0.7**	-0.9	0.2	0.2	0.2	-0.1	**0.9**	-1
Carabidae	0.2	0.5	0.4	**0.6**	-1	0.1	0.2	0.1	-0.2	**0.8**	-1
Chrysomelidae	-0.6	-0.3	-0.4	0.4	-0.8	-0.6	-0.6	-0.6	0.3	**0.6**	-0.5
Elateridae	0.5	**0.8**	**0.7**	**0.8**	-0.8	0.5	**0.5**	0.5	-0.2	**0.9**	-1
Entemobryidae	0	0.4	0.3	**0.7**	-0.9	0	0.1	0	0.1	**0.9**	-0.9
Eosentomidae	**0.5**	**0.8**	**0.7**	**0.7**	-0.8	**0.5**	**0.5**	0.5	-0.3	**0.8**	-1
Formicidae	**0.6**	**0.8**	**0.7**	**0.9**	-0.6	**0.5**	**0.6**	**0.6**	0.2	**1**	-0.8
Geophilidae	0.3	**0.6**	**0.6**	**0.6**	-0.9	0.3	0.3	0.3	-0.3	**0.8**	-1
Gryllidae	0	0.3	0.3	**0.6**	-1	0	0	0	-0.1	**0.8**	-0.9
Histeridae	0.3	**0.6**	**0.5**	**0.8**	-0.9	0.3	0.3	0.3	0	**0.9**	-1
Isotomidae	0.1	0.4	0.3	**0.7**	-1	0	0.1	0	0	**0.8**	-0.9
Japygigae	0.1	0.5	0.4	**0.7**	-1	0.1	0.2	0.1	-0.1	**0.8**	-1
Julidae	0	0.3	0.2	**0.6**	-1	-0.1	0	-0.1	-0.1	**0.8**	-0.9
Pauropodidae	0	0.4	0.3	**0.8**	-0.9	0	0.1	0	0.1	**0.9**	-0.9
Porcellionidae	0.1	0.4	0.4	**0.8**	-0.9	0.1	0.1	0.1	0	**0.9**	-0.9
Rhinotermitidae	**0.5**	**0.8**	**0.7**	**0.7**	-0.8	0.5	**0.5**	0.5	-0.2	**0.8**	-1
Scarabaeidae	-0.3	0	0	0.5	-1	-0.3	-0.3	-0.3	0	**0.7**	-0.8
Scolopendridae	**0.9**	**1**	**1**	**0.5**	-0.4	**0.9**	**0.9**	**0.9**	-0.4	**0.6**	-0.7
Scutigerellidae	0	0.3	0.2	**0.6**	-1	0	0	-0.1	-0.1	**0.8**	-0.9
Staphylinidae	**0.8**	**0.9**	**0.9**	**0.8**	-0.5	**0.7**	**0.8**	**0.8**	-0.1	**0.8**	-0.8
Termitidae	-0.3	0.1	0	**0.6**	-0.9	-0.3	-0.2	-0.3	0.2	**0.8**	-0.8
Theridiidae	0.1	0.4	0.3	**0.6**	-1	0	0.1	0	-0.1	**0.8**	-0.9
Trombiculidae	**0.5**	**0.8**	**0.7**	**0.9**	-0.7	0.5	**0.5**	**0.5**	0	**0.9**	-0.9
Trombidiidae	0	0.4	0.3	**0.7**	-1	0	0.1	0	0	**0.9**	-0.9

Individuals making the families of soil and litter arthropods correlate differently to soil physicochemical properties. Results indicated a negative correlation between the members of all identified families with sand soil texture and available phosphorus. On the contrary, they correlate positively with silt soil texture and C: N ratios. The families of Scolopendridae, Trombiculidae, Eosentomidae, Staphylinidae and Formicidae showed higher correlation (r ≥ 0.5) with soil pH, soil organic carbon, total nitrogen, cation exchange capacity, C: N ratios, and aggregate stability (Table 10).

Documentation in a previous research indicated that the identified families of soil and litter arthropods have different functional groups (Table 11), and contribute differently to soil properties. The main functional groups of soil and litter fauna communities are predators / parasites, detritivores / decomposers, geophages / bioturbators and phytophagous /pests. The family of Formicidae make an exception compared to other families because it contributes to all identified ecological functions (Table 11). However, ecological functions are generalized to orders and few are specifically for the identified families. The taxon that contribute positively to a given functional group is indicated by the + sign in the table 11.

Table 11: Functional groups of soil-associated arthropods (Adapted from Brown et al., 2017): G and B: Geophagous and bioturbators; D/D: Detritivorous/Decomposers; Pg and Ps: Phytophagous/Pests, Pd and Pt: Predators/Parasites.

Taxa	**G/B**	**D/D**	**Pg/ Ps**	**Pd/Pt**
Acari	-	+	+	+
Theridiidae	+	-	+	+
Geophilidae	+	-	-	+
Carabidae	+	-	-	+
Elateridae	+	+	+	+
Histeridae	+	+	-	+
Staphylinidae	-	-	-	-
Scarabaeidae	+	+	+	
Staphylinidae	+	+	-	+
Collembola	-	+	+	-
Julidae	+	+	+	
Diplura	-	+	-	+
Formicidae	+	+	+	+
Porcellionidae	+	+	+	-
Isoptera	+	-	-	-
Gryllidae	+	+	+	-
Pauropodidae	-	+	-	+
Eosentomidae	-	+	-	-

Table 11 – cont

Taxa	G and B	D and D	Pg and Ps	Pd and Pt
Scolopendridae	-	-	-	-
Scutigerellidae	-	+	+	+

4. Discussion

Low levels of soil pH found in plots of exotic tree species were also found in other studies and were likely due to soil acidification by accumulation of basic cations in biomass, increasing production of organic acids from decomposing litter and by increasing cation leaching (Nsabimana et al., 2008). Higher levels of soil pH found in plots of native tree species, coffee and banana plantations were attributed to the availability of high exchangeable base cations in other studies (Sharma, 2011). On the other hand, high soil C:N ratios found in exotic and native tree species reveal high level of mineralization of nitrogen, based on the findings of other research where C:N ratio is an index of N mineralization (Nsabimana et al., 2008).

Higher levels of soil organic carbon found in forest plantations were probably a result of high litter fall from trees and shrubs (Kassa et al., 2017), and to different land uses and managements (Flieβbach et al., 20017). During our field data collection, we found that twice per year, organic fertilizers fertilize each plot of coffee plantation and banana, and this might be the cause of high levels of available phosphorus in this study as it was found in another study (Eylachew, 1987). We also observed that the majority of coffee plots were weeded but not well mulched and this practice might be the major cause of soil erosion and hence the source of higher levels in sand soil texture (Kassa et al., 2017). Higher levels in electrical conductivity, and cation exchange capacity found in forests and banana plantations might be enhanced by the loss of capacity of clay soils to adsorb base cations (Hertemink, 2003).

High abundance of soil and litter arthropods was found to mainly occur in soil and litter of exotic and native forest plots than in the soil and litter of coffee and banana plantations. Previous study associated these differences to the environmental stability, plant diversity, availability of soil nutrients, litter quality and water retention in the soils of forest plantations than those under coffee and banana plantations, where annual tillage disturbs soils and litter, and reduce the abundance of inhabiting arthropods (Beeby, 1993).

Eosentomidae (Protura) showed strong correlation with soil pH, soil organic carbon, total nitrogen, cation exchange capacity, aggregate stability and silt soil texture (Table 10). The preference source of food for proturans in general is decaying organic matter and fungi. Proturans are also predators of other small organisms such as nematodes and protozoans and they are bioturbators that reworks on soils and sediments through burrowing, ingestion and defecation of sediment grains (Marshall et al., 2009). In this way, proturans participate actively in litter breakdown and increase the surface area contact for microbial attack, enhance decomposition rates and release nutrients into the soil (Bagyaraj et al., 2016).

This study also indicated that the family of Scolopendridae (Centipedes: Chilopoda) has a positive correlation with soil pH, soil organic carbon, total nitrogen, electrical conductivity, cation exchange capacity, aggregate stability, and silt soil textures. Less is known about the contribution of the ecological functions of this family to soil quality. However, general information about all millipedes is that they are predators that increase soil organic matter through mineralization (Del Toro et al., 2012), and they create galleries in the soil (McGavin, 2002) that increase water infiltration and retention in the soil (Prather et al., 2013). There is a needed of research to proof if this is the same for the family of Scolopendridae.

Trombiculidae (Acari) is another family that showed high positive correlation with soil pH, soil organic carbon, total nitrogen, aggregate stability and silt soil texture. Trombiculidae are phytophagous and predators (Table 11), participating in litter breakdown, increasing surface area contact for microbial attack, enhancing decomposition rates and releasing nutrients in the soil (Del Toro et al., 2012; Prather et al., 2013). Another family that showed high correlation with studied soil physicochemical parameters is the family of Staphylinidae, which correlated with soil pH, soil organic carbon, total nitrogen, electrical conductivity, cation exchange capacity, aggregate stability and silt soil texture. Members of this family are predators that decompose the pray and enrich soils by increasing soil organic contents in soil (Schomann et al., 2008).

The family of Formicidae was more abundant and occurred in all land uses (Table 8). Higher abundance of the individuals of this family was also documented in the literature and these insects represent more than 50% of all eukaryotic species (Grimaldi and Engel, 2005), and they have the ability to live in all lands of the planet (Ramon and Donoso, 2015). Positive correlation with soil pH, soil organic carbon, total nitrogen, electrical conductivity, cation exchange capacity, aggregate stability, clay and silt textures were documented in other studies (Tejada et al., 2006; Adler and Drake, 2008). Formicidae are either predators, soil engineers, seed dispersers, plant symbionts, and participate in nutrient cycling that enrich soil in nutrients (Del Toro et al., 2012; Culliney, 2013). Other ecological activities include building of tunnels and chambers above and below ground that modify soil physical properties and increase soil aeration and water retention (Eldridge and Pickard, 1994). Ants were suggested to be good indicators of environmental conditions in many and different soil ecosystems (Vasconcellos et al., 2013; Nsabimana et al., 2013).

5. Conclusions and recommendations

Community composition of soil and litter arthropods correlate differently to soil physicochemical parameters. The families of Scolopendridae, Trombiculidae, Eosentomidae, Staphylinidae and Formicidae showed higher correlations wit soil physicochemical parameters than other identified families. Their functional groups have different contribution to soil properties, and they mainly increase soil organic matter, which is essential for soil health. In addition, Formicidae discriminated between native, banana, coffee, clay; sandy, aggregate stability, pH, available phosphorus, electrical conductivity and cation exchange capacity and. However, studies that are more detailed should aim to identifying which species of ants correlate well with more soil physicochemical parameters and functional activities of each species to determine its contribution to soil processes.

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5

Use of ants (Hymenoptera: Formicidae) as biological indicators of soil quality

General introduction to chapter 5

The use of soil and litter arthropods as biological indicators of soil quality indicated that families of soil and litter arthropods correlate differently with soil physicochemical parameters. The families of Scolopendridae, Trombiculidae, Eosentomidae, Staphylinidae and Formicidae had strong correlation with soil physicochemical parameters. Formicidae discriminated between native, banana, coffee, clay, sandy, aggregate stability, pH, available phosphorus, electrical conductivity and cation exchange capacity making this family particular from others. This chapter recommended more detailed study to identifying which species of soil and litter arthropods can be the most closely associated with soil physicochemical parameters.

Because skills in taxonomy limited us to do the taxonomy of all identified soil and litter families of soil and litter arthropods to species level, only ants (Hymenoptera: Formicidae) were selected due to their high abundance and due to their strong correlation with all studied soil physicochemical parameters, exception for available phosphorus and sand soil texture. The main objectives of this chapter include: (1) Identifying collected soil and litter ants to species level, (2) Testing the variations in abundance, diversity and evenness of identified soil and litter ant species, and (3) Studying the relationships between soil and litter ant species and soil physicochemical parameters in native and exotic tree species and in varieties of banana and coffee plantations as well as their ecological functions contributing to soil quality.

Use of soil and litter ant species (Hymenoptera: Formicidae) as biological indicators of soil quality under different land uses in southern Rwanda

Nsengimana V., Kaplin, B. A., Francis, F., Kouakou, M. M., Wouter, D., and Nsabimana D. (2017). Use of soil and litter ant species (Hymenoptera: Formicidae) as biological indicators of soil quality under different land uses in southern Rwanda. *Journal of Environmental Entomology,* 2018, pp. 1-8, doi. 10.1093/ee/nvy144.

Abstract

The use of soil and litter arthropods as biological indicators is a way to assess environmental changes, where ant species in particular may serve as important indicators of soil quality. This study aimed at relating the abundance of soil and litter ant species to soil parameters under different tree stands of monodominant species, both native and exotic, and varieties of coffee and banana plantations. Soil and litter arthropods were collected by pitfall sampling techniques. Soil cores were collected and analysed for soil organic carbon, total nitrogen, available phosphorus, pH, aggregate stability, cation exchange capacity, electrical conductivity, silt, clay and sandy soil textures. Variations were found in soil physicochemical parameters. In relation to ants, 30 species belonging to 14 genera, and 4 subfamilies, the Formicinae, Dorylinae, Myrmicinae and Ponerinae were identified in this study. Higher abundance was found in coffee plantations. Species of *Tetramorium laevithorax* showed higher abundance in exotic tree species, *Myrmicaria* SP02 showed higher abundance in native tree species, *Myrmicaria opaciventris* showed higher abundance in coffee plantations while *Odontomachus troglodytes* showed higher abundance in banana plantations. Species of *Camponotus cinctellus* and *Odontomachus troglodytes* occurred in all land uses, which is a sign of tolerance to a wide range of soil properties. Species of ant species correlated differently to soil physicochemical parameters and the contribution of their ecological functions to soil quality are not yet well known. We recommend further studies to focus on their ecological functions and make more research in taxonomy of soil and litter ants.

Keywords: Dorylinae; Formicinae; Myrmicinae; Ponerinae; soil quality; physicochemical parameters

1. Introduction

Ants are one of the most important and abundant arthropod groups in most tropical ecosystems (Hölldobler and Wilson, 1990), distributed into the family of Formicidae with 21 subfamilies, 283 genera with about 15 000 living ant species (Mahalakshmi and Chanaveerapa, 2016), and more than 13 000 species recognized worldwide (Bolton, 2014). Most of ants are beneficial to humans as source of food (DeFoliart, 1999), pharmaceutical and biomedical applications (Reddy and Yang, 2011), and provide ecological services as seed dispersers, pollination and biological controller agents (Lengyel et al., 2010). Some other ants are detrimental to humans through the attack to livestock and painful stings (Ascunce et al., 2011).

Ants were one of the first and now most commonly used as biological indicators of land use and land conservation status (Majer, 1983). They play crucial ecological roles as predators, soil engineers and nutrient cyclers (Del Toro et al., 2012). They were used as an integrative measure of soil quality assuming their importance in regulating soil processes that are vital to the continued formation of soil and as protection against soil degradation (Doran et al., 1994; Hawksoworth, 1991). In tropical soils, movements of ants through soil physically modify, maintain and create suitable habitats for other soil invertebrates (Ruiz et al., 2008).

Ants showed numerous advantages over vertebrates and other arthropods, mainly other insects, because they are extremely abundant, have a relatively high species richness and high trophic levels, and are responsive to changing environmental conditions (Majer, 1983). In addition, ants are easily recognized, identified, and easily collected (Majer, 1983). Further, ants constitute a large fraction of animal biomass in terrestrial ecosystems (Graham et al., 2009) and are the most divergent group among all social insects (Mahalakshimi and Channaveerapa, 2016). Furthermore, ants play an important role in soil ecosystems by participating in leaf and litter decomposition, soil aeration, soil mixing, soil porosity and texture (Fatima et al., 2008), and they contribute to nutrient transport at different soil horizons (Bagyaraj et al., 2016).

Previous research has indicated that since ants respond predictably to land changes, their abundance and species richness may predict soil conditions and be used to inform management of agricultural land to promote crop growth and ecosystem services (Peck et al., 1998). However, this might be challenged by a lack of their taxonomy to species level and the study of their relationships with soil physicochemical parameters. This research fills the gap by focussing on the identification of soil and litter ants to species level and by studying their relationship with soil physicochemical parameters.

The specific objectives were: (1) To identify collected soil and litter ants to species level, (2) To test the variations in abundance, diversity and evenness of identified soil and litter ant species, (3) To test the variations in soil physicochemical parameters, and (4) To study relationships between soil and litter ant species, soil parameters in stands of native and exotic tree species and in banana and coffee plantations as well as the ecological functions of soil-litter ants in relation to soil quality.

2. Materials, methods and data analysis

This study was conducted at the Arboretum of Ruhande and the Rubona agricultural research station, in southern Rwanda (Chapter IV, Figure 2; Paper 3). Sampling and analysis of soil cores was done in May 2017 (Chapter IV; Paper 3). Soil and litter ants were sampled between April (end of the rain period) and July (starting of dry period) 2017 by the use of pitfall sampling technique. Specimens were identified to species level in the laboratory of Royal Belgium Institute of Natural Sciences, Brussels, Belgium. Details about the identification and taxonomy are given in the following paragraph.

The identification was done by using Bolton (1994), and genus names were updated following Fisher and Bolton (2016). Within each genus, specimens were identified to species level by different identification keys (Bolton, 1987; Bolton and Fisher, 2008; Garcia et al., 2010; Rigato, 2016). Specimen were then compared with image banks (AntWeb, 2002), and finally with the ant collection from the museum of Royal Belgium Institute of Natural Sciences (RBINS) for definitive species identification. When the name of the species was not found in the identification keys, it was designed by the abbreviation SP followed by the number from 01 (SP01). Reference collection is permanently housed at RBINS under the reference number IG 33.894 and at the Centre of Excellence for Biodiversity and Natural Resources Management, College of Science and Technology, University of Rwanda.

One-way analysis of variance (ANOVA) for several sample tests was used to study variations in abundance of soil and litter ant species and soil physicochemical parameters under plots of forest tree species, coffee and banana plantations (Sayad et al., 2012). Only the most abundantly caught species were used for statistical analysis (Dekoninck et al. 2007) and rare species were down weighted by the use of the parallel discrimination rates calculated by taking the homogenized canonical coefficients times correlation coefficients (PDR = HCC x r).

The greater the positive parallel discrimination rates value (Borcard et al., 1992), the more effective the variable is at discriminating between plots of native and exotic tree species and between coffee and banana plantations to reduce their influence on the ordination results (ter Braak and Smilauer, 1998). Treatment effects on ant species and soil physicochemical parameters were analysed with non-metric multidimensional scaling (NMDS) and the analysis of similarity (ANOSIM) based on Bray-Curtis similarity (Ashford et al., 2013). Shannon diversity and species evenness were calculated to provide more information on sampled soil and litter ant species (Dekoninck et al., 2010). All these statistics were performed using PAST software.

3. Results

3.1. Ant community composition

A total of 1680 individuals of ants comprised 30 species, 14 genera and 4 subfamilies were identified in this study (Table 12). Within the subfamily Dorylinae, two species were identified including *Dorylus congolensis* and *Dorylus* SP02. Nine species were identified in the subfamily of Formicinae and the genus *Camponotus* was the most dominant with six species (Table 12). The genus *Polyrhachis* had only one species, *Polyrhachis militaris* while the genus *Lepisiota* had two species, *Lepisiota* SP01 and *Lepisiota* SP02.

The subfamily Myrimicinae included six genera and fourteen species with the dominance of genus *Tetramorium* that had six species: *Tetramorium laevithorax, Tetramorium zonacaciae*, *Tetramorium mossamedense, Tetramorium dedefra, Tetramorium delagoense* and *Tetramorium simillimum* (Table 12). We also identified one species in the genus *Crematogaster*, two species in the genus *Myrmicaria* and three species in the genus *Pheidole.* Further, the genera *Meranoplus* and *Monomorium* each had one species each (Table 12). The subfamily Ponerinae was represented by four genera: The genus *Bothroponera* with two species, the genus *Odontomachus* with one species, the genus *Phrynoponera* and *Mesoponera* each with one species.

3.2. Abundance, diversity and evenness of ant species

Higher abundance (total number of the mean individual ants collected) of collected soil and litter ant species was found in plots of coffee (6.32±5.12) plantations than in the plots of exotic (1.93±0.45) and native (1.91±0.48) tree stands and lowest abundance in plots of banana plantations (1.12±1.06). Species of *Tetramorium laevithorax* showed higher abundance in plots of exotic tree species, species of *Myrmicaria* SP02 showed higher abundance in plots of native tree species, species of *Myrmicaria opaciventris* showed higher abundance in plots of coffee plantations, while species of *Odontomachus troglodytes* showed higher abundance in plots of banana plantations and occurred in all land uses we sampled (Table 12).

The test for treatment effects on soil and litter ant species indicated that there were no significant differences in abundance of collected soil and litter ant species in plots of exotic tree species ($F = 0.8$, $df = 5$, $p > 0.05$), native tree species ($F = 0.5$, $df = 2$, $p > 0.05$), coffee ($F=0.2$, $df = 2$, $p > 0.05$) and banana ($F = 0.4$, $df = 2$, $p > 0.05$) plantations. The non-metric multidimensional scaling based on the Bray-Curtis similarity index indicated greater conformity between samples (stress = 0.17), while the composition of ant species differed significantly among plots of exotic and native tree species and plots of coffee and banana plantations ($R = 33\%$, $p < 0.05$).

Table 12: Abundance (mean ± standard deviation) of identified ant species in different land uses in southern Rwanda (Names of authors adapted from Antweb, accessed 12 October 2017)

Subfamily and species	Authors who described the species for the first time	Abundance by land use (mean ± sd)			
		Exotic tree species	Native tree species	Coffee plantations	Banana plantations
Dorylinae					
Dorylus congolensis	Santschi, 1910	0	0.2 ± 0.7	0	0
Dorylus SP02	Fabricius, 1793	0.1 ± 0.33	0	0	0
Formicinae					
Camponotus cinctellus	Gerstäcker, 1859	5.0 ± 0.6	0.4 ± 0.7	2.0 ± 1.0	4.0 ± 3.6
Camponotus maculatus	Fabricius, 1782	0.1 ± 0.3	0.1 ± 0.3	0	0
Camponotus SP03	Mayr, 1861	0.6 ± 1.6	0.1 ± 0.3	0	0
Camponotus SP04	Mayr, 1861	0.3 ± 0.1	0	0	0
Camponotus SP05	Mayr, 1861	0.2 ± 0.7	0.1 ± 0.3	0	0
Camponotus SP06	Mayr, 1861	0.4 ± 0.7	0.2 ± 0.4	0	1.0 ± 0.7
Lepisiota SP01	Santschi, 1910	0.2 ± 0.7	0	0	0
Lepisiota SP02	Santschi, 1910	0	0	0.3 ± 0.6	0
Polyrhachis militaris	Fabricius, 1782	0.1±0.0	0	0	0
Myrmicinae					
Myrmicaria opaciventris	Emery, 1893	2.0 ± 0.2	19.1 ± 4.5	171.3 ± 137.4	0
Myrmicaria SP02	Emery, 1893	15.3 ± 4.7	27.2 ± 6.3	0	0
Pheidole SP01	Westwood, 1839	1.0±1.5	0.9±1.4	10.3±6.6	0
Pheidole SP02	Westwood, 1839	0.5 ± 0.0	0	0	1.7 ± 0.9
Pheidole SP03	Westwood, 1839	0.3 ± 1.0	0.7 ± 1.3	0	6.7 ± 6.5
Tetramorium laevithorax	Emery, 1895	17.2 ± 24.3	0	2.3 ± 0.4	4.3 ± 0.5
Tetramorium zonacaciae	Weber, 1943	0.3 ± 1.0	1.6 ± 0.7	0	0.3 ± 0.6
Tetramorium delagoense	Forel, 1894	0	0.1 ± 0.3	0	0
Tetramorium simillimum	Smith, 1851	0	0	1.0 ± 0.7	0
Tetramorium mossamedense	Bollton, 1980	0.3±1.0	0	0	0
Tetramorium dedefra	Bolton, 1976	0	0.1±0.3	0	0

Table 12 – cont

Subfamily and species	Authors who described the species for the first time	Abundance by land use (mean ± sd)			
		Exotic tree species	Native tree species	Coffee plantations	Banana plantations
Meranoplus inermis	Emery, 1895	0	0.1 ± 0.3	0	0
Monomorium SP01	Mayr, 1855	0	0	0.3 ± 0.6	0
Creamatogaster SP01	Bolton, 1976	0.3±1.00	0	0	0
Ponerinae					
Bothroponera talpa	André, 1890	0	0.2 ± 0.4	0	0
Bothroponera crassa	Emery, 1877	0	0	0.1 ± 0.3	0.3 ± 0.6
Odontomachus troglodytes	Santschi, 1914	13.2 ± 4.9	5.3 ± 4.3	1.7 ± 1.2	15.7 ± 8.9
Phrynoponera gabonensis	André, 1892	0.4 ± 0.0	0.6 ± 0.7	0	0
Mesoponera subiridescens	Wheeler, 1922	0	0.1 ± 0.3	0	0

Higher diversity was found in plots of exotic tree species (H' = 1.99 ± 0.34) and banana plantations (H' = 1.53 ± 0.39) in comparison to plots of native tree species (H' = 1.34 ± 0.74) and coffee plantations (H' = 1.46 ± 0.43), while higher evenness was found in plots of coffee (E' = 0.66 ± 0.12) and banana plantations (E' = 0.33 ± 0.18) in comparison to plots of exotic tree species (E' = 0.28± 0.22) and native tree species (E' = 0.24 ± 0.519). In plots of native and exotic tree species, the average species diversity was lower (H' = 0.49 ± 0.54) while the average evenness was higher (E = 0.54±0.15) in comparison to plots of coffee and banana plantations (H' = 0.52 ± 0.68 and E = 0.41 ± 0.0.46). However, these differences were not significant (F = 0.306, P > 0.05).

The parallel discrimination rates calculated by taking the homogenized canonical coefficients times correlation coefficients (PDR = HCC x r) indicated high rates for the species of *Myrmicaria opaciventris*, *Myrmicaria* SP02, *Odontomachus troglodytes*, *Tetramorium laevithorax*, *Camponotus cinctellus*, *Pheidole* SP01, *Pheidole* SP03, *Tetramorium zonacaciae*, *Pheidole* SP02, *Camponotus* SP06, *Phrynoponera gabonensis*, *Bothroponera talpa*, *Camponotus maculatus*, and *Tetramorium simillimum* and they are more abundant than others. These species were used for the study of the relationship between soil and litter ants and soil physicochemical properties.

Table 13: Pearson correlation between soil – litter ant species and soil physicochemical parameters (positive correlations $r \geq 0.5$ are in bold)

Ant Species	pHw	SOC	Tot. N	C:N	Av. P	EC	CEC	AS	Clay	Silt	Sand
Myrmicaria opaciventris	0.1	-0.3	-0.7	0.4	0.4	-0.3	0	**0.7**	-0.4	-0.4	0.4
Myrmicaria SP02	-0.1	**0.6**	0.4	**0.6**	-0.7	**0.5**	-0.1	-0.5	0.4	**0.6**	-0.6
Odontomachus troglodytes	0.3	-0.2	0.3	-0.8	0.1	0.4	0.4	-0.3	-0.1	-0.1	0.1
Tetramorium laevithorax	-0.7	0.5	**0.7**	0.1	-0.4	-0.4	-0.6	-0.6	**0.7**	**0.5**	-0.6
Camponotus cinctellus	0.2	-0.4	0	-0.8	0.4	0	0.3	0	-0.2	-0.3	0.3
Pheidole SP01	0	-0.4	-0.8	0.3	**0.6**	-0.6	-0.1	**0.8**	-0.4	-0.5	**0.5**
Pheidole SP03	**0.7**	-0.6	-0.2	-1	0.5	0.4	**0.7**	0.1	-0.5	-0.5	0.5
Tetramorium zonacaciae	-0.3	0.1	-0.5	**0.7**	0.2	-0.5	-0.4	0.5	-0.1	-0.1	0.1
Pheidole SP02	**0.5**	-0.9	-0.9	-0.7	**1**	-0.3	0.5	**0.9**	-0.9	-1	**1**
Camponotus SP06	**0.6**	-0.5	0	-0.9	0.3	**0.5**	**0.7**	0	-0.4	-0.3	0.3
Phrynoponera gabonensis	0	0.2	-0.3	**0.7**	-0.1	-0.1	-0.1	0.2	0	0.1	0
Bothroponera talpa	-0.6	0.2	-0.3	**0.7**	0.1	-0.8	-0.6	0.4	0.1	0	0
Camponotus maculatus	-0.2	-0.2	-0.6	0.4	0.5	-0.7	-0.3	**0.7**	-0.3	-0.4	0.4
Tetramorium simillimum	0.1	-0.5	-0.8	0.2	**0.7**	-0.6	0	**0.9**	-0.5	-0.6	**0.6**
Camponotus SP05	-0.9	**0.9**	**0.9**	**0.6**	-0.8	-0.3	-0.9	-0.8	**1**	**0.9**	-0.9

3.3. Relationship between ant species and soil physicochemical parameters

Statistical analysis of the correlation of identified soil and litter arthropods indicated that species of ants respond differently to soil physicochemical parameters (Table 13). Species of *Odontomachus trogrodytes* and *Camponotus cinctellus* occurred in all land uses and correlate with less soil physicochemical parameters. Some other species including *Tetramorium zonnacaciae* and *Bothroponera talpa* discriminated between soil organic carbon, available phosphorus and aggregate stability and showed correlation with few soil physicochemical parameters, exception for C:N ratios. However, less is known about the contribution of each ant species to soil physicochemical parameters. Ecological functions are more generalized to all ants at the level of families and /or genus.

4. Discussion

Results of this study indicated that soil and litter ant species are differently distributed in exotic and native tree species and plantations of coffee and banana and differently correlated to soil physicochemical parameters (Table 12, Table 13). Only species of *Odontomachus troglodytes* and *Camponotus cinctellus* occurred in all land uses probably due to their wide range of tolerance in soil properties (Vanthomme et al., 2016). Species of *Bothroponera talpa* and *Tetramorium zonacaciae* discriminated between native and exotic tree species and between soil organic carbon, available phosphorus and aggregate stability.

Other species of the genus Tetramorium and Camponotus correlate positively with one or more soil physicochemical properties (Table 13). The ecological function of each species is not well known, but the majority of the genus *Tetramorium* are predators or scavengers (Bolton, 1980), while the species of the genus *Camponotus* are omnivorous (Feldhaar et al., 2007). These modes of nutrition may speed up the return of the organic matter concentrated in animal and plant tissues in soil (Petal, 1978). Other study indicated the relationship between soil organic matter, soil conductivity, water holding capacity, soil and silt soil textures (Cardoso et al., 2013). For example, the greater levels of soil organic matter allow a better aggregation of soil particles resulting in an increase in soil porosity, which in turn improves soil permeability for air and improves soil water retention (Tejada et al., 2006).

Results of this study also indicated the correlation between species of *Myrmicaria opaciventris* with aggregate stability, while species of *Myrmicaria* SP02 correlated with soil organic carbon, C:N rations, electrical conductivity and silt soil texture. Soil organic carbon is an index of sustainable land management (Woomer et al., 1994) used to indicate the soil fertility, structure, and stability (Laishram et al., 2012). Species of *Myrmicaria* are carnivorous that may increase soil organic contents (Bolton, 1980; Petal, 1978), and hence affects the aggregate stability, electrical conductivity and silt soil texture. However, there is a need of further studies to find out more about the contribution of each species to soil quality.

Species of Pheidole correlated differently to soil physicochemical parameters. *Pheidole* SP01 correlated with available phosphorus, aggregate stability and sand soil, *Pheidole* SP02 correlated with soil pH, available phosphorus, aggregate stability and sand soil, while *Pheidole* SP03 correlated with cation exchange capacity and soil pH. The contribution of each species to soil quality is not known, but general information highlighted that species of Pheidole are ecosystem engineers that have large impact on soil ecosystem. This is reflected in the alteration of soil properties due to burrowing activities, the accumulation of soil organic matter and other nutrients in the soil, which in turn alters soil physicochemical and biological processes (Cammeraat and Risch, 2008). Correlation with soil phosphorus and sand soil might probably be a sign of tolerance to higher levels of available phosphorus and sand soil types.

5. Conclusion

Some species of ants showed positive correlation with soil physicochemical parameters while some others showed negative correlation. Less is unknown about the contribution of each ant species to soil properties. To explain the contribution of soil and litter ant species to soil quality in this study, we used general information about the functional activities of orders and/or families and it was not possible to make a conclusion about which species that can be used as a reference bioindicator. We recommend further studies to explore the ecological function of each species that contribute to soil quality. In addition, further studies may focus on the taxonomy of ant species in other regions of Rwanda to explore the diversity of the species of ants.

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6

Discussion

1. Variation in soil physicochemical parameters

Soil of forest plantations are more stable than those under coffee and banana plantations where annual tillage disturbs soils and hence reduce the abundance of inhabiting soil and litter arthropods. Low levels of soil pH found in plots of exotic tree species were also found in another study and were likely due to soil acidification by accumulation of basic cations in biomass, increasing production of organic acids from decomposing litter and by increasing cation leaching (Nsabimana et al., 2008). Higher levels of soil pH found in plots of native tree species, coffee and banana plantations were attributed to the availability of high exchangeable base cations in another study (Sharma, 2011).

Higher levels of SOC found in forest plantations were probably related to high litter fall from trees and shrubs (Kassa et al., 2017) and to different land uses and managements (Flieβbach et al., 2007). Other study justified higher levels of available phosphorus found in coffee and banana plantations to probably be enhanced by fertilizing and mulching management practices (Eylachew, 1987), while higher levels in electrical conductivity, and cation exchange capacity found in forests and banana plantations might be enhanced by the loss of capacity of clay soils to adsorb base cations (Hertemink, 2003). Higher levels in total nitrogen found in exotic and native tree species were found in other study and were probably related to the decomposition of the litter fall from trees, shrubs and herbs (Kassa et al., 2017).

Higher levels of cation exchange capacity vary with exchangeable base cations (Kassa et al., 2017). In native and agroforestry tree species, these soil parameters were found to be influenced by organic matter and clay contents in the topsoil, from which the organic matter formed by trees and shrubs litter underwent a complete microbial breakdown and decomposition (Nsabimana et al., 2008). For our study, higher levels in soil cation exchange capacity might be due to the decomposition of maize straws and banana leaves used for mulching and to the application of organic manure.

Furthermore, high levels of soil aggregate stability found in plots of forest plantations might be due to less disturbances (Bini et al., 2013), microbial activities (Qin et al., 2010) and to the dynamics of soil organic matter which allows a better aggregation of soil particles and permeability of water (Sharma, 2011; Tejada et al., 2006). Variations in sand, silt and clay soil textures were found to be influenced by the canopy of trees and shrubs, which protect litter and soil, surface from leaching and from soil erosion (Kassa et al., 2015).

Ratios of C:N (mass of carbon to the mass of nitrogen) were also higher in plots of exotic and native tree species and this was the inverse in cation exchange capacity. This trend was also found in another study, and it is a sign of low mineralization rate at high C:N ratios associate to the decrease in soil nutrients (Nsabimana et al., 2008). Another study indicated that land use change from arable land to afforested land result in an increase of total organic carbon content and to the decrease of soil organic matter (Pollakova et al., 2016).

2. Community composition of soil litter arthropods and soil quality

Higher abundance and diversity of soil and litter arthropods found in plots of exotic and native tree species probably reflects environmental stability due to higher plant diversity (Beeby, 1993). The families of Scolopendridae (Centipedes – Chilopoda), Trombiculidae (Acari – Arachnida), Eosentomidae (Protura), Formicidae (Hymenoptera) and Staphylinidae (Coleoptera) showed strong correlation with studied soil physicochemical parameters than other identified families.

Scolopendridae showed strong correlations with all studied soil physicochemical parameters, exception for phosphorus, clay and sand soil. Centipedes in which the family of Scolopendridae belongs, were mainly found to be bioturbators and predators (Brown et al., 2017) that ingest and transport soil nutrients to different soil horizons (Toyota et al., 2006). Predation increases soil organic matter and hence increases soil nutrients (Tejada et al., 2006). Bioturbation regulates soil physical properties and processes and contributes to changes in dynamics of soil organic matter, nutrient cycling and soil biological activity (Lavelle, 1996).

Trombiculidae correlated with soil physicochemical parameters in the same way with Scolopendridae. However, Acari (mites and ticks) are decomposers, phytophagous and predators (Brown, 2017). Decomposers are litter transformers that affects soil processes through nutrient mineralization, organic matter protection and decomposition (Lavelle, 1996). Mineralization is the process by which chemical compounds are oxidized in organic matter, and the nutrients in those compuds are released in soluble inorganic forms that may be available to plants (White, 2005). This is an important process by which Trombiculidae enrich the soil.

Eosentomidae and Staphylinidae correlated with soil physicochemical properties in the same way with Scolopendridae and Trombiculidae. In relation to soil properties, little is known about this family. Generally, proturans in which it is classified are decomposers (Brown et al., 2017) that participate actively in breaking down the litter and hence releasing nutrients in the soil through mineralization (Lavelle, 1996). Staphylinidae are bioturbators, decomposers and predators that release nutrients in the soil through mineralization process (White, 2005).

Other study indicated that Formicidae were sensitive to soil pH and prefer the lowest polluted soil with high soil pH (Santarufo et al., 2012). Some other authors (McIntyre et al., 2001, Eava et al., 2004) report Formicidae tolerance to metal contamination, while others suggested that they may have potential as biological indicators of soil conditions and management for crop growth and ecosystem services in agroecosystems (Santarufo et al., 2012).

Formicidae play ecological roles improving the soil quality in different ways. They are predators, soil engineers, plant symbionts, and participate in nutrient cycling (Del Toro et al., 2012; Culliney, 2013). Other ecological activities including building of tunnels and chambers above and below ground increase soil porosity and hence soil aeration and facilitate water retention (Eldridge and Pickard, 1994). These are the reasons why they were suggested to be good biological indicators of environmental conditions in many ecosystems (Nsabimana et al., 2013; Vasconcellos et al., 2013).

3. Ant species and soil physicochemical parameters

Higher abundance and diversity of ant species were found in plots of varieties of coffee plantations and in plots of native and exotic tree species. Results of this study also indicated that soil and litter ant species are differently distributed in land use and respond differently to soil physicochemical parameters. Other studies explained the distribution of ant species as the result of their adaptation to recovering environments and their ability to take advantage of a broad range of resources (Vasconcellos et al., 2013). However, only species of *Odontomachus troglodytes* and *Camponotus cinctellus* occurred in all land uses due to their tolerance of a wide range of soil properties (Vanthomme et al., 2016).

Other species of Camponotus showed positive correlations with soil physicochemical parameters. Specifically, *Camponotus* SP05 correlated with soil organic carbon, total nitrogen, and clay and silt soil textures, *Camponotus maculatus* correlated with soil aggregate stability, while *Camponotus* SP06 correlated with soil pH, electrical conductivity, and clay and silt textures. These positive correlations might be due to the mode of nutrition of these ant species. Where the majority of *Camponotus* are omnivores (Feldhaar et al., 2007). This feeding system may speed up the return of the organic matter from the decomposition of animals and plants in the soil (Petal, 1978), and hence improves soil conductivity, enhances water holding capacity, clay and silt soil textures (Cardoso et al., 2013).

Species of *Bothroponera talpa*, and *Tetramorium zonacaciae* discriminated between soil organic carbon, sandy soil texture, aggregate stability, native tree species and coffee plantations. Soil organic carbon is an index of sustainable land management (Woomer et al., 1994) used to indicate the soil fertility, structure, stability, and extent of erosion (Laishram et al., 2012). The occurrence of higher topsoil organic carbon in native tree species can be due to the leaf litter fall from trees and shrubs added to the surface soil (Nsabimana et al., 2008) or from dead trees and shrub roots and mycorrhizal fungi contribution of organic matter in the subsoil (Yimer et al., 2007). However, little is known about the biology of *Tetramorium* (Bolton and Fisher, 2008) and *Bothroponera* (Joma and Mackay, 2015) and less is known about their contribution to soil quality.

Other species of the genus *Tetramorium* correlated differently to soil properties. *Tetramorium simillimum* correlated with aggregate stability and it is the only one species of identified *Tetramorium* that correlate positively with soil available phosphorus and sand soil texture. Species of *Tetramorium laevithorax* correlated positively with soil total nitrogen, and clay and silt soil textures. Some *Tetramorium* species nest in decaying wood, leaf litter, or directly into the soil, while some others are arboreal or live in mounds of termites (Bolton, 1980). The information about how these species may contribute to soil quality are not well known.

Species of *Myrmicaria opaciventris* showed positive correlation with aggregate stability, while species of *Myrmicaria* SP02 correlated with soil organic carbon, electrical conductivity, and silt soil texture. Other study indicated that soil aggregates serve as refuge for some ants, which in turn affect soil through their secretions cementing substances, and the stimulation of microbial activities (Preston et al., 2001. Due to the lack of information, we cannot confirm if this is the reason justifying the positive correlation between species of the genus Myrmicaria identified in this study and above mentioned soil physicochemical properties.

Species of Pheidole showed a particularity to other species as all identified species correlated positively with available phosphorus and sand soil texture. In addition, *Pheidole* SP01 correlated with aggregate stability, *Pheidole* SP02 correlated with soil pH and aggregate stability, while *Pheidole* SP03 correlated with soil pH and cation exchange capacity. Recent study indicated that species of the genus Pheidole are general scavengers, feeding on a wide range of prey (Sarnat, 2015). However, the contribution of these ant species to soil quality particularly available phosphorus and sand soil texture is less known.

In relation to soil pH, other studies indicated that some ant species have the ability to shift soil pH towards a neutral value by increasing pH levels in acidic soils and by reducing pH levels in basic soils (Frouz et al., 2003). However, variations in soil pH might be due to other factors. In agricultural land use, it was found that soil pH might be influenced by the decrease in base forming cations through a continuous nutrient cation uptake by plants, leaching and soil erosion (Abegaz and Adugna, 2015). Further, other study indicated that high subsoil pH and their variations might be related to the availability of high exchangeable base cations (Sharma, 2011). Furthermore, other studies concluded that the decrease in soil pH might result from the accumulation of organic matter, while its increase may result from an increase in basic cations (Frouz et al., 2003).

7

Conclusion and perspectives

1. Conclusion

Soil and litter arthropods can be used as indicators of the soil quality under different land uses. Pitfall sampling techniques is more effective for capturing the diversity and abundance of arthropods in comparison to other sampling methods, specifically Berlese-Tullgren funnels and hand sorting. Community composition of soil and litter arthropods can differently correlate with soil physicochemical parameters and their functional groups can indicate quality.

The families of Scolopendridae, Trombiculidae, Eosentomidae, Formicidae and Staphylinidae showed higher correlation with soil physicochemical parameters. In addition, Formicidae discriminated between native, banana, coffee, clay, sandy, aggregate stability, pH, available phosphorus, electrical conductivity and cation exchange capacity. The positive correlation might be explained by ecological functions of soil and litter arthropods, which are known for some of the identified families, while they are generalized to higher taxonomic ranks mainly orders for some other families, and remains unknown for species of soil and litter ants. There is a need of further research about the contribution of each family of soil and litter arthropods as well as ant species to soil properties, so that specific conclusion are given for each family and ant species.

The analysis of the diversity and abundance of collected soil and litter arthropods indicated a high decreasing in soil and litter arthropod diversity and abundance from native tree species to exotic tree species and to the varieties of coffee and banana plantations. This allows us to conclude that there is an important role of native tree species in conservation of soil and litter arthropods. However, some exotic tree species and varieties of coffee plantations can provide alternative suitable habitat for some soil and litter ant species. This is confirmed by the findings of this study, where individual ant species were decreasing in diversity and abundance from exotic tree species and coffee plantations to native tree species and varieties of banana plantations. Banana plantations are not suitable habitats for soil and litter arthropods.

2. Future directions

This research did not provide all information related to soil and litter arthropods and soil properties, specifically in taxonomy and in determination of the role of each identified family and species to soil properties. However, it opened the door to a new area of research in Rwanda. There is a need of further studies before we make a general conclusion on the use of soil and litter arthropods as biological indicators of soil quality. Future studies may explore:

(i) The use of soil and litter arthropods as biological indicators of soil quality in other land uses and ecological regions of Rwanda,
(ii) The impacts of climate and altitudinal variations in soil and litter arthropods and soil physicochemical parameters,

(iii) The variation of soil-litter arthropods in relation to microbial and enzymes indicators of soil quality,
(iv) The impacts of functional richness, functional evenness and functional divergence on primary components of functional diversity,
(v) The taxonomy of the community composition to species level,
(vi) The contribution of each identified family and ant species to soil properties.

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Peer review publications and manuscripts

This PhD thesis is a sum of four manuscript papers including one published paper (Paper 2), two papers accepted for publication (Paper 1 and Paper 4) and one manuscript under review (Paper 3).

Paper 1: Nsengimana, V., Kaplin, B.A., Francis, F., Nsabimana, D. (2018). Use of soil and litter arthropods as biological indicators of soil quality in forest plantations and agricultural lands: A Review. *Entomologie Faunistic – Faunistic Entomology* [En ligne], Volume 71 (2018), URL : https://popups.uliege.be:443/2030-6318/index.php?id=4005

Paper 2: Nsengimana, V., Kaplin, B.A., Francis, F., Nsabimana, D. (2017). A comparative study between sampling methods for soil and litter arthropods in conserved tree plots and banana crop plantations in Rwanda. *Int. J. Dev. and Sust. 6 (8), 900-913.*

Paper 3: Nsengimana, V., Kaplin, B.A., Francis, F., Nsabimana, D. (2018). Use of communities of soil and litter arthropods as biological indicators of soil quality under different land uses in southern Rwanda. ***Manuscript.***

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Oral presentations and communications

Nsengimana Venuste. (2018). Insect diversity: ecological importance and conservation status. Geosciences, Biodiversity and Environmental Conservation. Seminar. Center of excellence in Biodiversity and natural resources management. College of Science and Technology, University of Rwanda (09/01/2018 - 12/01/2018).

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