University of São Paulo
"Luiz de Queiroz" College of Agriculture

Do agroforestry systems improve soil functioning? a comparison with other land uses

Julia Rossi Pereira

Dissertation presented to obtain the degree of Master in Science. Area: Soil and Plant Nutrition

Piracicaba
2022

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versão revisada de acordo com a resolução CoPGr 6018 de 2011

Advisor:
Prof. Dr. **MIGUEL COOPER**

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To my beloved mother,
In memoriam of my loving grandmothers and my dear father.

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“The health of soil, plant, animal and man is one and indivisible.”

Albert Howard

CONTENTS

RESUMO

Os sistemas agroflorestais melhoram o funcionamento do solo? uma comparação com outros usos da terra

As mudanças climáticas em curso impõem uma série de desafios às atividades agrícolas e florestais. Faz-se necessário o desenvolvimento de sistemas agrícolas resilientes, capazes não somente de assegurarem a produção de alimentos, fibras e biocombustíveis, mas que também garantam a manutenção de processos ecossistêmicos essenciais à humanidade e demais formas de vida. Por serem componentes fundamentais dos ecossistemas terrestres, os solos desempenham importantes funções ambientais, econômicas e sociais e sustentam uma série de Serviços Ecossistêmicos por meio de seu funcionamento. Contudo, o solo é um recurso natural não-renovável em curto prazo e seu mau uso e o manejo inadequado podem levar ao seu esgotamento e provocar problemas em curto, médio e longo prazo. Assim, é fundamental que durante o desenvolvimento de formas alternativas de produção e ocupação da terra, olhe-se atentamente para os solos, buscando compreender os processos físicos, químicos e biológicos que acontecem dentro do solo e como tais sistemas e práticas utilizadas interferem nos atributos do solo e, consequentemente, no seu funcionamento. Como alternativa às práticas agrícolas convencionais, os Sistemas Agroflorestais (SAFs) tem sido sugeridos por pesquisadores de diversas áreas da ciência devido aos seus benefícios ambientais, sociais e econômicos, principalmente nas zonas tropicais e subtropicais úmidas. No Brasil, onde predominam solos altamente intemperizados recobertos por formações florestais, os SAFs se apresentam como alternativas aos sistemas agrícolas simplificados baseados em monoculturas por se aproximarem das condições naturais do território. Contudo, nem todos os benefícios das práticas agroflorestais foram esclarecidos e a ampla variedade de sistemas e práticas impõem desafios a total compreensão dos seus efeitos sobre os solos. Diante disso, esse trabalho foi elaborado em duas partes, sendo a primeira uma revisão sistemática da literatura científica disponível em duas das principais bases de dados de alcance mundial, com vistas a elucidação do conhecimento científico atual sobre os efeitos dos SAFs sobre os atributos e processos dos solos e principais lacunas de conhecimento. E a segunda parte, uma análise dos atributos físico-hídricos de um solo sob quatro formas de uso (SAF, cultivo convencional, silvicultura de Eucalipto e pousio), a fim de identificar a influência desses sistemas produtivos sobre o funcionamento hidrológico da camada superficial do solo e identificar as principais diferenças entre elas.

Palavras-chave: Funcionamento do solo, Hidrologia do solo, Saúde do solo, Manejo do solo, Agrossilvicultura

ABSTRACT

Do agroforestry systems improve soil functioning? a comparison with other land uses

The climatic changes in course impose a series of challenges to agricultural and forestry activities. It is then necessary the search and development of resilient farming systems capable of not only assure food, fiber and fuel production, but that also guarantee the maintenance of ecosystemic processes that are essential to humanity and to other forms of life. As they are critical components of terrestrial ecosystems, soils play important environmental, economic and social functions, and underpin a number of Ecosystem Services through its functioning as well. However, soil is a non-renewable resource at short-term, and it misuse and mismanagement might lead to its depletion, resulting in negative short-, medium- and long-term impacts. Thus, it is necessary to take a closer look at soil when researching alternative land-use and production systems, in order to better comprehend physical, chemical and biological processes occurring within the soil and how these practices might affect soil attributes and, as a consequence, its functioning. As an alternative to conventional practices, Agroforestry Systems (AF) have been recommended by researches on account of its environmental, social and economic benefits, especially at humid and sub-humid tropical and subtropical zones. In Brazil, highly weathered soil covered by forest formations are predominant, AF arise as good alternatives to simplified monoculture-based agriculture, since they resemble territory’s natural conditions. But some ecological benefits of agroforestry practices are still unclear and the great variety of arrangements and practices of AF impose challenges to the total comprehension of its effects over soils. Therefore, this work was drafted in two parts where the first part is a systematic review of scientific literature available on two main databases of worldwide relevance, in order to outline the current scientific knowledge about Agroforestry Systems effects on soils attributes and processes and to identify tits main approaches and shortcomings. And the second part is an analysis of the hydro-physical properties of a soil subjected to four land-use systems (AF, conventional tillage, Eucalyptus forestry and grass fallow), aiming at detecting theses land-use influence over soil’s superficial layer hydrological functioning, and identify the main differences between them.

Keywords: Soil functioning, Soil hydrology, Soil health, Soil management, Agrosilviculture

1. GENERAL INTRODUCTION

Soil is one of the most important and essential natural resources for humanity. Since it is known of, soil had an intimate relationship with humans' existence and, until today human life is unimaginable without it (Lal, 2015; Sing and Sing, 2017). The concept of soil had evolved over decades from a simply medium for plant growth to a living dynamic organism which is essential to Earth System functioning (Bockheim et al., 2005). Soil is an important component of ecosystems and besides providing essentials goods to human life, interferes on air and water quality, hence influencing on environmental quality and regulation (Bünemann et al., 2018). Soils are relevant not only as sources of food, fuel, fibers, but they also provide Ecosystem Services such as climate and flood regulation, pharmaceutical and genetics resources pool, building materials and foundation support, etc. (Blum, 2005; Pepper et al., 2009; Adhikari and Hartemink, 2016). Soil functioning depend on inherent attributes, derived from their genesis, and dynamic attributes, affected by land-use and management. In 1994, the concept of Soil Quality was coined as *"the capacity of a soil to function within ecosystem boundaries to sustain biological productivity, maintain environmental quality, and promote plant and animal health"* (Doran and Parkin, 1994; Bünemann et al., 2018). Later, the concept of Soil Health was used as a reference to the capacity to function and provide environmental benefits besides biomass production (Harris and Romig, 2017; Rinot et al., 2019) and it is more often used is non-scientific circles (Bünemann et al., 2018).

However, soil formation takes hundreds to thousands of years, this makes soils a non-renewable resource, and their degradation may cause several negative social-economic issues through time, such as productivity decline, air and water pollution and rural depopulation. Soil degradation is defined as the loss of soil's capacity to develop its functions (Claret and Martínez-Casanovas, 2017). It is estimated that around 33% of world's soils are degraded (FAO/ITPS, 2015). Because of its influence over air and water quality, soil quality has significant influence over environmental quality and, as a consequence, over human health (Doran and Parkin, 1994; Carter et al., 1997; Abrahams, 2002; Pepper et al., 2009; Lal, 2020). This may have natural or anthropic causes, but soil degradation is primarily caused by soil misuse and mismanagement which are directly related to social-economic and political matters (Oldeman, 1992). Perturbations caused by human activities may alter soil chemical, physical and biological attributes, acting over the processes occurring within the soil, leading to alterations of soil system functioning and might hinder their capacity to provide goods and services (Targulian and Krasilnikov, 2007). Due to its intimate relationship with the hydrosphere, soil degradation directly affects the quantity and quality of freshwater (Targulian et al., 2018). This process increases the pressure over native areas leading to a vicious circle of social impoverishment and environmental quality degradation, which might have a greater impact in underdeveloped countries (Oldeman, 1992; Lal, 2020).

Agricultural lands represent the largest areas occupied by anthropogenic activities (4.75 billion ha), thus influencing 50% of Earth's habitable lands (FAOSTAT, 2021). In Brazil, cultivated lands represent 263 million ha (i.e., 31% of the territory) (MAPBIOMAS, 2021). Its expansion has been occurring towards Cerrado and Amazon biomes which losses might have global consequences. Between 1985 and 2019, 87.2 million ha were deforested, 44 million ha in the Amazon and 28.5 million ha in the Cerrado (MAPBIOMAS, 2021), the Brazilian savanna. The Atlantic Forest, which is another important forest biome of the Brazilian territory has only 15% of its original vegetation cover remaining, which is mostly restricted to Conservation Units. Most of these areas were taken over by urbanization and agricultural activities such as commodity crop production and extensive cattle grazing. Decline of natural vegetation cover might have consequences in different space and time scales that are already being perceived, such as extreme and more frequent droughts and floods and raise in global temperature (Foley et al., 2005; ILSTEDT et al., 2007). Furthermore, the Green Revolution advents, even though provided increasing productivity and technological advances to agriculture, also arouse socioeconomic and environmental issues. In terms of environmental consequences, native vegetation suppression, greenhouse gases (GHG) emissions and water resources pollution can be mentioned (Doran, 2002). In addition, the depletion of agricultural land productivity increased the dependence on external inputs to yield maintenance.

But it is precisely due to their great terrestrial extension that agriculture and livestocking are key activities to mitigate, stop and reverse land degradation, to promote native forests preservation and to cope with the global environmental changes in course (Altieri et al., 2015). For this reason, it is necessary to support the development, use and promotion of sustainable production practices and systems capable of providing soil and water conservation and boost soil health (Doran, 2002; Banwart, 2011). In the last decades, sustainable soil management practices have been proposed, such as conservation tillage, crop rotation, intercropping and cover cropping (Ernest et al., 2015). Agroforestry (AF) has been recommended as an alternative land-use and management system that could provide environmental and social-economic benefits (Young, 1989; Benites, 1990; Nair, 1993, 2011; Sanchez and Buresh; Leakey, 1997; Jose, 2009; Wilson and Lovell, 2016; Newman, 2018).

Because of that, these systems are often mentioned in discussions related to the Sustainable Development Goals (Goparaju et al., 2020). The World Agroforestry Centre (ICRAF) defines AF as the *“land-use systems and technologies where woody perennials (trees, shrubs, palms, bamboos, etc.) are deliberately used on the same land management unit as agricultural crops and/or animals, either in some form of spatial arrangement or temporal sequence* (...) *which components interact both economically and ecologically”* (Newman, 2018, ICRAF, 2021). The great range of designs, compositions and purposes encompassed by AF may affect the benefits and limitations of these systems. Yet, AFs are usually associated with benefits to soil, air and water quality, even though most of them are not completely comprehended (Dollinger and Jose, 2018).

This study was drafted in two parts: in the first part a systematic review was done in order to outline the scientific knowledge of Agroforestry Systems effects on soils attributes and processes and to identify the main approaches and shortcomings of the scientific output. In the second part, we analyzed and compared hydro-physical attributes of a soil subjected to four different land-uses, in order to understand the impact of land-use and management practices over soil hydrological functions. We expect that these results can contribute to the scientific knowledge on the hydrology study field as well provide guidelines to conservative agricultural practices and land planning that intend to favor environmental quality preservation and improvement.

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2. SOILS AND AGROFORESTRY: WHAT DO WE KNOW?

Abstract

Soils provide a role of benefits to humans and non-human beings known as Ecosystem Services. Due to its susceptibility to land-use and management practices, soil health must be a concern when searching for sustainable food systems. Agroforestry practices have been suggested as management systems that conciliate environmental, social and economic benefits and have presented many positive results so far. In order to understand the current scientific production status on Agroforestry Systems (AF) that took soil attributes and processes into consideration, a systematic review of the literature retrieved in Web of Science and Scopus was done, with no limit of time. Data were gathered and reviewed in order to obtain information about the state of art of soil studies on AF, aiming to propose directions for future studies. Our results review a growing interest on this matter during the last decade, mainly by Brazilian institutions. Most studies were made on agrisilvicultural systems of the tropical and sub-tropical zones. Assessed soils were mainly sandy loam and clay loam texture Cambisols, sampled down to 30cm depth. Chemical soil attributes were proposed by 92,9% of the studies while biological attributes were assessed by 34,5%, showing a gap on studies related to soil hydro-physical and biological attributes. Ecosystem services were not addressed in most papers, but 56% of the studies assessed soil attributes or processes that are related to provisioning of food, fiber and fuel services. The analyzed scientific output presents a shift from a soil fertility approach based on crop yield, towards a holistic and environmental approach based on an integrated soil quality assessment and soil health concept.

Keywords: Soil Health, Agrisilvicultural, Ecosystem Services, Sustainable agriculture

2.1. Introduction

Soil is considered to be one of the most complex biomaterials on Earth (Young and Crawford, 2004; Pepper et al., 2009) and it’s increasingly recognized as a key component of ecosystems due to its influence on air and water quality (Doran and Parkin, 1994; Bünemann et al., 2018). It’s a zone of interaction between the atmosphere, the biosphere, the hydrosphere and the lithosphere and plays a key role on ecosystems dynamics, not only locally, but also at a global scale (Targulian et al., 2018; Macías and Camps-Arbestain, 2020). Through their functioning, soils provide a role of benefits to humans and non-human beings known as Ecosystem Services (Costanza et al., 1997, 2014; MEA, 2005; Adhikari and Hartemink, 2016). Among the soil provided ecosystem services are food, fuel and fiber production, water regulation and purification, gene pool, etc. (Adhikari and Hartemink, 2016; Rodrigues et al., 2021).

The capacity of the soil to function and provide ecosystem services is known as *soil quality* (Doran and Parkin, 1994; Greiner et al., 2017; Liu et al., 2020) and it depends on soil attributes and is highly affected by anthropic activities. Soil functioning can be assessed through soil quality indicators, which can be physical (e.g., bulk density, texture, structure, porosity and aggregate stability), chemical (e.g., organic matter, pH, CEC, etc.) or biological soil attributes (e.g., microbial biomass, enzymatic activity, etc.) and soil processes (e.g., erosion, infiltration).

Due to the importance of soil to the supply of ecosystem services and to its susceptibility to management practices, the knowledge related to soil functions must be widely explored when searching for strategies to develop sustainable food systems. Disturbances caused by human activities interfere on processes occurring within soil through the alteration of soil dynamic attributes (Oldeman, 1992), hindering soil functioning and thus, reducing the provision of goods and services by soils. Among the main anthropic causes of soil degradation are land misuse and soil mismanagement, which are intimately related to economic activities such as agriculture and livestock production (Lal, 1997; Foley et al., 2005; FAO, 2011, 2015).

During the last decades, the use of agroforestry practices has been suggested as a management system that conciliates environmental, social and economic benefits (Nair, 1993; Sanchez et al., 1997; MEA, 2005; Jose, 2009; Wilson and Lovell, 2016). The ecological and economic integration of trees or shrubs to crops and/or livestock in space and time aiming at a greater range of purposes (ICRAF, 2020), although ancient, has only been in the focus of scientific research for the last four decades (Newman, 2019). The combination of land-uses results in a large scope of outlines and their study are reunited under the discipline of Agroforestry Systems (AF): a multidisciplinary study field that involves agronomy, forestry, environmental sciences, soil science, social and economic sciences, etc. (Liu et al., 2019). A major effort has been done in finding long term sustainable production systems and agroforestry has presented many positive results (Muchane et al., 2020).

Several reviews were done intending to investigate the scientific output status on different aspects of AF (Montambault and Alavalapati, 2005; Liu et al., 2019) using different methodologies. However, to the best of our knowledge, no one has reviewed the state of the art on soil research in agroforestry systems and their contribution to ecosystem services. For this reason, we felt the need to search and review the scientific output about soil and AF.

Thus, this study aims to 1) make a qualitative diagnose of indexed scientific production relating soil attributes and agroforestry practices; 2) identify geographical distribution of study sites and research institutions; and 3) understand the main approaches of these studies and the relation with ecosystem services.

2.2. Materials and Methods

To attain the objectives, a systematic review was done by means of comprehensive, transparent and replicable methods to identify, select and analyze relevant research outputs (Siddaway et al., 2018).

2.2.1. Data collection and treatment

The survey was realized in two online databases: Main Core Collection of ISI Web of Science, which reunites a broad range of cutting-edge research papers, and Scopus, which encompasses the largest range of titles and abstracts. By using both databases, we intended to evaluate the largest number of papers, in order to obtain representative results of the scientific production reality.

As we intended to obtain the status and characteristics of soil research in AF sites, we set the following search terms: *(("agroforest* system*" OR "agroforest* practice*") AND ("soil attribute*" OR "soil propert*" OR "soil feature*" OR "soil characteristic*")),* which were searched in titles, abstracts and key-words.

The search was restricted to articles (whereas they usually present complete research results) and reviews. We did not limit the search to any language nor time period. The research was made on June 30, 2020 therefore, all the papers published up to this date were considered in this search.

Retrieved data from both databases were exported in .csv and .txt format to MS Excel (v.365), in which they were combined and the duplicated files were removed. Some adjustments were needed for data standardization. This first step resulted in 212 studies whose files were downloaded, identified and organized by the article’s number of citations. 11 files couldn’t be found. The papers were submitted to further analysis, firstly, by revising their titles, abstracts and key-words; and secondly, by analyzing the full text.

2.2.2. Data analysis and papers' review

Initially, the papers were selected according to the following criteria: 1) it must generate or use soil data and 2) it must use soil samples from AF sites. The application of these criteria resulted in the elimination of 32 papers that didn't satisfy both criteria resulting in a total of 169 papers that were submitted to further analysis. Even though reviews do not fit these criteria, we recognize them as important sources of historical information and key discussions on interdisciplinary concepts, that is why they were considered.

Using MS Excel (v.365) tools we gathered information about a) publication year, b) journal, c) language, d) article number of citations and e) institution. Next, a manual analysis of each study was done, and the following information were recovered: f) study site location, g) AF type, h) soil classification, i) soil texture, j) evaluated soil attributes, k) maximum soil sampling depth and l) soil related ecosystem services and lower-level ES. To enable the analysis, soil classification information was collected and standardized by correlation to FAO's WRB (IUSS Working Group WRB, 2014).

We classified the articles into the soil ecosystem services to which these studies contribute to. Based on Adhikari and Hartemink (2018), we firstly classified the papers into four ES categories (cultural, provision, regulation and support) according to the authors objectives and next, we classified them into what they called "lower-level ecosystem services", in order to obtain more detailed information.

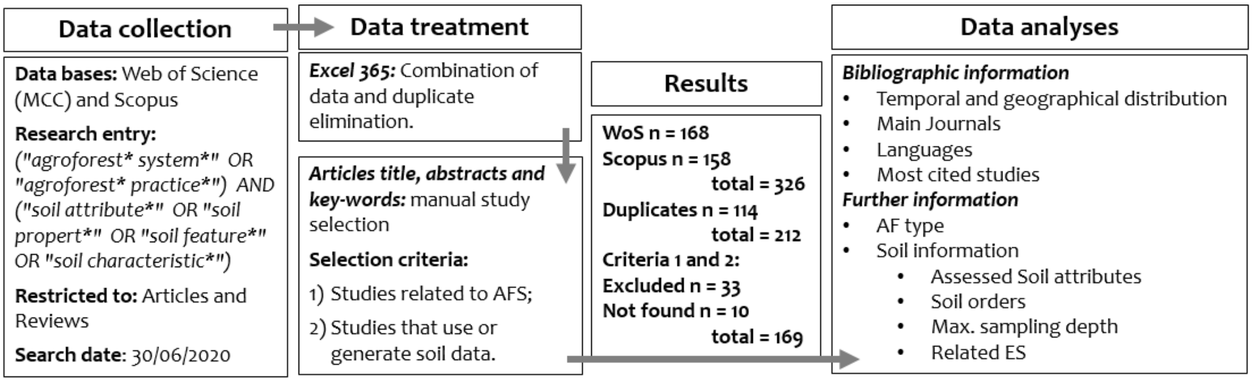


Figure 1. Synthesis of the methodology used in this research.

2.3. Results and discussion

2.3.1. Temporal evolution and main aspects of the scientific output

The oldest retrieved paper dates from 1986. No record published before was retrieved by our search strategy, but this does not mean that no studies were previously published on this matter. Soil seems to have been a concern for AF researchers before 1986. For instance, Young (1989) published the book "*Agroforestry for soil conservation*", which presents studies from 1985 and earlier. Other studies that were not found by our search strategy and are worth-mentioning by this research are (Lal, 1989a, 1989b, 1989c, 1989d, 1989e). Among them, only the first was retrieved, nonetheless they comprise a very complete study sequence. The reasons that they were not recovered by our survey might be related to the terms used for the search and to the limitations imposed by the methodology itself.

Until 2004, the number of publications per year was 2 or less, when a slight increase is noticed. As from 2011, the number of publications per year started following a significant growth trend until 2019, when the highest number of publications (24) was reached (Fig.2). Also, the last decade (2010-2019) concentrate the majority of the studies related to soil assessment in AF (66.3%; 113). The rising interest on soil issues by AF researchers, mainly after 2010, might reflect the increasing global environmental concerns and the recognition of the importance of soil to ecosystems functioning and environmental quality (Foley et al., 2005; Udawatta et al., 2008). There is a growing awareness on the critical role of soil on ecological processes and to human health (Abrahams, 2002), especially after the Global Assessment of Human Induced Soil Degradation – GLASOD project (Bridges and Oldeman, 1999) publication. The increased understanding of soil processes that marked the 1990's enabled the development and refinement of global models, that allowed the establishment of linkages between soils and global biophysical and socio-economic phenomena (Bockheim at al., 2005). Besides, this period was marked by the further conceptual development of Soil Quality and Soil Health that latter evolved to Soil Security concept, based on new pedologic theories of Earth System Science and the Critical Zone (Bockheim and Gennadiyev, 2010; Banwart et al., 2017; Targulian et al., 2018).

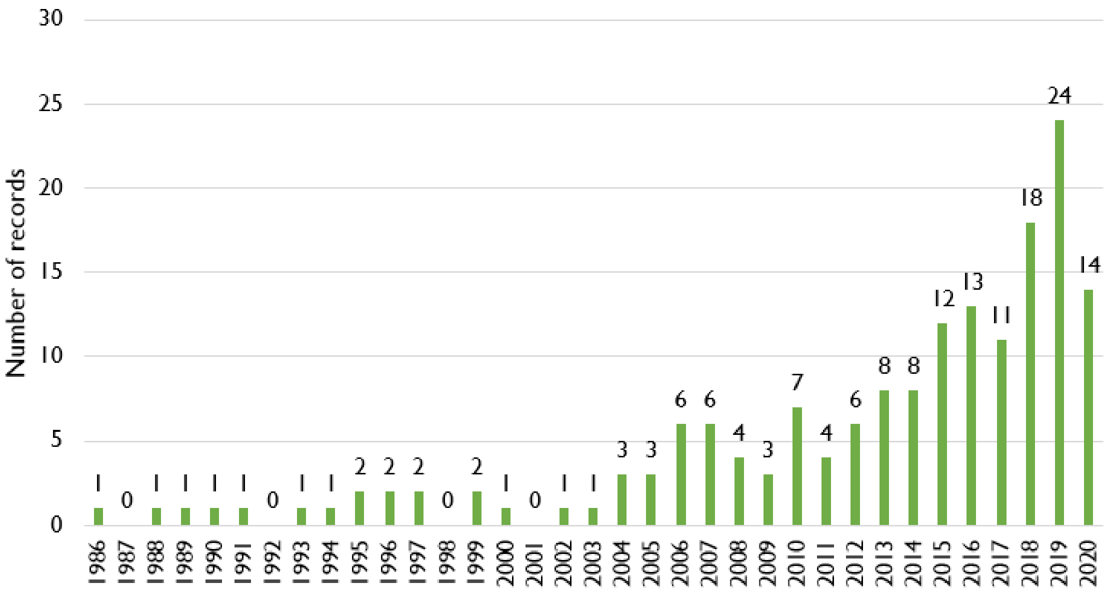


Figure 2. Number of publications per year.

In 2012, FAO created the Global Soil Partnership which next established the Intergovernmental Technical Panel on Soils (ITPS) in 2013. From this multiple-stakeholders international partnership derived the International Year of Soils promoted by FAO in 2015, in order to call attention to soil issues and to support worldwide educational, political and scientific initiatives related to soil knowledge promotion and resource conservation, based on scientific evidence (FAO, 2015). This initiative's first pillar of action is to *"promote sustainable management of soil resources for soil protection, conservation and sustainable productivity"* as well as to mitigate soil degradation and reclaim degraded areas, especially in regions where people are most vulnerable (FAO, 2015).

Most papers had the participation of researchers from Brazilian (31) and North-American (29) institutions (Figure 3a), but it is noteworthy that only 6 studies took place within the USA territory (Fig. 3b) suggesting cooperation linkages between North-American institutions and scientists from other countries, mainly in the tropical and sub-tropical regions. Brazil (31), India (24) and China (21) concentrate the majority of study sites of the 43 identified countries (Fig. 3b). In terms of institutions, Chinese Academy of Sciences leads the number of publications, followed by the Indian Council of Agricultural Research (ICAR) and by Brazilian Agricultural Research Corporation (EMBRAPA) (Tab. 1). Most studies took place in humid and sub-humid regions, characterized by high mean annual precipitation and temperature. Regarding climatic information, most studies provided precipitation and temperature data.

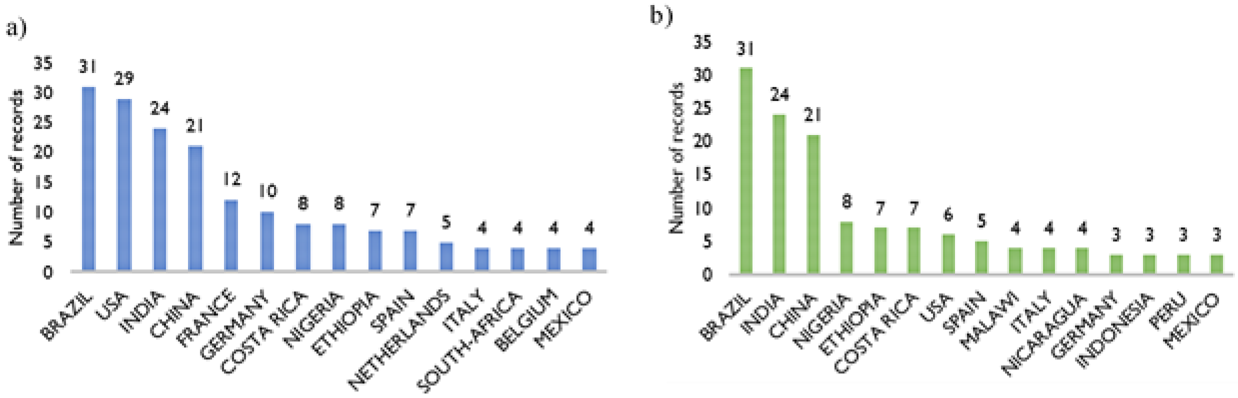


Figure 3. Number of publications per author's country (a), and number of publications per study site location (b).

Table 1. Number of publications per institution

Institutions	**Number of publications**	**Percentage**
Chinese Academy of Sciences/China	22	13,02%
Indian Council of Agricultural Reasearch (ICAR)/India	11	6,51%
Empresa Brasileira de Pesquisa Agropecuária (EMBRAPA)/Brazil	9	5,33%
Centro Agronómico Tropical de Investigación y Enseñanza (CATIE)/Costa Rica	8	4,73%
Centre de Coopération Internationale en Recherche Agronomique pour le Développement (CIRAD)/France	8	4,73%
Universidade Federal Rural do Rio de Janeiro (UFRRJ)/Brazil	7	4,14%
Nanjing University/China	6	3,55%
Universidade Federal de Viçosa (UFV)/Brazil	6	3,55%
United States Department of Agriculture (USDA)/USA	6	3,55%
Ghent University/Belgium	5	2,96%
University of Goettingen/Germany	5	2,96%
Wageningen University & Research/Netherlands	5	2,96%
Universidad de Santiago de Compostela/Spain	4	2,37%
Universidade Estadual de Santa Cruz/Brazil	4	2,37%

Most of the retrieved studies were published in the journals *Agroforestry Systems* (34; 20.2%) and *Agriculture, Ecosystems and Environment* (17; 10.1%) as indicated in Figure 4. The first one encourages biophysical and socioeconomic studies that demonstrate the benefits of integrated systems addressed as AF to commodity production and other Ecosystem Services (Springer Nature, 2020). The latter one is interested in scientific research *"dealing with the interface between agroecosystems and the natural environment, specifically how agriculture influences the environment and how changes in that environment impact agroecosystems"* (Elsevier, 2020). Soil science scope journals (e.g., Catena, Geoderma, Revista Brasileira de Ciência do Solo) encompass 16.5% (28) of the retrieved articles (Fig. 4). 91% (153) of the studies were published in English, 6% (10) were published in Portuguese, 1% in Spanish and 3% are available in both English and Portuguese.

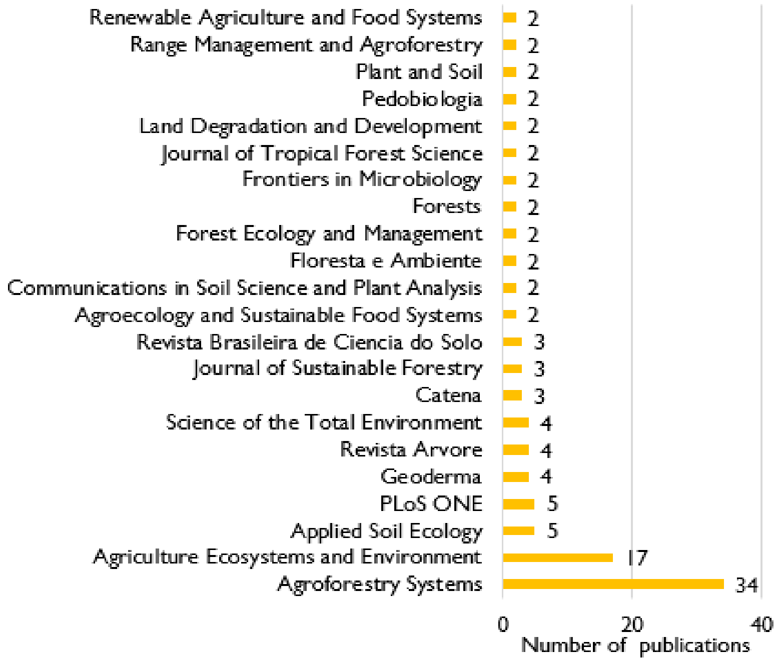


Figure 4. Number of publications per journal.

Classification of Agroforestry Systems is varied and they can be classified according to its many aspects and purposes. The classification system most commonly used takes its composition into account and is based on three main components: trees/shrubs, crops and animals. For this research, AF were addressed in three categories: agrosilvopastoral, agrisilvicultural, and silvopastoral (Nair, 1993; Sinclair, 1999) [Fig. 5]. 86% of the analyzed studies were carried out on agrisilvicultural systems, which integrate trees or shrubs and crops in the same management unit. On the other hand, systems that integrate animals with trees and crops, like silvopastoral and agrosilvopastoral, were studied by only 14% of the analyzed papers. A recent study by Valani et al. (2021) showed that the assesment of soil quality is still neglected in integrated crop-livestock-forest systems, equivalent to agrosilvopastoral AF, while in crop-livestock systems soil quality is more frequently assessed.

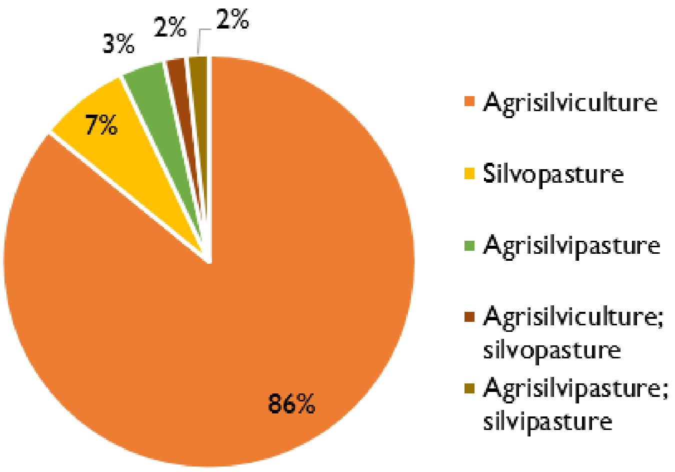


Figure 5. Relative proportion of types of Agroforestry System analyzed by the retrieved output.

2.3.2. Soil information and related ecosystem services

According to our survey, chemical soil attributes were more frequently assessed (92.9%) than physical (72%) and biological (34.5%) ones, respectively (Fig. 6). 42.3% of the papers assessed both physical and chemical attributes, 23.2% integrated chemical, physical and biological soil attributes, and only 10.7% assessed chemical and biological attributes. Among the chemical attributes, Soil Organic Carbon and Organic Matter contents, pH, available macro and micronutrients and Cation Exchange Capacity were the most frequently assessed. Soil Organic Carbon is related to many soil functions and is a versatile soil quality indicator. For example, Le Bissonais et al. (2018) linked SOC to aggregate stability and resistance to erosion in AF under different climatic conditions and soils; Pardon et al. (2017) linked soil carbon levels to nutrient cycling and supply for plant growth; and Zhang et al.(2020) correlated soil microbial community composition to SOC abundance and nature in intercropping systems. Other chemical analyses are related to soil fertility assessment and site characterization for agronomic purposes.

Bulk Density (49%) and Particle Size Distribution (38%) were the most analyzed physical attributes followed by soil water content [21%] (hydro-physical) and total porosity [20%] (structure-related). Just as soil carbon, soil bulk density is related to many soil functions, such as structural support for crops, water and gas movement (Benegas et al., 2014), and to soil fauna abundance (Moço et al., 2010). Further, it is an easy-to-measure and easily accessible soil property. Conversely, Particle Size Distribution is an inherent soil attribute, hardly affected by management practices and thus, not a good soil quality indicator.

Soil biological attributes were less frequently assessed, probably due to their required high-cost methodologies. In accordance, Bünemann et al. (2018) reviewing soil quality assessment studies, stated the absence of biological and biochemical soil quality indicators in 40% of the analyzed papers. Microbial biomass, inorganic Nitrogen and soil respiration were the most analyzed biological attributes in the analyzed papers.

The analyses of the assessed soil attributes reveal a knowledge gap related to hydro-physical and biological belowground information, which might hinder the comprehension of soil-plant-atmosphere interactions in AF, as well as their interactions with other environmental components at different scales. This might be related to the high cost of the assessments of these attributes, as well as to their seasonal variations.

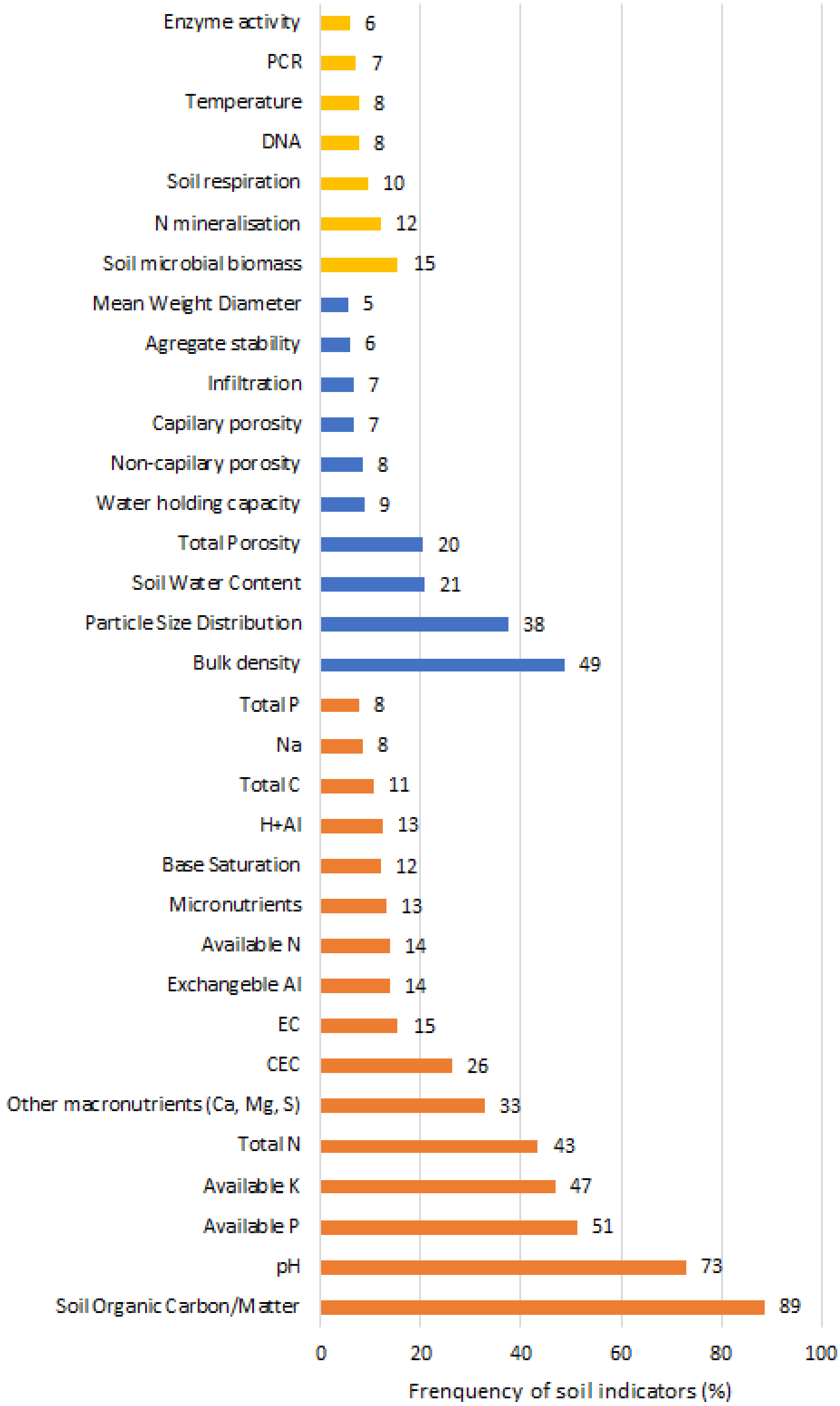


Figure 6. Frequency of assessed soil attributes on the retrieved studies.

As the analyzed soil attributes are directly related to soil sampling depth, we identified that the majority of the studies (65%; 110) used samples collected at the surface layer (30cm), 18% (31) used samples collected down to depths between 31 and 90cm and 10% (16) processed samples down to 91cm or deeper (Fig. 7). It's worth noticing that sampling depth is also closely related to the objective of the research, suggesting a bigger interested on surface layers, most related to agronomic research. The studies that sampled deeper soil layers are mostly related to carbon sequestration or cycling (Makumba et al., 2007; Howlett et al., 2011; De Oliveira Marques et al., 2015; Mosquera-Losada et al., 2015; Guo et al., 2018; Kumar et al., 2018; Kalita et al., 2020; Khaleel et al., 2020) and soil fertility (Makumba et al., 2006; Datta and Singh, 2007; Panwar et al., 2011; Mafongoya and Jiri, 2016).

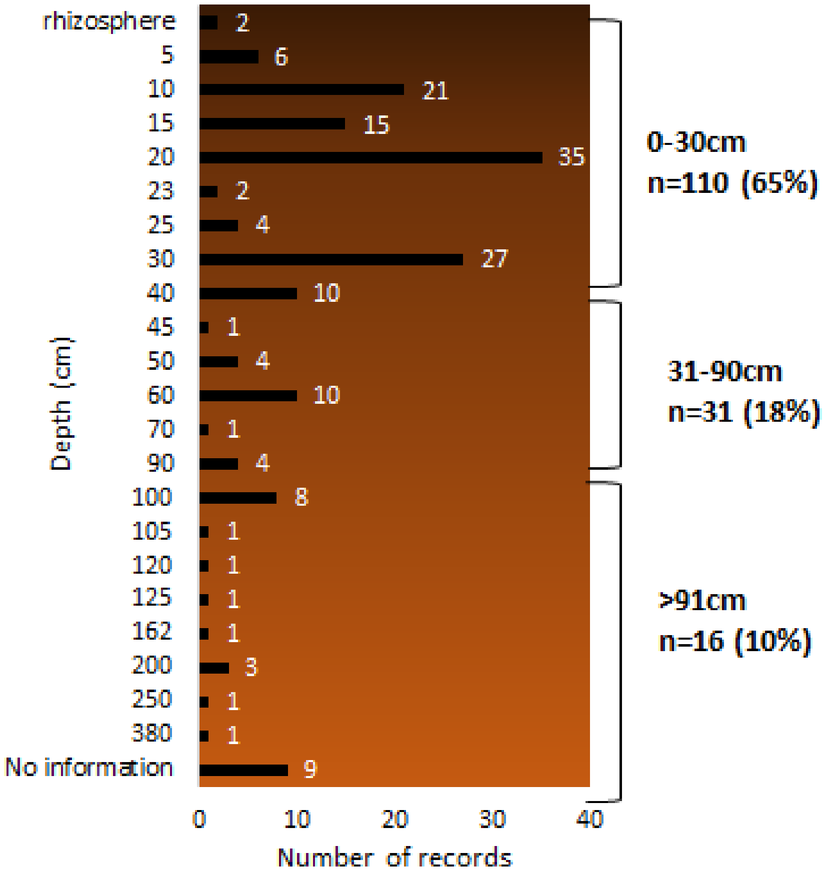


Figure 7. Maximum sampling depth analyzed on the retrieved studies.

Agroforestry Systems have been studied in a wide variety of soil textures (Fig. 8), but there's a concentration of studies on sandy loam (20.0%), clay loam (18.6%) and sandy clay loam (10.7%) textural classes. On the other hand, there is a lack of studies on silt, silty clay loam and silty clay soils.

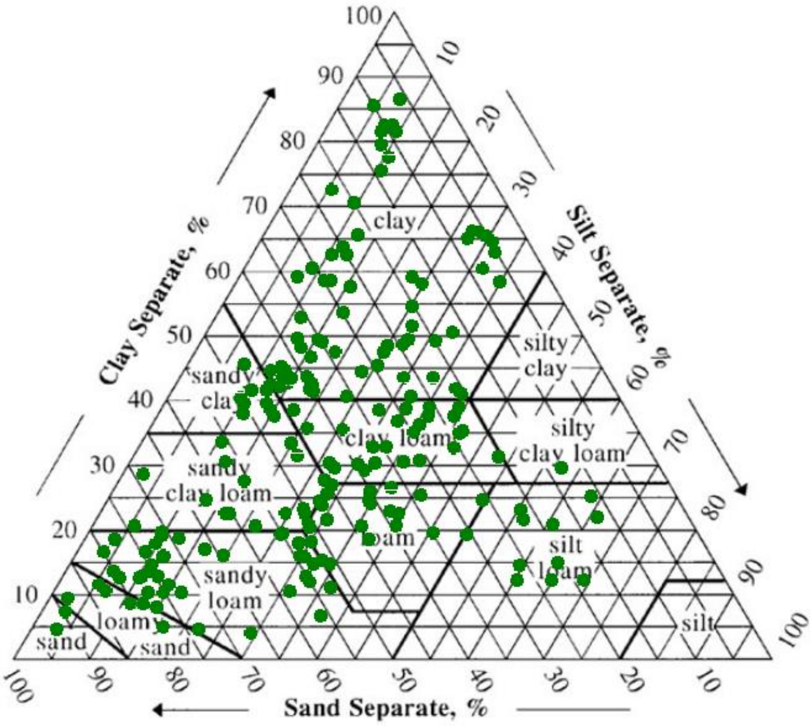
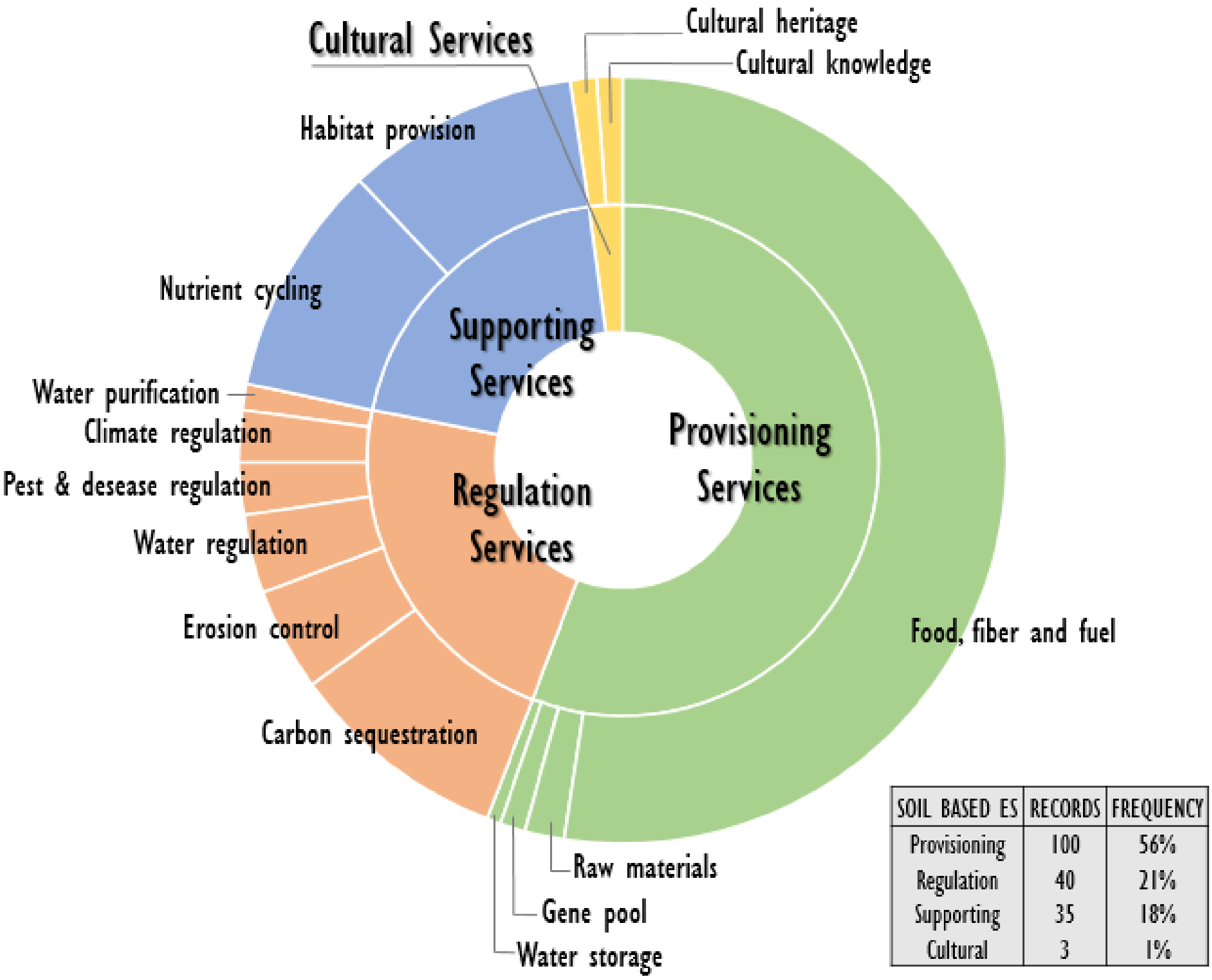


Figure 8. The green points on the textural triangle refer to the Particle Size Distribution of every samples used on the retrieved studies.

Regarding soil classification, from the 169 analyzed studies, 45 (26.6%) papers did not present any information on this matter. Many studies evaluated more than one taxonomic unit, totaling 185 identified units. Cambisols (35; 18.9%), Luvisols (31; 17.3%), Ferralsols (21; 11,4%) and Acrisols (21; 11,4%) were the most analyzed soil orders. Others include a wide range of soil orders such as Leptosols (4.9%), Fluvisols (4.9%), Regosols (4.9%), Planosols (4.3%), Vertisols (3.2%) and so on. 80 identified soil taxa were originally classified according to WRB, 81 were classified according to USDA's Soil Taxonomy and 18 were classified according to the Brazilian System of Soil Classification - SiBCS. Only 2 articles used folk or indigenous classifications. Although most studies presented some kind of soil classification, it's important to highlight that a considerable amount were wrongly classified, mainly due to incorrect morphological descriptions. Soil categorization is an important communication tool, since it provides summarized information about the object in question such as attributes, genetic relations, potentialities and management limitations (Buol et al., 2011). The lack of or misclassification may hinder scientific communication and research on this matter.

According to our results, a great part of the retrieved studies focus on provisioning ecosystem services (56%; 94), mainly related to food, fiber and fuel provision (Fig. 9). Supporting and regulating services related to soil functions were assessed by 18% (31) and 21% (35) of the papers, respectively, and the majority concentrated on nutrient cycling and carbon sequestration services. In contrast, only three papers investigated aspects related to cultural services (1%) (Imbert et. al, 2003; Nath et. al, 2015; Ketema et. al, 2018). It is valuable to note that 5% of the studies assessed soil aspects related to more than one ES, while most of the studies did not address ES at all.



SOIL BASED ES	RECORDS	FREQUENCY
Provisioning	100	56%
Regulation	40	21%
Supporting	35	18%
Cultural	3	1%

Figure 9. Frequency and number of publications that assessed each Ecosystem and lower-level Ecosystem Service.

2.3.3. Knowledge gaps and recommendations for future studies

As major soil threats are driven by human activity, mainly land misuse and mismanagement, integrated production systems such as AF are highly recommended as mitigation strategies to soil degradation. Agroforestry's multifunctionality and resilience capacity in facing the consequences of a changing climate, especially in tropical regions and underdeveloped countries may also explain the rising interest on this matter. These regions may be more affected by accelerated climatic changes that, if combined to socio-economic aspects, may intensify the pressure over natural resources, leading to a vicious circle of land degradation and poverty (Lal, 2020).

Agroforestry practices have been indicated as a more sustainable productive system for at least 3 decades, due to its positive impacts on soil health (Muchane et al.,2020). However, "as defined in the World Soil Charter, sustainable soil management comprises activities that maintain or enhance the supporting, provisioning, regulating and cultural services provided by soils without significantly impairing either the soil functions that enable those services or biodiversity" (FAO, 2015). Since Ecosystem Services are underpinned by soil functions, our research reveals that most studies assessed chemical and physical soil attributes related to traditional fertility assessment, focusing on nutrient cycling and availability to the crop grown, while other critical soil functions are still underrated by the literature, such as soil cultural ES.

Yet, there seems to be a shift from an agronomic towards an ecological perspective in the studies' approach, following the soil quality framework change stated by Bünemann et al. (2018). The retrieved studies from the early 1990's (Kang et al., 1994; Schroth et al., 1995) and 2000's focus on crop productivity, whereas studies published from 2010 onwards present a more holistic and integrative approach. These studies not only evaluate biomass production, but also investigate the effects on soil, air and water quality. The increasing application of soil quality assessment through the integration of chemical, physical and biological attributes may provide a better understanding of the short-term and long-term effects of agroforestry practices on soil and on other ecosystem components (Karlen et al., 2003).

The application of ES approach may contribute to understand the potential of the AF multifunctionality, especially those related to climatic change and food security. In addition, this approach can be useful to compare and assess systems with such great variety on structure, composition and functions, providing information that could be used to generate economic and public policies (MEA, 2001; Reid et al., 2005).

The participation of soil scientists in these studies could help mitigate conceptual and methodological problems that might occur. A deep understanding of soil as a four-dimensional dynamic, multiphase and multiscale system can help agroforestry scientists to better interpret research results and also provide a better comprehension of belowground interactions on these systems. Due to its high complexity, these analyses may require more accurate methodologies in order to consider multiple variables, which may involve more advanced technology and modelling studies, under a multidisciplinary approach.

2.4. Conclusions

This research revealed that soil conservation is an old concern for agroforestry research and has been receiving increased attention during the last decade, especially in tropical humid and sub-humid countries, due to biophysical and socioeconomic reasons. Brazil is the top-publisher country with a great contribution of EMBRAPA, while the Chinese Academy of Sciences is the world top-publisher institution. The assessed scientific output presents a shift from a soil fertility approach based on crop yield, towards a holistic and environmental approach based on integrated soil quality assessments. However, it is necessary to further investigate soil biological and hydro-physical aspects related to regulation and supporting ecosystem services, in order to clarify management effects on belowground processes and ecological interactions. For that, we recommend cooperation between agroforestry researchers and soil scientists in order to improve research assessments.

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3. LAND-USE EFFECTS OVER SOIL STRUCTURE AND HYDRO-PHYSICAL BEHAVIOR

Abstract

This study aimed at characterizing the soil hydro-physical behavior in four different land-uses: a) a coffee-based agrosilvicultural Agroforestry System (AF), b) a cropland-used for fodder maize production (CR), c) a *Eucalyptus* plantation for timber (EP), and d) an area under fallow (FW); and compare them in order to investigate land-use effects over soil hydrological functions at plot scale. We hypothesized that Agroforestry Systems were capable of improving soil structural conditions and, as a consequence, also improve soil hydrological functioning. In order to do that, we collected disturbed soil samples, soil cores and soil aggregates at four depths – 0-10cm, 10-20cm, 20-30cm, 30-40cm – with four replicates in each land-use, totaling 192 soil samples. These samples were used to determine soil particle size distribution, particle density, bulk density (BD), total porosity (TP), microporosity (Mic), macroporosity (Mac), soil resistance to penetration (PR), Mean Weight Diameter (MWD) and organic carbon content (OC). In addition, field saturated hydraulic conductivity (Ks) was estimated by the steady version of the simplified method based on a Beerkan infiltration run (SSBI) in order to determine water infiltration capacity. Soil hydro-physical attributes (Ks, BD, TP, Mic, Mac, MWD and OC) were initially subjected to Shapiro-Wilk and Levene's Tests for normality and variance homogeneity assumptions. One way analysis of variance (ANOVA) was performed considering land-use (AF, CR, FW and EP) as explanatory variable, and Tukey's Test (p 0.05) was applied in order to identify the differences between the mean values. Pearson's correlation analysis and Principal Component Analysis (PCA) was applied to analyze the interrelationship between the variables. Differences between land-uses were observed at the surface layer (0-10cm), and to a lesser extent, at 10-20cm. We observed high Ks (36-360 mm.h^{-1}) in CR and EP, and very high (360 mm.h^{-1}) in AF and FW. Lower BD values were observed in AF and FW (1.28 g.cm^{-3}), and higher values on EP (1.46 g.cm^{-3}) and CR (1.41 g.cm^{-3}) in the 0-10 cm and 10-20cm layers. At 0-10 cm, FW showed the highest Mac (28.5%), and EP the lowest (16.8 %). At all depths the Mean Weight Diameter was higher in EP (2.48 – 2.74mm) and lower in CR (1.27 - 1.97 mm). Our results indicate good aggregation and porosity conditions at AF, similar to the ones observed at FW. CR presented signs of structure degradation, such as sealing, while EP presented signs of surface compaction. As expected, the studied coffee-based Agroforestry System improved soil structure and soil infiltration rate, when compared to a cropland under conventional tillage, a Eucalyptus plantation and an area under fallow. According to our results, AF with low wheel trafficking and minimum soil disturbance are capable of improving water infiltration and reduces runoff.

Keywords: Soil hydrology, Agrosilviculture, Ultisol, Soil Health, Soil functioning

3.1. Introduction

Soils cover the largest area of terrestrial surface and play important regulation functions on the Earth System, but are highly threatened by anthropic activities (Lal, 2014; Adhikari and Hartemink, 2016; Bünemann et al., 2018; Targulian et al., 2018). Soil misuse and mismanagement might lead to the depletion of this essential natural resource and to a series of negative impacts on different time and space scales. Related to the hydrological cycle, soils regulate water flows and the recharge of groundwater tables and watercourses, as well as storing and filtering water. The loss of their capacity to perform these functions, as a result of soil degradation processes, contribute to the occurrence of floods and to freshwater quality reduction and availability (Lal, 2014). Besides that, other soil functions might be compromised such as biomass production, carbon storage and nutrient cycling (Ilstedt et al., 2007; Smettem, 2017; Rabot et al., 2018). For this reason, it is necessary to ensure proper land-use and management practices that contribute to soil improvement and water resources conservation, especially in the current moment of climatic instability caused by global warming. The continuous global temperature rising may intensify rainfall variability and extreme events such as floods and droughts, which may become more frequent, leading to problems of crop yield reduction and freshwater scarcity. Additionally, at humid tropical and subtropical zones where highly weathered soils (e.g., Oxisols and Ultisols) are predominant water-risk susceptibility may be enhanced by the suppression of native vegetation and its replacement by monoculture-based agricultural systems and conventional tillage (ILSTED et al., 2007). The alterations on soil’s chemical, physical and biological attributes by these disturbances might trigger degradation processes and cause the loss of many ecosystem benefits and services.

Among these processes of soil degradation, soil erosion is considered the biggest challenge to sustainable agriculture in the tropical and subtropical areas, even though it is a global problem (Lal, 2014; Claret and Martínez-Casanovas, 2017; FAO, 2019). Nonetheless, soil erosion might be linked to other soil physical degradation processes, such as compaction and sealing, caused by long-term inappropriate agricultural and forestry activities, which compromise water flow partitioning and, as a consequence, may reduce infiltration, enhance runoff and sediment transportation (Cresswell et al., 1992; Bronick and Lal, 2005). A key factor to understand and prevent soil physical degradation, as well as environmental quality decline, is soil structure. The shape and arrangement of primary soil particles and aggregates forming pore spaces of different types result from the interactions of soil forming factors, and the short-term human-induced changes (Kladivko, 2017). Also, soil structure is related to all the processes occurring within the soil, including soil hydrological functions such as infiltrating, conducting and storing water (Cresswell et al., 1992; Rabot et al., 2018). For this reason, land-uses and crop/soil management practices that preserve and improve soil structure are crucial to guarantee water conservation and good environmental quality.

For that matter, integrated agricultural systems that incorporate perennial species (i.e., trees and bushes) have been suggested as viable alternatives to conventional systems, especially due to its social-economic and environmental benefits (Sanchez et al., 1997; Foley et al., 2005; Branca et al., 2013; Basche and Edelson, 2017; Chen et al., 2017; Thierfelder et al., 2017). The presence of trees and, to a lesser extent, bushes on management units provides litter, that feed soil fauna, and a network of deep roots inside the soil, that approximate soil particles and involve them with organic acids and might contribute to the formation of aggregates and macropores. The voids and pore spaces formed between aggregates provide pathways for roots and rapid water movement (Truman and Franzmeier, 2017), facilitating the entrance and transportation of fluids and gases in the soil. Nevertheless, the actual impacts of Agroforestry Systems (AF) on soil hydro-physical behavior are not well comprehended, as diagnosed in the previous chapter, just as other assumed benefits to soils, despite being broadly assumed (Rao et al., 1997; Dollinger and Jose, 2018).

Thus, this investigation was done in order to enlighten this matter through the analyses of soil attributes related to soil structure and water dynamics on the surface and subsurface layers of a soil subjected to long term conventional land-uses and a well stablished AF. This study aimed at characterizing and comparing the soil hydro-physical behavior in four different land-uses, assuming the hypothesis that AF improves the soil structural condition and, consequently, improves its hydrological functioning.

3.2. Materials and Methods

3.2.1. Study areas

The study took place at Fazenda Areão, an experimental farm of ESALQ/USP, located in the municipality of Piracicaba, São Paulo State, Brazil (22°41,716' S e 47°38,478' W). It’s located at 560 m above sea level in an undulating landscape. The region climate is classified as Cwa, subtropical with dry winter and hot summer, with a mean annual temperature of 21.7°C and mean annual rainfall of 1,346mm, with maximum rainfalls between October and April. The climate is transitioning to Aw, tropical with dry winter, and there is a regional tendency in decreasing the frequency of low intensity rains and increasing the frequency of high intensity rains (Dias et al., 2017).

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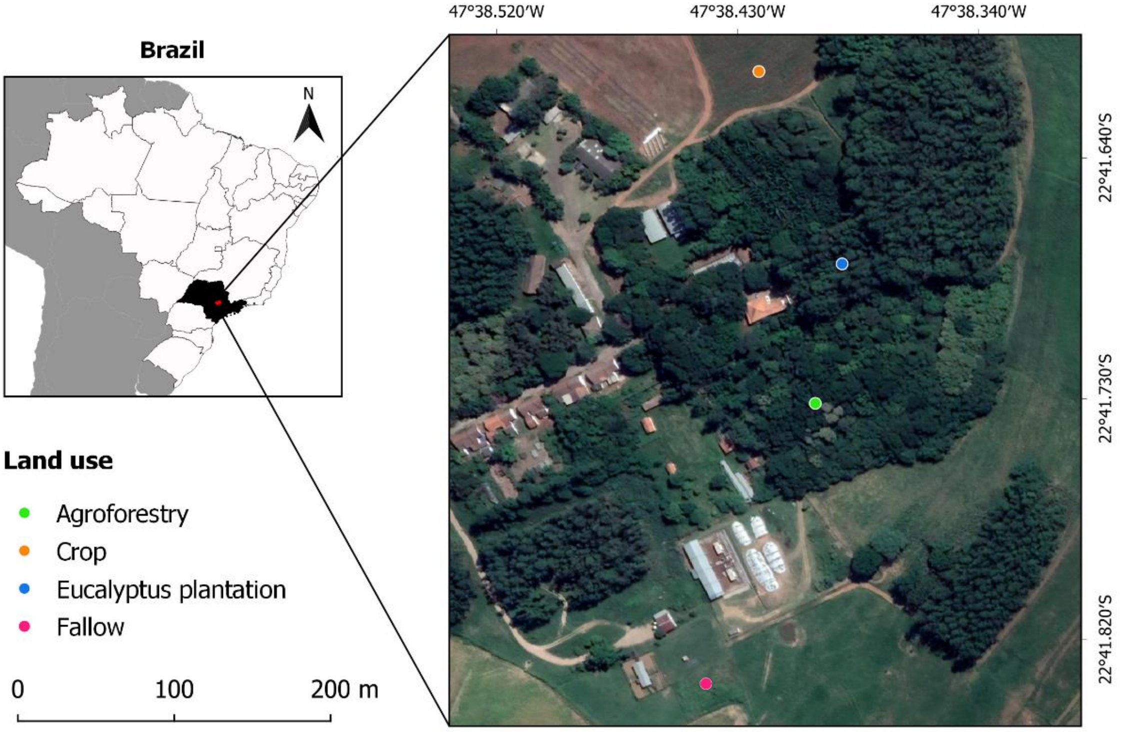


Figure 10 Geographic location of the study sites at Fazenda Areão, located in the municipality of Piracicaba, São Paulo state.

Areas under different land-uses and management systems were chosen for this investigation: i) a *Eucalyptus* plantation (EP), ii) a cropland, currently used for maize (*Zea mays*) production for silage (CR), iii) a coffee-based Agroforestry System (AF), and iv) an area under fallow (FW). All areas have been used by the same activity for at least 15 years. The soils of the sampling areas are classified as an ARGISSOLO VERMELHO-AMARELO according to the Brazilian Soil Classification System (Santos et al., 2018). This soil is equivalent to Soil Taxonomy’s Ultisol and WRB’s Acrisol (IUSS Working Group WRB, 2014). Soil texture varies from sand clay loam to clay (Soil Science Division Staff, 2017), and the transition between A and Bt horizons vary from 10 cm to 30 cm deep.

The *Eucalyptus* plantation is composed of different *Eucalyptus* species arranged in traditional spacing (3 m x 2 m). The area has 0,4 ha and was previously used for recreational purposes with no register of agricultural, livestock or forestry activities. It has been used for *Eucalyptus* breeding for timber for the last 10 years. Before seedling, the soil was decompacted by subsoiling on the seedling rows and weed control was done by trimming. Fertilization and liming were done at the tree row after seedling planting. Pruning is performed annually during winter period and the residues are left on the field.

The cropland area has been used for maize production in rotation with soybean, managed under conventional tillage. The area extends for 1 ha. Soil is annually tilled by plowing and harrowing, amended and fertilized before sowing, according to crop needs. No residue is left on the field since the entire plant is harvested for silage production. Soil sampling occurred three months before planting.

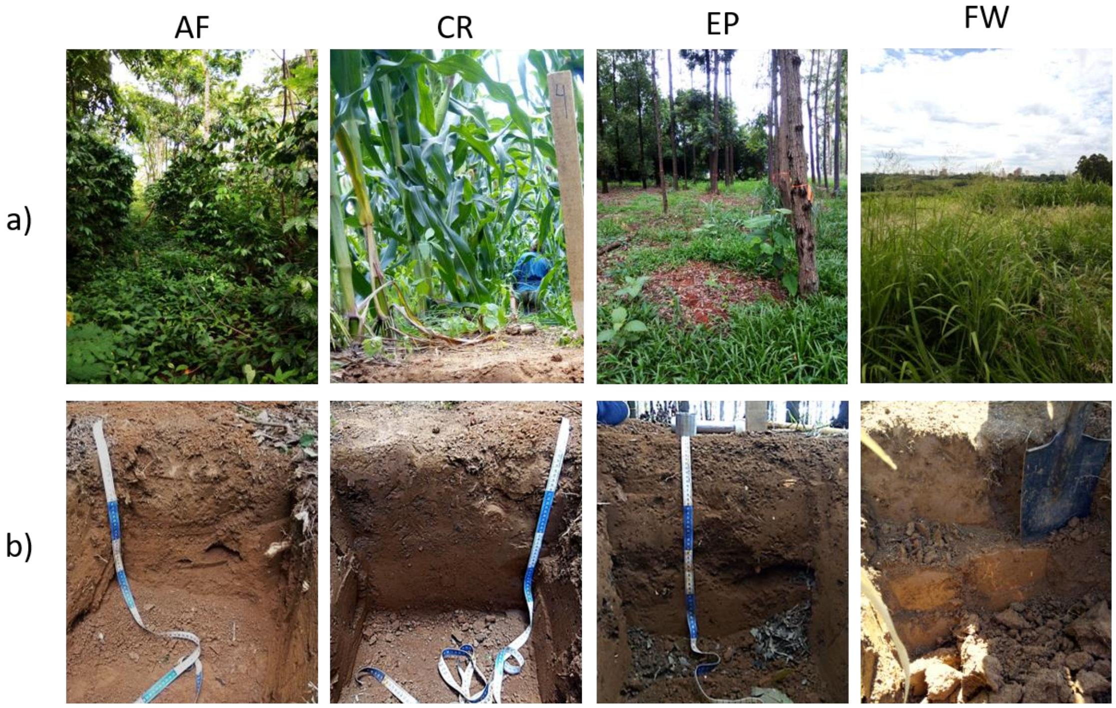


Figure 11. Pictures of the study sites (a); and trenches used for sampling (b). AF, Agroforestry; CR, Cropland; EP, Eucalyptus Plantation; FW, Fallow.

The Coffee-based Agroforestry System is characterized as an Alley Cropping (Nair, 1993; Sinclair, 1999) composed of native and exotic tree species (e.g., *Inga vera* Willd., *Hovenia dulcis* Thunb., *Anadenanthera colubrina* var. cebil, *Centrolobium tomentosum* Guillem. ex Benth, etc.) distributed in 100 m rows, spaced 6.5 m from each other, with coffee (*Coffea arabica* L.) in the interrows. The area was first occupied by an abandoned conventional coffee plantation. In 1996, tree seedlings were planted in single rows every two coffee lines. Previously to canopy formation maize was cultivated in the interrows of the coffee plants, followed by cassava (*Manihot esculenta)*, planted after canopy formation. Since canopy was formed, manual pruning of trees, especially *Leucaena leucocephala*, and coffee plants were the major management practices carried out in the area, besides the annual coffee harvesting. The tree lines were only managed in the first years and some individuals declined, and were not replaced. Machinery has not been used in this area since AF was implanted.

The area under fallow has 0,05 ha and was previously used as a “grass display” for main plant species used for grazing in Brazil, but has not been disturbed for the last 15 years. There are also no records of tillage, wheel trafficking or grazing in this area.

3.2.2. Soil sampling and analytical procedures

Soil sampling and infiltration tests were carried out in February 2021. In each site, four small pits (30 cm x 30cm x 50 cm) were opened for sampling. In EP, the pits were placed between the tree lines and the interrows, avoiding tracks, while in AF, the pits were placed between the coffee and the tree row. Disturbed and undisturbed soil samples and aggregates samples were collected from 0-10 cm, 10-20 cm, 20-30 cm and 30-40 cm layers. This provided a total of 64 disturbed, 64 undisturbed soil samples and 64 aggregate samples used for physical and chemical analysis.

Field saturated hydraulic conductivity (Ks) was obtained by the simplified method of BEST proposed by Bagarello et al. (2017) following the procedure described by Lassabatère et al. (2006). For this, a steel cylinder of 0.16m diameter was inserted 0.01m into the soil surface after removal of crop residues, pasture or litter. A known volume of water (150 mL) was poured into the cylinder and the infiltration time was recorded for at least 8 turns in each plot until reaching the steady state. In each area, 9 repetitions were done, totaling 36 infiltration tests. The Saturated Hydraulic Conductivity (Ks) was then calculated through the simplified Beerkan infiltration method (SSBI-Steady version) using the following equation:

$$Ks = \frac{i_s}{\frac{\gamma \gamma_w}{r\alpha^*} + 1} \qquad (1)$$

Where i_s (mm.h^{-1}) is the slope of the linear regression fitted to the final portion of the cumulative infiltration time series data points (L(t) vs. t) describing steady state conditions, r (mm) is the cylinder radius, and γ_w and γ are dimensionless constants, fixed at 1.818 and 0.75, respectively. Finally, α^* is the sorptive number expressing the relative importance of the capillary over gravity forces during water movement in unsaturated soils and, in this case, it was assumed to be equal to 0.012 mm^{-1}, since it represents the suggested approximation value for most field soils, especially tropical soils and has been already used in previous studies of soils of the Atlantic Forest. Surface soil layer disturbed samples were collected in the same infiltration spots to determine initial and final soil gravimetric water content required for Ks determination.

Undisturbed soil samples were collected using steel cylinders of approximately 100cm³ which were used to determine soil bulk density (BD), total porosity (TP), macroporosity (Mac), microporosity (Mic) and penetration resistance (PR). Disturbed samples were used to determine particle size distribution (PSD), by the hydrometer method, with sand separation (Camargo et al., 2009); Flocculation Degree (FD) was measured from Water Dispersed Clay (WDC); Particle Density (PD) and chemical attributes for soil characterization and Organic Carbon content determination.

Bulk density was determined dividing the sample's dry weight (105°C/48h) by the volume of the soil cores, which were assumed to be the steel cylinders' volumes (Blake and Hartge, 1986). Total porosity (%) was calculated from Bulk and Particle Density (Danielson and Sutherland, 1986), being the last one determined using a helium gas pycnometer (Flint and Flint, 2002). Mic (%) was estimated by the difference between soil sample weight submitted to -6 kPa tension and the dry weight of the soil sample, in relation to soil core volume. Mac (%) was calculated by the difference between TP and Mic. Soil cores at field capacity were taken to a benchtop electronic penetrometer for PR (MPa) determination.

In order to assess the structural quality and susceptibility to erosion, Aggregate Size Distribution was determined by wet sieving according to Yoder (1936), using a modified method adapted from Van Bavel (1950), cited by Kemper and Rosenau (1986). 50g of air-dried soil aggregates, previously passed through sieves with 9.51 mm and 4.76 mm openings, were slowly saturated with water using paper filters for 20 minutes and were set on the top of a set of five sieves: 2.00 mm, 1.00 mm, 0.5 mm, 0.25 mm and 0.053 mm. The sieves were placed on a sieve-machine holder and submerged in water to the point that the soil sample was completely covered. To separate the aggregates by size, the sieves were subjected to an oscillatory motion for 15 minutes at a rate of 42 rotations per minute. After aggregate separation, the soil retained in each sieve was transferred to previously weighed beckers and dried for 48h at 105°C. After cooling, these samples were weighed and the Mean Weight Diameter (MWD) was determined as follows:

$$MWD = \sum_{i=1}^{n} \bar{x}_i w_i \qquad (2)$$

Where $\bar{x}_i$ is the mean diameter of each size fraction, w_i is the proportion of the total sample weight occurring in the respective size fraction and n is the total number of size fractions, excluding the one that passes through the finest sieve. 10g of soil aggregates were used to determine water gravimetric content for mass correction.

3.2.3. Data analysis

Soil hydro-physical parameters (Ks, BD, TP, Mic, Mac, MWD and OC) were initially subjected to Shapiro-Wilk and Levene's Tests for normality and variance homogeneity assumptions. One way analysis of variance (ANOVA) was performed considering land-use (AF, CR, FW and EP) as the explanatory variable, and Tukey's Test ($p<0.05$) was applied in order to identify the differences between mean values. Pearson's correlation coefficient was calculated and the principal component analysis (PCA) was performed in order to identify interrelationship between the analyzed variables (BD, TP, Mic, Mac, MWD and OC). All statistical analysis and graphics were executed using the R software and R Studio environment (R Core Team, 2020).

3.3. Results

Significant differences between LU were predominantly obtained in the 0-10 cm soil layer and, to a lesser extent on 10-20cm layer. Generally, higher infiltration rates were observed in AF and FW; improved levels of Bulk Density, Porosity and Aggregation were also observed in these areas. In deeper layers, most attributes showed similar results between LU, except for BD, Mic and MWD results which statistical differences were observed in 30-40cm. Further results are detailed bellow.

Table 2. Soil characteristics of the studied areas.

Land-use	Soil layer	pH	Ca	Mg	H+Al	CEC	Clay	Silt	Sand	VCS	CS	MS	FS	VFS	WDC	FD	Texture*
	cm		$mmol_c. kg^{-1}$				$g. kg^{-1}$									%	
Agroforestry System	0-10	5,3	65,0	14,9	13,8	97,8	294	237	469	62,6	65,6	89,8	146,3	104,4	157,0	47,1	Sandy Clay Loam
	10-20	4,7	32,1	9,5	20,2	63,4	345	229	426	49,6	37,3	66,1	181,1	92,1	117,0	64,8	Clay Loam
	20-30	4,7	27,4	9,3	11,9	49,4	428	195	377	42,4	30,1	56,3	159,8	88,1	91,2	75,3	Clay
	30-40	4,6	26,8	8,2	15,7	23,9	485	169	346	43,8	29,0	51,3	146,1	75,7	71,6	82,8	Clay
Cropland	0-10	5,1	26,6	9,3	8,8	50,6	316	161	523	42,6	61,9	103,0	208,1	107,5	160,5	40,4	Sandy Clay Loam
	10-20	5,1	30,8	11,3	3,7	47,8	332	159	509	48,6	63,7	94,6	200,2	101,7	100,1	62,7	Sandy Clay Loam
	20-30	5,0	28,2	9,9	3,8	43,1	363	149	488	45,7	55,6	85,9	196,0	104,3	81,6	73,0	Sandy Clay
	30-40	4,9	26,8	9,4	6,2	43,4	379	151	470	40,4	51,1	82,8	191,0	104,7	79,8	76,0	Sandy Clay
Eucalyptus Plantation	0-10	4,7	37,2	11,5	23,8	75,9	327	202	471	37,0	50,7	87,8	193,5	101,7	173,2	46,7	Sandy Clay Loam
	10-20	4,5	18,7	7,6	20,3	48,7	427	173	400	33,0	34,0	64,0	171,8	97,5	78,4	80,8	Clay
	20-30	4,5	20,1	8,0	18,0	47,8	546	131	322	26,0	26,1	49,8	138,3	82,0	73,2	86,4	Sandy Clay Loam
	30-40	4,3	21,6	8,1	20,0	50,9	607	115	278	27,0	24,4	40,2	118,5	68,0	60,0	90,1	Clay
Fallow	0-10	5,7	41,6	15,7	0,4	62,3	327	320	354	22,2	31,6	69,7	149,0	81,2	137,0	57,7	Clay Loam
	10-20	5,6	35,0	13,8	0,3	51,2	350	314	336	19,3	26,6	56,2	146,3	87,4	90,9	73,5	Clay Loam
	20-30	5,4	32,5	12,0	1,1	47,1	389	302	309	21,4	23,4	56,5	134,0	73,5	84,3	78,3	Clay Loam
	30-40	5,4	35,5	12,0	0,6	49,2	490	266	244	17,9	17,7	37,0	103,8	67,3	65,0	86,1	Clay

VCS = Very Coarse Sand; CS = Coarse Sand; MS = Medium Sand; FS = Fine Sand; VFS = Very Fine Sand; WDC = Water Dispersed Clay; FD =Flocculation Degree.
*Reference: USDA, 2017

3.3.1. Infiltration rate

Ks means varied from high (36-360 mm.h^{-1}) in CR and EP to very high (360 mm.h^{-1}) in AF and FW (Soil Science Division Staff, 2017). CR and EP presented Ks of 93.0 mm.h^{-1} and 154.9 mm.h^{-1}, respectively, while the AF and FW sites presented a mean Ks of 515.5 mm.h^{-1} and 492.8 mm.h^{-1}, respectively (Fig. 12). The field measurements at AF, FW and EP presented great variability, ranging from 135.9 mm.h^{-1} to 1,425.6 mm.h^{-1} in AF; from 98.5 mm.h^{-1} to 920.0 mm.h^{-1} in FW and from 11.46 mm.h^{-1} to 468.15 mm.h^{-1} in EP. In CR, infiltration rates were more homogeneous than in other LU. The lowest infiltration rate was found in EP and the highest was found in AF.

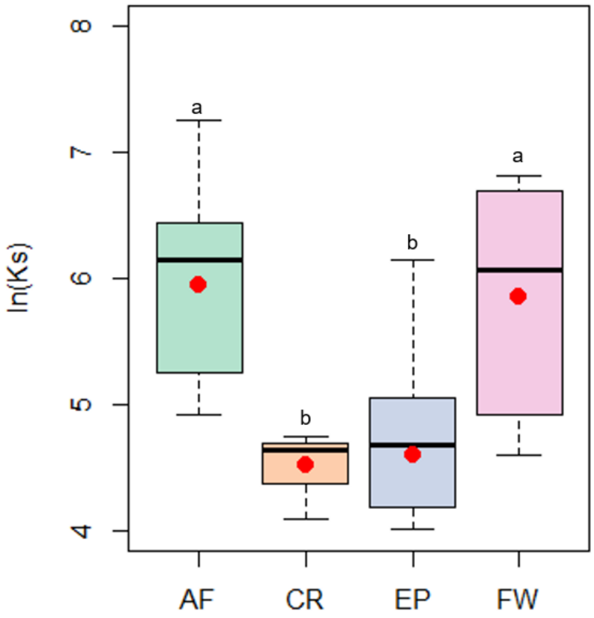


Figure 12. Boxplot of the natural logarithm of the saturated hydraulic conductivity [ln(Ks)]. The letters refer to the Tukey Test results for means comparison at 95% confidence interval. Land-uses followed by the same letter do not differ statistically. The red dots correspond to the mean values.

3.3.2. Soil Bulk Density, Total Porosity, Macro and Microporosity

Bulk density showed no significant differences at 0-10 cm, neither in deeper layers, except for the 30-40 cm layer (Fig. 13a). However, lower BD values were found in AF and FW (1.28 g.cm^{-3}), and higher values in EP (1.46 g.cm^{-3}) and CR (1.41 g.cm^{-3}) in the 0-10 cm and 10-20 cm layers (Table 3). All LU showed a tendency of BD increasing with depth, except for EP, which decreased from the 20-30 cm layer to the 30-40 cm layer (1.58 g.cm^{-3} and 1.50 g.cm^{-3}, respectively).

TP means were not significantly different except for the 0-10 cm layer (Fig. 13b). At the surface layer, total porosity was higher in AF (56.5%) and FW (58.3%), intermediate in CR (52.5%) and the lowest TP was presented in EP (48.0%) (Table 3). Results also show a decreasing trend of TP with depth, except in the EP area, where the results did not show considerable variation within the soil profile. The decrease of TP with depth is noticeable at 0-10 cm, 10-20 cm and 20-30 cm. From 20-30 cm to 30-40 cm, there are no considerable variations of TP in any LU. Besides that, no significant differences in TP means were found between LU in the subsurface layers.

In relation to Pore Size Distribution, differences in Macroporosity were more evident in the surface layer, while the opposite was noticed for the Microporosity results (Fig. 13d; Table 3). There is a decreasing trend of Mac with depth in all LU. At 0-10 cm, FW showed the highest Mac (28.5%), CR (25.0 %) and AF (22.0%) presented intermediate values, and EP the lowest (16.8 %). At 10-20 cm and 20-30 cm AF and FW showed similar results and the results followed the same trend noticed in the surface layer. At 30-40 cm, Mac is higher on CR (12.5%), intermediate in EP and FW (10.3%) and lower in AF (9.8%).

In contrast with Mac results, the effects of LU on Microporosity are less pronounced at 0-10 cm and became progressively more pronounced with depth (Fig. 13c; Table 3). There is an increasing trend of Mic in EP with depth. CR showed the lowest means and results did not vary much with depth (from 28.0 % to 29.0%). Mic was higher in AF at 0-10 cm (34.0%) than the other LU. In deeper layers, the AF means (31.3%; 32.5%) showed similar results to the ones obtained for FW (30.5%; 32.0%). However, AF results showed great variability at 20-30 cm and 30-40 cm.

3.3.3. Mean Weight Diameter

At all depths the Mean Weight Diameter was higher in EP (2.48 – 2.74mm) and the lowest means were found in CR (1.27 - 1.97 mm), although significant differences were not found at 0-10 cm and 10-20 cm layers (Fig. 14b; Table 3). FW and AF showed intermediate and similar results at all depths, except for the 20-30 cm layer, where there was a decrease in MWD in AF from 2.24 mm to 1.75 mm. The same decrease was observed in CR at the same depths, followed by slight increase in MWD at 30-40 cm, that put CR and AF in the same class.

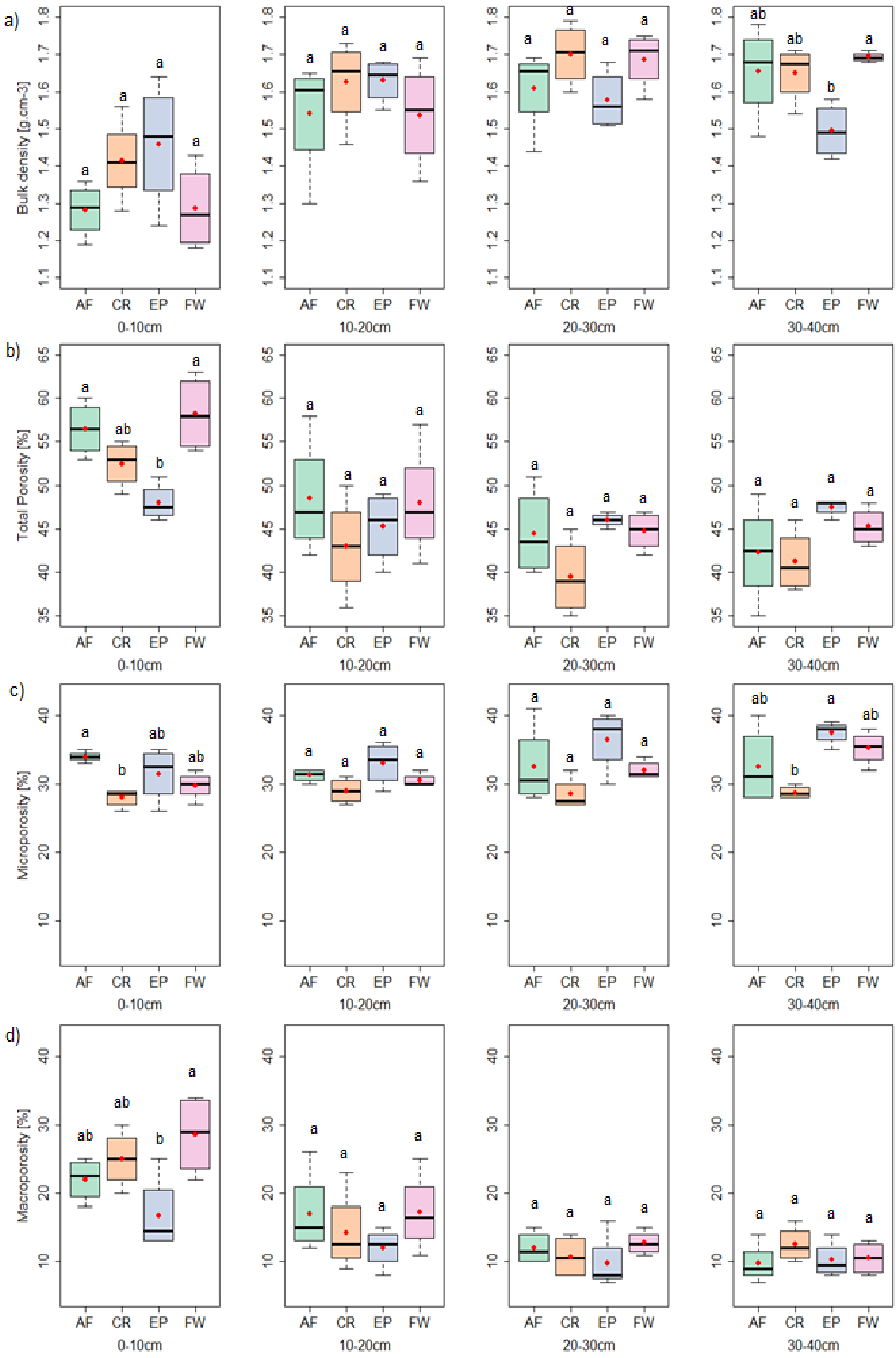
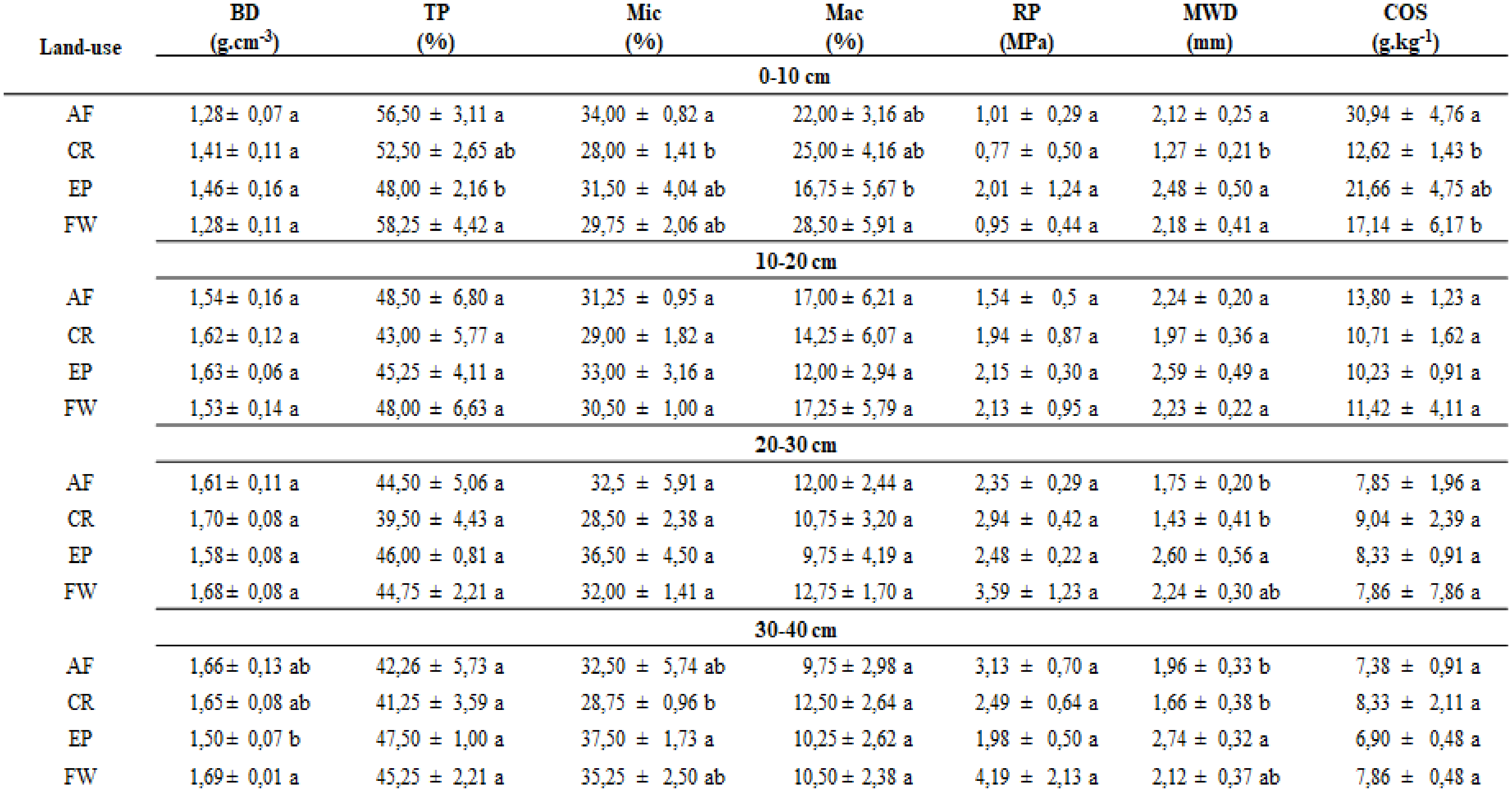


Figure 13. Boxplot of (a) Bulk Density, (b) Total Porosity, (c) Microporosity and (d) Macroporosity for each land-use at 0-10cm, 10-20cm, 20-30cm and 30-40cm soil layers. The letters refer to the Tukey Test results for means comparison at 95% confidence interval. Averages followed by the same letter do not differ statistically. The red dots correspond to the mean values.

Table 3. Average means and standard deviations for soil hydro-physical attributes: bulk density (BD), Total Porosity (TP), Microporosity (Mic), Macroporosity (Mac), resistance to penetration (PR), Mean Weighted Diameter (MWD) and Soil Organic Carbon content (SOC). Averages followed by the same letter do not differ statically.



Land-use	BD ($g.cm^{-3}$)	TP (%)	Mic (%)	Mac (%)	RP (MPa)	MWD (mm)	COS ($g.kg^{-1}$)
				0-10 cm			
AF	1,28 ± 0,07 a	56,50 ± 3,11 a	34,00 ± 0,82 a	22,00 ± 3,16 ab	1,01 ± 0,29 a	2,12 ± 0,25 a	30,94 ± 4,76 a
CR	1,41 ± 0,11 a	52,50 ± 2,65 ab	28,00 ± 1,41 b	25,00 ± 4,16 ab	0,77 ± 0,50 a	1,27 ± 0,21 b	12,62 ± 1,43 b
EP	1,46 ± 0,16 a	48,00 ± 2,16 b	31,50 ± 4,04 ab	16,75 ± 5,67 b	2,01 ± 1,24 a	2,48 ± 0,50 a	21,66 ± 4,75 ab
FW	1,28 ± 0,11 a	58,25 ± 4,42 a	29,75 ± 2,06 ab	28,50 ± 5,91 a	0,95 ± 0,44 a	2,18 ± 0,41 a	17,14 ± 6,17 b
				10-20 cm			
AF	1,54 ± 0,16 a	48,50 ± 6,80 a	31,25 ± 0,95 a	17,00 ± 6,21 a	1,54 ± 0,5 a	2,24 ± 0,20 a	13,80 ± 1,23 a
CR	1,62 ± 0,12 a	43,00 ± 5,77 a	29,00 ± 1,82 a	14,25 ± 6,07 a	1,94 ± 0,87 a	1,97 ± 0,36 a	10,71 ± 1,62 a
EP	1,63 ± 0,06 a	45,25 ± 4,11 a	33,00 ± 3,16 a	12,00 ± 2,94 a	2,15 ± 0,30 a	2,59 ± 0,49 a	10,23 ± 0,91 a
FW	1,53 ± 0,14 a	48,00 ± 6,63 a	30,50 ± 1,00 a	17,25 ± 5,79 a	2,13 ± 0,95 a	2,23 ± 0,22 a	11,42 ± 4,11 a
				20-30 cm			
AF	1,61 ± 0,11 a	44,50 ± 5,06 a	32,5 ± 5,91 a	12,00 ± 2,44 a	2,35 ± 0,29 a	1,75 ± 0,20 b	7,85 ± 1,96 a
CR	1,70 ± 0,08 a	39,50 ± 4,43 a	28,50 ± 2,38 a	10,75 ± 3,20 a	2,94 ± 0,42 a	1,43 ± 0,41 b	9,04 ± 2,39 a
EP	1,58 ± 0,08 a	46,00 ± 0,81 a	36,50 ± 4,50 a	9,75 ± 4,19 a	2,48 ± 0,22 a	2,60 ± 0,56 a	8,33 ± 0,91 a
FW	1,68 ± 0,08 a	44,75 ± 2,21 a	32,00 ± 1,41 a	12,75 ± 1,70 a	3,59 ± 1,23 a	2,24 ± 0,30 ab	7,86 ± 7,86 a
				30-40 cm			
AF	1,66 ± 0,13 ab	42,26 ± 5,73 a	32,50 ± 5,74 ab	9,75 ± 2,98 a	3,13 ± 0,70 a	1,96 ± 0,33 b	7,38 ± 0,91 a
CR	1,65 ± 0,08 ab	41,25 ± 3,59 a	28,75 ± 0,96 b	12,50 ± 2,64 a	2,49 ± 0,64 a	1,66 ± 0,38 b	8,33 ± 2,11 a
EP	1,50 ± 0,07 b	47,50 ± 1,00 a	37,50 ± 1,73 a	10,25 ± 2,62 a	1,98 ± 0,50 a	2,74 ± 0,32 a	6,90 ± 0,48 a
FW	1,69 ± 0,01 a	45,25 ± 2,21 a	35,25 ± 2,50 ab	10,50 ± 2,38 a	4,19 ± 2,13 a	2,12 ± 0,37 ab	7,86 ± 0,48 a

3.3.4. Penetration Resistance

The soil resistance to penetration results also did not show significant differences between LU (Fig. 14c). The results varied from low (0.1 - 1 MPa) to very high (4 - 8 MPa) resistance classes (Soil Science Division Staff, 2017). The results showed an increasing trend with depth, except for the Eucalyptus Plantation area. In the 0-10 cm layer, CR showed the lowest mean (0.77 MPa); AF and FW showed intermediate (1.01 MPa; 0.95 MPa) results and EP presented the highest mean (2.01 MPa) (Table 3). At 10-20 cm, EP and FW presented close results (2.15 MPa; 2.13 MPa) classified as high resistance, and AF (1.54 MPa) and CR (1.94 MPa) showed moderate PR. FW is more heterogeneous, especially in the 20-30 cm and 30-40 cm layers. CR means increase from 0-10 cm to 20-30cm layers (0.77 MPa; 1.94 MPa; 2.94 MPa) and slightly decreases in the 30-40 cm (2.49 MPa), following the same trend as EP, whose RP results ranged from 2.01 MP, at 0-10 cm, to 2.48 MPa, at 30-40cm. FW presented the highest PR value at 20-30 cm (3.59 MPa) and 30-40 cm (4.19 MPa), classified as high and very high, respectively.

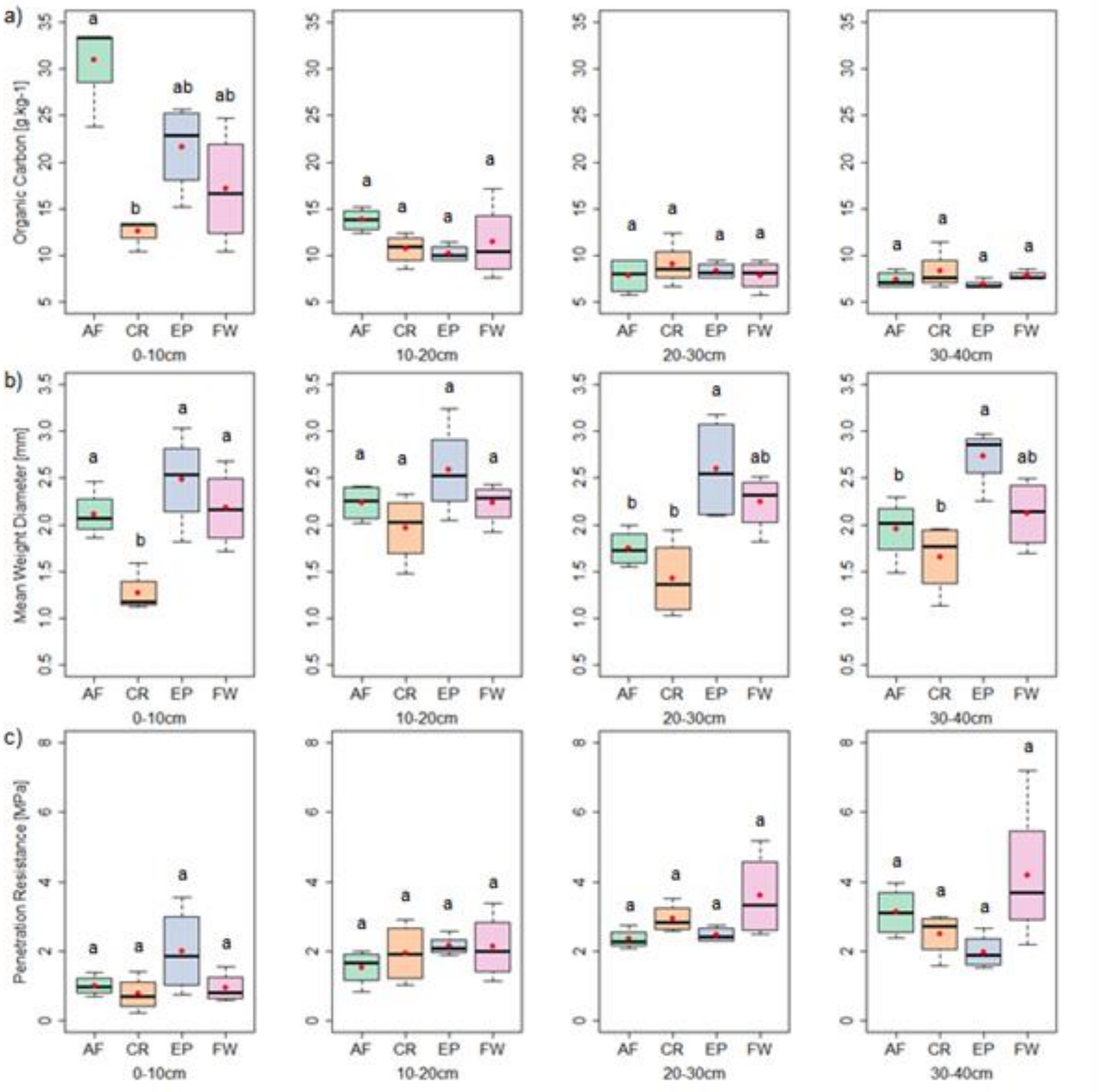


Figure I. Boxplot of (a) Organic Carbon content, (b) Mean Weight Diameter and (c) Penentration Resistance for each land-use at 0-10cm, 10-20cm, 20-30cm and 30-40cm soil layers. The letters refer to the Tukey Test results for means comparison at 95% confidence interval. Averages followed by the same letter do not differ statistically. The red dots correspond to the mean values.

3.3.5. Soil Organic Carbon

At the surface layer, AF showed the highest SOC content (30.94 g.kg^{-1}), followed by EP (21.66 g.kg^{-1}) and FW (17.14 g.kg^{-1}) (Table 3). CR showed the lowest SOC content (12.62 g.kg^{-1}). Also, CR results at 0-10 cm were more homogeneous than the other LU (Fig. 14a). At all LU, there is a decreasing trend of SOC between 0-10 cm and 20-30 cm, but not between the 20-30 cm and the 30-40 cm layer (Fig. 14a). Due to its low SOC content in the surface layer, this decrease is more subtle in CR results than the ones observed in the other LU.

3.3.6. Correlation analyses

Pearson’s correlation analyses showed that at 0-10cm (Fig. 15a; Table 4a), the highest positive correlation was found between TP and Mac (0.84) and between BD and PR (0.79). The highest negative correlation at this depth was found between BD and TP (-0.81), BD and Mac (-0.76), Mac and PR (-0.74) and Mic and Mac (-0.63). The lowest correlations were found between BD and MWD (0.02), PR and OC (0.08), TP and MWD (-0.04), Mac and OC (-0.1) and TP and Mic (-0.12). The variables least correlated to each other are MWD and OC, whose correlations ranged from 0.45 to -0.28 (MWD) and from 0.54 to -0.33 (OC). At 10-20cm (Fig. 15b; Table 4b), TP and Mac (0.9), BD and PR (0.81), Mic and MWD (0.7), TP and OC (0.62) and TP and MWD (0.61) were the highest correlations. And, BD and TP (-0.92), BD and Mac (-0.92), TP and PR (-0.75) and Mac and PR (-0.72) were the highest negative correlations. The lowest positive correlation PR and OC (0.04), Mac and OC (0.08). The lowest negative correlation was found between Mic and Mac (-0.01). At 20-30cm (Fig. 15c; Table 4c), the highest correlations were found between BD and Mic (-0.82), negatively correlated, TP and Mic (0.78), positively correlated and BD and TP (-0.73), negatively correlated. The lowest correlations were found between Mac and PR (-0.02) and BD and OC (-0.03). At 30-40cm (Fig. 15d; Table 4d), TP and Mac (0.84) have the highest correlation, followed by BD and TP (-0.81), and between BD and PR (0.79). And the lowest correlations were found between BD and MWD (0.02) and between TP and MWD (-0.04).

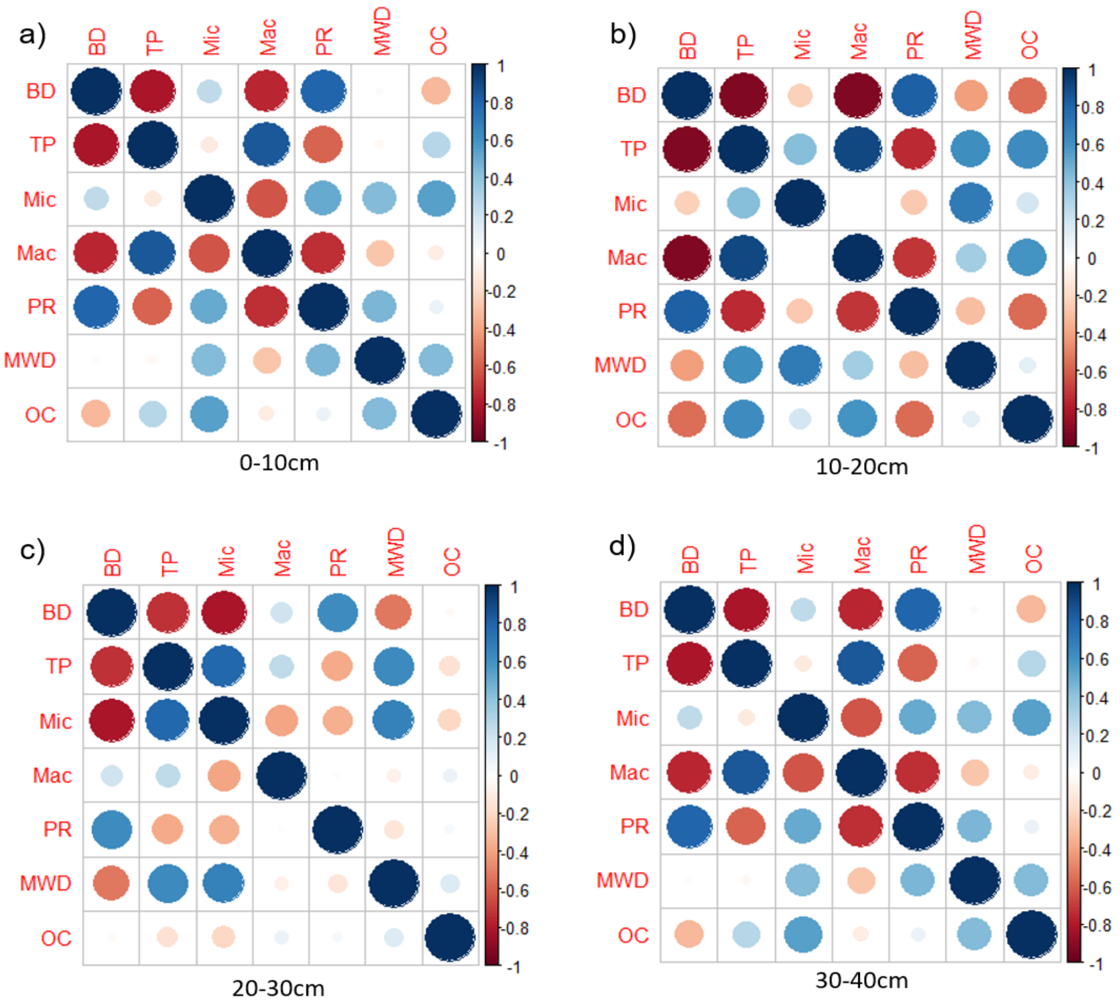


Figure 14. Correlation between soil hydro-physical attributes: bulk density (BD), total porosity (TP), Microporosity (Mic), Macroporosity (Mac), penetration resistance (PR), mean weighted diameter (MWD) and Organic Carbon content (OC), at each studied depth. The larger the circle, the higher the correlation, either positively (blue) or negative (red).

The Principal Component Analysis of 0-10cm layer showed that the Principal Component 1 (PC1) corresponds to 51.5% of the data variability, and Principal Component 2 (PC2) accounts for 28.6%, totaling 80.1% (Fig. 16a; Table 5a). PC1 is positively correlated to Bulk Density, Penetration Resistance, Microporosity and Mean Weight Diameter, and it is negatively correlated with Total Porosity and Macroporosity. Organic Carbon content does not relate with PC1. The PC2 is positively correlated with Bulk Density and negatively correlated to Microporosity, Mean Weight Diameter and Total Porosity. This component is not influenced by Macroporosity neither Penetration Resistance. It is possible to identify clusters of points of the same color on the biplot. CR is almost linearly distributed at the top of the biplot. AF points

Table 4. Pearson's correlation matrix of soil hydro-physical attributes at each studied depth.

a) 0-10cm

	BD	TP	Mic	Mac	PR	MWD	OC
Bulk Density	1,00						
Total Porosity	-0,81	1,00					
Microporosity	0,25	-0,12	1,00				
Macroporosity	-0,76	0,84	-0,63	1,00			
Penetration Resistance	0,79	-0,59	0,50	-0,74	1,00		
Mean Weight Diameter	0,02	-0,04	0,43	-0,28	0,45	1,00	
Organic Carbon	-0,33	0,28	0,54	-0,10	0,08	0,43	1,00

b) 10-20cm

	BD	TP	Mic	Mac	PR	MWD	OC
Bulk Density	1,00						
Total Porosity	-0,92	1,00					
Microporosity	-0,24	0,42	1,00				
Macroporosity	-0,92	0,90	-0,01	1,00			
Penetration Resistance	0,81	-0,75	-0,27	-0,72	1,00		
Mean Weight Diameter	-0,42	0,61	0,70	0,34	-0,31	1,00	
Organic Carbon	-0,55	0,62	0,18	0,59	-0,56	0,11	1,00

c) 20-30cm

	BD	TP	Mic	Mac	PR	MWD	OC
Bulk Density	1,00						
Total Porosity	-0,73	1,00					
Microporosity	-0,82	0,78	1,00				
Macroporosity	0,20	0,25	-0,40	1,00			
Penetration Resistance	0,62	-0,38	-0,36	-0,02	1,00		
Mean Weight Diameter	-0,53	0,63	0,67	-0,08	-0,14	1,00	
Organic Carbon	-0,03	-0,16	-0,21	0,08	0,04	0,14	1,00

d) 30-40cm

	BD	TP	Mic	Mac	PR	MWD	OC
Bulk Density	1,00						
Total Porosity	-0,81	1,00					
Microporosity	0,25	-0,12	1,00				
Macroporosity	-0,76	0,84	-0,63	1,00			
Penetration Resistance	0,79	-0,59	0,50	-0,74	1,00		
Mean Weight Diameter	0,02	-0,04	0,43	-0,28	0,45	1,00	
Organic Carbon	-0,33	0,28	0,54	-0,10	0,08	0,43	1,00

are grouped at the bottom of the biplot close to the PC1 axe. EP cluster is located on the right side of the biplot and is positively influenced by PC1. FW can be divided into two clusters: one on the bottom-left and another on the center top of the biplot. Bulk Density and Total porosity are negatively correlated, as well as Macroporosity and Penetration resistance. Conversely, BD and PR are positively correlated, as well as Mic, MWD and SOC. TP and Mac are also positively correlated.

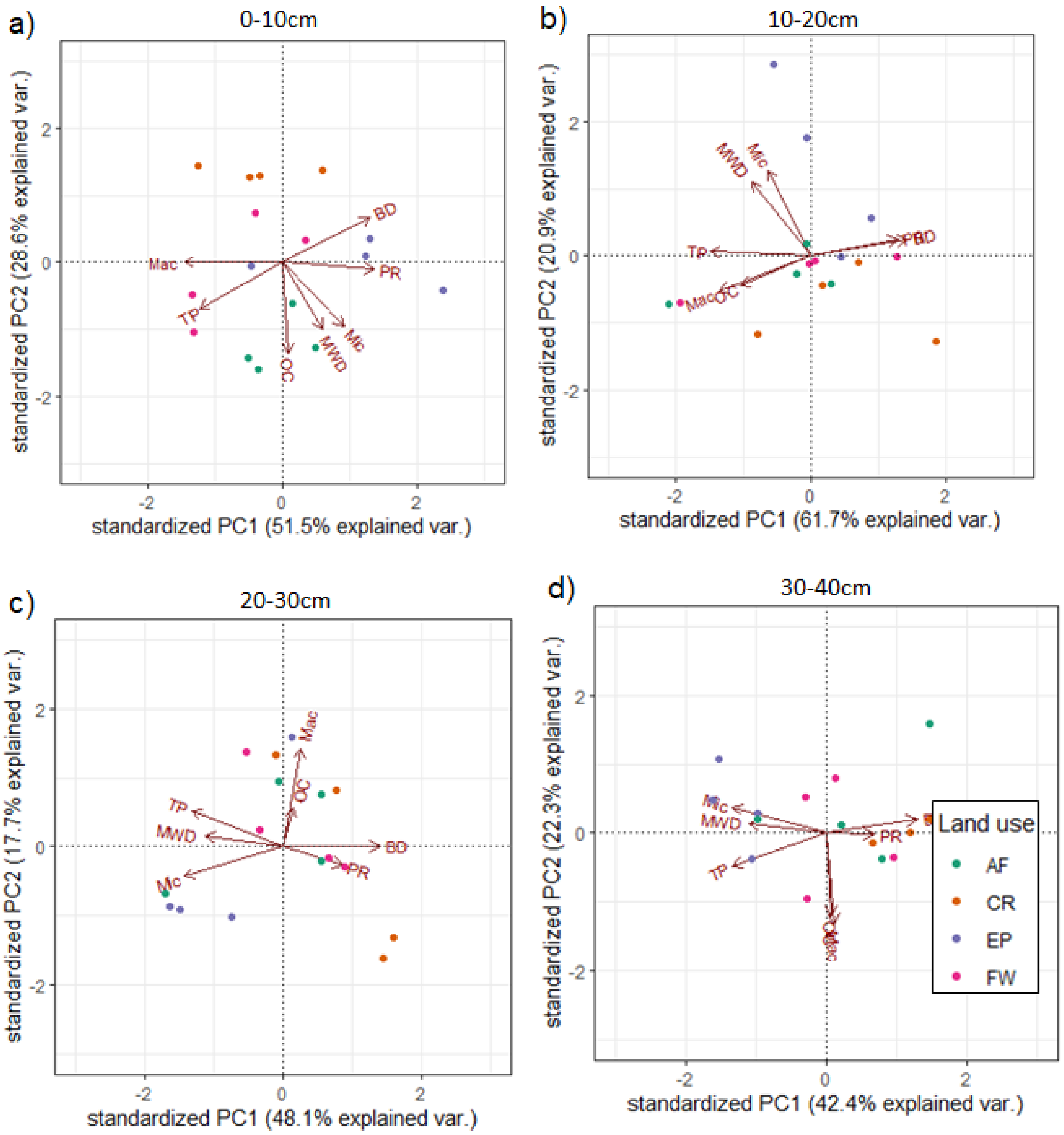


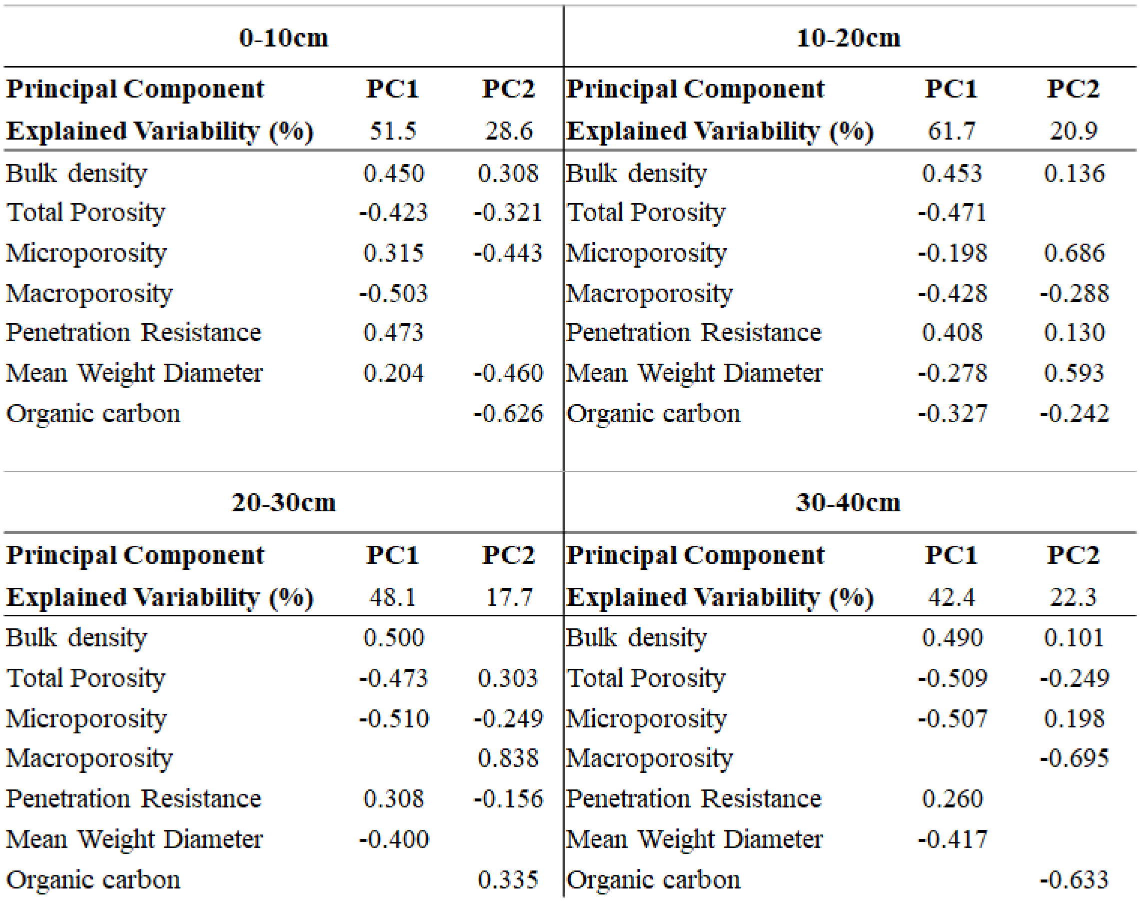
Figure 15. Biplots of Principal Component Analysis (PCA) based on soil hydro-physical attributes of each studied depth. Points of the same color account for the same land-use.

At 10-20cm layer (Fig. 16b; Table 5b), the Principal Components represented on the biplot account for 82.6% of data variability. PC1 accounts for 61.7% and PC2 accounts for 20.9%. PC1 is positively correlated with BD and RP, and is negatively influenced by TP, MWD, Mac, Mic and, in lesser extent, by SOC. PC2 is positively correlated with MWD and Mic, and negatively correlated with Mac and SOC.

At 20-30 cm (Fig. 16c; Table 5c), PC1 corresponds to 48.1% of data variability, and PC2 explains 17.1% of data variability. They sum up 65.8% of data variability. PC1 is positively influenced by BD, PR, Mac, and to a lesser extent by SOC. Also, it is negatively influenced by Mic, MWD, and TP. PC2 is positively related to Mac, TP, MWD and SOC, and is negatively correlated to Mic and PR. Mac has no significant interaction with MWD and TP. BD and PR are highly correlated.

The PCs at 30-40cm explain 64.7% of data variability (Fig. 16d; Table 5d). PC1 corresponds to 42.4%. In addition, it is positively influenced by BD and PR, and negatively influenced by Mic, MWD and TP. PC2 is positively correlated with Mic, MWD and BD, and it is negatively correlated with TP, SOC and Mac. PC2 accounts for 22.3% of data variability.

Table 5. Correlation between each variable and the two main components of the Principal Component Analysis of each studied depth.



0-10cm			**10-20cm**		
Principal Component	**PC1**	**PC2**	**Principal Component**	**PC1**	**PC2**
Explained Variability (%)	51.5	28.6	**Explained Variability (%)**	61.7	20.9
Bulk density	0.450	0.308	Bulk density	0.453	0.136
Total Porosity	-0.423	-0.321	Total Porosity	-0.471	
Microporosity	0.315	-0.443	Microporosity	-0.198	0.686
Macroporosity	-0.503		Macroporosity	-0.428	-0.288
Penetration Resistance	0.473		Penetration Resistance	0.408	0.130
Mean Weight Diameter	0.204	-0.460	Mean Weight Diameter	-0.278	0.593
Organic carbon		-0.626	Organic carbon	-0.327	-0.242
20-30cm			**30-40cm**		
Principal Component	**PC1**	**PC2**	**Principal Component**	**PC1**	**PC2**
Explained Variability (%)	48.1	17.7	**Explained Variability (%)**	42.4	22.3
Bulk density	0.500		Bulk density	0.490	0.101
Total Porosity	-0.473	0.303	Total Porosity	-0.509	-0.249
Microporosity	-0.510	-0.249	Microporosity	-0.507	0.198
Macroporosity		0.838	Macroporosity		-0.695
Penetration Resistance	0.308	-0.156	Penetration Resistance	0.260	
Mean Weight Diameter	-0.400		Mean Weight Diameter	-0.417	
Organic carbon		0.335	Organic carbon		-0.633

3.4. Discussion

3.4.1. Land-use implications on soil hydro-physical properties and hydrological functioning

Since soils are responsible for the delivery of innumerous important Ecosystem Services, it is necessary to clarify land-use effects on the capacity of agricultural soils to sustain their hydrological processes, such as water infiltration. The analyses of the hydro-physical attributes allowed to infer the importance of soil structure on soil functioning and the effects of land-use (LU) on its structural conditions. Our results showed differences of the soil hydro-physical behavior between LUs specially in the surface layer (0-10 cm) where statistical differences were significant. To a lesser extent, 10-20 cm layer was also influenced by LU. The results obtained in the surface layer allowed to divide LU in two groups according to structural conditions: i) AF and FW, which presented good porosity and aggregation, and ii) EP and CR, which results evidence degraded structure. Therefore, our results indicate that the Coffee-based AF was beneficial to soil conservation through the improvement of soil structure at the soil surface layer, just as the fallow area. Improved infiltration rates, low BD and intermediate MWD support the hydrological function of water entry, and impair soil erosion, by the improvement and maintenance of the porous network. Ketema and Yimer (2014) found similar results when compared agroforestry based systems and maize-based conventional tillage systems in Southern Ethiopia. Muchane et al. (2020) also stated that AF practices might contribute to the regulation of soil erosion, through structural improvement.

The higher infiltration rates found in AF and FW indicate better soil permeability than in EP and CR, which may be linked to improved structural conditions in the first areas. Increased infiltration rates were found by Murta et al. (2021) on an Ferralsol/Oxisol under a agrosilvicultural AF when compared to no-tillage soy-maize rotation system. Udawatta and Anderson (2008) using computed tomography technics found higher Total Porosity and Macroporosity under agroforestry buffers than under row crop, besides finding lower Bulk Density and higher Saturated hydraulic Conductivity under AF. Similar results were found in FW, which may explain the greater infiltration rates found in this area, since rapid water movement takes place in larger pores and it is attributed to better aggregation conditions, whereas these macropores occur between soil aggregates (Truman and Franzmeier, 2017). In AF, however, the results obtained for Mac were not expected, since they were equivalent to the ones found in CR. These results could be related to the high contribution of biopores to TP in AF, and may also explain the values obtained for Mic in this area. Biopores are originated from macrofauna activity and root decay and these larger pores form preferential flow pathways inside the soil, that show greater continuity and connectivity (Souza et al., 2017), contributing to higher hydraulic conductivity. Souza et al. (2017) also observed structure improvement on Coffee-based Agroforestry Systems intercropped with Peach Palm and Gliricidia by reduced BD and higher TP and attributed this to biopores formation. Yet, the core method used in this work is pointed out to not being sensitive enough to large macropores and biopores, that may have interfered in our results.

Moreover, the great variability of Ks observed in AF, FW and, more subtly, in EP may also be related to the biopores influence over water movement and partitioning within the soil. Great variability of infiltration rates was also observed by Jiang (2017) and by Zhu et al. (2017) in Rubber-based Agroforestry Systems, and was attributed to the root system of perennial crops, trees, and bushes. Kiepe (1995) stated the effect of tree distance in soil physical properties and observed higher Macroporosity closer to tree trunks, attributing this to the root system. On the contrary, Benegas et al. (2014) considered the effect of shade trees on infiltrability of Coffee-based AF on an Andisol from Costa Rica negligible and affirmed that well managed coffee plants are as beneficial to topsoil as trees. In addition to macrofauna and root activities, the absence of tillage or traffic in AF and FW guaranteed soil structure maintenance and, consequently, the preservation of the porous network (Ketema and Yimer, 2014; Lozano-Baez et al., 2021).

Both AF and FW areas presented intermediate MWD, which favor water infiltration. The formation of soil macroaggregates (>0,250mm) results from biological activity, especially fungi and plant roots (Tisdall and Oades, 1982; Oades, 1984; Bronick and Lal, 2005). Additionally, management practices such as pruning favor soil hydro-physical attributes (Barreto; Chaer; Fernandes, 2012; Benegas et al., 2014), due to the residues left aboveground (Tisdall and Oades, 1982). The protection of soil surface provided by litter and pruning residues left on the field reduce the surface exposure to raindrop impact, decrease evaporation, modify temperature and feed soil fauna (Tisdall and Oades, 1982). Besides being a result of pedogenetic processes, aggregation is not only controlled by management, but it is a result of biological activity, through the incorporation of OM, primarily on the surface layer (Tisdall and Oades, 1982; Oades, 1984; Bronick and Lal, 2005; Kladivko, 2017). Weerasekara et al. (2016) attributed higher Water Stable Aggregates observed under AF to the microbial activity enhancement and to the organic matter (OM) accumulation. Therefore, the addition of OM favors aggregate stability, since it is one of the main aggregate agents in soils (Guimarães et al., 2014), especially in Ultisols, besides Al and Fe sesquioxides (Barthès et al., 2008; WANG et al., 2015). However, the low positive correlation found between MWD and OC suggest that this is not the main factor influencing aggregation. This process is possible through macrofauna and microbial activity, which is favored by OM input. The disturbance caused by macro-organisms approximate soil particles, through their movements as well as add and mix these particles with OM through ingestion and egestion of organic materials (Bronick and Lal, 2005; Kladivko, 2017). At the same time, plant roots, fungi and bacteria tangle soil particles involving them with organic compounds that work as binding agents (Bronick and Lal, 2005; Kladivko, 2017).

Despite the scarcity of studies, the greater richness and abundance of soil micro-organisms and macrofauna in AFs in relation to conventional crop and forestry systems were observed in tropical and subtropical regions (Udawatta et al., 2019). Costa, Souza-Motta and Malosso (2012) observed greater diversity of filamentous fungi on AFs in relation to cassava monocultural systems, and obtained equivalent results in a native Atlantic Forest environment. Similar levels of microbiological indicators were found by Cezar et al. (2015) in a multistrata successional AF and in a natural regeneration area of Atlantic forest Biome. Also, Da Silva et al. (2016) reported highest invertebrate abundance under AFs compared to cassava monocultures in southeastern Brazil. Panwar et al. (2011) stated greater Microbial Biomass Carbon and Nitrogen under AF home gardens in relation to rice and maize monocultures in India. Udawatta et al. (2009) observed higher enzyme activity under AF than under row-crop systems in Missouri, USA, likewise Unger et al. (2013). Spurgeon et al. (2013) reported larger earthworm populations in AFs when compared to croplands. Nonetheless, soil biological indicators usually show lower results in AFs than that of native forests, which is attributed by these researchers to logging and management practices. Besides that, just as plant richness is lower in monocultures, lower plant diversity in AF compared to native forests may explain the differences found between these LU. Yet, it is important to reinforce that there is a lack of studies that investigate soil biological attributes in AFs, especially in Brazil, that points to the urge to further research on this matter, as reported in the second chapter of this dissertation, since they are closely related to soil health.

Differently from these areas, in CR and EP soil is frequently disturbed by mechanical operations, even though in different ways. In EP, heavy machinery is used in forestry operations and its impacts over soil structure are well known (Greacen and Sands, 1980; Worrell and Hampson, 1997; Vossbrink and Horn, 2004). Heavy vehicle traffic causes the compression of soil aggregates and the approximation of soil particles in forest soils (Da Silva et al., 2008), reducing TP and Mac (Wolkowski, 1990; Batey, 2009). The decreased TP, increased PR, BD and Mic observed on the surface layer (0-10cm), when compared to the other LU, might indicate the occurrence of a compaction process, which is corroborated by low Ks found in this area. Also, the larger MWD observed in EP could be addressed to compaction, due to the coalescence of smaller aggregates and decrease of Mac, as a consequence of external pressure, forming larger aggregates and enhancing its proportion in the soil (Gupta et al., 1989; Wolkowski, 1990; Batey, 2009). Even though larger aggregates prevail in compacted areas, they are usually less stable when submitted to wet sieving procedures, due to the breakage of stable bonds formed during natural aggregation process by machinery compression (Gupta et al., 1989; Da Silva et al., 2008). Yet, OC content observed in EP surface layer may favor aggregate stability and reduce susceptibility slaking and, consequently, to soil erosion (Tisdall and Oades, 1982), even though runoff may be favored by low Ks. Nonetheless, Le Bissonais et al. (2007) and Xiao et al. (2017) demonstrated the relevance of the clay content to increased aggregate stability in soils with low OC content, which may be related to the high MWD found in all soil layers in this area. It is noteworthy that macrofaunal activity was also observed in this area, with predominance of ants and earthworms, but in contrast to AF and FW, the contribution of biopores were not relevant to enhance infiltration rates.

The results obtained for Ks, BD, TP, MWD and OC in CR surface layer reflect long term effect of soil tillage in croplands, that are well known. Soil tillage causes the disruption of macroaggregates as a result of soil and crop management operations (Bronick and Lal, 2005; Dorner et al., 2010; Pires et al., 2017). This ensues pore discontinuity that may hinder infiltration processes, due to reduction of macropores, responsible for the rapid water flow (Dorner et al., 2010). Besides that, aggregate shearing exposes the OM contained inside macroaggregates to decomposition by microorganisms resulting in low aggregate stability in the long term as a consequence of OM depletion (Oades, 1984; Bronick and Lal, 2005), that may explain the low OC content found in this area. Together with exposed soil surface, the low MWD and OC observed at 0-10cm layer suggests that the soil surface at the CR area is more prone to breakdown by raindrop impact, and consequently, to soil erosion (Barthès and Roose, 2002; Barthès et al., 2008). In addition, the degree of flocculation observed in CR's surface layer is the lowest among LU, indicating higher susceptibility to dispersion. Both OC and FD results observed in this area suggests susceptibility to surface sealing, which may favor runoff erosion by reduced infiltration (Le Bissonais, 2016). Despite Ks, BD and TP obtained in CR, PR results were similar to the ones found in AF and FW. This may be explained by the effect of soil tillage, that aim to improve soil conditions for crop growth.

Finally, the PCAs of the subsurface layers (20-30cm, 30-40cm) suggest predominance of pedogenetic processes rather than physical degradation processes caused by LU and management, as suggested by the plot distribution at the biplot center. This reflects the lack of significant differences between LU observed in the statistical analyses. Nonetheless, some outliers correspondent to CR and EP plots are noticeable at both biplots, that may suggest little influence of LU in depth. For this reason, it is necessary to further investigate deeper soil layers to understand these differences through other analyses, such as water retention curves and saturated hydraulic conductivity, considering the entire soil profile. In addition, it might be necessary to consider other attributes (e.g., texture and hydraulic conductivity) to understand the differences observed between these areas.

In summary, the analyses of soil structure indicators enabled the comprehension of soil and crop management effect over soil hydrology, mainly in the surface layer. Our results highlight the relevance of minimum soil disturbance to soil conservation and emphasize the importance of biological activity and OM input to the maintenance soil functioning.

3.5. Conclusions

The analyzed attributes were useful to verify the effects of LU over soil structure and enabled the characterization of soil hydro-physical behavior submitted to different LU, as well as the comparison between them at the surface layers. However, the chosen analyses were not suitable for the investigation of deeper soil layers, since they were not sensitive enough to distinguish between management and pedogenetic processes.

As expected, the Agroforestry System improved soil structure when compared to forestry and row crop under conventional tillage system and presented similar results to the grass fallow. Agroforestry practices with reduced wheel trafficking and no-tillage, associated with pruning of trees and bushes and the deposition of residues overground, promoted good aggregation and porosity conditions and improved soil surface hydro-physical behavior, evidenced by higher infiltration rates. On the other hand, row crop conventional management practices improved soil physical conditions for crop growth, but undermined soil aggregation through long term tillage and wheel trafficking. The annual soil disturbance caused soil structure degradation and organic carbon depletion, reducing infiltration rates and enhancing susceptibility to soil erosion. Lastly, long term Eucalyptus forestry practices favored soil surface compaction and reduced soil permeability due to wheel trafficking. Even though providing good aggregation conditions, porosity indexes obtained in this area indicated poor conditions which were reflected by lower infiltration rates.

This study showed that among the evaluated land-uses, Agroforestry Systems came out as a better strategy to improve rainfall partitioning, to ensure soil hydrological functioning and to guarantee the important role that soil plays in the hydrological cycle.

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4. FINAL CONSIDERATIONS

The growing awareness about the environmental impacts of conventional agricultural practices combined with the concerns raised by the climatic changes in course, demand the development of resilient and multifunctional production systems capable of facing these challenges over the coming decades. Due to its role on natural and managed ecosystems, soil must be put in the center of this process and should be seen as a key player in the search for solutions to the related social, economic and environmental issues. Soil's influence over air and water quality and its high susceptibility to use and management by human activities, especially those related to agriculture due to great terrestrial extension used by them, make these activities critical to their conservation. In this context, Agroforestry Systems have been suggested as strategies to cope with these needs, mainly in tropical and subtropical humid zones, where the population most impacted by the consequences of a changing climate are located. However, even though they are broadly assumed by researchers, the benefits of agroforestry practices to environmental quality maintenance are not totally well comprehended, especially what regards to soil attributes and processes. Thus, this work aimed at clarifying the current scientific knowledge about agroforestry practices and soils, defining its main approaches and contributing to knowledge gap filling, assuming that these systems have positive impacts on soil health. To this end, this research was drawn up in two parts whereby the first part consisted in gathering the scientific output available on two major data bases and, through the analyses of peer reviewed articles, were identified bibliographical aspects, the main approaches and soil indicators used by researchers. Next, an observational study was done based on the defined gaps, in order to fill them.

The systematic review of the retrieved studies showed the development of researchers' interest by the impacts of agroforestry practices on soils, which followed the shift of the soil concept from a mere substrate for plant growth and nutrient supply towards the comprehension of soil as a living dynamic functional system of terrestrial ecosystems, and a non-renewable resource that must be preserved. This analysis demonstrated that these systems are mostly located in underdeveloped countries of tropical and subtropical regions, and that most research result from the international cooperation between research institutions of developed and underdeveloped countries. Regarding the pedological aspects, soils from sloping terrain and different textures, that also presented physical or chemical limitations prevail in the study areas. Besides that, the most analyzed were chemical attributes related to soil fertility and plant nutrition, followed by physical attributes, and biological attributes, which are still incipient. Most samples were taken from shallower depths (i.e., until 30cm). Lastly, most investigations were related to food, fiber and fuel provision Ecosystem Services, to the detriment of other benefits provided by soils.

Given these conclusions, the second part was drafted as an investigation about the effects of different land-uses over soil hydro-physical behavior, through the analyses of soil structure physical indicators. In the third chapter of this dissertation, the research sought out to test the hypothesis that AF have positive effects over soil and may contribute to its hydrological functions of water infiltration, and may stand out as a viable strategy in this matter when compared to more conventional land-uses (e.g., conventional tillage, Eucalyptus forestry and grass fallow). The obtained results corroborated this hypothesis, proving the improvement of soil infiltration rates through the amelioration of porosity and aggregation conditions provided by the root network, the soil protection by litter and canopy cover, as well as the feed and maintenance of soil fauna. Yet, the lack of great soil disturbances by mechanical operations during soil and crop management turn up as highly significant to soil structure preservation and surface permeability maintenance.

Lastly, future studies should focus on deeper soil layers to understand the influence of deep rooting systems over soil structure and water dynamics, through visual analysis soil structure, hydraulic conductivity and water retention curves. Also, the evaluation of biological attributes might provide a better understanding of aggregate formation and stability due to the close relation between soil biota and structure. Yet, the search for more sustainable agricultural systems is filled with challenges and requires the effort and cooperation of a number of actors, science disciplines and technological resources, in order to evolve.