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Impacts of Land Use Changes on Soil Functions and Water Security: Insights from a Three-Year-Long Study in the Cantareira System, Southeast of Brazil

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Abstract: Maintaining soil functions is crucial for human well-being, but there is a lack of integration between soil, water security, ecosystem services, and climate change. To bridge this knowledge gap and address erosion-induced soil and water losses and considering intrinsic impacts of soil structure, a three-year-long study was conducted focused on three dominant soil types (Typic Hapludult, Typic Dystrudept, and Typic Usthortent) combined with different land uses (native forest, eucalyptus plantation, rotational grazing, and extensive grazing) in a critical water supply region for the São Paulo metropolitan area in Southeastern Brazil. Surface runoff, evaluated for erosion resistance, was measured using the Cornell infiltrometer, and soil electrical resistivity tomography estimated soil water content to a depth of 1.5 m for groundwater recharge analysis. Soil hydraulic properties were also measured. The results revealed that native forest soils had higher hydraulic conductivity, particularly in the surface layer, compared to eucalyptus and pastures. Native forests in Typic Hapludult showed a higher runoff rate (200 to 250 mm h^{-1}) due to a naturally dense subsoil layer that negatively impacted water infiltration and recharge with a high erosion potential, therefore reducing the amount of water stored. Typic Usthortent maintained a higher soil water content in pastures than in other land uses and also showed a low rate of water infiltration, resulting in perched water in the surface layer. In Typic Dystrudept, the native forest presented higher hydraulic conductivity (0–5 cm: 115.9 cm h^{-1}) than eucalyptus (0–5 cm: 36.4 cm h^{-1}), rotational grazing (0–5 cm: 19.4 cm h^{-1}), and extensive grazing (0–5 cm: 2.6 cm h^{-1}), but there were no significant differences in soil water content among land uses. This work illustrates the crucial role of native forests in affecting deep water recharge, reducing the soil surface erosion, mainly in soils without naturally subsoil layer, maintaining recharge potential. For Ultisols, pastures preserved soil structure and are therefore less impacted by soil management. With these results, a contribution is made to soil and water conservation, providing support for sustainable management practices in erosion-prone areas.

Keywords: ecosystem services; erosion resistance; groundwater recharge; soil security; land use

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1. Introduction

The soil is an essential component for human well-being, and its maintenance requires attention to ensure that it provides its ecosystem functions. Although the literature on the role of soils in providing ecosystem services (ESs) has grown recently, there is a lack of integration between soil, water security, and climate change [1,2]. 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 ESs [3–5], including water supply regulation, erosion control, and climate regulation.

Native forests play a critical role in preventing erosion due to their dense cover vegetation and root system which helps in the soil aggregation. Lense et al. [6] reported that a 12% rise in deforestation in the Xingu River watershed resulted in an astonishing 312% surge in erosion rates. This significant correlation underscores the critical role of native vegetation in erosion prevention and highlights the urgent need for its preservation. In addition, native forest is indispensable for global groundwater storage due to their deep-rooted trees which facilitate water transportation to deeper soil layers, enabling more extended storage periods before evaporation or absorption by plants [7,8]. However, several studies have reported that in temperate regions, soil covered with native forest has a lower overall water content during the dry season [9–11]. 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 [12–14].

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 layer of high bulk density may have limitations in water infiltration and, consequently, have more water runoff and lower water storage along the profile. Furthermore, clayey soils retain more water than sandy soils due to the latter presenting higher macropore continuity and greater water transport capacity throughout the entire profile, despite its increased susceptibility to erosion. Understanding these factors is essential for adequately managing soil water resources and promoting water security [15].

The Cantareira Water Supply System is a crucial water production area that provides several ecosystem functions to the metropolitan area of São Paulo, with emphasis on water supply, covering an area of approximately 2300 km^2 and extending to 75 cities in the states of Minas Gerais and São Paulo in Southeastern Brazil [16]. Livestock accounts for a large portion of land use within the Cantareira System, comprising 46% of the landscape. Native forests cover 35% of the area, plantation forests cover 16%, and reservoirs and water bodies represent 3%. In the region, there are widespread degraded pastures [16] 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 [17]. 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. Therefore, it is essential to constantly monitor the provision of ecosystem services and the mitigation of degrading actions in these areas for water recharge.

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 planted forest and pasture on the soil's ability to provide such services. Understanding the modification in soil functions due to land use change and intrinsic factors will be fundamental for formulating policies that promote sustainable development, soil conservation, maintenance of quality water supply, and payment schemes for water-related environmental services, as implemented in other parts of Brazil [5,18–20].

In this context, soil water infiltration and runoff surface are critical physical processes that respond to changes in soil structure as affected by management practices. Enhancing water infiltration conditions in the soil leads to reduced erosion and promotes underground aquifer recharge [21]. As it is linked to soil water dynamics, it serves as a vital indicator of agronomic performance and potential environmental impacts in a specific area. Once infiltrated, the water content can be monitored to facilitate decision-making and assist in understanding environmental recharge processes. For that, 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 [22]. 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 [23–26]. Furthermore, the acquisition of indicators related to soil hydrology has always been limited by methodological constraints [27]. In this regard, the Cornell sprinkler infiltrometer [28] has emerged as an alternative to simplify the process of measuring infiltration and surface runoff, without compromising the reliability of the results. This infiltrometer enables the monitoring and assessment of soil structural quality, providing valuable insights for soil and water conservation studies.

Therefore, the main hypotheses of this study are the following: (i) surface runoff may vary among different land uses and soil types with lower rates in the native forest; (ii) accurate estimation of soil water content and its spatial–temporal changes through electrical resistivity tomography might require specific calibration tailored to individual soil types; (iii) the spatial–temporal patterns of soil water content might potentially be affected by soil uses, and these patterns may also show discrepancies depending on the soil type. This study aimed (i) to evaluate surface runoff in soils under different uses; (ii) to model ρ–θ relationship in soils for θ estimation; (iii) to evaluate the temporal dynamics in contrasting soil types: Inceptisol, Ultisol, and Entisol; and (iv) to verify the land use effect on maintaining water content throughout the seasons and identify priority areas for preservation. In addition, the information obtained will contribute to the planning and proper management of water resources, promoting water security and ensuring the availability of quality water for the population and for the region's ecosystems.

2. Materials

Study Area

The study was established in the Cantareira water supply system in Southeastern Brazil, with sampling performed in the municipalities of Joanópolis (22°56′16″ S 46°05′50″ W, altitude of 1200 m), Nazaré Paulista (23°12′20″ S 46°21′12″ W, altitude of 800 m), and Piracaia (23°01′39″ S 46°19′35″ W, altitude of 840 m) (Figure 1). In each area, the representative land uses adopted by local farmers—native forest (NF), eucalyptus (E), rotational grazing (RG), and extensive grazing (EG)—were evaluated. The predominant climate in the region is classified as Cwb (Köppen) with cold and dry winters and hot and humid summers [29]. The average annual rainfall is 1570 mm, and yearly temperatures range from 18 to 20 °C [16]. The soils were classified as *Argissolo Vermelho Amarelo*, *Cambissolo Háplico*, and *Neossolo Regolítico*, according to the Brazilian System of Soil Classification [30], and as Ultisol (Typic Hapludult), Inceptisol (Typic Dystrudept) and Entisol (Typic Usthortent), according to Soil Taxonomy [31] (Figure 1).

In February 2019, disturbed and undisturbed soil were randomly sampled in trenches (40 × 40 × 40 cm) 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).

Particle size distribution in disturbed samples was determined by the hydrometer method [32]. Undisturbed samples were collected using steel cylinders (2.5 cm in height × 6.3 cm diameter) for the determination of soil bulk density (BD), total porosity (TP), macroporosity (MAC), and microporosity (MIP) [33,34]. The saturated hydraulic conductivity (KS) was measured with a constant-charge permeameter [35] in steel cylinders (8.0 cm in height and 6.4 cm diameter). Additional soil characterization and land use management information for each site is available in Santana et al. [36].

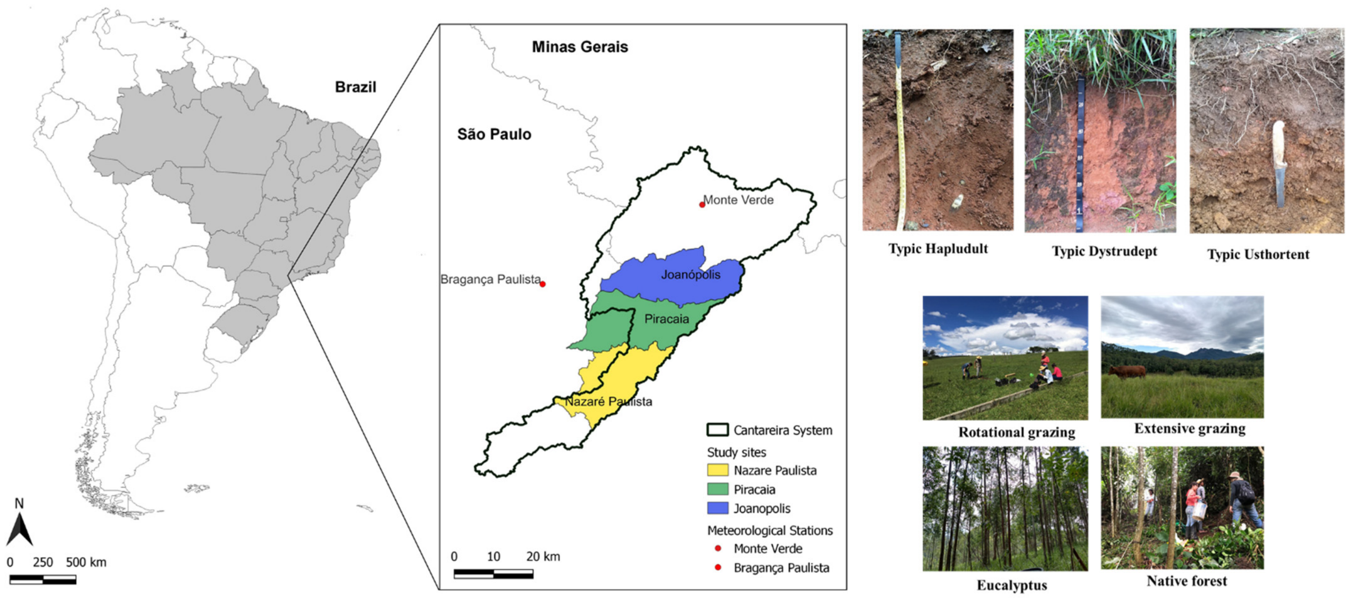

Figure 1. Location of the Cantareira System and study sites, soil types, and land uses. The gray color represents Brazil.

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	TP	MAC	MIP
		cm	-----------------%---------------			Mg m^{-3}	cm h^{-1}	--------------m^3 m^{-3}------------		
Typic Hapludult/ Piracaia/	NF	0–5	38	22	40	1.14	117.21	0.51	0.15	0.36
		30–35	45	18	37	1.59	54.53	0.48	0.07	0.41
	E	0–5	33	18	49	1.26	6.13	0.50	0.17	0.33
		30–35	56	15	29	1.39	34.87	0.48	0.14	0.34
	RG	0–5	23	16	61	1.32	14.60	0.51	0.15	0.36
		30–35	40	13	47	1.58	2.01	0.47	0.10	0.37
	EG	0–5	26	12	62	1.44	1.80	0.51	0.12	0.39
		30–35	28	15	57	1.52	0.74	0.45	0.08	0.37
Typic Dystrudept/ Nazaré Paulista	NF	0–5	36	15	49	0.88	115.90	0.46	0.18	0.29
		30–35	415	42	19	39	15.58	0.56	0.16	0.40
	E	0–5	33	14	53	1.19	36.39	0.50	0.19	0.31
		30–35	43	12	45	1.48	2.97	0.46	0.11	0.35
	RG	0–5	40	17	43	1.31	19.45	0.48	0.09	0.39
		30–35	46	14	40	1.40	8.52	0.51	0.14	0.37
	EG	0–5	34	19	47	1.45	2.61	0.46	0.09	0.37
		30–35	42	16	42	1.52	4.18	0.47	0.13	0.35
Typic Usthortent/ Joanópolis	NF	0–5	55	12	33	0.67	221.81	0.62	0.24	0.37
		30–35	29	20	51	1.11	150.54	0.56	0.20	0.35
	E	0–5	38	23	39	0.77	4.06	0.65	0.18	0.46
		30–35	45	32	23	1.20	234.76	0.53	0.19	0.35
	RG	0–5	43	16	41	0.87	44.47	0.66	0.24	0.41
		30–35	44	22	34	1.24	82.09	0.64	0.29	0.34
	EG	0–5	55	13	32	0.96	7.33	0.67	0.19	0.48
		30–35	27	17	56	1.27	95.07	0.52	0.24	0.27

BD: soil bulk density; KS: hydraulic conductivity; TP: total porosity; MAC: macroporosity (>0.05 mm); MIP: microporosity.

In order to characterize the weather patterns during the experimental campaign, agrometeorological data were obtained from the Meteorological Database for Teaching and

Research (BDMEP) of the National Institute of Meteorology [37]. Figure 2 depicts the weekly precipitation and the average monthly precipitation, which were measured at the two closest meteorological stations 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.

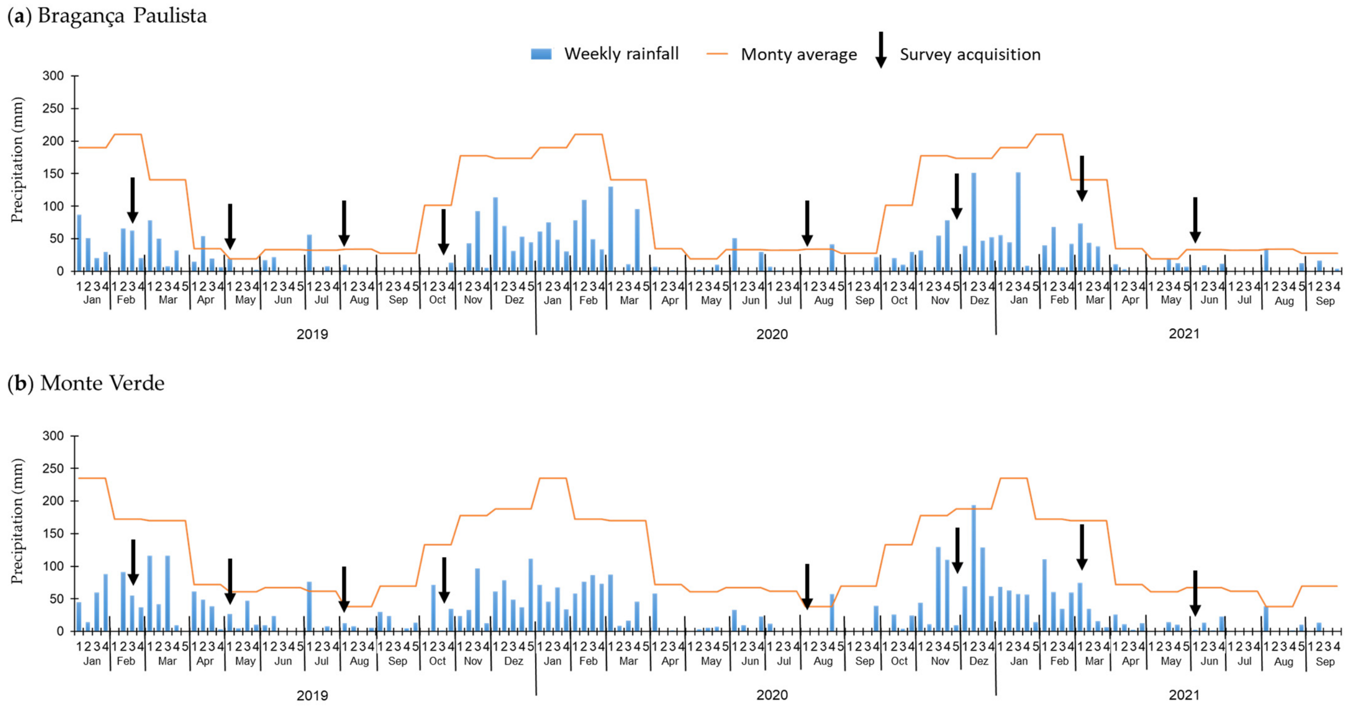

Figure 2. Weekly rainfall during the studied period in (**a**) Bragança Paulista (monthly average rainfall from 2004 to 2021); and (**b**) Monte Verde (monthly average rainfall from 2017 to 2021). The black arrows indicate the timing of the electrical resistivity tomography acquisitions.

3. Methods

3.1. Surface Runoff

Around sampling points, 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 et al. [28] using harvested rain. The infiltrometer is a portable rainfall simulator consisting of 69 drippers at the bottom with a diameter of 0.00063 m 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. A high intensity of rainfall was simulated in order to quantify the runoff.

The surface runoff was determined by Equation (1):

$$SR = [(V_t \times 1000)/(45{,}730 \times t)], \quad (1)$$

where SR is surface runoff (mm h^{-1}); V_t is water volume collected (mL); 45,730 is ring area (mm^2); and t is the time interval (hours) between the runoff collections (utilizing 0.05 h in this study).

3.2. Soil Electrical Resistivity Surveys

3.2.1. Description of ρ Measurements

The measurement of the soil electrical resistivity (ρ) was carried out in the study areas in the period of 2019 (summer, fall, winter, and spring), 2020 (winter and spring), and 2021 (summer and fall). 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 for the 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 soil type.

The ρ was directly measured with the X5xtal 250 Resistivity Meter (Auto Energia, Alvinópolis, MG, 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 [22]. 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):

$$\rho = (\mathrm{K} \times \Delta\mathrm{V})/\mathrm{I}, \quad (2)$$

$$\mathrm{K} = 2\pi\mathrm{a}, \quad (3)$$

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

3.2.2. Description of 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. [38]. 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, a Wenner arrangement (A–M–N–B) of electrodes [22] 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, Alvinópolis, MG, Brazil). The electrical conductivity of water was assumed constant during the measurement 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) [33]. The value of θ was calculated by Equation (4):

$$\theta = \mathrm{w}\ (\mathrm{BD}/\mathrm{Dw}), \quad (4)$$

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):

$$\theta = \mathrm{a}\ \rho^{\mathrm{b}}, \quad (5)$$

where a and b are fitting parameters (dimensionless).

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 R (3.6.1) statistical environment [39].

4. Results and Discussion

4.1. Runoff with Cornell Infiltrometer

Figure 3 illustrates the surface runoff obtained from the Cornell Sprinkle infiltrometer test. For Typic Hapludult (Figure 3A), it was observed that the native forest began producing runoff after 6 min, whereas the other land uses exhibited runoff in the initial minute. Upon reaching a plateau, the land uses showed runoff rates ranging between 200 and 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. Chittolina et al. [40] 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 [17].

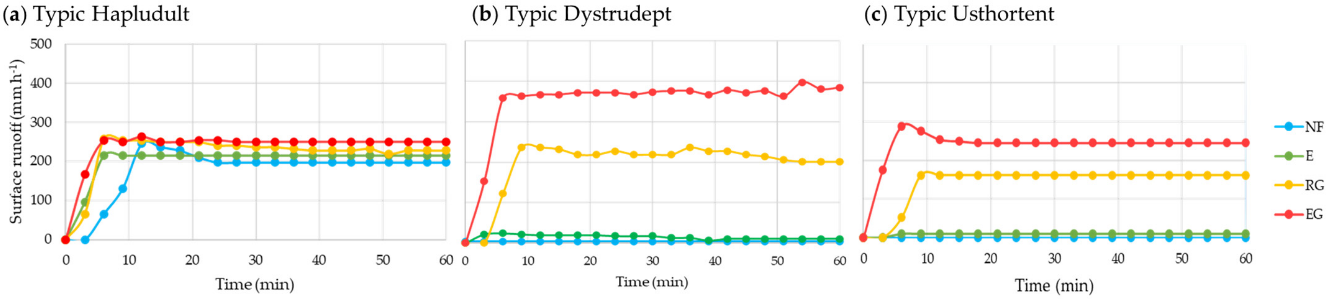

Figure 3. Surface runoff determined by Cornell Sprinkle infiltrometer for Typic Hapludult (**a**), Typic Dystrudept (**b**) and, Typic Usthortent (**c**), under native forest (NF), eucalyptus (E), rotational grazing (RG), and extensive grazing (EG).

The native forest for Typic Dystrudept showed low runoff rates (Figure 3B), with values of approximately 5 mm h^{-1}, and the eucalyptus-initiated runoff reached a plateau at 11 mm h^{-1} after 3 min. 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 [41], 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 erosion reduction, 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 de Menezes et al. [42] in the Mantiqueira Range Region, southern, Brazil.

There was no surface runoff observed in the native forest and eucalyptus for Typic Ustorthent (Figure 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 maintaining a plateau at 245 mm h^{-1}. Nevertheless, RG began producing runoff after 9 min 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. [43], 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 Inceptisol (Typic Dystrudept) and Entisol (Typic Usthortent), 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.

Generally, in the forest formation areas, the occurrence of a low surface runoff rate contributes to water recharge and soil preservation, resulting in soil losses below the tolerance limit in the majority of the Cantareira System [44].

4.2. *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, which can be applied to various model types: power, logarithmic, or even exponential [22,45,46]. However, soil texture is a differential for a better fit of this relationship. Archie's power equation [47] 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. [48], 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.

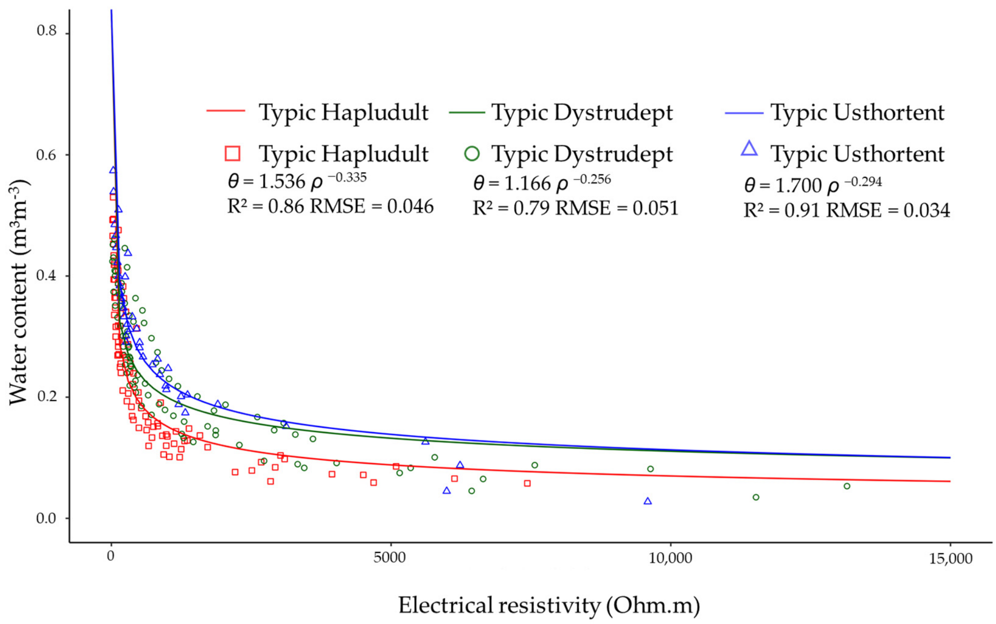

Figure 4. ρ–θ modeling calibration curves (lines) for soil type: Typic Hapludult, Typic Dystrudept, and Typic Usthortent and its observed data.

4.3. *Seasonal Water Content Distribution*

The soil water content estimated by ρ for each monitoring period is presented in Figures 5–7. In 2019, for Typic Hapludult (Figure 5), it is possible to observe that the native forest was the land use that kept the water in profile up to 1.50 m deep throughout the summer until the winter seasons (from February to August, respectively), especially during the driest period (i.e., winter). 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 a surface runoff rate of 200 mm h^{-1} (Figure 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 shallow depths, and drying out the subsurface soil layer throughout the seasons, indicated by the pale colors in the Figure 5E. 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, which showed greater soil dryness from a depth of 13 cm. This result is consistent with the high bulk density, greater impermeability (<KS) (Table 1), and high runoff rates (Figure 3A) of the extensive pasture, which may have impeded the water's reach to this depth, indicating drying during the evaluation period. Despite the aggressive and penetrating nature of grass roots, achieving this effect requires the implementation of appropriate management practices. In previous studies, low groundwater recharge potentials 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 [49]. According to a study conducted by Bispo et al. [50] in a Typic Hapludult in Atlantic Forest in Brazil, it was reported that surface runoff was reduced by 41% in well-managed pastures. Sone et al. [51] suggest integrating crops and livestock as an alternative to extensive pastures, noting a 60% increase in water infiltration and a 50% reduction in soil loss rates.

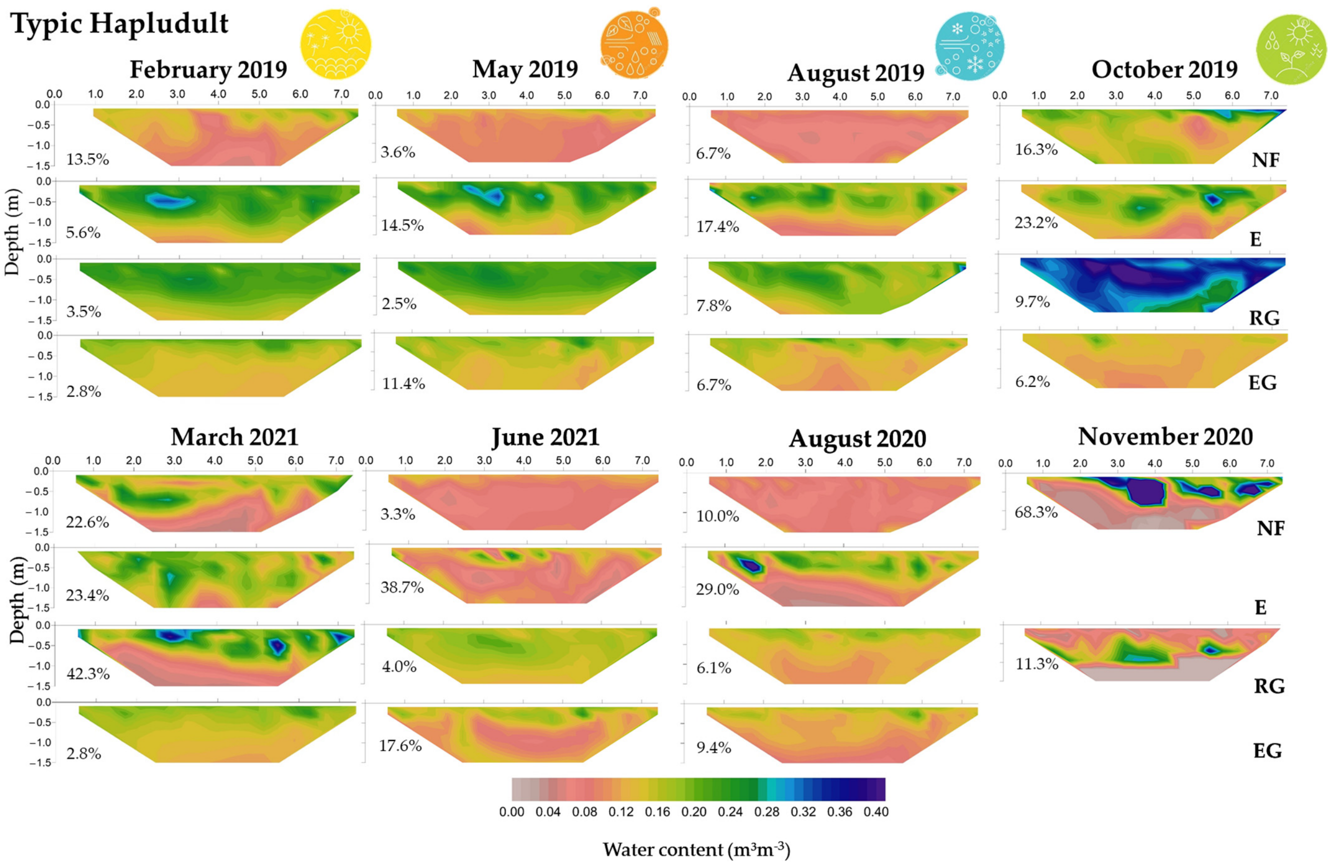

Figure 5. Estimated soil water content (m^3 m^{-3}) for the Typic Hapludult under native forest (NF), eucalyptus (E), rotational grazing (RG), and extensive grazing (EG) during the monitoring periods. The absolute error is indicated by the percentages on the lower left side.

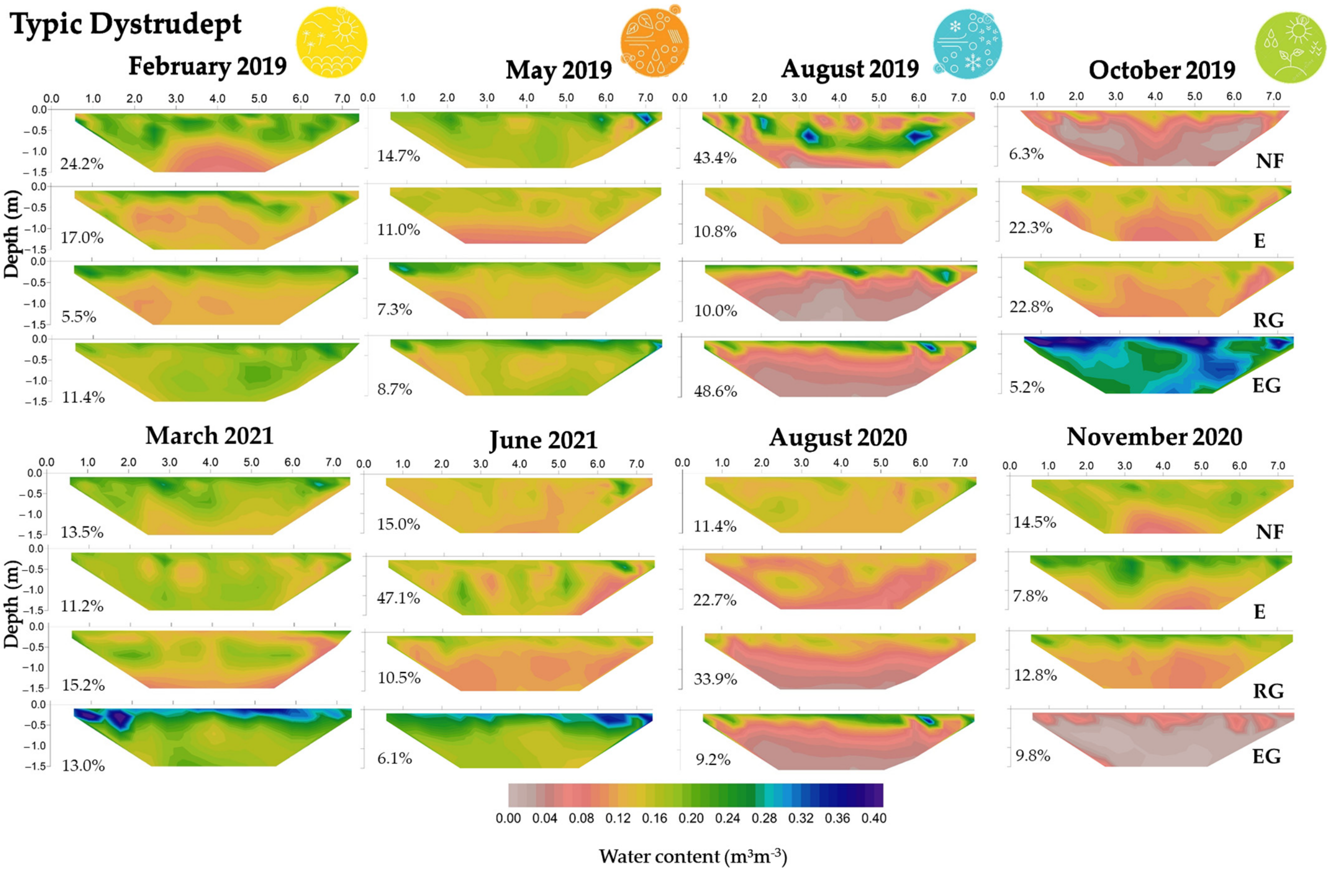

Figure 6. Estimated soil water content ($m^3\ m^{-3}$) for the Typic Dystrudept under native forest (NF), eucalyptus (E), rotational grazing (RG), and extensive grazing (EG) during the monitoring periods. The absolute error is indicated by the percentages on the lower left side.

In the spring of 2019 (October), there was a significant precipitation event (Figure 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 a depth of approximately 0.50 m. 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 (Figure 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 [52]. Yu et al. [11] 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 due to it 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; this may be due to evapotranspiration, as a result of voluminous and dense root system tropical forest [53] or groundwater recharge, due to the good soil water–air relationship in this use. This is indicated in Table 1 by the good porous and KS conditions compared to other uses.

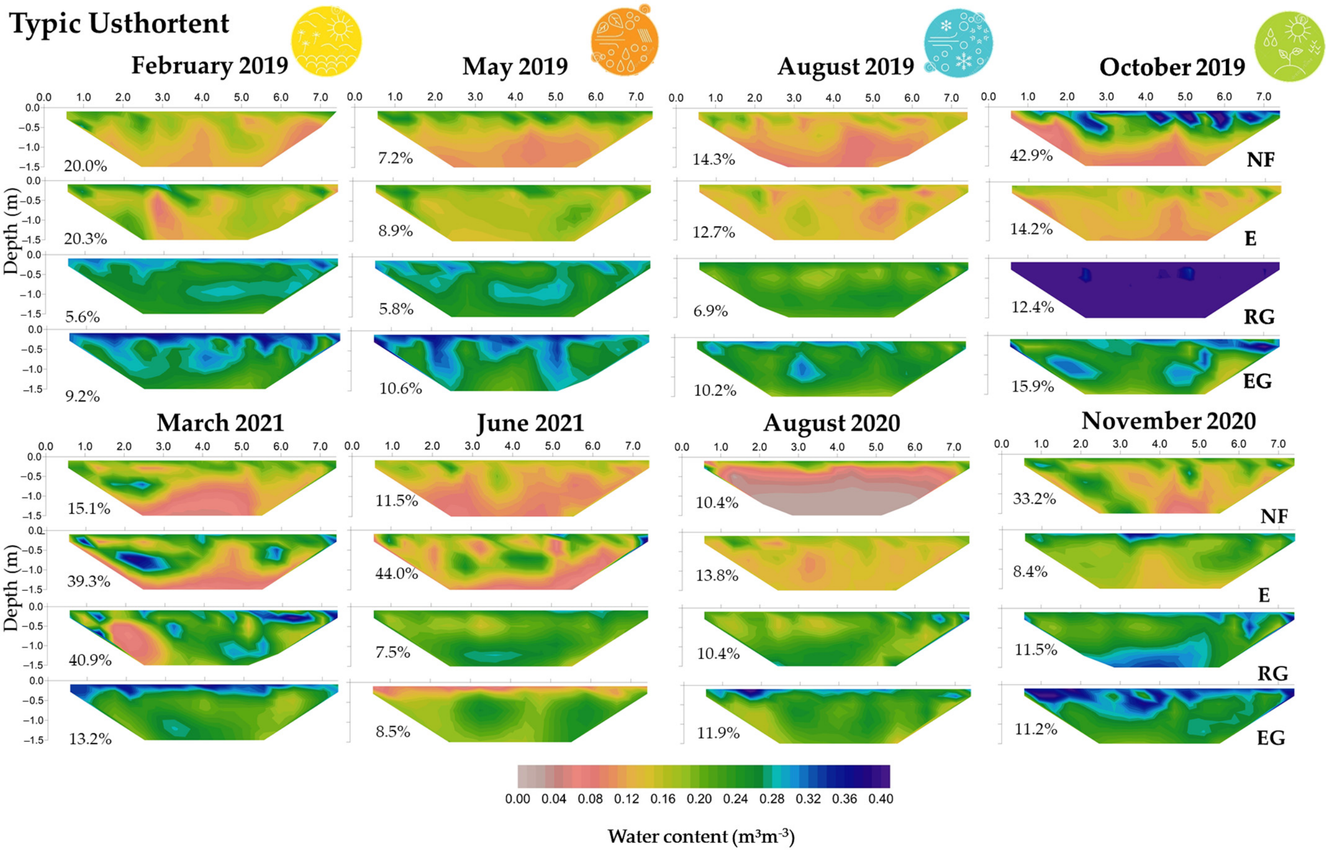

Figure 7. Estimated soil water content (m^3 m^{-3}) for the Typic Usthortent under native forest (NF), eucalyptus (E), rotational grazing (RG), and extensive grazing (EG) during the monitoring periods. The absolute error is indicated by the percentages on the lower left side.

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 condition. 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 the lowest 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 [54].

Salemi et al. [55] 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 areas. 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 it has the highest organic matter content. According to Centeno et al. [56], the enhanced aggregation and pore space in the forest soil have a positive effect on water conductivity.

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 (Figure 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 in the water balance.

In addition to root water uptake, planting density is a critical factor in determining the water use efficiency of eucalyptus trees. The influence of planting density on water use efficiency in forestry has been the subject of extensive research, and studies have demonstrated that higher planting densities can lead to increased water use [55]. Nevertheless, the impact of planting density on the ecosystem's water balance is complex and influenced by multiple factors. In this regard, Hakamada et al. [57] have made a valuable contribution to the understanding of this topic by studying different eucalyptus clones and plant densities in Brazil. Their study reported that planting fast-growing trees in tighter spacings might have an adverse effect on the ecosystem's water balance, potentially depleting stored soil water. Moreover, the results indicated 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 [49].

5. Conclusions

In a broader context, this study holds significant universal implications, shedding light on the consequences of converting native forests to pastures as a localized agricultural practice. This conversion exhibited a notable surge in potential surface runoff within the soil, amplifying sediment transport towards water bodies. Notably, the Typic Hapludult, eucalyptus roots demonstrated the ability to extract water from deep soil layers by penetrating through the compacted layer. In the less weathered soil, Typic Usthortent, water infiltration was impeded and water remained in the studied soil layer.

The investigation underscored the pivotal role of inherent soil properties in governing water dynamics. Consequently, a soil-specific calibration model was devised to establish a correlation between soil electric resistivity and water content. This model exhibited remarkable accuracy, enabling robust water content estimation.

Furthermore, the research emphasized the impact of land use changes, highlighting the critical role of native forests in facilitating deep water recharge. This is attributed to their greater root penetration capacity inducing biopores, evapotranspiration potential, and lower surface runoff rates. In contrast, pastures with shallow roots can only retain water in surface layers, making them inefficient in recharging groundwater. Therefore, the quality of pastures, determined by grass management and animal stocking rate, is paramount in ensuring water security. Nevertheless, further research beyond the 2.0 m is necessary to enhance the understanding of groundwater recharge.

By comprehensively addressing these interrelated factors, this study not only contributes to regional water resource management strategies but also offers a universal framework for understanding the intricate dynamics between land use, soil properties, and groundwater recharge.

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