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Interactions between land use and soil type drive soil functions, highlighting water recharge potential, in the Cantareira System, Southeast of Brazil

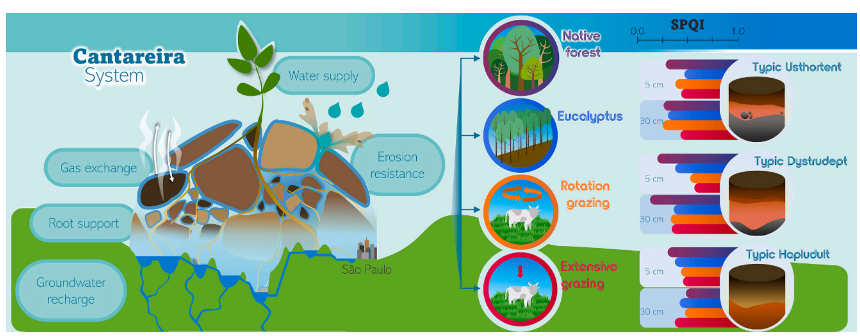
Monna Lysa Teixeira Santana [a], Flávia Franco dos Santos [a], Karine Maciel de Carvalho [a], Devison Souza Peixoto [a], Alexandre Uezu [b], Junior Cesar Avanzi [a], Milson Evaldo Serafim [a,c], Márcio Renato Nunes [d], Harold Mathias van Es [e], Nilton Curi [a], Bruno Montoani Silva [a,*]

[a] Department of Soil Science, Federal University of Lavras, Av. Doutor Sylvio Menicucci 1001, CEP 37200-900 Lavras, Minas Gerais, Brazil
[b] Faculty for Environmental Conservation and Sustainability (ESCAS), Institute for Ecological Research-IPÊ, 47 km Dom Pedro I hwy, Nazaré Paulista 12960-000, Brazil
[c] Federal Institute of Education, Science and Technology of Mato, Avenida Europa, n° 3000, Vila Real/Distrito Industrial, CEP: 78201-382 Cáceres, Mato Grosso, Brazil
[d] Soil, Water, and Ecosystem Sciences Department, University of Florida, Gainesville, FL 32611, USA
[e] Section of Soil and Crop Sciences, School of Integrative Plant Science, Cornell University, Ithaca, NY 14853, USA

HIGHLIGHTS

- The impact of land use on ecosystem services may be assessed by soil functions
- Soil properties constitute the key for a correct assessment of soil physical quality using the Nexus approach
- Change from native forest to anthropogenic explorations negatively impacts soil quality at topsoil due to soil compaction
- Soil types determine water recharge potential in the Cantareira System
- Conservation priority areas should additionally consider intrinsic factors

GRAPHICAL ABSTRACT



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ABSTRACT

Most of the soil quality assessment protocols are focused on crop production and conservation management, while studies on vital soil functions, such as water recharge potential, should be incorporated into 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 that drive water recharge potential, biomass production, and water erosion in the Cantareira System, Brazil. The assessment considered three soils (Typic Hapludult, Typic Dystrudept, and Typic Usthortent) and four land uses

Abbreviations: ES, ecosystem service; NF, native forest; E, eucalyptus; RG, rotational grazing; EG, extensive grazing; BD, soil bulk density; MAC, macroporosity; MIP, microporosity; AWC, available water capacity; RFC, relative field capacity; DP, drainable porosity; K_{sat}, saturated hydraulic conductivity; BIR, basic infiltration rate; SSI, structural stability properties; GMD, geometric mean diameter; PR, penetration resistance; SPQI, soil physical index.

* Corresponding author.
E-mail addresses: monnalysa@gmail.com (M.L.T. Santana), flaviafranco1995@gmail.com (F.F. dos Santos), karine_engagri@gmail.com (K.M. de Carvalho), devison.speixoto@gmail.com (D.S. Peixoto), aleuezu@ipe.org.br (A. Uezu), junior.avanzi@ufla.br (J.C. Avanzi), milson.serafim@ifmt.edu.br (M.E. Serafim), marcionunes@ufl.edu (M.R. Nunes), hmv1@cornell.edu (H.M. van Es), ntcuri@gmail.com (N. Curi), brunom.silva@ufla.br (B.M. Silva).

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Soil structure
Nexus approach

(native forest, rotational grazing, extensive grazing, and eucalyptus), which constitute the main soils and land uses in the Cantareira System region. Representative soil samples were collected at 0–5 and 30–35 cm depth and analyzed for several soil physical quality indicators, which were used to calculate a Soil Physical Quality Index based on soil functions. Converting the native forest to eucalyptus and pasture reduced the overall soil physical quality and water recharge potential. The groundwater recharge potential function in the topsoil has the highest score of 0.72 for Typic Dystrudept in native forest contrasting with 0.16 for extensive pasture. Typic Dystrudept obtained the highest value of the SPQI value (0–5 cm: 0.85; 30–35 cm: 0.90) for native forests when compared to Typic Hapludult (0–5 cm: 0.76; 30–35 cm: 0.57) and Typic Usthortent (0–5 cm: 0.75; 30–35 cm: 0.72). Our findings sustain that land use effects on soil functions depends on soil type. Inclusion of soil type into the Nexus approach increases the understanding of natural resources and derived benefits of water, energy and food in the Cantareira System.

1. Introduction

Soil is a complex system that plays a crucial role in ensuring food security, providing ecosystem services, mitigating climatic changes, protecting landscapes, and promoting human development. The concept of soil health has been embraced to better understand the effectiveness of sustainable management (Karlen et al., 2019). It 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 uses to sustain plant and animal production (Doran and Zeiss, 2000). Although it is often considered 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; Bünemann et al., 2018). It encompasses the impact of soil on water quality, plant, and animal health, and the maintenance or improvement of provisioning services (Hatfield et al., 2017; Serafim et al., 2019), regulation (de Sosa et al., 2018), and support (Ferreira et al., 2019).

Within this framework, the water-food-energy Nexus represents an integrated perspective on 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 has gained prominence in the international community as a response to climatic changes and social shifts, including population and economic growth, globalization, and urbanization (Hoff, 2011). The Nexus perspective has been considered in studies from year 2011 (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 still a gap concerning the approach to soil functioning (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), which 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., 2021). Therefore, the evaluation of soil functions should be based on a combination of soil properties and processes that are correlated with the specific soil functions of interest (Bünemann et al., 2018; Nunes et al., 2018; Rabot et al., 2018). For example, soil structure and derived physical properties are related to water infiltration, redistribution, plant uptake and drainage processes, thereby impacting soil functions such as biomass production, water erosion, and water recharge potential.

The assessment of soil functions related to water recharge potential is of paramount importance for stakeholders within the Cantareira Water Supply System in Brazil. It stands as one of the world's largest water supply systems, having the capability to provide water to the metropolitan region of São Paulo, Brazil with approximately 6 million users (SABESP, 2022). This area constitutes a biodiversity hotspot of the Atlantic Forest biome. During the period from 2013 and 2015, the Cantareira Water Supply System faced its most severe water scarcity crisis, experiencing precipitation levels of only 67 % of the 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). This water crisis can in part be attributed to significant deviations in precipitation patterns and temperature trends observed in recent years (Chiodi et al., 2021; Nobre et al., 2016). Taking into account the expansion of agricultural and livestock activities for food and energy production, the identification of priority environments for water recharge potential in large reservoirs remains a challenge (Chiodi et al., 2021; de Freitas et al., 2022).

The integrated assessment of intrinsic and dynamic soil properties and their interactive impacts on soil functions are crucial to guiding land use and management practices to sustain or enhance soil functionality. In addition, the synthesis of qualitative and quantitative soil information using soil quality indices is highly valuable to better understanding the land use and management threats and their impacts on soil functions (Bünemann et al., 2018). Based on the Karlen and Stott (1994) approach, soil quality may be evaluated via a tool, a statistical- or expert-based index based on additive functions (Silva-Olaya et al., 2022; Simon et al., 2022), which may be focused on soil physical quality (SPQI) using soil properties related to soil structure. The SPQI has been employed to assess land use changes across diverse scenarios, enabling the evaluation of soil functions related to supporting plant root growth, providing water for plants, facilitating gas exchange between the soil and atmosphere, increasing resistance to water erosion and preventing soil degradation (Cherubin et al., 2016; Bieluczyk et al., 2023; Barbosa et al., 2019; Alvarenga et al., 2012). In our study, the assessment expands on previous studies by evaluating, for the first time, groundwater recharge potential as an additional soil function within the Cantareira Water Supply System. Also, the soil type was included as an intrinsic factor of soil functions, which may interact with land uses and drive changes (Bagnall et al., 2022; de Paul Obade and Lal, 2016; Bilgili et al., 2017; Lisboa et al., 2019). This has been sparsely researched in Brazil with only 5 papers on “soil quality/health” discussing soil type as an inherent factor and mainly in terms of texture variation (Simon et al., 2022).

In this context, our main hypotheses were: (i) the conversion of native vegetation areas to food and energy production (i.e., pasture and reforestation) decreases soil quality and water recharge potential; (ii) rural farmers' initiatives to adopt better pasture management practices (i.e., rotational instead of continuous grazing) contribute to the improvement of ecosystem services; and (iii) for the same land use, soil type influences the soil quality index for water recharge potential and water erosion functions. Thus, we aimed to: (i) evaluate the physical properties linked to relevant soil ecosystem services in the Cantareira Water Supply System within the predominant land uses and management systems (native forest, eucalyptus, rotational and continuous grazing) on three soil types (Typic Hapludult, Typic Dystrudept, and Typic Usthortent); (ii) evaluate the water recharge potential based on intrinsic soil properties, and (iii) assess soil quality via Soil Physical Quality Index (SPQI) and multivariate analyses 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 towns of Piracaia (23°01′39″ S 46°19′35″ W, altitude of 840 m), Nazaré Paulista (23°12′20″ S 46°21′12″ W, altitude of 800 m) and Joanópolis (22°56′16″ S 46°05′50″ W, altitude of 1200 m). The Cantareira System encloses livestock (46 %), native forest (35 %), planted forestry (16 %), and reservoirs and water bodies (3 %), in an area of about 2300 km^2, with a slope ranging from 0 to 66° (Uezu et al., 2017). The native vegetation is represented by Atlantic Forest. Degraded pastures are prevalent in the region, resulting in insufficient biomass production for effective land protection and exposing the soil to erosion. Each studied site was selected based on representative land uses and management systems adopted by local farmers - native forest, eucalyptus, rotational grazing, and extensive grazing. *Eucalyptus grandis* and *E. saigna* have been harvested every 5 to 7 years, and the spacing varies between 3 × 3 m and 3 × 3.5 m. Extensive grazing has been established at 30 years ago, using *Urochloa brizantha* and *U. decumbens*, *Megathyrsus maximus*, and *Setaria anceps*, with a rate of 0.7–1.7 AU ha^{-1}, without ameliorants addition. Rotational grazing has been introduced at 2014, incorporating species such as *Urochloa brizantha*, *U. decumbens*, *Megathyrsus maximus*, and *Setaria anceps*, with a rate of 1.5–3.0 AU ha^{-1} and paddock in the rotation of 2 to 3 days.

The geology is mainly represented by gneiss. The predominant climate in the region is framed as Cwb (Köppen), with cool and dry winters and hot and humid summers (Alvares et al., 2013). The average annual rainfall is 1570 mm and annual temperatures range from 18 to 20 °C (Uezu et al., 2017). The studied soils were classified as Typic Hapludult, Typic Dystrudept, and Typic Usthortent, according to the US Soil Taxonomy (Staff, 2014), or Red Yellow Argisol, Haplic Cambissol and Regolitic Neossol according to the Brazilian Soil Classification System (Santos, 2018).

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 trenches (40 × 40 × 40 cm), in a total of 12 sampling points (3 soils × 4 land uses). Disturbed and undisturbed soil samples were collected at 0–5 and 30–35 cm within each sampling point. 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 sampling process to differentiate the subsurface of soil types' potential to impact water recharge.

At each sampling point and soil layer, four disturbed samples were collected to measure particle size distribution and organic matter content (Table 1). Four undisturbed samples were also collected using 2.5 cm in height × 6.3 cm diameter steel cylinders to measure soil bulk density, macroporosity, available water capacity, relative field capacity, and drainable porosity. Additionally, five undisturbed samples were collected using 8.0 cm height × 6.4 cm diameter steel cylinders to measure saturated hydraulic conductivity. Penetration resistance (PR, 10 replicates) and basic infiltration rate (BIR, 3 replicates) were measured around the sampling point.

In the laboratory, the soil samples were water-saturated during 24 h by capillary action and weighed after that. Following, samples were subjected to a −6 kPa matric potential using an automated tension table. After reaching equilibrium, samples were weighed and oven-dried at 105 °C for 24 h to determine the dry soil mass (Teixeira et al., 2017). Soil bulk density (BD, Mg m^{-3}), total porosity (water content at saturation, m^3 m^{-3}), and soil microporosity (MIP, m^3 m^{-3}) were determined according to Dane and Topp (2002). MIP was determined by the soil water

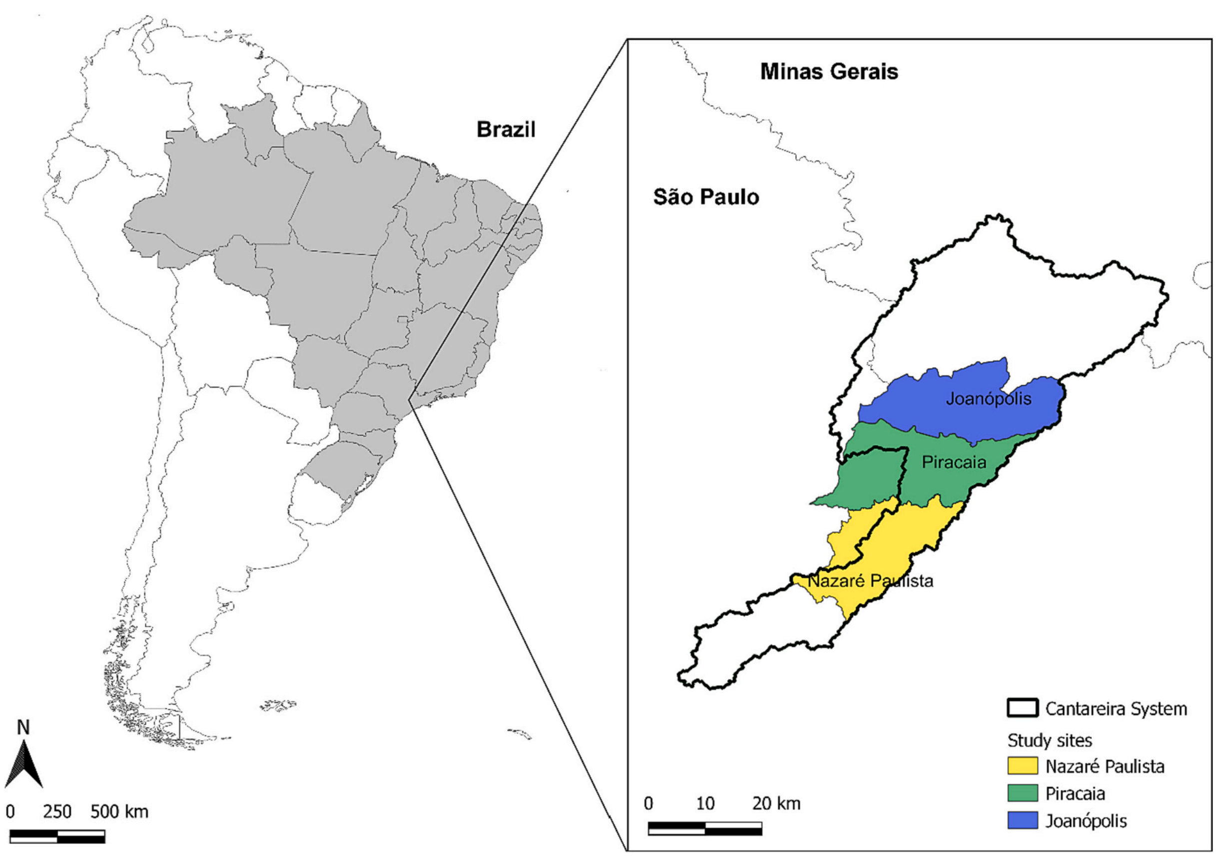

Fig. 1. Location of the Cantareira System and study sites.

Table 1
Soil classification and attributes under native forest (NF), eucalyptus (E), rotation grazing (RG), and extensive grazing (EG).

Town	Soil classification[a]	Land use	Depth	Clay	Silt	Sand	SOM.[b]
			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

Particle size distribution: determined from soil samples by the hydrometer method (Gee and Bauder, 2002).
[a] US soil taxonomy.
[b] SOM: soil organic matter – oxidation with $Na_2Cr_2O_7$ + 4 N + H_2SO_4 10 N.

content at the matric potential of −6 kPa. Macroporosity (MAC, m^3 m^{-3}) was calculated by the difference between total porosity and microporosity (Reynolds et al., 2008).

Plant available water capacity (AWC, m^3 m^{-3}) was calculated by the difference between the water content at field capacity (θ_{FC}) and at permanent wilting point (θ_{PWP}) (White, 2006). The θ_{FC} was based on the equilibrium water content at −10 kPa matric potential using on an automated tension table (Ecotech, Germany), and the θ_{PWP}, was based on the equilibrium water content at −1500 kPa matric potential using a Richards Porous Plate Extractor (Soil Moisture Equipment Corp, USA). The obtained values were framed according to Reynolds et al. (2009) in terms of maximum root growth and function as: AWC values exceeding 0.20 m^3 m^{-3} - ideal; AWC values between 0.15 and 0.20 m^3 m^{-3} - good; AWC values between 0.10 and 0.15 m^3 m^{-3} – limited; and AWC values above 0.10 m^3 m^{-3} - poor or dry.

Relative field capacity (RFC, m^3 m^{-3}), which indicates the soil's ability to store water and air relative to total porosity, was determined by according to 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 field capacity at −10 kPa matric potential (m^3 m^{-3}), θ_S is the total porosity based upon the saturation water content (m^3 m^{-3}), and AC is the aeration capacity (m^3 m^{-3}). The optimum balance to provide air and water for maximum root growth and function occurs 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 (Beltran, 1986; Pizarro, 1985). The DP was calculated according to Otto (1988) (Eq. (2)):

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

Saturated hydraulic conductivity (K_{sat}, cm h^{-1}) was determined with a constant-charge permeameter (Klute, 2015). The values were based on Darcy equation (Eq. (3)) and were corrected for a temperature of 20 °C (Eq. (4)):

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

where $K_{sat,T}$ is the saturated hydraulic conductivity (cm h^{-1}) measured at temperature T, 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 above the soil sample (cm), and t is the percolation time (t).

$$K_{sat} = K_{sat,T} \times \left(\frac{\mu_T}{\mu_{20}}\right), \tag{4}$$

where K_{sat} is the K_{sat} at 20 °C, μ_T is the water viscosity at the measured temperature, and μ_{20} is the water viscosity at 20 °C.

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

$$I = K \times t^a, \tag{5}$$

where I is the infiltration rate (cm min^{-1}), t is the time (min), and K and a are the empirical constants 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)):

$$SSI = (1.724 \times SOC)/(Silt + Clay) \times 100, \tag{6}$$

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

Aggregate stability was measured according to the methodology of

Yoder (1936), modified by Grohmann (1960), and the geometric mean diameter (GMD, mm) of stable aggregates were assessed after wet sieving. The 10 × 10 × 10 cm undisturbed samples were collected from each sampling site and soil layer, passed through 8- and 4-mm meshes sieves, being the analysis performed only on the material retained in the last sieve (4 mm). Then. the samples were transferred to a set of 4.76, 2.00, 1.00, 0.50, and 0.25 mm sieves and were vertically shaken during 15 min, at 42 oscillations per minute. So, the material retained in each sieve was oven-dried at 105–110 °C to determine the soil dry mass in each aggregate size class and the geometric mean diameter (GMD, mm) of aggregates was calculated (Eq. (7)):

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

where W_i is the weight of the sample of each aggregate size class (g), and D_i is the mean diameter of the i_{th} class of aggregates (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 having an angle of 30° was used, as described in detail by Stolf (1991) and Vaz et al. (2011). Due to the known high spatial variability and consequence influence on soil water content (Benevenute et al., 2020; Peixoto et al., 2019), ten repetition points were selected for each sampling point aiming to evaluated the soil water content close to the field capacity. Soil moisture at each sampling point was determined by the gravimetric method. PR data were discretized into 0–15 and 15–35 cm depths using an electronic spreadsheet (Stolf et al., 2014).

2.3. Calculation of the soil physical quality index (SPQI)

The soil physical quality index was calculated based on Karlen and Stott (1994) and Cherubin et al. (2016). Soil physical indicators were selected to assess five representative soil physical functions for the maintenance of ecosystem services, namely: (i) support root growth (*supp. root*); (ii): supply water for plants (*suppl. water*); (iii): allow gas exchange between soil and atmosphere (*allow gas exch.*); (iv): resistance to erosion (*resist. erosion*), and (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 SPQI (Cherubin et al., 2016; Alvarenga et al., 2012). For f(*supp. root*) BD and PR were used; for f(*suppl. water*), K_{sat}, AWC, and RFC were considered; for f(*allow gas exch.*), MAC and SSI were employed; for f(*resist. erosion*), GMD, SSI, and BIR were applied; and for f(*suppl. water*), DP, BIR, and K_{sat} were used.

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 favorable or unfavorable in terms of soil function. For "more is better" indicators (MAC, K_{sat}, 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 it received a 1 score. For "optimum" indicators (AWC and RFC), observations were scored as "more is better" up to a threshold, and "less is better" above the threshold (AWC = 0.20 and 0.60 < RFC < 0.70, respectively) (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 literature, to certain indicators that have a greater influence on each function were assigned different weights (for BD and PR a weight of 0.50 was assigned; and for K_{sat}, AWC, RFC, MAC, SSI, GMD, BIR, and DP a weight of 0.33 each was assigned). These weighted scores were added to calculate the SPQI.

2.4. Statistical analyses

The mean values for the various indicator scores were compared among the four groups, defined by land use within each location (soil type) and soil layer, by analysis of variance (ANOVA) followed by Tukey tests ($P < 0.05$) to examine 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 at the surface layer (Fig. 2A). Overall, extensive grazing had the highest BD values. The NF had the lowest BD in all soil types, except at the subsurface layer of the Typic Hapludult, which has a naturally denser layer (accumulation of illuvial clay) starting at this depth. 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 at the subsurface layer. At the surface layer, the Typic Dystrudept followed an increasing order of BD encompassing NF < E < RG < EG, and at 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, independently of soil layer (Fig. 2B). The MAC values ranged from 0.09 to 0.24 m^3 m^{-3} at the topsoil, and from 0.07 to 0.29 m^3 m^{-3} at the subsurface layer. Although statistical differences were observed, the AWC (Fig. 2C) did not present limiting values for root growth, with values being framed as good and ideal (Reynolds et al., 2009). In the Typic Hapludult, only the soil under eucalyptus showed statistically lower AWC at the surface layer. Considering soil under pastures, higher AWC values were observed 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. At the subsurface layer, only the Typic Hapludult showed differences among land uses, with eucalyptus also presenting the lowest average values.

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

In general, soils under native forest showed the highest K_{sat} values, which were significantly higher than the other land uses at the surface layer (Fig. 4A). At the subsurface layer, significant differences were observed among land uses only in the Typic Dystrudept, also with native forest showing the highest K_{sat}. In the Typic Hapludult, the BIR of land use with 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 land use with native forest. The BIR was not able to differentiate the rotational from extensive pasture land use, both showing the lowest values.

The highest SSI values were found in NF areas, mainly at the superficial soil layer (Fig. 5A). In all land uses, SSI was influenced by soil depth. At the surface layer, the NF in Typic Dystrudept was the only land which presented SSI > 9 %, while land uses E (Typic Hapludult), RG, and ER (Typic Dystrudept) had SSI values lower than 5 %. All land uses in the Typic Usthortent showed SSI values < 5 %. At the subsurface soil 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 at the superficial soil layer, presenting high values ranging from 4.40 and 4.84 mm. At soil subsurface layer, extensive grazing in Typic Hapludult differed from the other land uses, and the rotational grazing was associated with lowest GMD, while native forest and eucalyptus did not show statistical differences between them. The Typic Dystrudept and the Typic Usthortent soils showed statistical differences

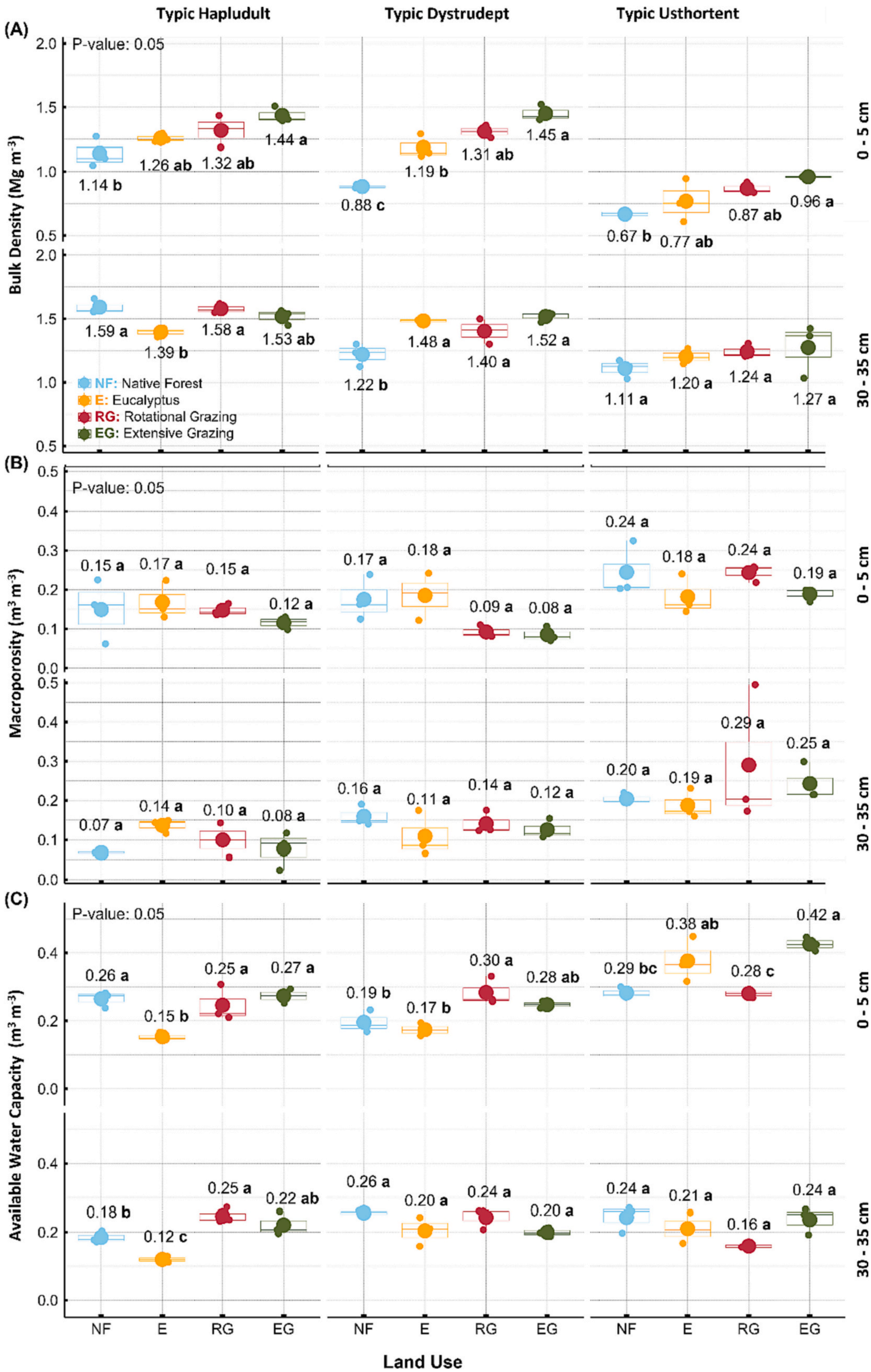

Fig. 2. Soil bulk density (A), macroporosity (B), and available water capacity (C) under native forest (NF), eucalyptus (E), extensive grazing (EG), and rotational grazing (RG). Means followed by the same letter do not differ significantly between land uses according to Tukey's test.

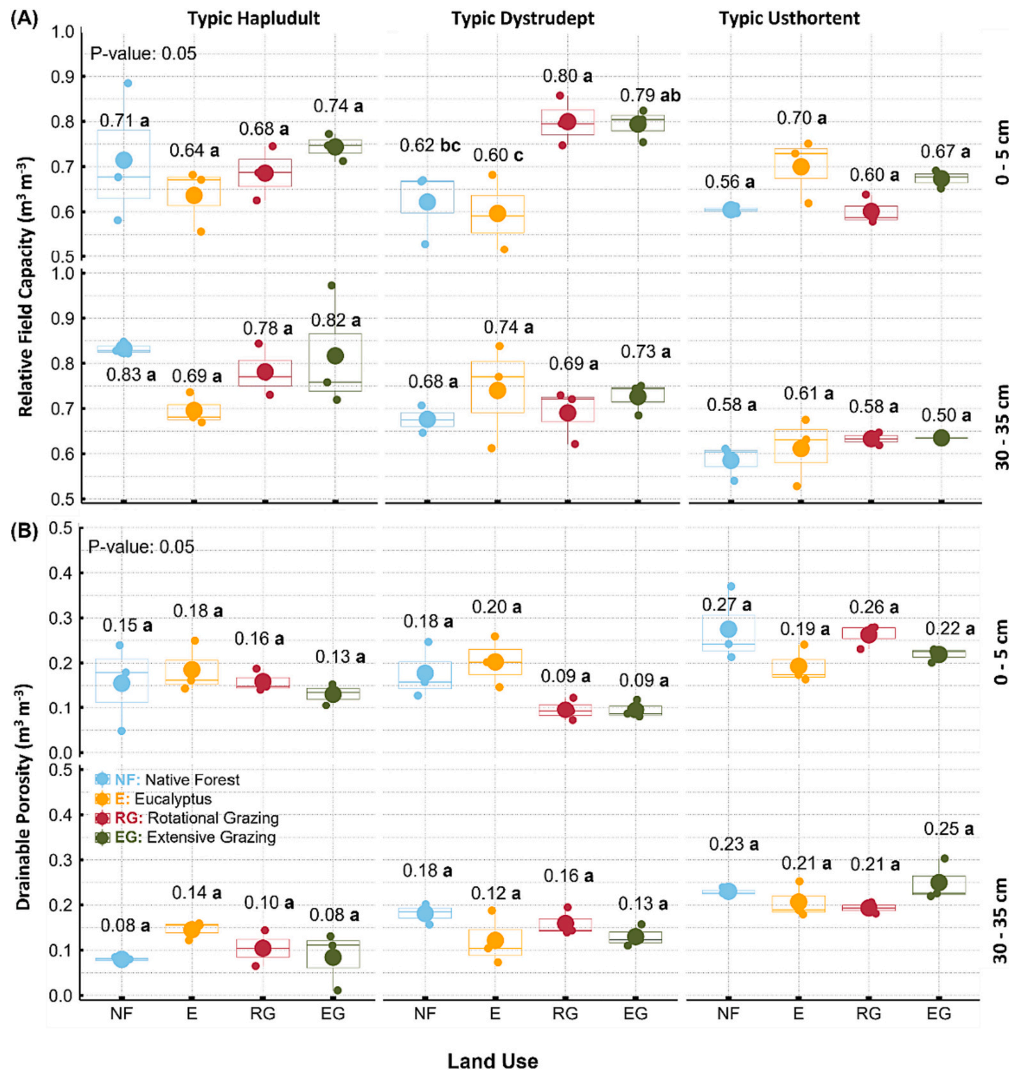

Fig. 3. Relative field capacity (A) and drainable porosity (B) under native forest (NF), eucalyptus (E), extensive grazing (EG), and rotational grazing (RG). Means followed by the same letter do not differ significantly among land uses according to Tukey's test.

among native forest and the other land uses, where the land use under pastures showed higher GMD values. However, all land uses displayed GMD values exceeding 4 mm.

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

Table 2 presents the overall scores for each function and SPQI for the 0–5 cm and 30–35 cm soil layers. For the supporting root growth function, the highest index values for the surface layer were found under NF for the Typic Dystrudept and Typic Usthortent. For the supplying water for plants function, 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 at both soil layers, even in NF areas. 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 soil layers, respectively. Regarding the gas exchange function, there was a significant difference among land uses for the Typic Dystrudept in the 0–5 cm soil layer, and for the Typic Hapludult at the 30–35 cm soil layer. For the resistance to erosion function, there was a difference among land uses in all soils and layers, except for the 30–35 cm layer of the Typic Usthortent. At the surface layer, the index of groundwater recharge potential function was significantly lower for EG than NF areas in all soils. For the Typic Dystrudept and Typic Usthortent, the groundwater recharge potential function decreased more when NF areas were changed to anthropic land uses. At the subsurface soil 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 areas was higher than the other land uses and the index for RG areas was superior than E and EG land uses.

Regarding the SPQI, a significant difference among land uses was found at the surface soil layer, where the index for NF areas was higher for all three soils. At 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 than the other land uses.

Principal component analysis (PCA) showed that the relationships between the soil physical properties and soil functions vary by land use and soil type. At 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, which was mainly influenced by the high values of soil bulk density. For Typic Dystrudept (Fig. 6B), ellipses for native forest and

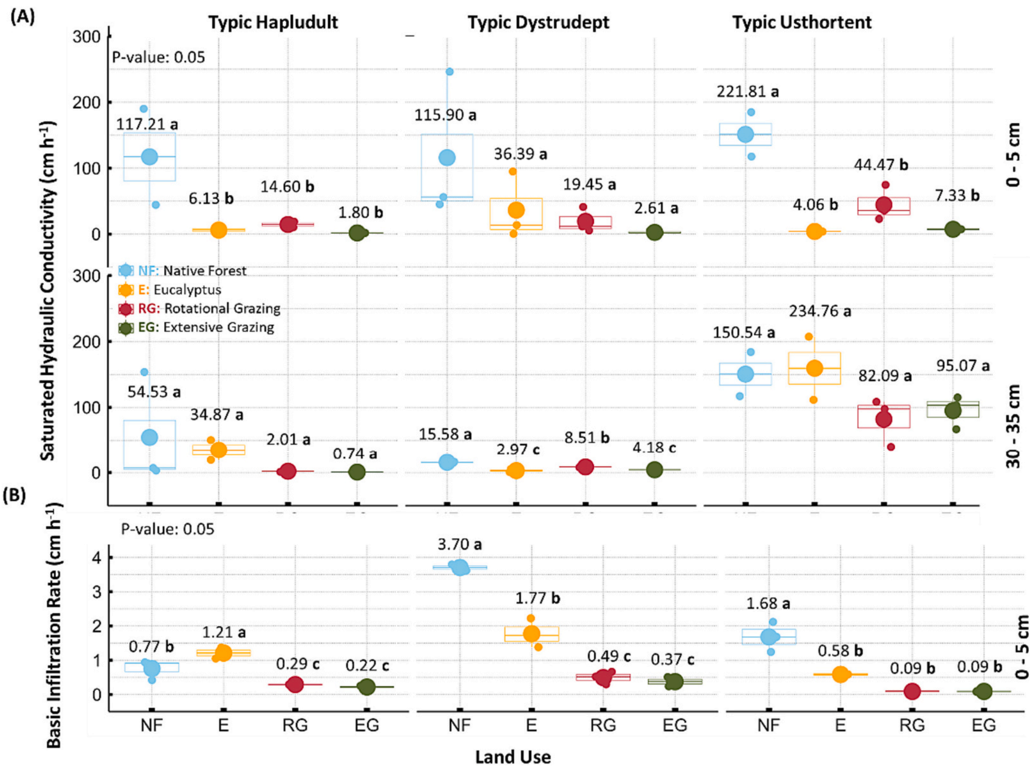

Fig. 4. Saturated hydraulic conductivity (A) and basic infiltration rate (B) under native forest (NF), eucalyptus (E), extensive grazing (EG), and rotational grazing (RG). Means followed by the same letter do not differ significantly among land uses according to Tukey's test.

eucalyptus areas were more similar than the ellipses for the two pastures systems, due to SPQI and soil functions. For Typic Usthortent (Fig. 6C), all land uses were grouped into different ellipses. Native forest areas were distinguished from the other land uses by all functions (mainly root growth support), for the except resistance to erosion function. Also, the highest BIR values were found for the native forest areas. At the 30–35 cm layer, soil type also influenced the SPQI and soil functions among land uses. Native forest areas were grouped apart from the other land uses in Typic Hapludult (Fig. 6D) and Typic Dystrudept (Fig. 6E) soils, with high influence on the supplying water function. For Typic Usthortent soil (Fig. 6F), it was not possible to differentiate among land uses, since all the ellipses were crossed.

4. Discussion

Well-functioning soils are expected to provide food and clean water, while buffering climatic changes and protecting natural resources. This assessment provides information that helps to understand how crucial soil functions respond to anthropogenic processes and their interactions with natural factors in the Cantareira System, Brazil. Overall, results showed that: (i) both intrinsic (soil type) and dynamic (land use and management) factors drive soil functions (e.g., water recharge potential) 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 layer. Therefore, land use and management strategies for improving soil functionality in the Cantareira System, especially water recharge potential, should take into account the intrinsic factors like soil type.

Soil intrinsic factors influenced the SPQI and the groundwater recharge potential functions, reflecting soil formation and pedogenic processes. In addition, this assessment showed the value of combining several parameters to determine the SPQI. 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 this study, in association with several years of research, we verified the need to additionally consider the type of soil and layer in the assessment of ecosystem services.

At the surface layer, land use affected all response variables except MAC and DP, while at the subsurface layer, a significant effect of land use was observed only for MAC, RFC, and DP. This suggests a greater influence of land use on the surface soil layer compared to the subsurface layer (Serafim et al., 2019). Conversely, the impact of soil type was more relevant at the subsurface layer, where distinct pedogenetic variations are recognized since long time.

The differential response of the surface layer to land use changes, as compared to the subsurface layer, also reflects animal trampling leading to soil compaction (Bonetti et al., 2019). Soil structure degradation was observed in both rotational and extensive grazing, but it was more significant in extensive grazing. Even though the trampling intensity under extensive grazing is 4 to 5 times less than under rotational grazing, it still led to soil structure degradation. This may be attributed to reduced biomass addition and root activity under extensive grazing, which makes the soil more susceptible to trampling effects (Franzluebbers et al., 2012). In contrast, rotational grazing promotes a denser vegetation cover and higher soil organic matter content, thereby enhancing the soil's load-bearing capacity within a range of elastic deformations, as well as resilience to the impact of animal traffic.

The native forest showed greater structural stability at the surface layer than the other land uses (no differences for the Usthortent soil), which is partly explained by its higher carbon content and microbial activity (de Brito et al., 2019; Reynolds et al., 2009). In contrast, the subsurface layers show minimal differences among land uses, characterized by low values of SSI, which were influenced by its low carbon content. Besides soil aggregation, conversion of native forest to other land uses also affected other soil processes. For instance, saturated hydraulic conductivity at the surface layer was generally higher under the native vegetation than in the other land uses. This is a tradeoff of converting native forests into managed agriculture systems (Horel et al.,

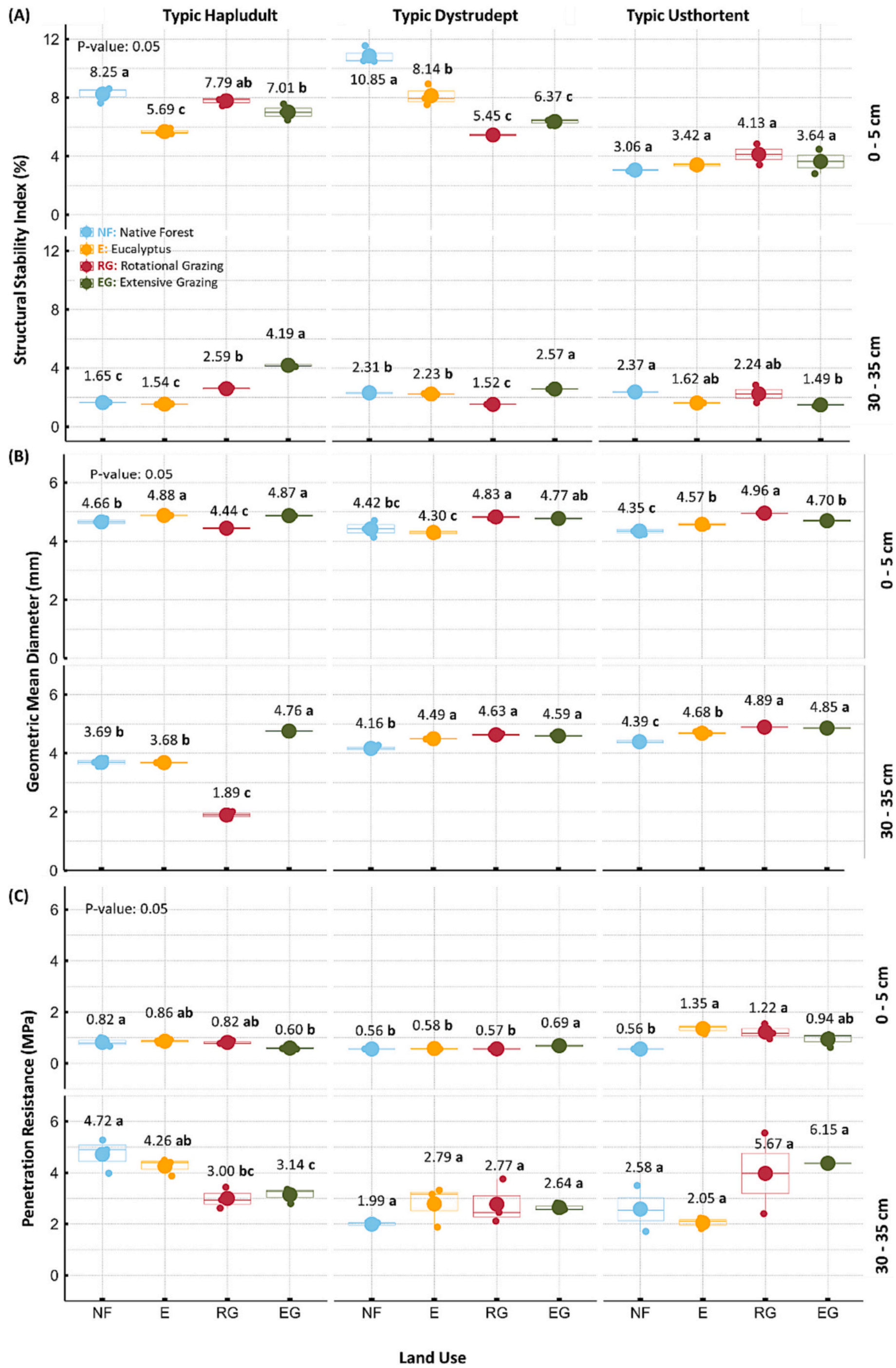

Fig. 5. Structural stability index (A), geometric mean diameter of aggregates (B), and penetration resistance (C) under native forest (NF), eucalyptus (E), extensive grazing (EG), and rotational grazing (RG). Means followed by the same letter do not differ significantly among land uses according to Tukey's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

2015; 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 abundance of macrofauna components in eucalyptus (Boeno et al., 2019) and the replacement of long forest roots by with shallow grass roots (Lal, 1996) may have contributed to reduce K_{sat}. At the subsurface layer this difference was significant only for the Typic Dystrudept soil, although NF was generally higher than other land uses. High variability in K_{sat} measurements and difficulty to determine statistically significant are commonly reported in the literature (Carvalho et al., 2022). Drainable porosity was not influenced by land use at the two soil layers. K_{sat} was a more insightful variable by measuring the actual hydraulic effectiveness of the pores, while drainable porosity relates only to the volume of pores without considering their tortuosity or interruptions (Batista et al., 2020).

Anthropogenic processes negatively influenced the basic infiltration rate in the Typic Dystrudept and the Typic Usthortent soils (Archer et al., 2013). Among them, eucalyptus was better than pasture areas, and in the Typic Hapludult soil it even surpassed native vegetation. These results confirm that water infiltration was not favored by pastures systems (Mello et al., 2019). Considering the increasing world interest in water production, the reduction of pasture areas within the watershed and/or a reduction in the animal stocking rate should be considered. Higher infiltration rates were observed in the eucalyptus areas compared to the pasture areas, including older eucalyptus plantations where there was

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 ($P < 0.05$).

time for the accumulation of roots and litter (Zhao et al., 2020). Although a high rate of water infiltration may be commonly observed in eucalyptus areas, and this should converge to an increase of the recharge of aquifers, attention should be paid to the cultivation systems carried out. The benefits of the eucalyptus forest for water recharge potential would more likely occur in plantations with low plant density and slow growth (Campoe et al., 2020).

Individual variables are very useful for diagnosis and land use planning mainly when focus on promoting soil water recharge potential. 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 Nexus perspective, encompassing water, energy, food, and soil, Moghadam et al. (2023) developed an indicator for the management of hydrographic basins. This indicator, ranging from 0 to 1, exhibits relatively low values for pastures (0.19) and higher values for almond plantations (0.78). This values disparity may primarily be attributed to the soil degradation from grazing and erosion. Specific variables related to the movement of water in the soil were more sensitive to land use environments for different soils. In this sense, although the index is important for understanding the overall quality of the environment, its application should be in line with the specific land use planning to promote water production.

For the general understanding of the effects of land uses on the environment, indices should be encouraged that represent sets of processes, such as the composite SPQI within the Nexus approach. The land uses with eucalyptus and extensive and rotational pastures result in a drastic reduction of this index for the three studied soils, mainly at the 0–5 cm soil layer. At the 30–35 cm soil layer, this trend was observed only in the Typic Hapludult soil, which seems to be associated with a well-developed blocky structure, resulting from illuvial clay accumulation. Such soil structure tends to present greater resilience to the effects of land use systems (Azevedo et al., 2023), compared to the incipient horizon of Typic Dystrudept and C horizon of Typic Usthortent.

5. Conclusions

This study comprehensively assesses soil quality through the interactions between soil physical properties under diverse land uses in the Cantareira System, Brazil. Natural soil variability is an important intrinsic factor for understanding and quantifying soil functions in the context of land use change. This contributed new insight in the Cantareira System and can assist in the determination of priority areas for conservation and restoration practices.

The conversion of native forest to anthropogenic land uses (eucalyptus and pasture) reduced the water recharge potential and the overall soil physical quality. The alteration of continuous grazing by rotational grazing as adopted by local farmers had a marginal benefit on promoting the ecosystem services in the Cantareira System. But soil types directly influence the water recharge potential of environments. The land uses effect depends on soil type and followed the decreasing order: Typic Dystrudept > Typic Usthortent > Typic Hapludult. Hence, Inceptisols were the most vulnerable and potentially need more conservation practices to maintain their water recharge potential function. Finally, our results provide evidence that the soil physical quality is sensitive to different land use and management systems, supporting decisions at farm level. The Nexus approach, taking into account the interdependence among water, energy, food, and soil systems, may optimize the use of natural resources in a sustainable and equitable manner.

CRediT authorship contribution statement

Monna Lysa Teixeira Santana: Conceptualization, Methodology, Formal analysis, Writing – original draft, Writing – review & editing. **Flávia Franco dos Santos:** Conceptualization, Formal analysis, Writing – review & editing. **Karine Maciel de Carvalho:** Conceptualization, Formal analysis, Writing – review & editing. **Devison Souza Peixoto:** Conceptualization, Methodology, Formal analysis, Writing – review & editing. **Alexandre Uezu:** Conceptualization, Methodology, Writing – review & editing. **Junior Cesar Avanzi:** Conceptualization, Methodology, Formal analysis, Writing – review & editing, Supervision. **Milson Evaldo Serafim:** Conceptualization, Writing – review & editing. **Márcio Renato Nunes:** Conceptualization, Writing – review & editing. **Harold Mathias van Es:** Conceptualization, Writing – review & editing, Supervision. **Nilton Curi:** Conceptualization, Writing – review & editing. **Bruno Montoani Silva:** Conceptualization, Methodology, Formal analysis, Writing – original draft, Writing – review & editing,

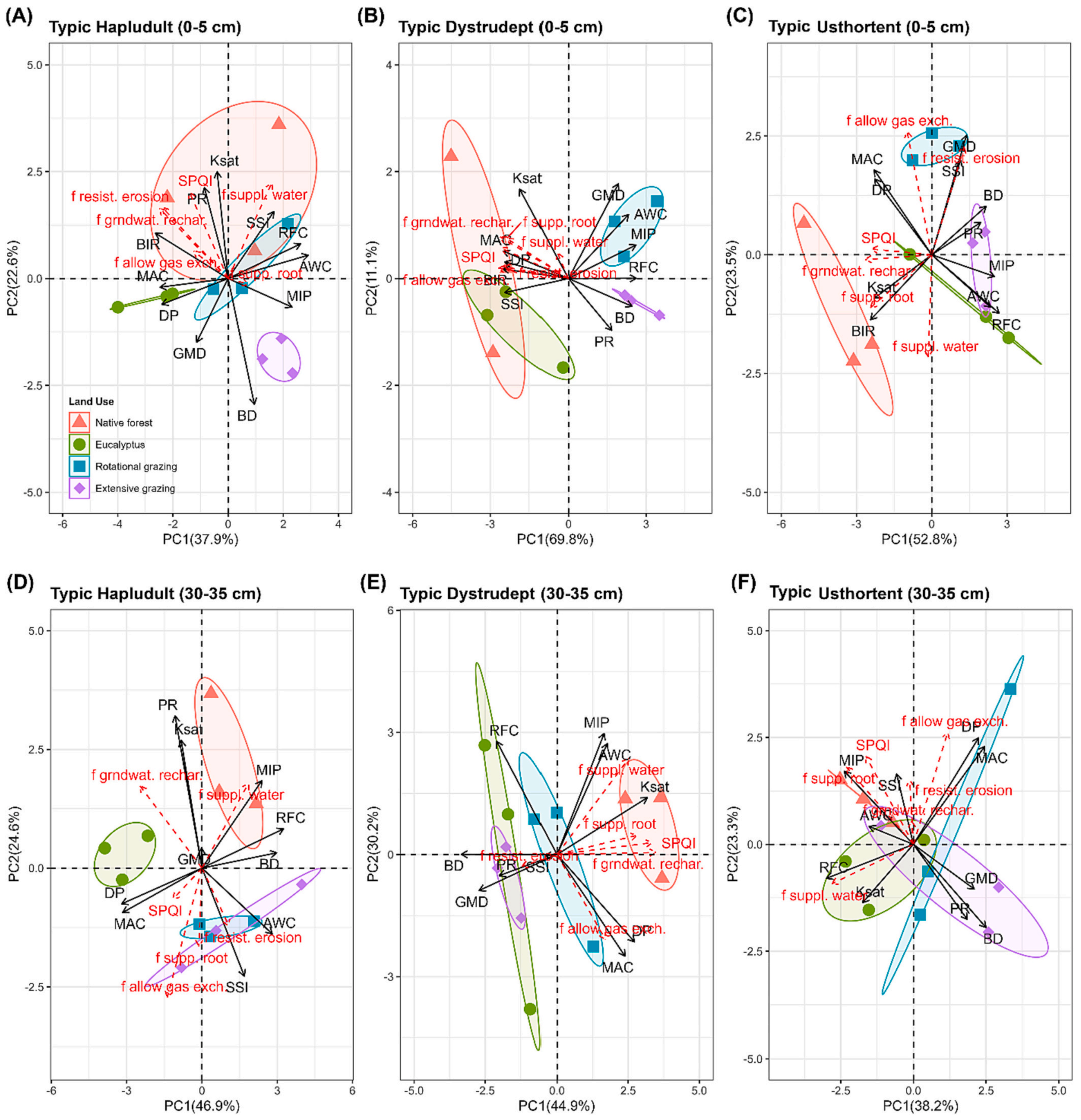

Fig. 6. Principal component analysis for Typic Hapludult at 0–5 cm (A) and at 30–35 cm depth (D), Typic Dystrudept at 0–5 cm (B) and at 30–35 cm depth (E), and Typic Usthortent at 0–5 cm (C) and at 30–35 cm depth (F). BD: soil bulk density; RP: resistance to penetration; Ksat: saturated hydraulic conductivity; AWC: available water capacity; RFC: relative field capacity; MAC: macroporosity; MIP: microporosity; GMD: geometric mean diameter of aggregates; 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 to erosion; groundwater recharge potential.

Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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