UNIVERSIDADE FEDERAL DE LAVRAS

MONNA LYSA TEIXEIRA SANTANA

SOIL HEALTH AND ECOSYSTEM SERVICES RELATED TO WATER RECHARGE IN THE CANTAREIRA SYSTEM

LAVRAS – MG

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Tese apresentada à Universidade Federal de Lavras, como parte das exigências do Programa de Pós-Graduação em Ciência do Solo, área de concentração em Recursos Ambientais e Uso da Terra, para obtenção do título de Doutor.

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Orientador
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MONNA LYSA TEIXEIRA SANTANA

SOIL HEALTH AND ECOSYSTEM SERVICES RELATED TO WATER RECHARGE IN THE CANTAREIRA SYSTEM

SAÚDE DO SOLO E SERVIÇOS ECOSSISTÊMICOS RELACIONADOS A RECARGA DE ÁGUA NO SISTEMA CANTAREIRA

Tese apresentada à Universidade Federal de Lavras, como parte das exigências do Programa de Pós-Graduação em Ciência do Solo, área de concentração em Recursos Ambientais e Uso da Terra, para obtenção do título de Doutor.

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À Deus.

À minha família, pelo amor incondicional e apoio inabalável.

Dedico

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“Quando você quer alguma coisa, todo o universo conspira para que você realize o seu desejo”

(Paulo Coelho)

RESUMO

O conceito de saúde/qualidade do solo está diretamente ligado aos serviços ecossistêmicos e tem sido cada vez mais utilizado para incorporar a sustentabilidade ambiental na governança integrada dos recursos naturais. No entanto, a maioria dos protocolos de avaliação da qualidade do solo concentra-se na produção de culturas e em seu manejo de conservação, e funções vitais do solo, como a recarga de água, carecem de estudos para serem incorporadas no monitoramento dos impactos na qualidade ambiental. Cerca de 7 milhões de pessoas na região mais economicamente desenvolvida do Brasil dependem do Sistema Cantareira de Produção de Água. Nessa região, a atividade agrícola é principalmente baseada em pastagens e florestas de eucalipto para produção de alimentos e energia, além de ser um ponto de preservação da Mata Atlântica. Três estudos foram realizados para avaliar a qualidade/saúde do solo no Sistema Cantareira em três classes de solo representativas: Argissolo Vermelho Amarelo, Cambissolo Háplico e Neossolo Litólico. O primeiro estudo teve como objetivo avaliar as propriedades físicas do solo diretamente ligadas aos serviços ecossistêmicos: recarga de água, produção de biomassa e resistência à erosão. Amostras de solo foram coletadas em duas camadas e analisadas em laboratório, calculando-se funções físicas do solo usando essas propriedades. A conversão da floresta nativa para uso antrópico (eucalipto e pastagem) reduziu a qualidade física do solo e sua capacidade de recarga de água. A intensificação das pastagens, através do pastejo rotativo em vez do pastejo contínuo, teve pouco efeito na promoção dos serviços ecossistêmicos do Sistema Cantareira. O uso do Cambissolo Háplico obteve o maior valor do Índice de Qualidade Física do Solo para as florestas nativas, quando comparado com o Argissolo Vermelho Amarelo e o Neossolo Litólico. No segundo estudo, foi monitorado o teor de água no solo ao longo de três anos, utilizando a técnica de resistividade elétrica. Observou-se que a floresta nativa no Argissolo não reteve muita água no perfil avaliado, sugerindo que a água foi absorvida pelas plantas (evapotranspiração) e/ou reposta ao lençol freático. Para o Cambissolo, verificou-se que os solos sob florestas nativas tinham maior condutividade hidráulica do que os solos ocupados por eucaliptos e pastagens. O Neossolo manteve um teor de água mais elevado em pastagens, associado a uma baixa taxa de infiltração de água, resultando em água estagnada na camada superficial. O terceiro capítulo avaliou a saúde do solo utilizando a metodologia *Comprehensive Assessment of Soil Health* (CASH) e comparou os resultados com o índice gerado no primeiro artigo. No entanto, o CASH, que utiliza principalmente bancos de dados de solos americanos, não foi capaz de avaliar com precisão o efeito do manejo e uso nos solos. É necessária a importância do banco de dados e uma melhor resolução dos mapas de solos brasileiros para a criação de indicadores representativos e capazes de avaliar a saúde e as funções do solo nos solos brasileiros.

Palavras-chave: Funções do solo. Qualidade física do solo. Recarga e armazenamento de água. Abordagem nexus.

ABSTRACT

The concept of soil health/quality is directly linked to ecosystem services and has been increasingly used to incorporate environmental sustainability into the integrated governance of natural resources. The assessment of soil functions is based on soil properties and processes correlated with these functions of interest. However, most soil quality assessment protocols focus on crop production and their conservation management, and vital soil functions such as water recharge lack studies to be incorporated in the monitoring of impacts on environmental quality. Around 12 million people in the most economically developed region of Brazil depend on the water supplied by the Cantareira Water Production System. In this region, most of the agricultural activity is with pasture and eucalyptus forests for food and energy production, in addition, it is a hotspot of the Atlantic Forest preserved. Three studies were carried out to evaluate soil quality/health in the Cantareira System in three soil classes representative: Typic Hapludult, Typic Dystrudept, and Typic Usthortent. The objective of the first study was to evaluate, through the nexus approach- water, energy, and food, the soil physical properties that are directly linked to the ecosystem services: water recharge, biomass production, and erosion resistance in the predominant soil use and management. Soil samples were collected in the 0-5 cm and 30-35 cm layers and subsequently analyzed in the laboratory and then calculated additive soil functions using soil physical properties. Overall, the conversion of the native forest for anthropic use (eucalyptus and pasture) reduced the soil's physical quality and water recharge capacity. The intensification of pastures replacing continuous grazing with rotational grazing had little effect on promoting the ecosystem services of the Cantareira System. Typic Dystrudept obtained the highest value of the Soil Physical Quality Index (SPQI) for the native forests when compared to Typic Hapludult and Typic Usthortent. The second study was to monitor soil water content over three years using the soil electrical resistivity technique. The native forest in Typic Hapludult did not retain much water in the evaluated profile, suggesting that the water was absorbed by plants (evapotranspiration process) and/or replenished groundwater. For Typic Dystrudept, the study found that soils under native forests had higher hydraulic conductivity than eucalyptus and pastures. The young Typic Usthortent soil maintained higher soil water content in pastures associated with a low rate of water infiltration, resulting in stagnant water in the surface layer. Soil health was assessed in the third chapter through the Comprehensive Assessment of Soil Health (CASH) in order to compare with SPQI. CASH, which has a database mostly of American soils, was not able to accurately assess the effect of management and use for the studied soils. It is necessary importance of the database and better resolution of maps of Brazilian soils for the creation of indicators that are representative and capable of evaluating the health and soil functions of Brazilian soils.

Keywords: Soil functions. Soil physical quality. Soil water recharge and storage. Nexus Approach.

SUMMARY

FIRST PART

GENERAL INTRODUCTION

Soil is a complex system in which physical, chemical, and biological characteristics and processes are involved and interact. In order to better understand the main components of the soil system and the synergy between them, the concept of soil health has been adopted. Soil health is defined as the capacity of the soil to function as a vital living system, within the limits of the ecosystem and land use, to sustain plant and animal productivity, maintain or improve water and air quality, and promote plant and animal health (DORAN and ZEISS, 2000).

The concept of soil health is closely linked to the ecosystem services (ES) approach, which is increasingly used to incorporate ecological sustainability into decision-making (ROBINSON et al., 2012; GRÊT-REGAMEY et al., 2015; BOUWMA et al., 2018). There is a great need for quantification of ecosystem service to support sustainable land use planning and the sustainable use of soil and water resources (VAN DER BIEST et al., 2013; RUTGERS et al., 2012; DE SOSA et al., 2018).

Ecosystem services are the benefits and services that people obtain from ecosystems (COSTANZA et al., 1998; MEA, 2005), grouped into four categories: (i) provisioning services (direct or indirect food for humans, freshwater, wood, fiber, and fuel); (ii) regulating services (regulation of gas and water, climate, floods, erosion, biological processes such as pollination and diseases); (iii) cultural services (aesthetic, spiritual, educational, and recreational); and (iv) supporting services (nutrient cycling, production, habitat, biodiversity).

Soils, as a critical and dynamic system, generate a multitude of functions, providing various ES (BOER and HANNAM, 2004), including food production, water and climate regulation, energy supply, and biodiversity (HAYGARTH and RITZ, 2009; MCBRATNEY et al., 2014; VOLCHKO et al., 2013; DROBNIK et al., 2018). However, the understanding of soil functions and ES is incomplete (DAILY et al., 2009; DOMINATI et al., 2019; BREURE et al., 2012). Hatfield et al. (2017) mentioned that soil is a neglected component in ES studies and policy-making.

Bünemann et al. (2018) reviewed the main approaches to soil assessment worldwide, focusing on the selection of relevant indicators based on relevant soil functions or ES, and observed that these relationships were evaluated qualitatively. The same was observed by Roper et al. (2017), who, when performing qualitative soil health assessment tests, found that none of the tests were able to differentiate between different soil management practices.

Assigning a value to soil and quantifying its ecosystem functions is a challenging and ongoing task (DAILY et al., 1997; MCBRATNEY et al., 2014). One approach to evaluation is the productivity chain, which values changes in soil productivity, quantified by crop yield, while considering production costs and market prices (GREINER et al., 2017). Another approach is the creation of ecosystem service models, which require detailed soil data to evaluate the influence of soil attributes on ecosystem functions and services, improving soil quality and reliability while being cautious about excluding or using limited soil information (ANDREW et al., 2004).

Establishing a set of biotic and abiotic indicators is essential to develop a viable index for assessing ecosystem services and soil health (EWING and SINGER, 2012). A transparent and repeatable methodology is necessary to assess and subsequently manage soil use and management (RINOT et al., 2019).

The Cantareira Water Producer System is one of the largest water capture systems with the capacity to supply the metropolitan region of São Paulo (WHATELY and CUNHA 2007). In addition to its importance for water supply, the area is a biodiversity hotspot (MYERS et al., 2000). Its surface area covers approximately 2,278.0 km², encompassing the municipalities of Bragança Paulista, Caieiras, Franco da Rocha, Joanópolis, Nazaré Paulista, Mairiporã, Piracaia, and Vargem in the state of São Paulo, and the municipalities of Camanducaia, Extrema, Itapeva, and Sapucaí-Mirim in the state of Minas Gerais (UEZU et al., 2017).

Between 2013 and 2015, Cantareira underwent its worst water crisis, pumping water below the minimum reservoir level (SABESP 2015). In addition to observing significant precipitation and temperature anomalies in recent years, biophysical aspects were crucial to the worsening of the crisis (NOBRE et al., 2016; CHIODI et al., 2021). These factors directly affect ecosystem services (ES), such as the availability of good quality water for human consumption, agricultural and industrial use, maintenance of stable hydrological cycles, and healthy freshwater ecosystems (DIB et al., 2020).

The Cantareira System Catchment main rural activities are livestock and forestry, mainly eucalyptus cultivation. It has an area of 35% forest cover, with 74% of this vegetation being secondary Atlantic Forest in an intermediate stage of succession, and 57% of the Permanent Preservation Areas being used by anthropogenic activities (UEZU et al., 2017). In 2011, 46% of the Cantareira System area was occupied by mostly degraded pastures, and 16% was occupied by eucalyptus plantations (UEZU et al., 2017). Land use and management directly affect soil physical and hydraulic properties related to soil ES, such as density, aeration, soil penetration resistance, water infiltration into the soil, water retention, and availability (FIDALSKI et al., 1999; NUÑEZ-MORENO and VALDEZ-GASCON, 1994).

Inadequate management can lead to soil health damage, causing soil compaction that reduces its water infiltration capacity, favoring erosive processes with water and soil losses (CHERUBIN et al., 2016; HICKMANN et al., 2012). Consequently, with less water recharge in the system, there will be a reduction in the groundwater supply process, affecting subsequently the environment. Therefore, the development and evaluation of management systems that promote the conservation and utilization of ecosystem services are of great importance.

The study of soil management and use through assessments of soil health and physical quality should be supported by analyses and indicators that describe soil environmental functions and are sensitive to identify the impacts, positive or negative, of soil use and management. Thus, the integrated evaluation of soil properties and their correlation with soil environmental processes becomes an important tool in decision-making to reduce pressure on natural resources and implement better land use and management practices to maintain ecosystem services, considering priority areas for preservation.

OBJECTIVES AND THESIS STRUCTURE

The general aim of this thesis was to assess soil health, as well as the potential for water recharge and storage variation, considering the main soils, their uses, and management in the Cantareira System. The specific aims were: i) assess the physical properties of three main soils (Typic Hapludult, Typic Dystrudept, and Typic Usthortent) that offer to soil ecosystem services such as water recharge and infiltration; ii) obtain the calibration equation for the ρ-θ relationship for each soil under study; iii) evaluate soil water storage throughout the seasons using soil electrical resistivity; iv) verify soil health through the Soil Physical Quality Index (SPQI) and multivariate analysis physical-hydraulic soil properties; v) compare the methodologies for soil health assessment: CASH and SPQI.

To address the objectives, this thesis was structured into three papers. The first paper evaluated the physical quality of soils for each use and soil type. Ten physical properties were evaluated and related to five soil functions, generating a soil physical quality index (SPQI) at the end. Paper 2 used the soil electrical resistivity methodology to evaluate the spatiotemporal water distribution during three years of evaluation. In addition, the Cornell infiltrometer was used to evaluate surface runoff to answer the question: where did the water go? Measurements were taken up to 1.5m depth in each season of the year. Paper 3 used the CASH methodology to evaluate soil health and present a comparison with the SPQI generated in paper 1. The CASH method weighs physical, chemical, and biological attributes, but uses a database of American soils, highlighting the importance of generating indices for tropical soils.

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SECOND PART - PAPERS

This paper was submitted and is under review at the Science of the Total Environment.

PAPER 1 – LAND USE AND INTRINSIC SOIL PROPERTIES AFFECT SOIL FUNCTIONS IN THE CANTAREIRA WATER SUPPLY SYSTEM, BRAZIL

Abstract

Most of the soil quality assessment protocols are focused on crop production and conservation management, while vital soil functions, such as water recharge, lack studies to be incorporated in the monitoring of impacts on environmental quality. Our objective was to evaluate, through the Nexus approach, how dynamic (land use and management) and inherent (soil type) factors impact soil physical properties and processes driving water recharge, biomass production, and soil erosion resistance in the Cantareira System, Brazil. The assessment considered three soils (Typic Hapludult, Typic Dystrudept, and Typic Usthortent) and four land covers (native forest, rotational grazing, extensive grazing, and eucalyptus), which are the main soils and land uses in the Cantareira System region. Soil samples were taken at 0-5 and 30-35 cm depth, respectively, and analyzed for several soil physical quality indicators, later used to calculate a Soil Physical Quality Index based on additive soil functions. Converting the native forest to anthropic uses (eucalyptus and pasture) reduced the overall soil physical quality and water recharge capacity. Typic Dystrudept obtained the highest value of the SPQI (0-5 cm: 0.85; 30-35 cm: 0.90/ ~0.87) for native forests when compared to Typic Hapludult (0-5 cm: 0.76; 30-35 cm: 0.57/ ~0.66) and Typic Usthortent (0-5 cm: 0.75; 30-35 cm: 0.72/ ~0.73). The nexus approach supports sustainable management of the Cantareira System by optimizing resource use and considering the interdependence of water, energy, food, and soil systems.

Keywords: ecosystem services; soil health; nexus approach; water recharge; soil type

1. Introduction

Soil is a complex system that plays a crucial role in ensuring food security, providing ecosystem services, mitigating climate change, protecting landscapes, and promoting human development. To better understand the effectiveness of sustainable management, the concept of soil health has been embraced (Karlen et al., 2019). Soil health is defined as the soil's capacity to function as a vital living system, extending beyond human health to broader sustainability goals that include planetary health within the limits of the ecosystem and land use to sustain plant and animal production (Doran and Zeiss, 2000). Although it is often approached as a synonym for soil health, soil quality refers to the soil’s ability to function effectively in agriculture and its immediate environmental context (Larson and Pierce,1991; Bunemam et al., 2018). It encompasses the impact of soil on water quality, plant, and animal health within entire ecosystems, and the maintenance or improvement of provision (Hatfield et al., 2017; Serafim et al., 2019), regulation (de Sosa et al., 2018), and support (Ferreira et al., 2019) services.

Within this framework, the water-food-energy nexus represents a complex and integrated perspective to the assessment of ecosystem services. It aims to facilitate the exchange of information and objectives while preserving the integrity of ecosystems (Hatfield et al., 2017). This approach gained prominence in the international community as a response to climate change and social shifts, including population and economic growth, globalization, and urbanization (Hoff, 2011). The nexus perspective has been considered in recent studies (e.g., Bakhshianlamouki et al., 2020; Bazilian et al., 2011; Endo et al., 2017; Kamrani et al., 2020; Mannan et al., 2018; Shannak et al., 2018), but there is remain a gap concerning the soil approach within this context (Hatfield et al., 2017). This gap arises from the challenge of assessing and quantifying soil functions (Bünemann et al., 2018; Greiner et al., 2017; Vogel et al., 2019). Soil functions are not directly measurable properties but rather integral characteristics derived from a multitude of interactions among physical, chemical, and biological processes in the soil (Nunes et al., 2021b). Therefore, the evaluation of soil functions should be based on a combination of soil properties and processes that are highly correlated with the specific soil functions of interest (Bünemann et al., 2018; Nunes et al., 2018; Rabot et al., 2018).

The assessment of soil functions related to water recharge holds paramount importance for stakeholders within the Cantareira System region. The Cantareira Water Supply System stands as one of the world’s largest water supply systems, with the capability to provide water to the metropolitan region of São Paulo, Brazil, accommodating approximately 7 million people

(Whately and Cunha, 2007). The area is also a biodiversity hotspot for the Atlantic Forest biome. During the period from 2013 and 2015, Cantareira Water Supply System faced its most severe water scarcity crisis, experiencing precipitation levels of only 67% of the anticipated total (based on historical averages). As a result, the water levels in the reservoir dropped below the minimum threshold, with only 5% of the available water remaining (SABESP, 2020). The escalation of the water crisis can be attributed to significant deviations in precipitation patterns and temperature trends observed in recent years (Chiodi et al., 2021; Nobre et al., 2016). The identification of priority environments for water recharge in large reservoirs, given the expansion of agricultural and livestock activities for food and energy production, remains a challenge (Chiodi et al., 2021).

The integrated assessment of inherent and dynamic soil properties and their interactive impact on soil functions is crucial to guide site-specific land management practices to sustain or enhance soil functionality. In addition, synthesizing qualitative and quantitative soil properties information using soil quality indices is also valuable to better understand management threats and impacts on soil functions (Bünemann et al., 2018). Based on Karlen et al. (1994) approach, soil quality can be evaluated using as a tool, a statistical- or expert-based index using simpler additive functions (Silva-Olaya et al., 2022; Simon et al., 2022), which can be focused on soil physical quality (SPQI) using soil properties related do soil structure. The SPQI has been employed to assess land use changes across diverse scenarios, enabling the evaluation of soil functions related to supporting root growth, providing water for plants, facilitating gas exchange between the soil and atmosphere, and resisting erosion and soil degradation (Cherubin et al., 2017; Bieluczyk et al., 2023; Barbosa et al., 2017; Alvarenga et al., 2012). In this study, this assessment expands upon previous studies by evaluating, for the first time, groundwater recharge potential as an additional and crucial soil function within the Cantareira Water Supply System.

In the context, our hypotheses are that: (i) the conversion of areas covered with native vegetation to food and energy production (i.e., pasture and reforestation) decreases soil quality and water recharge function; (ii) rural Farmers' initiatives to adopt better pasture management practices (i.e., rotational instead of continuous grazing) contribute to the improvement of ecosystem services; (iii) for the same land use, soil type influences the soil quality index for water recharge and erosion resistance functions. Thus, with this study we aimed to: (i) evaluate the physical properties directly linked to the relevant soil ecosystem services in the Cantareira System water supply, biomass production, and erosion resistance in the predominant management and land use (native forest, eucalyptus, rotational grazing, and continuous grazing) on three soil types (Typic Hapludult, Typic Dystrudept, and Typic Usthortent); (ii) to evaluate the water recharge potential based on intrinsic soil properties, and (iii) verify soil quality through the Soil Physical Quality Index (SPQI) and multivariate analysis of the physical-hydric properties.

2. Material and Methods

2.1. *Study area*

The study was carried out in the Cantareira System Catchment, Brazil (Fig. 1) in the cities of Piracaia (23°01’39” S 46º19’35” W, altitude of 840 m), Nazaré Paulista (23°12’20” S 46º21’12” W, altitude of 800 m) and Joanópolis (22°56’16” S 46º05’50” W, altitude of 1200 m). The landscape in the Cantareira System is composed of livestock (46%), native forests (35%), planted forestry (16%), and reservoirs and water bodies (3%), in an area of about 2,300 km², with a slope from 0 to 66 degrees, dominated by Oxisols, Ultisols and other less weathered soils (Uezu et al., 2017). Degraded pastures are prevalent in the region (Uezu et al., 2017), resulting in insufficient biomass production for effective land protection and exposing the soil to erosion. Each area was assessed based on representative land uses and management adopted by local farmers - native forest, eucalyptus, rotational grazing, and extensive grazing were evaluated. Eucalyptus is harvested every 5 to 7 years and the spacing varies between 3 x 3 m and 3 x 3.5 m with Eucalyptus grandis and E. saigna. Extensive grazing was established around 30 years ago, using Urochloa brizantha and U. decumbens, Megathyrsus maximus, and Setaria anceps with a stocking rate de 0.7 – 1.7 AU ha-1, with no additional farm inputs. Rotational grazing was introduced in 2014, incorporating species such as Urochloa brizantha, U. decumbens, Megathyrsus maximus, and Setaria anceps, with a stocking rate of 1.5 - 3.0 AU ha-1. The average duration of each paddock in the rotation is 2 to 3 days.

The predominant climate in the region is classified as Cwb (Köppen) with cool and dry winters and hot and humid summers (Alvares et al., 2013). The average annual rainfall is 1,570 mm and annual temperatures range from 18 to 20 °C (Uezu et al., 2017). The soils were classified as Argissolo Vermelho Amarelo, Cambissolo Háplico, and Neossolo Regolítico, according to the Brazilian Soil Classification System (Santos et al., 2006), and Ultisol (Typic Hapludult), Inceptisol (Typic Dystrudept) and Entisol (Typic Usthortent), according to the Soil Taxonomy (Soil Survey Staff, 2014).

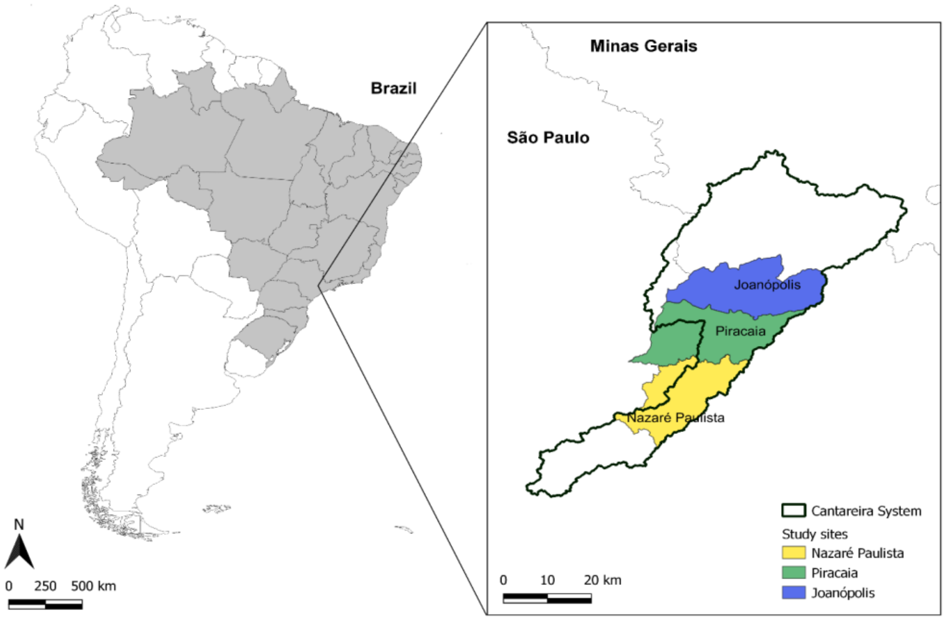

Fig. 1. Location of the Cantareira System and study sites.

Table 1. Soil classification and characteristics in the soil profile in the native forest (NF), eucalyptus (E), rotation grazing (RG), and extensive grazing (EG).

City	Soil classification [1]	Land use	Depth	Clay	Silt	Sand	OM [2]
			cm	--------	g kg^{-1}	------	dag kg^{-1}
Piracaia	Typic Hapludult	NF	0-5	378	222	401	4.93
			30-35	445	180	375	1.03
		E	0-5	335	178	486	2.92
			30-35	560	152	288	1.10
		RG	0-5	230	159	610	3.03
			30-35	396	129	475	1.36
		EG	0-5	255	125	621	2.65
			30-35	282	145	573	1.79
Nazaré Paulista	Typic Dystrudept	NF	0-5	364	145	491	5.51
			30-35	415	195	390	1.41
		E	0-5	330	142	528	3.34
			30-35	434	121	445	1.49
		RG	0-5	399	166	435	3.08
			30-35	459	139	402	0.91
		EG	0-5	337	188	475	3.34
			30-35	419	161	420	1.49
Joanópolis	Typic Usthortent	NF	0-5	549	119	332	2.09
			30-35	288	196	515	1.39
		E	0-5	380	233	387	2.19
			30-35	451	319	230	1.29
		RG	0-5	423	162	15	2.83
			30-35	440	225	335	1.89
		EG	0-5	555	129	316	3.27
			30-35	267	175	557	1.96

1 USDA Soil Taxonomy; [2] OM: organic matter.

2.2. *Soil sampling and measurements*

Soil sampling was carried out in February 2019. At each soil type (i.e., Typic Hapludult, Typic Dystrudept, and Typic Usthortent) and land use (i.e., native forest, eucalyptus, rotational grazing, and extensive grazing) soil samples were collected in soil trenches (40 x 40 x 40 cm), providing a total of 12 sampling points (3 soils x 4 land uses). Within each sampling point, disturbed and undisturbed soil samples were taken from A and B soil horizons. Specifically, the sampling depths were 0-5 cm (within the A horizon) and 30-35 cm (within the B horizon). The pedogenetic horizon of tropical soils constitutes the zone where notable modifications in soil physical properties occur, influencing soil water recharge, largely driven by land use and management practices. Thus, the 30-35 cm depth was included in the assessment to capture the soil's potential to impact water recharge.

At each point and soil layer, four disturbed samples were taken and used to measure soil particle size distribution and organic matter content (Table 1). Four undisturbed samples were collected in steel cylinders 2.5 cm height x 6.3 cm diameter and used to measure soil bulk density, macroporosity, available water capacity, relative field capacity and drainable porosity. At the same points, five undisturbed soil samples were collected in steel cylinders of 8.0 cm height per 6.4 cm diameter and used to measure saturated conductivity. An Uhland sampler was used to collect the undisturbed samples. Penetration resistance (PR) and basic infiltration rate (BIR) measurements were performed around the soil sampling trenches. To obtain an average value, ten replicates were obtained for PR measurements, while three replicates were collected for BIR measurements at each sampling point.

In the laboratory, the samples in the smaller rings were water saturated for 24 hours by capillary action and weighed. After saturation, samples were subjected to a potential of -6 kPa using an automated tension table. After equilibration, samples were weighed and oven-dried at 105 °C for 24 hours to determine the dry soil mass (Teixeira et al., 2017). Soil bulk density (BD, Mg m-3), and total porosity (water content at saturation, m3 m-3), and soil microporosity (MIP, m3 m-3) were assessed determined according to (Dane and Topp, (2002). MIP was determined based on, as well as soil microporosity (MIP, m3 m-3) by the soil water content at the matric potential of -6 kPa. Macroporosity (MAC, m3 m-3) was calculated by the difference between total porosity and MIP (Reynolds et al., 2008).

Plant available water capacity (AWC, m3 m-3) was estimated by the difference between the water content at field capacity (θFC) and permanent wilting point (θPWP) (White, 2006). The θFC was estimated by the equilibrium water content at -10 kPa in an automated tension table (Ecotech, Germany), and the θPWP, by the equilibrium water content at -1500 kPa in a Richards Porous Plate Extractor (Soil Moisture, USA). The obtained values were classified according to Reynolds et al. (2009), where AWC values exceeding 0.20 m3 m-3 are categorized as "ideal" for maximum root growth and function. AWC values between 0.15 and 0.20 m3 m-3 are classified as "good", while values ranging from 0.10 to 0.15 m3 m-3 are categorized as “limited”. AWC values above 0.10 m3 m-3 are considered “poor” or “dry”.

Relative field capacity (RFC, m3 m-3), which indicates the soil's ability to store water and air relative to total porosity, was determined as described by Reynolds et al. (2008) (Eq. 1):

$$RFC = \theta_{FC} \;/\; \theta_S \;=\; 1 \;-\; (AC \;/\; \theta_S), \tag{1}$$

where θ_{FC} is the water content at the estimated field capacity at -10 kPa (m^3 m^{-3}), θ_S is the total porosity estimated by the saturation water content (m^3 m^{-3}), and AC is the aeration capacity (m^3 m^{-3}). The ideal balance between soil water to provide air and water is achieved when RFC is between 0.6 and 0.7 (Reynolds et al., 2008).

Drainable porosity (DP, m^3 m^{-3}), also called effective porosity, is defined as the fraction of the total porosity in which water moves freely under gravity or the air content at field capacity (Beltran, 1986; Pizarro, 1985). The DP was calculated according to Otto (1988) using Eq. 2:

$$DP = \theta_S - \theta_{FC} \tag{2}$$

Saturated hydraulic conductivity (Ksat, cm h^{-1}) was determined in the large cylinder and was applied constant-charge permeameter method (Klute, 2015). The values were estimated by Darcy equation (Eq.3) and were corrected for a temperature of 20 °C (Eq. 4):

$$K_{sat} = \frac{(V*L)}{(A*H*t)}, \tag{3}$$

where, Ksat is the saturated hydraulic conductivity (cm h^{-1}), V is the volume of water collected (mL), L is the height of the sample (cm), A is the sample cross-section area (cm^2), H is the height of the water column on top of the soil sample (cm), and t is the percolation time (t).

$$K_{20} = K_t \times (\frac{\mu_T}{\mu_{20}}), \tag{4}$$

where: K_{20} is the Ksat at 20 °C, Kt is the saturated hydraulic conductivity at measured temperature (T °C), μ_T is the water viscosity at T °C, and μ20 is the water viscosity at 20 °C.

The basic infiltration rate (BIR, cm h^{-1}) was measured using the double-ring method (Arriaga et al., 2010; Kumke and Mullins, 1997; Tricker, 1978) with two concentric rings (20 and 40 cm in diameter). The infiltration adjustment curves were performed using the Kostiakov model (Eq. 5). An average of all three replications was used to plot the diagrams of the infiltration rate. The maximum steady-state was equivalent to the mean infiltration rate of the last three rates. All stages of infiltration testing and related charts were in accordance with the American Society for Testing and Materials (ASTM, 2009).

$$I = K \times t^{a}, \qquad (5)$$

where I is the infiltration rate (cm min^{-1}), t is the time (min), K and a are the empirical constant obtained by adjusting the model.

The structural stability index (SSI, %), a metric for the risk of soil structure degradation, was calculated according to Reynolds et al. (2009) (Eq. 6):

$$SSI = (1.724 \times OC) \,/\, (Silt + Clay) \times 100, \qquad (6)$$

where OC is the soil organic carbon content (g kg^{-1}). The van Bemmelen factor (1.724) was used to convert OC to OM (Cambardella et al., 2001).

Aggregate stability was measured using the methodology of Yoder (1936), modified by Grohmann (1960), and assessed the stable aggregates by the geometric mean diameter (GMD, %) after wet sieving. Undisturbed soil samples of about 10 x 10 x 10 cm were collected for each sampling site and were manually separated, then sieved in an 8- and 4-mm mesh, reserving for wet analysis only what was retained in this last sieve (4 mm). The samples were transferred to a set of sieves with 4.76, 2.00, 1.00, 0.50, and 0.25 mm and were vertically shaken for 15 minutes, at 42 oscillations per minute. Then, the material retained in each sieve was oven-dried at 105-110 °C to determine the soil dry mass in each size class and calculate the geometric mean diameter (GMD, %) (Eq. 7):

$$GMD = \, exp \frac{\sum Wi}{W} \, ln \, ln \, (Di) \, , \qquad (7)$$

where W_i is the weight of the sample of each size class (g), and D_i is the mean diameter of the i_{th} class (mm).

Penetration resistance (PR, MPa) was measured in the field to a depth of 35 cm. A dynamic impact penetrometer with a conical tip measuring 1.28 cm in diameter and an angle of 30° was used, as described in detail by Stolf (1991) and Vaz et al. (2011). Due to the high spatial variability and the influence of soil water content (Benevenute et al., 2020; Peixoto et al., 2019), ten repetition points were measured for each sampling site evaluated at a soil water content close to the field capacity. The soil moisture at each point was determined by the gravimetric method. PR data were discretized into two layers 0-15 and 15-35 cm using an electronic spreadsheet (Stolf et al., 2014)

2.3. *Calculation of the Soil Physical Quality Index*

The soil physical quality index was calculated based on steps outlined by Karlen et al. (1994) and used by Cherubin et al. (2016). Soil physical indicators were selected to assess five representative soil physical functions for the maintenance of ecosystem services, namely: f(i) support root growth (supp. root); f(ii): supply water for plants (suppl. water); f(iii): allow gas exchange between soil and atmosphere (allow gas exch.); f(iv): resistance of erosion (resist. erosion), and f(v) groundwater recharge potential (grndwat. rechar.). Based on the literature, a minimum dataset of ten soil physical indicators was selected and used to determine the index (Cherubin et al., 2016; Alvarenga et al., 2012). For the f(supp. root) BD and PR were used; for the f(suppl. water) Ksat, AWC, and RFC were considered; for the f(allow gas exch.) MAC and SSI were employed; for the f(resist. erosion) GMD, SSI, and BIR were applied; and for f(suppl. water) DP, BIR, and Ksat were used.

Next, the indicator interpretation was performed, using cumulative normal distribution functions (CND) to standardize soil data and derive interpretive scores (McBratney and Odeh, 1997) transforming each observed value into a dimensionless value, ranging from 0 to 1. The indicators were ranked in ascending or descending order, depending on whether a higher value was considered "good" or "bad" in terms of soil function. For "more is better" indicators (MAC, Ksat, SSI, BIR, GMD, and DP), each observation was divided by the highest observed value. For 'less is better' indicators (BD and PR), the lowest observed value was divided by each observation so that the lowest observed value receives a score of 1. For 'optimum' indicators (AWC and RFC), observations will be scored as ‘higher is better’ up to a threshold, then ‘lower is better’ above the threshold (AWC = 0.20 and $0.60 < RFC < 0.70$) (Reynolds et al. 2009; Reynolds et al., 2008). For the final step, we used the weight additive integration strategy (Rinot et al., 2019), to calculate individual scores for each soil physical function. Based on published literature, certain indicators that have a greater influence on each function were assigned different weights (BD and PR a weight of 0.50 each; Ksat, AWC, RFC, MAC, SSI, GMD, BIR, and DP a weight of 0.33 each). Finally, these weighted scores were added to calculate the SPQI.

2.4. *Statistical analysis*

The mean values for the various indicator scores were compared among the four groups, defined by land use within each location (soil type) and layer, by analysis of variance (ANOVA) followed by Tukey tests ($P<0.05$) to examine their respective confidence intervals ($P<0.15$; Payton et al., 2000). Similar analyses were performed for the SPQI. All statistical analyses were performed using R software version 3.1.1 (R Core Team, 2022).

3. **Results**

Converting native forest (NF) to pasture and eucalyptus increased BD in all soil types in the surface layer (Fig. 2A). Overall, extensive grazing had the highest BD values. The NF had the lowest BD in all soil types, except in the subsurface layer of the Typic Hapludult which has a naturally dense layer (accumulation of clay). The Typic Usthortent showed the lowest BD values in the upper layer among all land uses, ranging from 0.67 to 0.96 Mg m^{-3}, and no differences were observed among land uses in the subsurface layer. In the surface layer, the Typic Dystrudept followed an increasing order of BD along NF < E < RG < EG, and in the subsurface layer, only NF showed a significant and lower BD compared to the other land uses.

No differences were observed among land uses for MAC, independent of soil layer (Fig. 2B). The MAC values ranged from 0.09 to 0.24 m^3 m^{-3} in the topsoil and from 0.07 to 0.29 m^3 m^{-3} in the subsurface layer. Regarding AWC, there was no statistical differences among land uses (Fig. 2C). In the Typic Hapludult, only the soil under eucalyptus showed statistically lower AWC in the surface layer, while soil under pastures had higher AWC values in the Typic Dystrudept. For the Typic Usthortent, both soils under eucalyptus and extensive grazing presented statistically higher values compared to native forest and rotational grazing. In the subsurface layer, only the Typic Hapludult showed differences among land uses, with eucalyptus also presenting the lowest average.

The impact of land use on RFC was significant only in the surface layer of the Typic Dystrudept, in which native forest and eucalyptus had lower values when compared to pastures (Fig. 3A). RFC values range from 0.50 m^3 m^{-3} to 0.83 m^3 m^{-3}. No statistical differences were observed in DP among land uses (Fig. 3B). The measured values were around 0.17 m^3 m^{-3}.

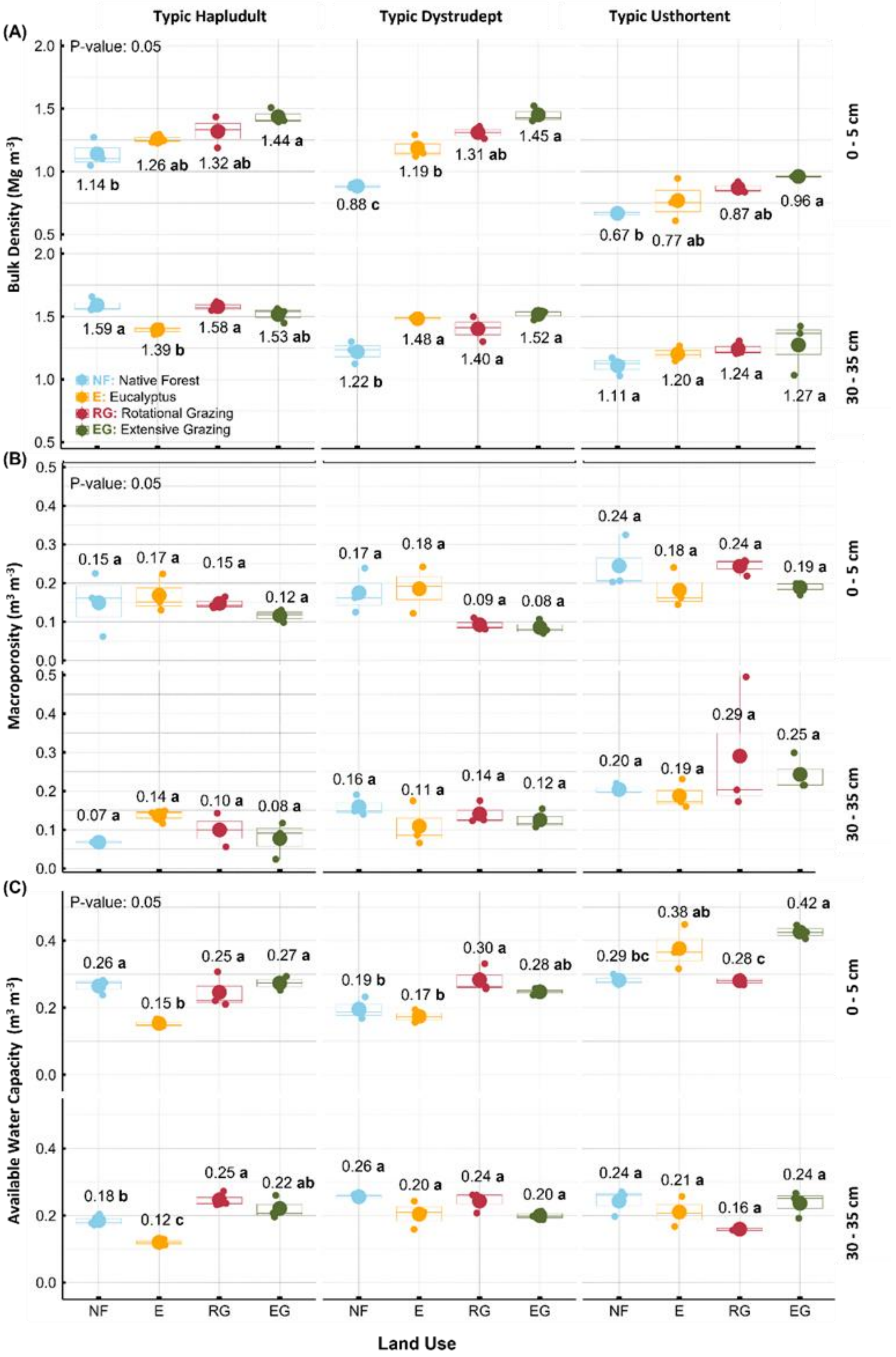

Fig. 2. Bulk density (A), macroporosity (B) and available water capacity (C) under native forest (NF), eucalyptus (E), extensive grazing (EG), and rotational grazing (RG). Means followed by the same letter do not differ significantly between land use according to Tukey's test.

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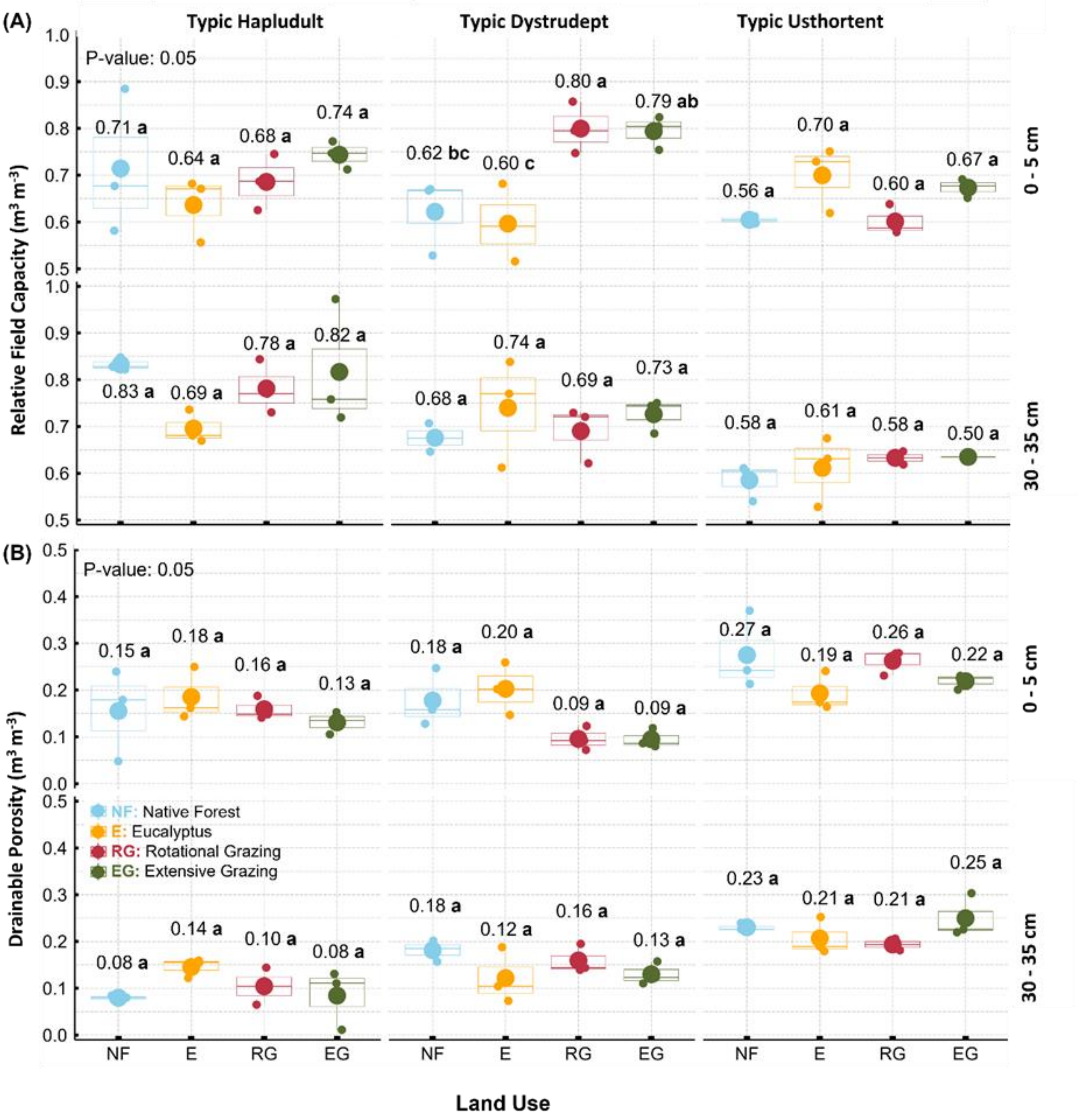

Fig. 3. Relative field capacity (A) and drainable porosity (B) under native forest (NF), eucalyptus (E), extensive grazing (EG), and rotational grazing (RG). Means followed by the same letter do not differ significantly among land uses according to Tukey's test.

In general, the soil under native forest showed the highest Ksat values which were significantly higher than the other uses of the three studied soils of the surface layer (Fig. 4A). In the subsurface layer, significant differences were observed among land uses only in the Typic Dystrudept, also with native forest showing the highest Ksat. In the Typic Hapludult, the BIR of eucalyptus was significantly higher compared to the other land uses (Fig. 4B), whereas in the Typic Dystrudept and Typic Usthortent, BIR was significantly higher in the native forest.

The BIR was not able to differentiate the rotational from extensive pasture management, which both showed the lowest values among the land uses.

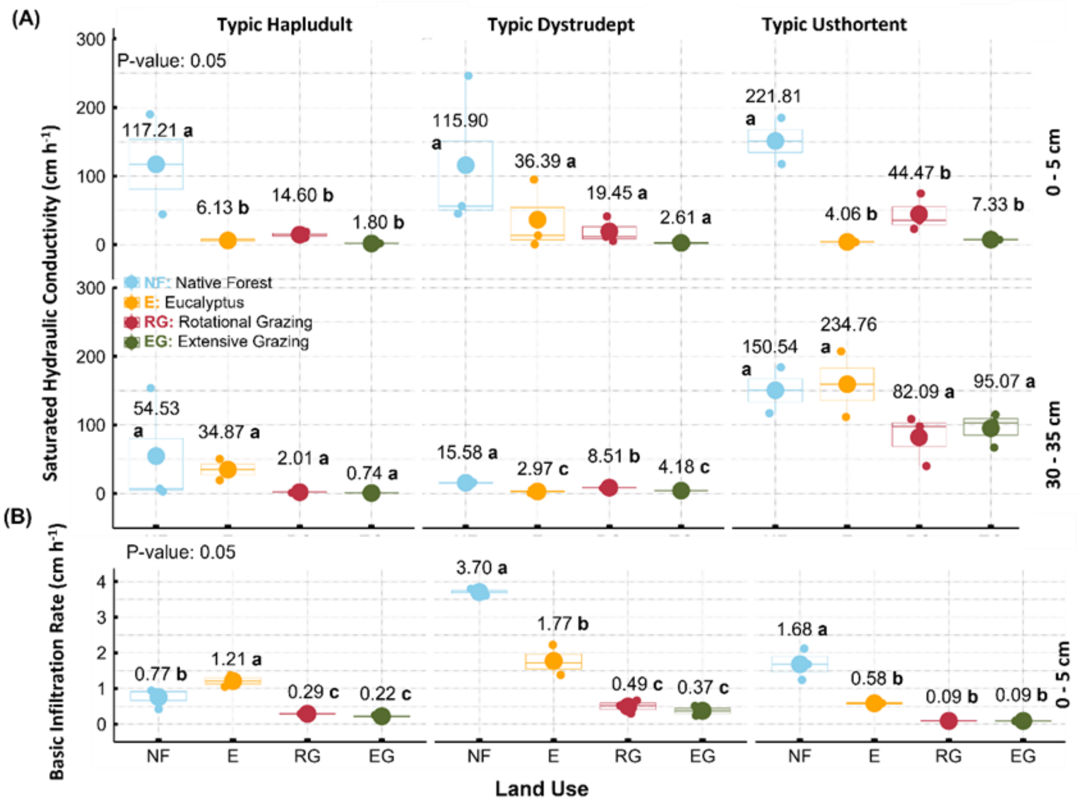

Fig. 4. Saturated hydraulic conductivity (A) and basic infiltration rate (B) under (NF), eucalyptus (E), extensive grazing (EG), and rotational grazing (RG). Means followed by the same letter do not differ significantly among land uses according to Tukey's test.

The highest SSI values were found in NF areas, mainly on the superficial horizon (Fig. 5A). In all land uses, SSI was influenced by soil depth. In the surface layer, the NF in Typic Dystrupted was the only land use to present SSI > 9%, while land uses E (Typic Hapludult), RG, and ER (Typic Dystrupted) had SSI lower than 5%. All land uses in the Typic Usthortent showed SSI < 5%. In the subsurface layer, all land uses presented SSI values lower than 5%.

The GMD (Fig. 5B) was not able to differentiate among land uses and soil types in the superficial layer, presenting high values that varied between 4.40 and 4.84 mm. In the subsurface, the extensive grazing in Typic Hapludult differed from the other land uses. Typic Dystrudept and Typic Usthortent did not show statistical differences among land uses.

Independent of land use, PR values were low (0.56 to 1.35 MPa) in the surface soil layer (Fig. 5C). PR was higher in the subsurface layer, with values ranging from 1.99 to 6.15 MPa depending on land use and soil type. In the Typic Hapludult, changing from NF to RG and EG significantly decreased PR, while in both Typic Dystrudept and Typic Usthortent, land use impact on PR was not significant. Also, in the subsurface, the Typic Hapludult tended to have the highest PR values among all studied soil types.

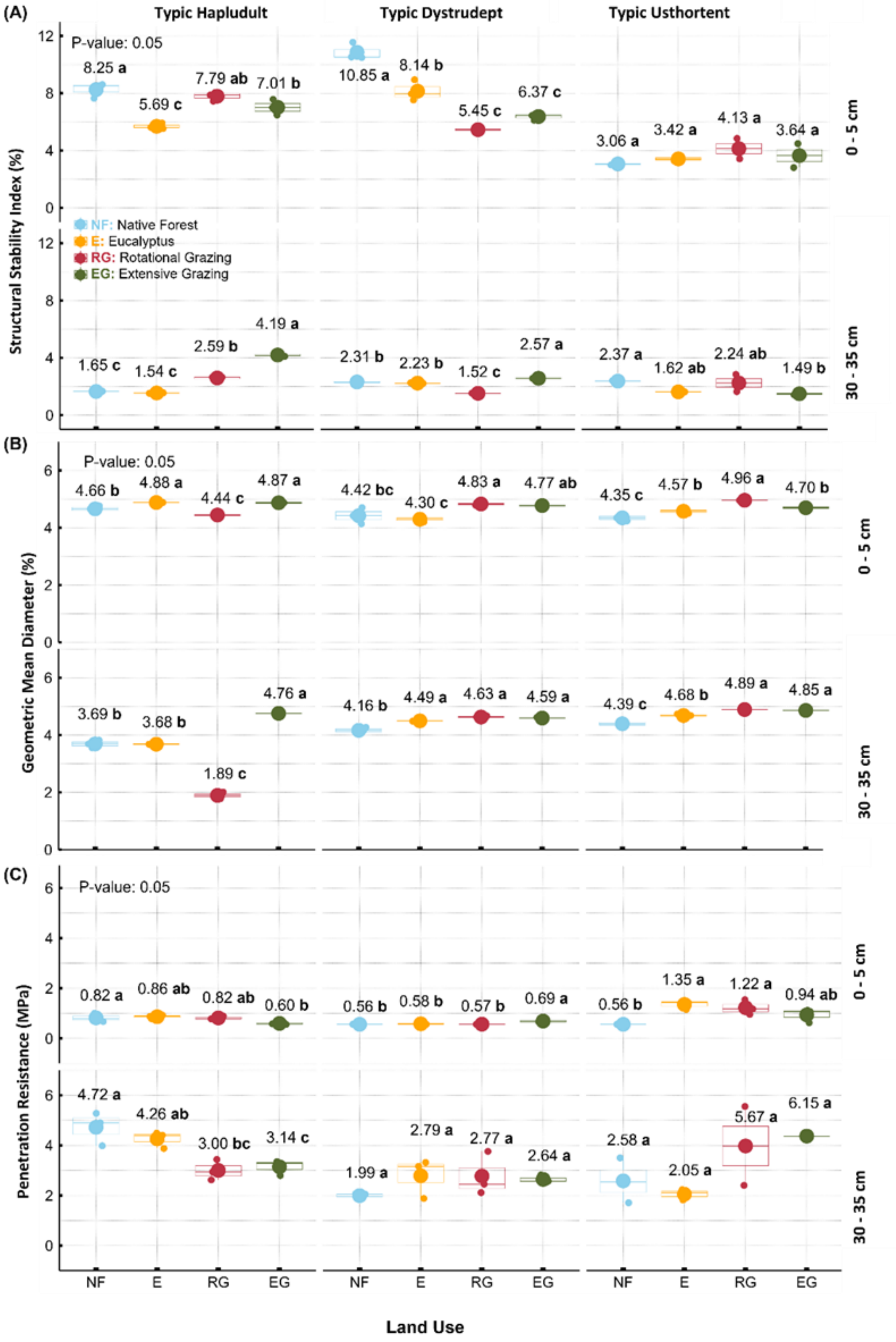

Fig. 5. Structural stability index (A), geometric mean diameter (B) and penetration resistance (C) under native forest (NF), eucalyptus (E), extensive grazing (EG), and rotational grazing (RG). Means followed by the same letter do not differ significantly among land uses according to Tukey's test.

Table 2 presents the overall scores for each function and soil physical quality index for the 0-5 cm and 30-35 cm layers. For the support root growth function, the highest index values for the surface layer were found under NF for the Typic Dystrudept and Typic Usthortent. For the function of supplying water for plants, the index was higher for NF than the other land uses in the Typic Dystrudept, while the Typic Hapludult had the lowest water availability values in both layers, even in NF. The index for Typic Usthortent showed no significant differences among land uses, with an average score of 0.60 and 0.66 for the surface and subsurface layers, respectively. Regarding the gas exchange function, there was significant difference among land uses for the Typic Dystrudept, in the surface layer, and for the Typic Hapludult in the 30-35 cm layer. For the function erosion resistance, there was difference among land uses in all soils and layers except for the 30-35 cm layer of the Typic Usthortent. In the surface layer, the index of groundwater recharge function was significantly lower for EG in the Typic Dystrudept. In Typic Dystrudept and Typic Usthortent, the index for NF was smaller, and the other land uses were similar. For the subsurface layer, no differences were observed for the index among land uses for the Typic Hapludult and the Typic Usthortent. In the Typic Dystrudept, the index for NF was larger than the other land uses and the index for RG was superior to E and EG.

Regarding the SPQI, a significant difference among land uses was found in the surface layer, where the index for NF was higher for all three soils. In the subsurface layer, no differences were observed for the index among land uses in Typic Hapludult and Typic Usthortent. In Typic Dystrudept, the score for NF was significantly higher.

Table 2. Soil physical functions and soil physical quality index (SPQI) in the 0-5 cm and 30-35 cm in the native forest (NF), eucalyptus (E), extensive grazing (EG), and rotational grazing (RG).

Layer	Soil Type	Land use	Soil functions					SPQI
			supp. root	*suppl. water*	*gas exch.*	*resist. erosion*	*grndwat. rechar.*	
0-5 cm	Typic Hapludult	NF	0.81 a	0.76 a	0.81 a	0.82 a	0.60 a	0.76 a
		E	0.74 a	0.42 b	0.70 a	0.85 a	0.55 ab	0.65 ab
		RG	0.74 a	0.55 b	0.78 a	0.67 b	0.31 ab	0.61 ab
		EG	0.84 a	0.58 ab	0.66 a	0.66 b	0.23 b	0.59 b
	Typic Dystrudept	NF	0.99 a	0.76 a	0.83 a	0.94 a	0.72 a	0.85 a
		E	0.85 b	0.46 b	0.73 a	0.68 b	0.48 ab	0.64 b
		RG	0.83 b	0.62 ab	0.43 b	0.53 c	0.20 b	0.52 bc
		EG	0.71 c	0.56 ab	0.45 b	0.54 c	0.16 b	0.49 c
	Typic Usthortent	NF	0.98 a	0.66 a	0.69 a	0.75 b	0.68 a	0.75 a
		E	0.64 b	0.59 a	0.63 a	0.81 ab	0.27 b	0.59 b
		RG	0.60 b	0.52 a	0.80 a	0.93 a	0.42 ab	0.65 ab
		EG	0.65 b	0.62 a	0.67 a	0.85 ab	0.31 b	0.62 ab
30-35 cm	Typic Hapludult	NF	0.72 a	0.63 a	0.42 b	0.58 b	0.48 a	0.57 a
		E	0.81 a	0.46 a	0.64 ab	0.56 b	0.61 a	0.61 a
		RG	0.89 a	0.57 a	0.63 ab	0.50 c	0.34 a	0.58 a
		EG	0.79 a	0.55 a	0.73 a	0.98 a	0.26 a	0.66 a
	Typic Dystrudept	NF	0.93 a	0.91 a	0.86 a	0.89 c	0.93 a	0.90 a
		E	0.73 a	0.61 b	0.72 a	0.91 b	0.39 c	0.67 b
		RG	0.76 a	0.76 ab	0.66 a	0.79 d	0.66 b	0.72 b
		EG	0.72 a	0.63 b	0.82 a	0.98 a	0.45 c	0.72 b
	Typic Usthortent	NF	0.82 a	0.72 a	0.70 a	0.94 a	0.42 a	0.72 a
		E	0.85 a	0.76 a	0.53 a	0.81 a	0.51 a	0.69 a
		RG	0.62 a	0.54 a	0.76 a	0.96 a	0.40 a	0.66 a
		EG	0.56 a	0.62 a	0.55 a	0.80 a	0.37 a	0.58 a

Means followed by the same letter do not differ significantly between land uses according to Tukey's test ($p<0.05$).

Principal component analysis (PCA) showed that the relationships between the soil physical properties and soil functions vary as a function of land use and soil type. In the 0-5 cm layer for the Typic Hapludult (Fig. 6A), only the extensive pasture diverged from the other land uses, reflecting a lower SPQI mainly influenced by the high values of soil density. For Typic Dystrudept (Fig. 6B), ellipses for native forest and eucalyptus forest are more similar than the ellipses for the two pastures, due to SPQI and soil functions. For Typic Usthortent (Fig. 6C), all land uses are grouped in different ellipses. Native forest distinguished from other land uses by all functions (mainly root growth support) except resistance to erosion function. Also, the highest BIR values were found for the native forest. In the 30-35 cm layer, soil type also influenced the SPQI and soil functions among land uses. Native forest was grouped apart from other land uses in Typic Hapludult (Fig. 6D) and Typic Dystrudept (Fig. 6E) soils, with great influence on the function of supplying water. In Typic Usthortent soil (Fig. 6F) it was not possible to differentiate among land uses, since all the ellipses crossed.

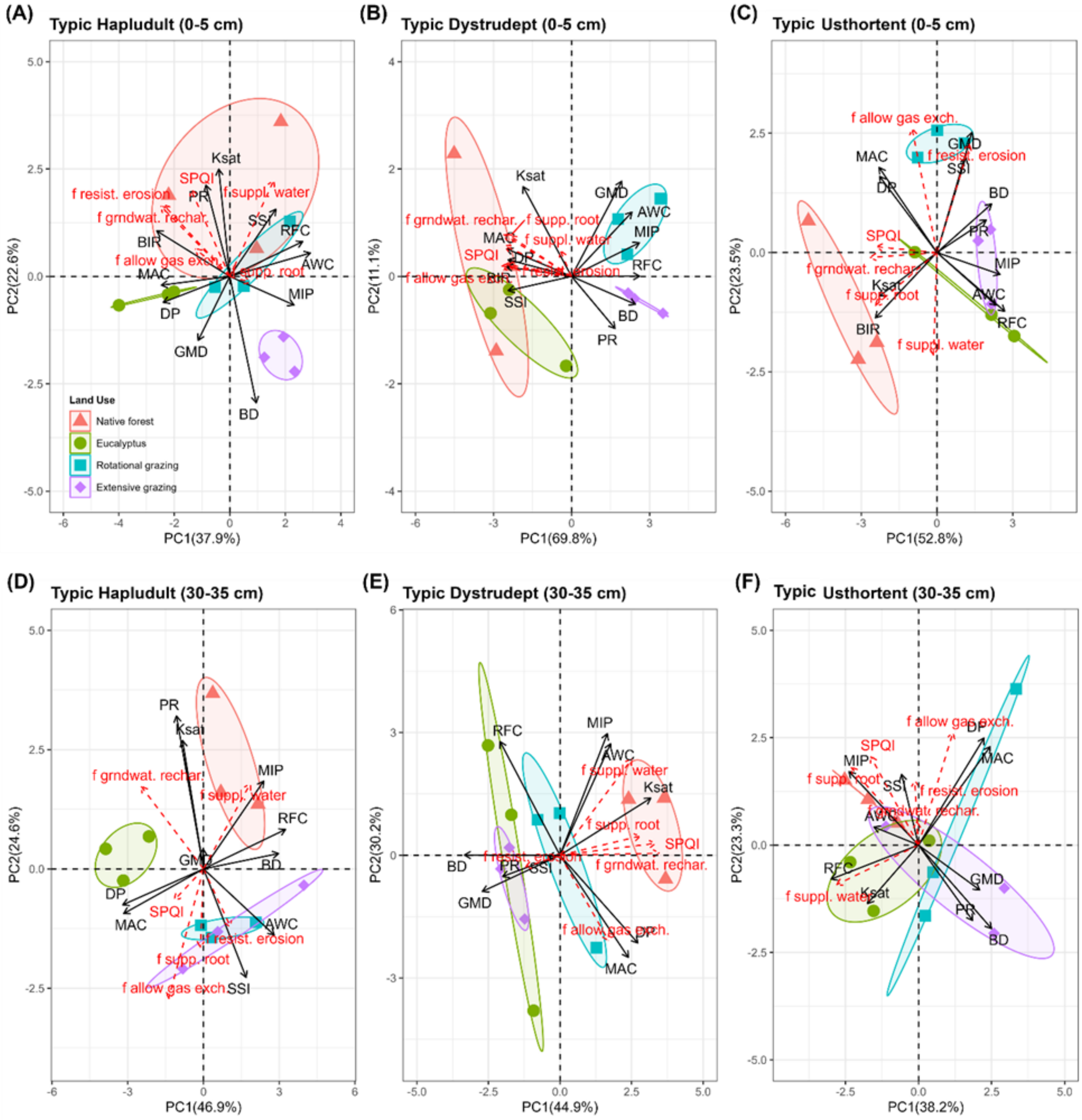

Fig. 6. Principal component analysis for Typic Hapludult 0-5 cm (A) and 30-35 cm (D), Typic Dystrudept 0-5 cm (B) and 30-35 cm (E), and Typic Usthortent 0-5 (C) and 30-35 cm (F). BD: bulk density; RP: resistance to penetration; Ksat: saturated hydraulic conductivity; AWC: available water capacity; RFC: relative field capacity; MAC: macroporosity; MIP: microporosity; GMD: geometric mean diameter; SSI: structural stability index; BIR: basic infiltration rate; DP: drainable porosity; Soil functions: support root growth; supply water for plants; allow gas exchange between soil and atmosphere; resistance of erosion; groundwater recharge potential.

4. Discussion

Well-functioning soils are expected to provide food and clean water to society while buffering climate change and protecting natural resources. This assessment provides information that helps to understand how crucial soil functions respond to anthropogenic (land use and management) and inherent factors (intrinsic soil characteristics) and their interactions in the Cantareira System, in Brazil. Overall, the results showed that (i) both inherent (soil type) and dynamic (land use and management) factors drive soil functions (e.g., water recharge) and (ii) that the effect (size and direction) of land use and management on dynamic soil properties and functions is site-specific i.e., depends on soil type and soil depth. Therefore, strategies for improving soil functionality in the Cantareira system, especially water recharge, must take into account the inherent factor (soil type) and its interaction with land use and management.

Soil intrinsic factors influenced the composite soil physical quality index and groundwater recharge functions, reflecting soil formation processes. In addition, this assessment showed the importance of combining several parameters to estimate soil quality indexes. The growing interest in monitoring restoration areas requires simple methodologies to assess progress and adapt practices to local conditions (Velasquez and Lavelle, 2019; Nunes et al., 2021a). A recent study addressing payments for hydrological services emphasized that indicators of ecosystem services vary spatially only with land use (Mayer et al., 2022). However, for the conditions of our study, we verified the need to additionally consider the type of soil in the estimation of ecosystem services.

In the surface layer, land use affected all response variables but DP, while in the subsurface layer, the significant effect of land use was observed only for PR, MAP, RFC, and DP. This suggests a greater land use impact within the surface than in the subsurface soil layer (Serafim et al., 2019). In contrast, the effect of soil type was more relevant in the subsurface layer, where pedogenetic differences are more distinct.

The greater response of the surface layer to land use change, as compared to the subsurface layer, also reflects the animal trampling which led to soil compaction (Bonetti et al., 2019). Soil structure degradation (i.e., compaction) was observed for both rotational and extensive grazing but was more significant in extensive grazing. Even though the trampling under extensive grazing is 4 to 5 times less than under rotational grazing, it also led to soil structure degradation. This reflects lower biomass addition and root activity under the former, which makes the soil more susceptible to the effects of trampling (Franzluebbers et al., 2012). Under rotational grazing, the vegetation cover and soil organic matter can increase the soil-bearing capacity within a range of elastic deformations, which is consistent with the lower effect of animals.

The impact of land use on soil microporosity was not significant, which can be associated with the mineralogy of the studied soils. These soils are poorly weathered, which intensifies the wetting and drying cycles, capable of restoring macroporosity and microporosity related to the water content (Bonetti et al., 2017).

The native forest showed greater structural stability in the surface layer than other land uses, which is partly explained by the higher carbon content and microbial activity (de Brito et al., 2019; Reynolds et al., 2009). In contrast, in the subsurface layer, the effect of land use on the SSI index was not significant and the carbon content is similar for all land uses. Besides soil aggregation, converting from native forest to other land use also affected other soil processes. For instance, hydraulic conductivity in the surface layer was higher under the native vegetation than in the other land uses independent of soil type, although a significant difference was not observed for the Typic Dystrudept. These results confirm the greater impact of land use in the surface than in the subsurface layer (Serafim et al., 2019). This is a tradeoff of converting native forests into managed agriculture, as also observed by Horel et al. (2015) and Zimmermann et al. (2010), as evidenced by an increase in soil compaction (BD; Fig. 2A) in eucalyptus and pasture areas. Other aspects such as reduced diversity and the abundance of macrofauna components in eucalyptus (Boeno et al., 2019) and the replacement of long forest roots with shallow grass roots (Lal, 1996) may have contributed to reducing Ksat. In the subsurface layer, although conductivity variation was observed among land uses, only in the Typic Dystrudept was this difference significant, probably due to the large variability in Ksat measurements (Carvalho et al., 2022). Drainable porosity was not influenced by land use in the two layers. Therefore, Ksat was a more insightful variable to reflect the quality of the environments since drainable porosity is related only to the number of pores without considering the tortuosity and interruptions of these pores, while Ksat tests the actual hydraulic effectiveness of the pores present (Batista et al., 2020).

Anthropogenic uses negatively influenced the basic infiltration rate in the Typic Dystrudept and the Typic Usthortent (Archer et al., 2013). Among them, eucalyptus was better than pasture areas, and in the Typic Hapludult, it even surpassed native vegetation. These results separate the presence and absence of cattle, and infiltration was not favored with pastures. Considering the interest in water production, the reduction of pasture areas within the watershed or a reduction in the animal stocking rate is to be considered. The highest infiltration rates were observed in the eucalyptus areas compared to the pasture areas. This was also observed in older plantations, where there was time for the accumulation of roots and litter (Zhao et al., 2020). Although commonly a high rate of water infiltration can be observed in areas with eucalyptus, and this should converge to a contribution to the recharge of aquifers, attention should be paid to the type of cultivation carried out. Eucalyptus clones with the potential for high productivity and planting density can promote high consumption of subsurface water (Ferreto et al., 2020), compromising water recharge (Reichert et al., 2021). Thus, the benefits of the eucalyptus forest for water recharge would more likely occur in plantations with low plant density and slow growth, such as genotypes destined for the timber industry (Campoe et al., 2020).

Individual variables are very useful for diagnosis and use planning with a focus on promoting soil water recharge. However, some authors (Marion et al., 2022; Rinot et al., 2019) report the difficulty of interpreting isolated variables and encourage the use of indices such as the SPQI. In the context of a nexus perspective encompassing water, energy, food, and soil, Moghadam et al. (2023) developed an indicator to manage hydrographic basins. The indicator, ranging from 0 to 1, yielded low values for pastures (0.19) and higher values for almond plantations (0.78). This disparity can largely be attributed to the degradation of grazing and erosion. Herein, the specific variables related to the movement of water in the soil were more sensitive in the distinction of environments, both to separate different soils and different uses. In this sense, although the index is important for understanding the overall quality of the environment, its use may be limited to meet the specific objective of land use planning to promote water production.

For the general understanding of the effects of uses on the environment, the use of indices has been encouraging the use of indexes that enclose a set and variables, such as the composite soil physical quality index and nexus approach. The managed use of eucalyptus and extensive and rotational pastures promoted a drastic reduction of this index, mainly in the 0-5 cm layer, for the three studied soils. In the 30-35 cm layer, this trend was observed only in the Typic Hapludult, which must be associated with a well-developed blocky structure. Such structure may have greater resilience to the effects of land use, compared to the incipient horizon of Typic Dystrudept and C horizon of Typic Usthortent.

5. Conclusions

The evaluation of soil physical properties provided an improved understanding of soil functions in areas of different land uses in the Cantareira System. The conversion of native forest to anthropogenic land uses (eucalyptus and pasture) reduced the water recharge capacity and physical soil quality. Overall, intensification of pasture management by replacing continuous grazing with rotational grazing has little effect on promoting the ecosystem services in the Cantareira System. But soil types directly influence the recharge potential of environments. The negative effect of the land use type depends on the use capacity of each soil and the different uses studied were affected differently following the order of Typic Hapludult > Typic Dystrudept > Typic Usthortent. Finally, our results provide evidence that the soil physical quality is sensitive to management practices and land use decisions. The nexus approach can contribute to the sustainable management of the Cantareira System by considering the interdependence between water, energy, food, and soil systems and optimizing the use of resources in a sustainable and equitable manner.

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PAPER 2 – SOIL WATER CONTENT DYNAMICS IN KEY BRAZILIAN PUBLIC WATER SUPPLY AREA

Abstract

The maintenance of soil functions is crucial for human well-being, but there is a lack of integration between soil, water security, ecosystem services, and climate change. This has led to the degradation of soil properties and a reduction in its capacity to provide important services. To address this knowledge gap, a three-year study was carried out on three dominant soil types (Typic Hapludult, Typic Dystrudept, and Typic Usthortent) combined with the land uses of native forest, eucalyptus, rotational grazing, and extensive grazing, in a critical water supply region for the Metropolitan Area of São Paulo, Brazil. Soil electrical resistivity tomography was applied to estimate the soil water content up to a depth of 1.5-meter Soil hydraulic properties, and surface runoff were measured. Native forest soils had higher hydraulic conductivity, particularly in the surface layer, compared to eucalyptus and pastures. The native forest in Typic Hapludult showed a higher runoff rate, due a naturally dense subsoil layer that negatively impacted water infiltration and recharge, therefore reducing the amount of water stored. In Typic Dystrudept, the native forest presented higher hydraulic conductivity than eucalyptus and pastures, but there were no significant differences in soil water content among land uses. The Typic Usthortent maintained a higher soil water content in pastures than in other land uses, and also low rate of water infiltration, resulting in perched water in the surface layer. In contrast, the deeper roots of native forests and eucalyptus were able to explore water at greater depths, consuming more water and resulting in drier soils over the seasons. The study illustrated the crucial role of native forests in affecting deep water recharge, owing to their greater root penetration capabilities and recharge potential. However, further research beyond a depth of 2 meters is imperative to attain a better understanding of groundwater recharge.

Keywords: Electrical resistivity; soil moisture; surface runoff; land use; soil structure; ecosystem services

1. Introduction

The soil is an essential component for human well-being, and its maintenance requires attention to ensure its functions. Although the literature on the role of soils in providing ecosystem services has grown recently, there is a lack of integration between soil, water security, and climate change (Carvalho De Melo et al., 2023; Pokhrel et al., 2021). Land use change, such as the conversion of native forests into extensive pastures, has led to the degradation of soil properties and functions, which can reduce its capacity to provide various ES (De Groot et al., 2002; MEA, 2005), including water supply regulation, erosion control, and climate regulation.

Globally, native forests play a crucial role as global groundwater storage due to their deep-rooted trees, which facilitate water transportation to deeper soil layers, enabling longer storage periods before evaporation or absorption by plants (Bassiouni et al., 2023; Rodríguez-Iturbe & Porporato, 2007). However, several studies have reported that in temperate regions, soil covered with native forest has a lower overall water content during the dry season (Jayawickreme et al., 2014; Kim et al., 2017; Yu et al., 2019). Well-managed pastures can also serve as soil cover and extract substantial amounts of water. Nevertheless, it should be noted that pasture water uptake is primarily limited to the superficial soil layer, specifically within the 0-50 cm depth range (Bengtsson et al., 2019; Milazzo et al., 2023; Sala et al., 1997).

In addition to land use, intrinsic soil factors, such as texture, structure, and hydraulic conductivity, also play a critical role in determining water permeability variation. Soils that have a subsurface layers of high bulk density may have limitations in water infiltration and, consequently, lower water storage along the profile. Soil texture, on the other hand, affects water retention capacity, with clayey soils retaining more water, while sandy soils, due to their higher macropore continuity, have a greater capacity for water transport throughout the entire profile. Young soils with little pedogenetic development are influenced by the soil's hydraulic conductivity, limiting or increasing its water transport capacity. Understanding these factors is essential for the adequate management of soil water resources and the promotion of water security (Leul et al., 2023).

The Cantareira System is a crucial water production area that has several ecosystem functions, with emphasis on water supply, capable of supplying water to the Metropolitan Area of São Paulo, covering an area of around 2,300 km² and extend to 75 cities in the states of Minas Gerais and São Paulo (Uezu et al., 2017). Although this system serves as an important role in preserving a threatened Atlantic Rain Forest hotspot and in providing fresh water, climate regulation, and other vital ecosystem services, its significant pressure from rural activity loss in supply capacity (Chiodi et al., 2021; Dib et al., 2020). The predominant land use in the Cantareira System consists of livestock (46%), native forests (35%), plantion forest (16%), and reservoirs and water bodies (3%). The land features a gradient ranging from 0 to 66 degrees and is composed of Oxisols, Ultisols, Inceptisol, and other soils that are less weathered. In the region, there are widespread degraded pastures (Uezu et al., 2017) that are incapable of generating sufficient biomass to ensure effective land preservation. The 2014/2015 water scarcity in the Cantareira System was an event of prolonged drought, which caused serious supply problems for a large population. Despite the regional scope of the event, its impacts were felt throughout the territory (Domingues & da Rocha, 2022). The dry season in the region typically occurs during the winter months, from May to September, with June, July, and August being the driest months. As a result of the water shortage, there was water rationing for the population not only in the catchment area but also in the Metropolitan Area of São Paulo. It is essential to constantly monitor the maintenance of ecosystem services and the mitigation of degrading actions in these areas for water recharge.

The suggestions above indicate methodological and thematic gaps under the interface of ES related to soil and land use change, including in the context of the Cantareira System. Despite the importance of the Cantareira System, the lack of methods for assessing ecosystem services has prevented a clear view of the real impacts of transitions between forest and pasture on the soil's ability to provide such services. Validating discussions on developing interventions and management options for the ecosystem's adequate use within ecological limits requires essential knowledge. Understanding the modification in soil functions due to land use change and intrinsic factors will be fundamental for formulating policies that promote sustainable development, maintenance of quality water supply, and payment schemes for water-related environmental services, as implemented in other parts of Brazil (Mamedes et al., 2023; Ruggiero et al., 2018; Taffarello et al., 2018).

In this context, geophysical methods, such as soil electrical resistivity (ρ) have been used in soil science to collect non-destructive information on soil heterogeneity, including soil water content. The ρ can be considered a useful tool for monitoring moisture patterns associated with water flow (Samouëlian et al., 2005). ρ is a function of various soil properties, such as the nature of solid constituents (texture and mineralogy), pore arrangement (porosity, pore size distribution, and connectivity), degree of saturation (water content), solute concentration in the soil solution and temperature (Garcia-Montiel et al., 2008; Grubbs et al., 2019; Jeřábek et al., 2017; Ranjy Roodposhti et al., 2019).

Therefore, the main hypotheses of this study are the following: i) the surface runoff varies among different land uses and soil types in the Cantareira System, with lower rates in the native forest; ii) soil-specific calibration of the electrical resistivity tomography is needed to accurate estimation of soil water content and its spatial-temporal variation; iii) the spatial-temporal patterns of soil water content can be influenced by soil uses, and these patterns can also vary depending on the soil type. This study aimed: i) to model ρ-θ relationship in soils for θ estimation; i) to evaluate the spatial-temporal dynamics in contrasting soil types: Inceptisol, Ultisol, and Entisol; ii) to verify the land use effect on maintaining water content throughout the seasons; iii) to infer whether native forests are able to store more water in the soil when compared to eucalyptus and pastures land uses.

2. Material and methods

2.1. *Study area*

The study was established in the Cantareira System, Brazil, with sampling performed in the municipalities of Joanópolis (22°56’16” S 46º05’50” W, altitude of 1200 m), Nazaré Paulista (23°12’20” S 46º21’12” W, altitude of 800 m), and Piracaia (23°01’39” S 46º19’35” W, altitude of 840 m) (Figure 1). In each area, we evaluated the representative land uses adopted by local farmers – native forest (NF), eucalyptus (E), rotational grazing (RG), and extensive grazing (EG). The predominant climate in the region is classified as Cwb (Köppen) with cold and dry winters and hot and humid summers (Alvares et al., 2013). The average annual rainfall is 1,570 mm and annual temperatures range from 18 to 20 °C (Uezu et al., 2017). The soils were classified as *Argissolo Vermelho Amarelo, Cambissolo Háplico,* and *Neossolo Regolítico,* according to the Brazilian System of Soil Classification (Santos et al., 2013), and as Ultisol (Typic Hapludult), Inceptisol (Typic Dystrudept) and Entisol (Typic Usthortent), according to Soil Taxonomy (Soil Survey Staff, 2014) (Figure 1).

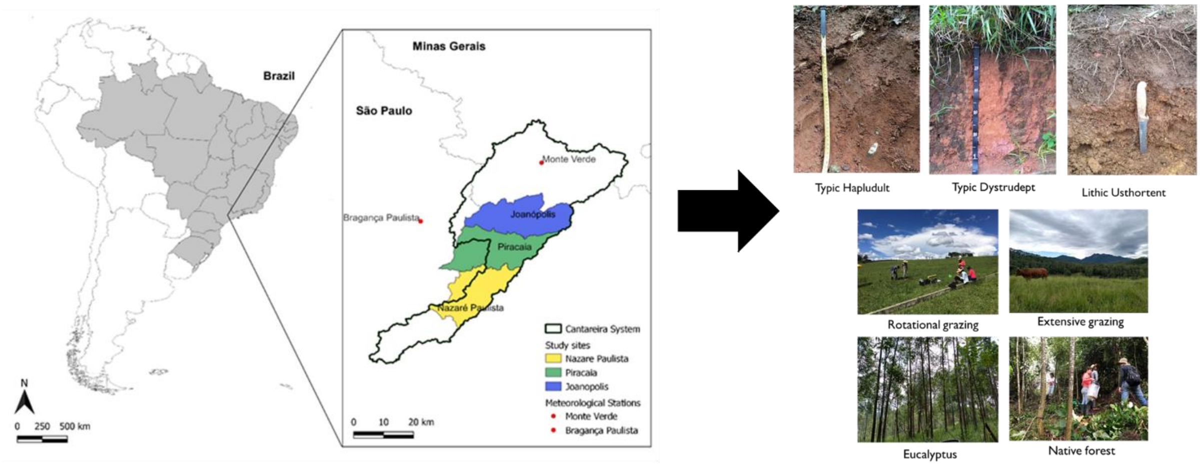


Figure 1. Location of the Cantareira System and study sites, soil types, and land uses.

In February 2019, disturbed and undisturbed soil were randomly sampled in trenches for each land use and soil type for physical parameters (Table 1). In each layer, eight samples were taken at the surface (0-5 cm) and the subsurface (30-35 cm).

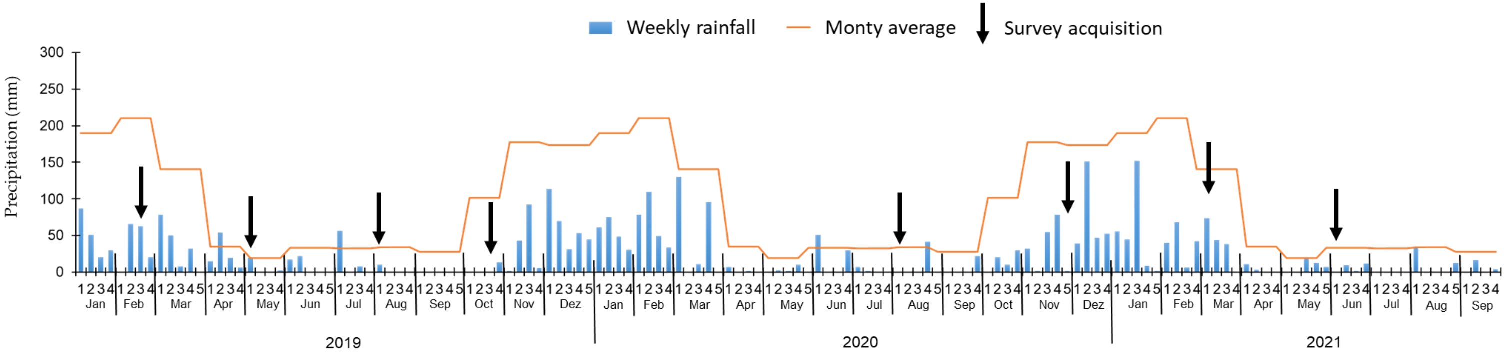
Table 1. Soil classification and characteristics in the soil profile in the native forest (NF), eucalyptus (E), rotation grazing (RG), and extensive grazing (EG).

Soil / City	Land Use	Depth	Clay	Silt	Sand	BD	KS	PT	MAC	MIP
		cm	--------	g kg^{-1}	------	Mg m^{-3}	cm h^{-1}	------	m^{3}m^{-3}	-----
Typic Hapludult/ Piracaia	NF	0-5	378	222	401	1.14	117.21	0.51	0.15	0.36
		30-35	445	180	375	1.59	54.53	0.48	0.07	0.41
	E	0-5	335	178	486	1.26	6.13	0.50	0.17	0.33
		30-35	560	152	288	1.39	34.87	0.48	0.14	0.34
	RG	0-5	230	159	610	1.32	14.60	0.51	0.15	0.36
		30-35	396	129	475	1.58	2.01	0.47	0.10	0.37
	EG	0-5	255	125	621	1.44	1.80	0.51	0.12	0.39
		30-35	282	145	573	1.52	0.74	0.45	0.08	0.37
Typic Dystrudept/ Nazaré Paulista	NF	0-5	364	145	491	0.88	115.90	0.46	0.18	0.29
		30-35	415	195	390	1.22	15.58	0.56	0.16	0.40
	E	0-5	330	142	528	1.19	36.39	0.50	0.19	0.31
		30-35	434	121	445	1.48	2.97	0.46	0.11	0.35
	RG	0-5	399	166	435	1.31	19.45	0.48	0.09	0.39
		30-35	459	139	402	1.40	8.52	0.51	0.14	0.37
	EG	0-5	337	188	475	1.45	2.61	0.46	0.09	0.37
		30-35	419	161	420	1.52	4.18	0.47	0.13	0.35
Typic Usthortent/ Joanópolis	NF	0-5	549	119	332	0.67	221.81	0.62	0.24	0.37
		30-35	288	196	515	1.11	150.54	0.56	0.20	0.35
	E	0-5	380	233	387	0.77	4.06	0.65	0.18	0.46
		30-35	451	319	230	1.20	234.76	0.53	0.19	0.35
	RG	0-5	423	162	15	0.87	44.47	0.66	0.24	0.41
		30-35	440	225	335	1.24	82.09	0.64	0.29	0.34
	EG	0-5	555	129	316	0.96	7.33	0.67	0.19	0.48
		30-35	267	175	557	1.27	95.07	0.52	0.24	0.27

BD: bulk density; KS: hydraulic conductivity; PT: porosity total; MAC: macroporosity; MIP: microporosity.

In order to characterize the weather patterns during the experimental campaign, agro-meteorological data were obtained from the Meteorological Database for Teaching and Research (BDMEP) of the National Institute of Meteorology (INMET, 2021). Figure 2 depicts the weekly precipitation and the average monthly precipitation, which were measured at the two meteorological stations closest to the study areas: Monte Verde, situated in the state of Minas Gerais in proximity to the city of Joanópolis, and the station in Bragança Paulista located in the state of São Paulo, close to the cities of Nazaré Paulista and Piracaia.

a) Bragança Paulista



b) Monte Verde

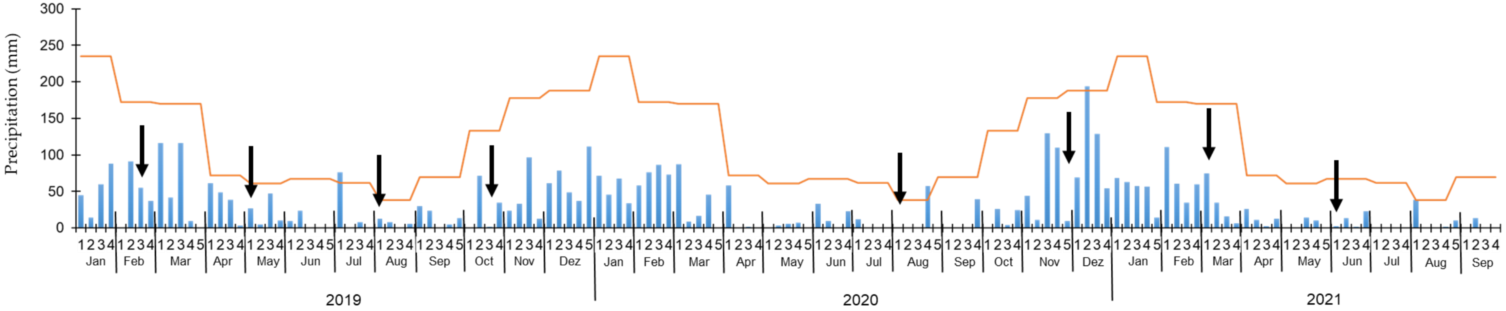


Figure 2. Weekly rainfall in a) Bragança Paulista (monthly average rainfall from 2004 to 2021); and b) Monte Verde (monthly average rainfall from 2017 to 2021). The black arrows indicate the timing of the electrical resistivity tomography acquisitions.

2.2. *Surface runoff*

Around sampling points, the surface runoff (SR) tests were performed, with two replicates for each land use. The SR was performed through a sprinkler infiltrometer (Cornell Sprinkler infiltrometer), described by van Es and Schindelbeck (2003). The infiltrometer is a portable rainfall simulator consisting of 69 drippers at the bottom with a diameter of 0.63 mm and a length of 0.19 m each, providing a capacity of 20.6 L. It is assembled on a cylinder with a diameter of 0.24 m and is capable of simulating various rain intensities through an air inlet regulation system.

The surface runoff was determined by equation 1:

$$SR = [(V_t*1000) /(45730*t)] \qquad \text{eq. 1}$$

where SR is surface runoff (mm h^{-1}); Vt is water volume collected (mL); *45730* is ring area (mm²) and t is the time interval (hours) between the runoff collections (we used 0.05 h in this study).

2.3. *Soil electrical resistivity surveys*

2.3.1 Description of ρ measurements

The measurement of the soil electrical resistivity (ρ) was carried out in the study areas in 8 seasons in the period of 2019, 2020, and 2021. Due to the limitations of COVID-19, it was not possible to carry out the measurements in the summer and fall of 2021 and in the eucalyptus and extensive pasture areas in the spring of 2021 Typic Hapludult. The measurement aims to evaluate the volumetric moisture in the soil profile and thus the water storage as a function of time, for each land use and type of soil.

The ρ was directly measured with the X5xtal 250 Resistivity Meter (Auto Energia, Minas Gerais, Brazil), with two multimeters in a dipole-dipole arrangement (A-B-M-N), where A-B are current electrodes and M-N are the potential electrodes (Samouëlian et al., 2005). The measurements were obtained from a horizontal transect of 7.78 m in length, with a spacing of 0.38 m between electrodes. The evaluated depth ranged from 0 to 1.50 m, with a total of 179 measurements being carried out in each land use. Hence, ρ was calculated by equations 2 and 3:

$$\rho = (K*\Delta V)/I \qquad \text{eq. 2}$$

$$K = 2\pi a \qquad \text{eq. 3}$$

where ρ is electrical resistivity (Ω.m); K is geometric coefficient; ΔV is potential difference (mV); I is injected electrical current (mA); a is spacing between electrodes (m).

2.3.2 *Description of the ρ-θ calibration test*

To model the ρ-θ relationship, a calibration test was performed on undisturbed soil sampled in situ with PVC (polyvinyl chloride) rigid plastic cylinders (both diameter and height of 0.1 m), as described by Melo et al. (2023). Undisturbed soil was sampled from two depths (0-10 and 35-45 cm depths), which represent the surface and subsurface layer, respectively. Duplicates were collected in each soil type (Typic Hapludult, Typic Dystrudept, and Typic Usthortent).

At the laboratory, Wenner arrangement (A-M-N-B) of electrodes (Samouëlian et al., 2005) was carried out with aluminum electrodes spaced 0.019 m apart and inserted at a depth of 0.05 m to determine ρ. Each soil sample was saturated by capillarity for 72 h, and the test was conducted by acquiring a set of ρ measurements and θ - obtained from the PVC soil sample weight and determination of gravimetric water content and the bulk density - as the soil dried by natural evaporation. Therefore, ρ and θ were measured in gradual degrees of water saturation acquired for 29 days with an X5xtal 250 Resistivity Meter (Auto Energia, Minas Gerais, Brazil). The electrical conductivity of water was assumed constant during the measurements process.

After this period, the soil samples were oven-dried at a temperature of 105-110 °C for 48 h to calculate the gravimetric water content (w) and the soil bulk density (BD) (Dane & Topp, 2002). The θ was calculated by equation 4:

$$\theta = w\ (BD / Dw) \qquad \text{eq. 4}$$

where θ is volumetric soil water content ($m^3\ m^{-3}$); w is the gravimetric water content ($kg\ kg^{-1}$); BD is the soil bulk density ($Mg\ m^{-3}$); and Dw is the density of water (considered as 1 $Mg\ m^{-3}$).

To estimate the θ through ρ data, the ρ-θ relationship was modeled for each soil type using the power equation 5:

$$\theta = a\ \rho b \qquad \text{eq. 5}$$

where *a* and *b* are fitting parameters (dimensionless).

2.3.3 *Statistical analysis*

For the analysis of spatial and in-depth variability of electrical resistivity, the ρ was derived by performing an inversion process executed in RES2Dinvx64 software (Geotomo Software, v.4.08) and 2D images were generated using Surfer 13.5.583 (Golden Software). The triangulation method was applied to interpolate the ρ points and obtain 2D tomograms at each treatment.

In order to verify the accuracy of the ρ-θ models for each treatment, the determination coefficient (R^2) and the root mean square error (RMSE) calculated between the observed and predicted θ values were used. The calibration models were evaluated using the RStudio 3.6.1 software (R STUDIO TEAM, 2022).

3. Results and discussion

3.1. *Runoff with Cornell Infiltrometer*

Figure 3 illustrates the surface runoff obtained from the Cornell Sprinkle Infiltrometer test. For Typic Hapludult (Fig. 3a) it was observed that the native forest began producing runoff after 6 minutes, whereas the other land uses exhibited runoff in the initial minute itself. Upon reaching a plateau, the land uses showed runoff rates ranging between 200 to 250 mm h^{-1} for NF and RG, respectively. However, there were no substantial differences in the runoff rates observed among the different land uses. Although our analyses did not show differences between land use and land cover changes, other studies conducted in the Posses sub-basin (Pontes et al., 2016; Bispo et al., 2017; Silva et al, 2022), sub-basin of the Cantareira System and predominantly composed of Typic Hapludult soils, have observed that variations in forest cover have an impact on flow generation and runoff, with greater forest cover generally resulting in lower runoff coefficients. Chitollina et al. (2023) found a runoff coefficient ranging from 25 to 37%, while studies conducted in other water supply areas of the Cantareira System found a runoff coefficient of 39% for the Jaguari river sub-basin and ranging from 29 to 42% for the Piracicaba River sub-basin (Domingues & da Rocha, 2022).

The native forest for Typic Dystrudept showed low runoff rates (Fig. 3B), with values of approximately 5 mm h^{-1}, and the eucalyptus-initiated runoff after 3 minutes and reached a plateau at 11 mm h^{-1}. In contrast, the grazing areas exhibited considerably higher runoff rates (average of RG: 215 mm h^{-1} and EG: 370 mm h^{-1}). Studies conducted in Dystrudept in the Atlantic Forest, The Mantiqueira Range (Pinto et at., 2017), near the Cantareira System, predominantly covered by forests and pastures, have shown that the native forest has a significant impact on base flow. The authors suggested that native forests offer more favorable conditions for water infiltration, resulting in greater groundwater recharge and, consequently, a higher base flow. Conversely, anthropogenic activities have a negative impact on soil permeability. In contrast, preserved areas such as natural forests have the potential to enhance infiltration, which can lead to a decrease in overland flow and sediment transport. As a result, the high runoff rate observed in pasture areas can be attributed to the replacement of native forests with this type of land use. This phenomenon is associated with the specific features of mountainous regions of the Atlantic Forest, which possesses a thick layer of litter, low soil bulk density, high organic carbon content, and greater biological activity when compared to pasture lands. Grazing lands do not facilitate water infiltration, as reported by Menezes et al. (2016).

There was no surface runoff observed in the native forest and eucalyptus for the Typic Ustorthent (Fig. 3C). However, the EG showed the highest runoff rates observed as early as the first minute of the test, reaching a maximum runoff rate of 288 mm h^{-1}, and maintained a plateau at 245 mm h^{-1}. Nevertheless, RG began producing runoff after 9 minutes and sustained a runoff rate of approximately 160 mm h^{-1}. It is evident that the adoption of pasture management practices has the potential to reduce surface runoff when compared to conventional grazing. In studies conducted by Oliveira et al. (2017), groundwater recharge decreased with increasing vegetation density in Brazilian Cerrado Entisols, where grasslands showed higher groundwater recharge rates when compared to areas with higher vegetation density, above 350 mm $year^{-1}$. This emphasizes the relevance of incorporating soil type and land use information in hydrological and climatic modeling. It is important to highlight those younger soils, such as Entisol and Inceptsol, in which soil structure is not well developed through a field evaluation, can still play an important role in water infiltration compared to soil that presents a dense subsoil horizon like Ultisol.

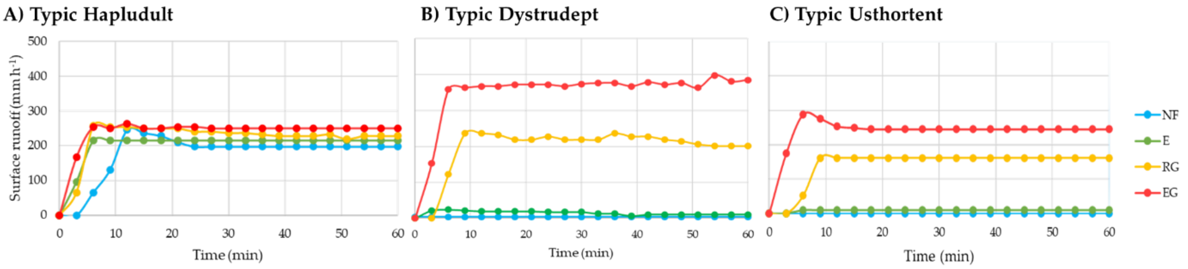


Figure 3. Surface runoff determined by Cornell Sprinkle Infiltrometer for the Typic Hapludult (A), Typic Dystrudept (B) and Typic Usthortent (C) under native forest (NF), eucalyptus (E), rotational grazing (RG), and extensive grazing (EG).

3.2 ρ-θ modeling

The ρ-θ modeling, parameters, and accuracies are shown in Figure 4. The model showed good accuracy with R^2 values between 0.79 and 0.91, and low RMSE values (between 0.034 and 0.051). It is known that soil moisture and electrical resistivity have non-linear and inverse mathematical relationships, can being applied to various models' types: power, logarithmic, or even exponential (Cosenza et al., 2006; McCarter, 1984; Samouëlian et al., 2005). However, soil texture is a differential for a better fit of this relationship. Archie's power equation (Archie, 1942) is often applied to saturated sandy soils due to the relationship between resistivity and the number of pores generated by the arrangement of particles. In studies conducted by Melo et al. (2021), the hypothesis that Archie's Law also applies to tropical clayey soils was accepted, showing a good correlation when using power calibration models. The authors evaluated clayey Oxisols, but the results of this study also showed good results for Entisols, Inceptisols, and Ultisols.

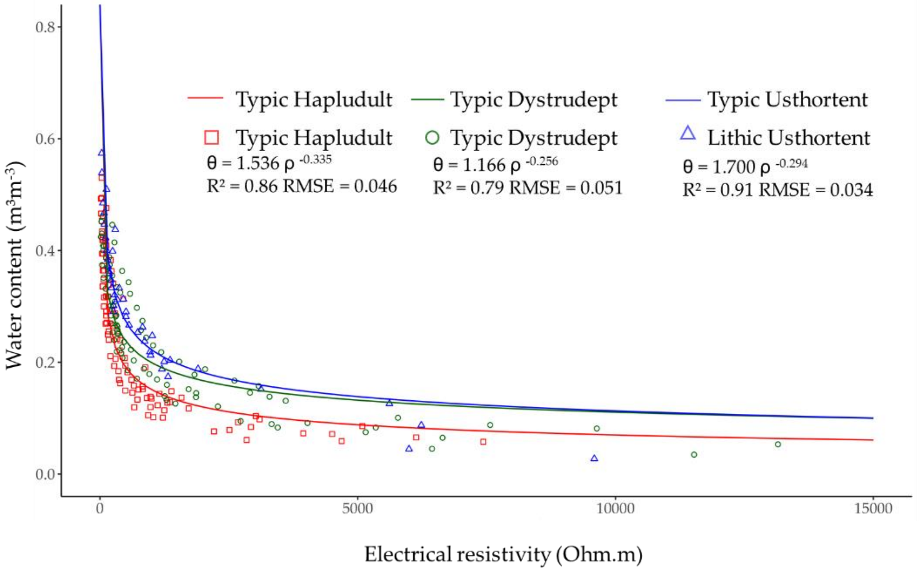


Figure 4. ρ-θ modeling calibration curves (lines) for soil type: Typic Hapludult, Typic Dystrudept and Typic Usthortent and its observed data.

3.3 Seasonal water content distribution

The soil water content estimated by ρ for each monitoring period is presented in Figures 7 to 9. In 2019, for Typic Hapludult (Figure 5), it is possible to observe that the native forest was the land use that least kept water in profile up to 1.50 m deep throughout the summer until winter seasons (from February to August, respectively), especially during the driest period -

winter. The Typic Hapludult was characterized by a dense pedogenetic horizon (starting near 30 cm depth), as demonstrated by a high bulk density (1.59 Mg m^{-3}) in the subsurface layer of the native forest, which may limit surface water infiltration (KS) (Table 1) and surface runoff rate of 200 mm h^{-1} (Fig. 3A). However, soil preparation for eucalyptus plantation may have contributed to the relief of subsurface consolidation, promoting root development below this restrictive layer, consuming water at depth and drying out the subsurface soil layer throughout the seasons, indicated by the pale colors in the Figure 5-E. Among the pastures, it was possible to visualize that the rotated grazing maintained more water throughout the seasons remaining stationary in the soil up to a depth of 1.0 m, unlike the extensive pasture that had a greater drying of the soil at depth. This result is consistent with the high bulk density, greater impermeability (<KS) (Table 1), and high runoff rates (Fig. 3A) of the extensive pasture, which may have impeded the water's reach to this depth, indicating drying during the evaluation period. Even though grassroots are known to be aggressive and capable of penetrating impediment layers, appropriate management practices should be implemented to achieve this effect. In previous studies, low groundwater recharge potential were observed for these pastures in this soil, directly related to the common pasture management practice of rotating heavier animals in the rotational area and heifers in the extensive area, leading to an animal stocking rate beyond the ideal and causing soil compaction from animal trampling, resulting in water accumulation indicating impaired drainage and inefficient root uptake with a low rate of evapotranspiration (Alvarenga et al., 2016). According to a study conducted by Bispo et al. (2017) in a Typic Hapludult in Atlantic Forest in Brazil, it was reported surface runoff was reduced by 41% in well-managed pastures.

In the spring of 2019 (October), there was a significant precipitation event (Fig. 2), which can be mainly observed by the water recharge in the native forest. The monitoring conducted in August 2020 showed a drier winter with no precipitation when compared to the previous year, in which eucalyptus was the only use that was able to maintain a water content greater than 0.24 m^3 m^{-3} up to approximately 0.50 m depth. During the dry period of the previous year, the extensive pasture exhibited the same drying pattern as before and dried out more compared to the rotated pasture, particularly deeper in the soil. In the following summer (March 2021), high precipitation events were observed (Fig. 2) after a long dry period, in which eucalyptus stored water along the soil profile up to 1.50 m. Nonetheless, the estimated percolation cannot be considered as water recharge since the water balance analysis only considered the 1.5 m soil depth, while certain tree species are adapted to extracting water from deeper layers (Rodrigues et al., 2021). Yu et al. (2019) conducted a study on the seasonal variation of soil moisture in medium-textured soil under different land uses to a depth of 5.0 m. They were able to infer that moisture levels stabilized with minor fluctuations below a depth of 2.0 m.

Next monitoring, in fall (June 2021), the beginning of the dry period was observed, with the native forest presenting a water content below 0.10 $m^3 m^{-3}$, maintaining the same behavior during dry seasons. In this year, the rotated grazing showed greater variability compared to the extensive pasture. Despite all climatic anomalies, and being a drier year, it is possible to observe a pattern in the soil water content, the same as in 2019, where the native forest was the driest land use, which may be due to evapotranspiration, as a result of voluminous and dense root system tropical forest (O'Connor et al., 2019), and groundwater recharge, by reason of its good soil water-air relationship in this use, as indicated in Table 1 by the good porous and KS conditions comparing to others uses.

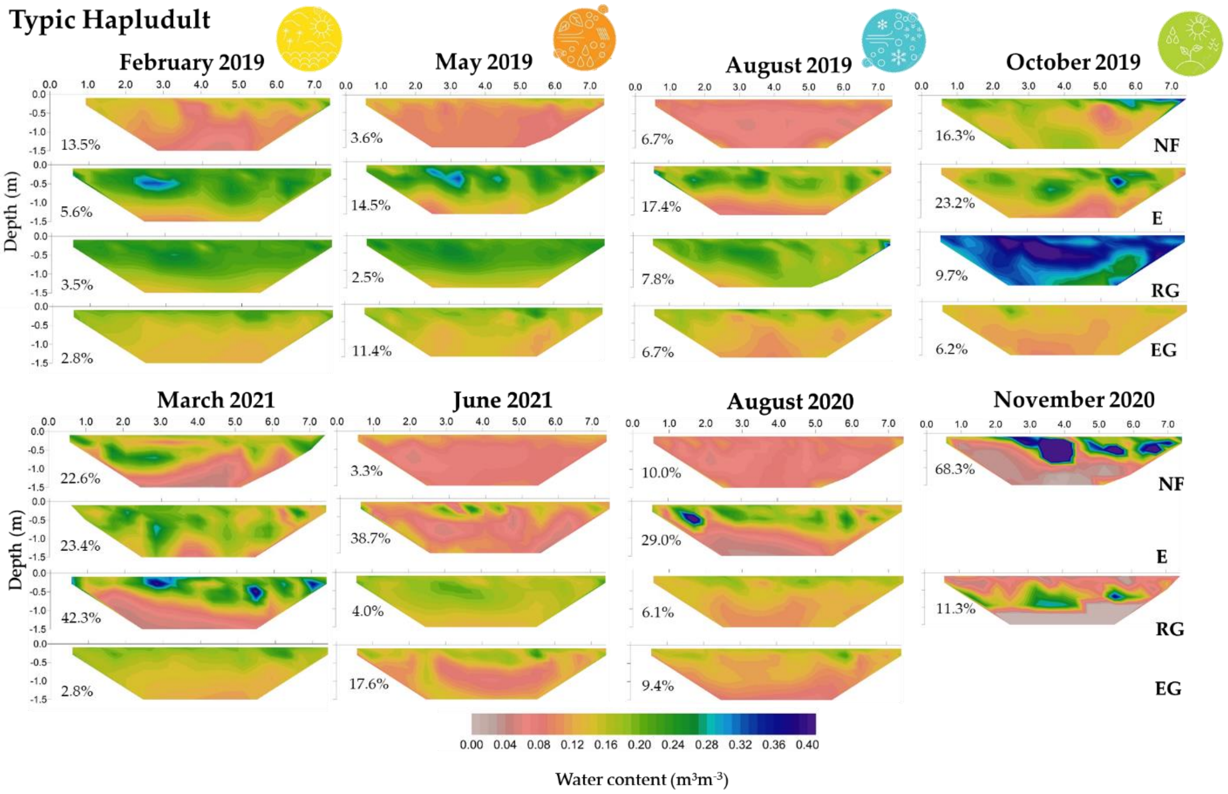


Figure 5. Estimated soil water content ($m^3 m^{-3}$) for the Typic Hapludult under native forest (NF), eucalyptus (E), rotational grazing (RG), and extensive grazing (EG) during the monitoring periods.

The water content for Typic Dystrudept (Figure 6) showed greater stability in maintaining water within the soil system throughout seasons when compared to Typic

Hapludult. The native forest exhibited higher water content in the soil profile and a more homogeneous behavior among the other land uses with soil moisture decreasing with depth, mainly for the second year. The pastures produced greater drainage, indicated by the low water content, particularly during the dry winter season (August), regardless of the monitoring year. Rotated grazing became drier compared to the EG. The extensive grazing exhibited an atypical behavior in October 2019. In the summer (March 2021), after a rainy season (Figure 2), it was observed that water remained stagnant in the soil surface of the EG land use. The extensive grazing exhibits low hydraulic conductivity-KS (0-5 cm: 2.61 cm h^{-1}; 30-35 cm: 4.18 cm h^{-1}; Table 1) resulting in surface water retention and inefficient water recharge meanwhile the native forest presented the highest values (0-5 cm: 115.90 cm h^{-1}; 30-35 cm: 15.58 cm h^{-1}) and low surface runoff rate. Furthermore, in regions where rainforests are predominant and forest conversion takes place, the substitution of deep-rooted native forest with shallow-rooted pasture can disrupt the hydrological cycle in various ways, like the increase in streamflow (Bruijnzeel, 2004).

Salemi et al. (2013) reported a significantly higher hydraulic conductivity at a depth of 15 cm in studies conducted on young soils (Entisols and Inceptisols) in the Atlantic Forest, when comparing soil under the forest with soils under eucalyptus and pasture. The observation made by the authors is consistent with the forest soil exhibiting the lowest recorded soil bulk density (1.19 Mg m^{-3}) at the same depth, as well as the highest degree of aggregation and pore space because of the highest organic matter content. According to Centeno et al. (2020), this enhanced aggregation and pore space in the forest soil has a positive effect on water conductivity.

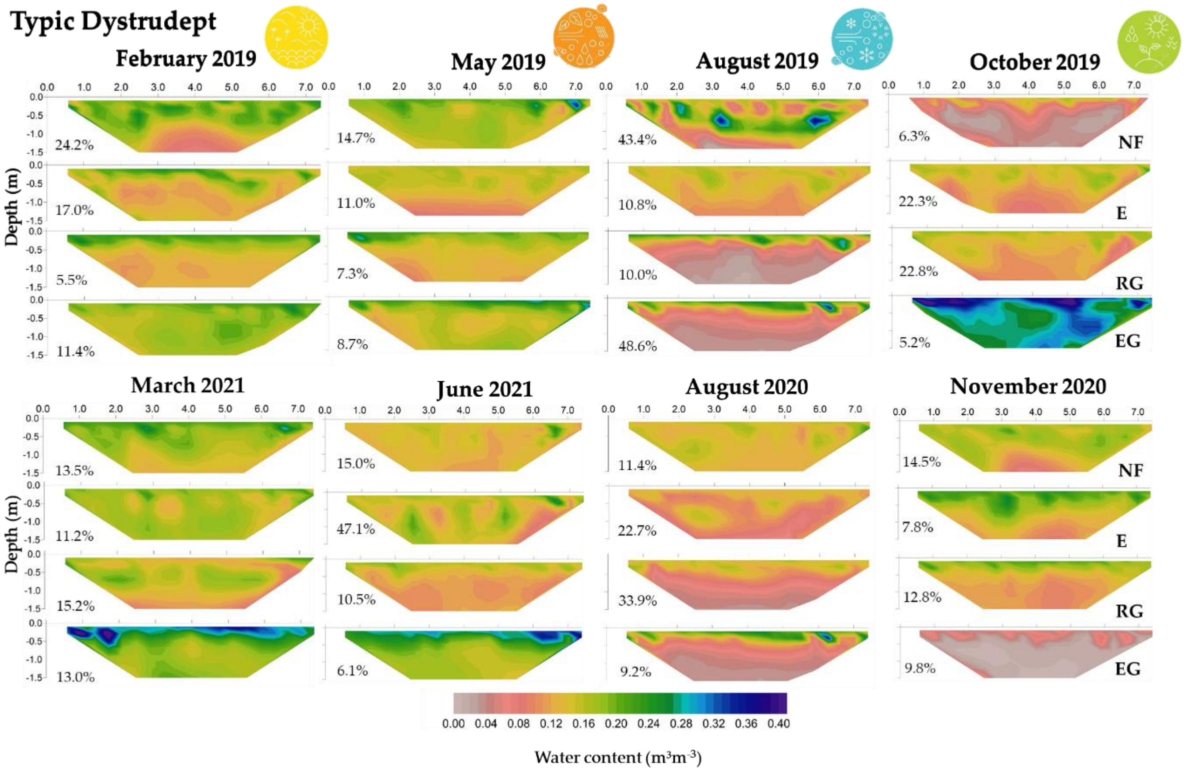


Figure 6. Estimated soil water content (m^3 m^{-3}) for the Typic Dystrudept under native forest (NF), eucalyptus (E), rotational grazing (RG) and extensive grazing (EG) during the monitoring periods.

The variation in water storage for Typic Usthortent is presented in Figure 7. It was possible to observe that pastures maintained a high soil moisture content likely associated with its low infiltration rate visualized by the high runoff rate (Fig. 3C). Typic Usthortent is a very young soil with stoniness characteristics and a poorly developed structure, which favored the maintenance of water in pastures throughout the monitoring period. In contrast, the deep and aggressive roots of the native forest and eucalyptus trees explored water deeply, resulting in drier soil throughout the seasons, indicating that actual evapotranspiration, potential percolation, and soil water storage variation were the most significant hydrological factors for assessing the water balance.

In addition to the consumption of water by the root’s, planting density is a critical factor in determining the water use efficiency of eucalyptus trees. The impact of planting density on water use efficiency in forestry has been a topic of research, and studies have shown that increasing planting densities can lead to higher water use (Boeno et al., 2019). However, the impact of planting density on the ecosystem's water balance is complex and influenced by several factors. In this context, Hakamada et al. (2020) have made a valuable contribution to the understanding of this subject by studying different clones and plant densities of eucalyptus in Brazil. The study reported that planting fast-growing trees in tighter spacings may have an adverse effect on the ecosystem's water balance, potentially resulting in the depletion of stored soil water. Results also suggested that forests consume more water than pasture, but the maintenance of forest cover in the watershed is required for soil and water conservation, reducing the impacts of soil erosion on water yield and its quality from springs (Alvarenga et al., 2016).

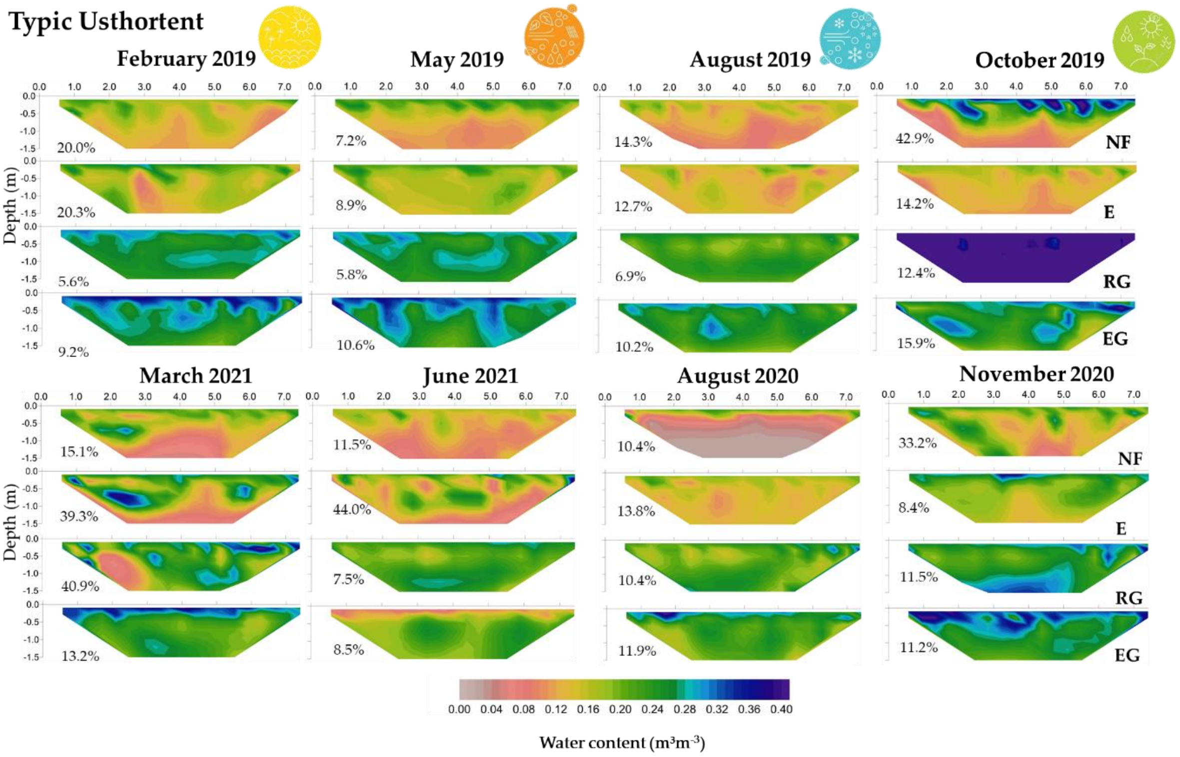


Figure 7. Estimated soil water content (m^3 m^{-3}) for the Typic Usthortent under native forest (NF), eucalyptus (E), rotational grazing (RG) and extensive grazing (EG) during the monitoring periods.

4. Conclusions

The spatial-temporal dynamics of water content were assessed for the main land uses and management conventionally adopted in the Cantareira water supply system watershed. Soil intrinsic properties and proved to be important in water dynamics. For this reason, soil-specific calibration for soil electric resistivity and water content correlation was modeled, and good accuracy was achieved, allowing for water content estimation. In general, the conversion of native forests to pastures as local farm management practice resulted in increased potential surface runoff among the soils. In the Typic Hapludult, eucalyptus roots were able to extract water from deep soil layers by penetrating through the compacted layer. In the less weathered soil, Typic Usthortent, water was unable to infiltrate and remained in the evaluated soil layer.

Moreover, the study highlighted the influence of land use changes, underscoring the critical role of native forests in deep water recharge, as they possess greater root penetration capacity, evapotranspiration potential, and lower surface runoff rates. In contrast, pastures with shallow roots can only retain water in surface layers and are inefficient in recharging groundwater. Therefore, the quality of pastures, determined by grass management and animal stocking rate, is crucial in ensuring water security. Nonetheless, further research beyond the 2.0 meters depth is essential to achieve a better understanding of groundwater recharge.

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PAPER 3 – COMPREHENSIVE ASSESSMENT OF SOIL HEALTH IN THE CANTAREIRA SYSTEM COMPARED TO LOCAL SOIL QUALITY INDEXES

Abstract

Soil health is an important aspect of sustainable land management, but evaluating it is complicated and requires an interpretive framework that considers soil biological, physical, and chemical properties and processes across land use and management practices. This study evaluates soil health using the Comprehensive Assessment of Soil Health (CASH) methodology and compares it with the Soil Physical Quality Index (SPQI). The study hypothesizes that soil health will be higher in native forests, the SPQI will be better at assessing land use changes, and a tropical soil database index is necessary for accurate evaluations. The objectives are to assess soil health using the CASH methodology, compare it with the SPQI, and identify the need for a tropical soil database index. The findings will contribute to the advancement of soil science and management, supporting decision-making processes for agricultural and environmental policies. This study will help to advance soil science and management in Brazil and other regions, contributing to sustainable land use and conservation.

Keywords: land use management; soil properties; soil type

1. Introduction

The definition and evaluation of soil health have become increasingly significant in remediating degraded soils and monitoring progress. Soil health refers to a specific soil's ability to perform multiple functions, including nutrient cycling, productivity maintenance, biodiversity preservation, water regulation, and climate moderation (Karlen et al., 1997). Establishing an approach to evaluate soil health in relation to desired outcomes has proven to be more complicated than anticipated. It is essential for all stakeholders, including farmers and policy-makers, to quantify the baseline soil health status and track changes over time concerning crop and soil management. Several research groups, such as the U.S. Department of Agriculture-NCRS, Cornell University, Luiz de Queiroz College of Agriculture, and Brazilian Agricultural Research Corporation, have developed evaluation approaches integrating relevant soil chemical measurements. To quantify the interactions among inherent and dynamic soil biological, physical, and chemical properties and processes across land use and management practices, an interpretive framework that provides a wide range of regionally relevant indicator options is required (Cherubin et al., 2017), such as a multi-indicator soil health index. This index should also consider inherent site-specific factors, be sensitive to anthropogenic activities, and facilitate broad-scale monitoring for sustainable land management (Bünemann et al., 2018; Lehmann et al., 2020). Nonetheless, relying only on actual counts or estimates of the abundance of specific soil organisms can become prohibitively expensive. Therefore, researchers at Cornell have focused on relatively low-cost indicators of biological activity or function, such as soil respiration rate and available forms of carbon and nitrogen to support the soil food web (Schindelbeck et al., 2008).

The Comprehensive Assessment of Soil Health (CASH) is the outcome of almost two decades of work analyzing thousands of soil samples gathered from commercial and research farms. The CASH provides an interpretive report card for farms, indicating aspects of soil health that range from optimum (green) to problematic (red). Importantly, the report offers recommendations for addressing soil constraints that could negatively affect farm profits or the environment. CASH scores multiple soil health measurements using cumulative normal distributions of a regional dataset from the northeastern United States (Idowu et al., 2009). CASH algorithms were expanded to include soils from other U.S. regions (Fine et al., 2017), however, the spatial extent is still limited, and the curves do not reflect the national or global distribution of soils.

In order to enhance the accuracy and reliability of soil health assessments, it is imperative to create indexing tools that take into account multiple soil attributes and describe relevant soil health status for various soil types. Such tools can be developed based on statistical approaches, expert opinions or expert-based frameworks. However, to be practical and easily understandable for producers and landowners, these tools must incorporate soil health indicators that reflect the chemical, biological, and physical soil processes, detect variations in soil functions due to management decisions, and be cost-effective (Williams et al., 2020). Additionally, the indicators must demonstrate the connection between soil functions and management targets, such as agricultural productivity and ecosystem services (Karlen et al., 2021).

In addition, a comprehensive database with the global representation of soils and intrinsic soil factors is necessary. The SoilHealthDB, which includes 354 geographic sites across 42 countries, has already been developed (Jian et al., 2020). This database can provide valuable information for the development and validation of soil health assessment tools, as well as help to identify regions or soil types that are particularly vulnerable to degradation or in need of conservation. Efforts are being made in Brazil with the creation of the PronaSolos program, which aims to be a national soil database that integrates existing data and generates new information on soil properties, functions, and management practices (Crespolini & Nascimento, 2021). The program seeks to provide a comprehensive understanding of Brazilian soils and their potential for sustainable use, as well as support decision-making processes for agricultural and environmental policies. With the participation of different institutions, such as research centers, universities, and government agencies, PronaSolos is expected to contribute significantly to the advancement of soil science and management in the country.

Based on these concepts, this study hypothesizes that: i) soil health will have a higher index for native forest regardless of soil type; ii) the SPQI will be better able to assess changes in land use compared to CASH; iii) an index with a database of tropical soils is necessary for a more accurate evaluation. The objectives of this study are: i) to evaluate soil health using the CASH methodology; ii) to compare the CASH with the Soil Physical Quality Index (SPQI) developed by Santana et al. (2023, *in press*).

2. Materials and methods

2.1. Study area

The study was conducted in three municipalities that belong to the Cantareira System: Nazaré Paulista, Piracaia, and Joanópolis. The design was similar to that employed by Santana et al. (2023, *in press*) which evaluated the primary land uses in the region: native forest, eucalyptus, rotational grazing, and extensive grazing on Typic Hapludult, Typic Dystrudept, and Typic Usthortent according to Soil Taxonomy (Soil Survey Staff, 2014).

2.2.Soil sampling and analysis

In May 2021, disturbed soil samples were randomly collected for each land use and soil type. Eight samples were taken for local, 4 from the surface layer (0-5 cm), and 4 from the subsurface layer (30-35 cm), resulting in a total of 96 samples. The samples were air-dried and sent to the Cornell Soil Lab in Ithaca, United States.

The Comprehensive Assessment of Soil Heath was carried out using a methodology proposed by (Moebius-Clune et al., 2016). The results of constraints on chemical, physical, and biological attributes for each soil type and land use are presented.

2.3. Comparasion between CASH and SPQI

The results obtained from the CASH methodology were compared with those obtained from the SPQI developed by Santana et al. (2023, *in press*). Ten physical soil attributes were evaluated to create a specific additive index for each soil type. In this study, the samples used were undisturbed soil samples in metal cores.

2.3.1 Physical Soil Health indicators

Indicators of the physical condition of the soil that were evaluated in this research included soil texture, stability of aggregates in water, and resistance to penetration of the soil surface and subsurface. At Cornell, particle size distribution was determined using the Kettler method (Kettler et al. 2001) through sieving and sedimentation. To assess the resistance of soil aggregates to disaggregation due to moisture and raindrop impact, a rainfall simulator was employed at Cornell, applying a force of 0.5 J for 5 minutes to soil in a sieve containing a known weight of soil aggregates sized between 0.25 to 2.00 mm. The Cornell rainfall simulator delivers 12.5 mm of water over 5 minutes (Moebius et al. 2007).

2.3.2 Chemical Soil Health indicators

The chemical properties of soil assessed in this investigation included pH, phosphorus, potassium, magnesium, iron, manganese, zinc, total carbon, and total nitrogen. Soil pH was determined in a soil suspension consisting of two parts waters to one part soil (Moebius-Clune et al., 2017). Phosphorus, K, Mg, Fe, Mn, and Zn were extracted with a modified Morgan's solution, an ammonium acetate plus acetic acid solution, buffered at pH 4.8 and the extracted slurry was analyzed using an inductively coupled plasma emission spectrometer.

2.3.3 Biological Soil Health indicators

The study analyzed several biological soil properties, including organic matter (OM), autoclave citrate extractable (ACE) protein, soil respiration (Resp), and permanganate oxidizable carbon (POXC). The OM content was determined using a loss-on-ignition method, where a sample of 10 g of soil was heated to 500 °C to remove carbonaceous material and retain mineral materials, and the difference in weight was recorded (Broadbent, 2016). The ACE protein index was determined using a modified version of the Autoclave Citrate Extractable Protein Index by Wright and Upadhyaya (1996), where 3 g of soil was mixed with 24 mL of extractable sodium and autoclaved at 121 °C for 30 minutes. A subsample of the resulting solution was analyzed using a colorimetric protein quantification assay. Soil respiration, which is indicative of microbial community activity, was measured using the heterotrophic Respiration method adapted from Zibilske (1994), where 20 g of air-dried soil was incubated for 4 days in a jar with 0.5 mol/L KOH to trap CO_2 released by microbial metabolic activity. The CO_2 was then quantified using an electrical conductivity meter. Lastly, permanganate oxidizable carbon, which is a readily available food source for soil microbes, was measured using a hand-held colorimeter to determine the absorbance of the soil potassium permanganate solution at 550 nm (Weil et al., 2017).

2.3.4 Overall Soil Health score

The CASH framework combined biological, chemical, and physical properties, to obtain an SH score for each soil type and land use. The soil health score ranges from 0 to 100 and is classified as very low (<40), low (40–55), medium (55–70), high (70–85), or very high (>85). The scores were calculated for both soil layers, but the framework was originally intended for the top 0-15 cm of soil.

2.4.Data and statistical analysis

The methodologies of CASH and SPQI were compared by land use, using analysis of variance (ANOVA) followed by Tukey's test ($p<0.05$). All analyses were performed using R software version 3.1.1 (R Core Team, 2022).

3. Results and discussion

3.1 CASH constraints

In Table 1, the indicators that showed some restriction to soil health for each soil use and type by the CASH method are presented. It can be observed that in the superficial layer, only the low pH value presented a limitation, with values ranging from 3.7 to 5.2. Tropical soils typically present low pH values and nutrient availability. When this limitation and aluminum toxicity occurs, it can be easily corrected through liming.

In the 30-35 cm layer, all soil types and uses presented restrictions related to pH, as well as limitations related to soil microbiology. The indicators of soil respiration, active carbon, and protein index suggest a low abundance of microbial activity and poor quality of organic matter. The accumulation of organic matter occurs mainly in the superficial soil horizons. A decrease in microbial population is expected with increasing depth. This trend is also observed for chemical quality when there is no fertilization, whereas physical quality is affected by subsurface compaction, although no restrictions were found by the methodology.

Table 1. Indicators that show constraints in soil health in native forest (NF), eucalyptus (E), rotated pasture (RG) and extensive pasture (EG)

Layer	Soil	Land	Constraints	Indicator	Value
0-5	Typic Hapludult	NF	Low pH: toxicity, nutrient availability	pH	4.2
		E	Low pH: toxicity, nutrient availability	pH	4.0
		RG	Low pH: toxicity, nutrient availability	pH	5.1
		EG	Low pH: toxicity, nutrient availability	pH	5.2
	Typic Dystrudept	NF	Low pH: toxicity, nutrient availability	pH	3.8
		E	Low pH: toxicity, nutrient availability	pH	4.2
		RG	Low pH: toxicity, nutrient availability	pH	4.9
		EG	Low pH: toxicity, nutrient availability	pH	4.6
	Typic Usthortent	NF	Low pH: toxicity, nutrient availability	pH	3.7
		E	Low pH: toxicity, nutrient availability	pH	4.6
		RG	Low pH: toxicity, nutrient availability	pH	5.2
		EG	Low pH: toxicity, nutrient availability	pH	5.0
30-35	Typic Hapludult	NF	Soil microbial abundance and activity	Soil respiration	0.3
			Energy source for soil biota	Active carbon	197
			Low pH: toxicity, nutrient availability	pH	4.6
		E	OM quality, organic N storage, N mineralization	ACE soil protein index	2.4
			Energy source for soil biota	Active carbon	279
			Low pH: toxicity, nutrient availability	pH	4.1
		RG	Organic matter quality, organic N storage, N mineralization	ACE soil protein index	2.0
			Energy source for soil biota	Active carbon	180
			Low pH: toxicity, nutrient availability	pH	5.2
		EG	Organic matter quality, organic N storage, N mineralization	ACE soil protein index	2.3
			Energy source for soil biota	Active carbon	5.0
			Low pH: toxicity, nutrient availability	pH	4.9
	Typic Dystrudept	NF	Energy source for soil biota	Active carbon	337
			Low pH: toxicity, nutrient availability	pH	4.3

	E	Organic matter quality, organic N storage, N mineralization	ACE soil protein index	2.9
		Energy source for soil biota	Active carbon	290
		Low pH: toxicity, nutrient availability	pH	4.4
	RG	Organic matter quality, organic N storage, N mineralization	ACE soil protein index	2.0
		Soil microbial abundance and activity	Soil respiration	0.3
		Energy source for soil biota	Active carbon	261
		Low pH: toxicity, nutrient availability	pH	4.4
		Plat K availability	Extractable potassium	16.4
	EG	Organic matter quality, organic N storage, N mineralization	ACE soil protein index	2.0
		Energy source for soil biota	Active carbon	222
		Low pH: toxicity, nutrient availability	pH	4.9
Typic Usthortent	NF	Soil microbial abundance and activity	Soil respiration	0.3
		Energy source for soil biota	Active carbon	197
		Low pH: toxicity, nutrient availability	pH	4.6
	E	Energy source for soil biota	Active carbon	285
		Low pH: toxicity, nutrient availability	pH	4.7
	RG	Organic matter quality, organic N storage, N mineralization	ACE soil protein index	2.2
		Soil microbial abundance and activity	Soil respiration	0.2
		Energy source for soil biota	Active carbon	219
		Low pH: toxicity, nutrient availability	pH	4.9
	EG	Organic matter quality, organic N storage, N mineralization	ACE soil protein index	2.9
		Soil microbial abundance and activity	Soil respiration	0.3
		Energy source for soil biota	Active carbon	250
		Low pH: toxicity, nutrient availability	pH	5.2

3.2 CASH x SPQI

Table 1 presents a comparison between the soil health and physical quality evaluation methodologies. For Typic Hapludult in the surface layer, the CASH method showed no significant difference from the SPQI, with the same increasing sequence of NF > E > EG > RG. The CASH metrics were initially formulated for use in soil contexts associated with agricultural practices (Moebius-Clune et al. 2017); nevertheless, implementing these metrics in non-agricultural soil environments can still offer a comprehensive perspective on ecosystem systems that is linked to soil health.

In Typic Dystrudept soil, there was a difference in the native forest, with SPQI showing the highest index value. CASH was superior and different in eucalyptus and extensive grazing, while there was no difference between methods for continuous grazing. In a study conducted by Barbosa et al. (2020), the authors found that the physical quality indicators' results did not correspond to the critical limits or optimal ranges proposed in the literature for the studied Typic Dystrudept, suggested to establish optimal range values that consider the particularities of each soil class in the local region.

For Typic Usthortent, regardless of the method, the native forest use continued to have the highest quality index (CASH = 82.1; SPQI = 75.2). Rotational grazing did not show any statistical difference (mean = 66.5).

In the subsurface layer, all SPQI values were statistically superior and different from the CASH values. This can be explained because the CASH methodology uses many biological indicators such as soil organic carbon, respiration, and active carbon, and in the 30-35 cm layer, there is a lower amount of organic matter and therefore less active microbiological activity, which underestimates the soil health.

Table 1. Comparison between Comprehensive Assessment of Soil Health (CASH) and Soil Physical Quality Index (SPQI) in the 0-5 cm and 30-35 cm in the native forest, eucalyptus, rotational grazing, and extensive grazing.

Layer	Soil	Land	CASH	SPQI
0-5	Typic Hapludult	Native forest	74.5 a	76.1 a
		Eucalyptus	62.4 a	65.2 a
		Rotational grazing	56.6 a	61.2 a
		Extensive grazing	59.8 a	59.4 a
	Typic Dystrudept	Native forest	69.3 b	85.0 a
		Eucalyptus	78.4 a	64.2 b
		Rotational grazing	65.0 a	52.1 a
		Extensive grazing	82.6 a	48.6 b
	Typic Usthortent	Native forest	82.1 a	75.2 a
		Eucalyptus	78.2 a	58.9 b
		Rotational grazing	67.7 a	65.3 a
		Extensive grazing	79.7 a	61.9 b
30-35	Typic Hapludult	Native forest	47.9 b	56.6 a
		Eucalyptus	48.2 b	61.6 a
		Rotational grazing	41.4 b	58.6 a
		Extensive grazing	41.4 b	66.2 a
	Typic Dystrudept	Native forest	46.9 b	90.5 a
		Eucalyptus	43.7 b	67.4 a
		Rotational grazing	41.6 b	72.5 a
		Extensive grazing	47.1 b	72.3 a
	Typic Usthortent	Native forest	52.1 b	72.1 a
		Eucalyptus	46.6 b	69.3 a
		Rotational grazing	48.2 b	65.7 a
		Extensive grazing	44.3 b	58.3 a

Means followed by the same letter do not differ significantly between land uses according to Tukey's test ($p<0.05$)

4. Conclusions

Comprehensive understanding of soil health indicators following native forest conversion to agricultural land use is critical to comprehend soil functioning. The decline in soil health indicators and reduction in CASH scores that typically occur due to land conversion underscore the necessity of developing indicators that are better suited to detect the intrinsic and potential factors of tropical soils. Programs aimed at providing a comprehensive understanding of Brazilian soils, such as the one mentioned, play a crucial role in supporting decision-making processes for agricultural and environmental policies. Prioritizing soil health is necessary to ensure the long-term productivity and sustainability of agricultural lands while also preserving the health of ecosystems.

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