Linking Soil Water Changes to Soil Physical Quality in Sugarcane Expansion Areas in Brazil

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Abstract: Brazil is the world's largest sugarcane producer with projections for expanding the current area by 30% in the coming years, mainly in areas previously occupied by pastures. We assess soil water changes induced by land-use change (LUC) for sugarcane expansion in the central-south region of Brazil. For that purpose, soil samples were collected in a typical LUC sequence (native vegetation–pasture–sugarcane) in two contrasting soil textures (i.e., sandy and clayey). Soil hydro-physical properties such as pores size distribution, bulk density, soil water content, water tension, and drainage time at field capacity, plant-available water, and S-index were analyzed. Our data showed that long-term LUC from native vegetation to extensive pasture induced severe degradation in soil physical quality and soil water dynamics. However, conventional tillage used during conversion from pasture to sugarcane did not cause additional degradation on soil structure and soil water dynamics. Over time, sugarcane cultivation slightly impaired soil water and physical conditions, but only in the 10–20 cm layer in both soils. Therefore, we highlight that sustainable management practices to enhance soil physical quality and water dynamics in sugarcane fields are needed to prevent limiting conditions to plant growth and contribute to delivering other ecosystem services.

Keywords: land-use change; soil water retention curve; soil quality; soil compaction; bioenergy production

1. Introduction

Brazil is the world's largest sugarcane producer, accounting for 40% of global production. Currently, the sugarcane area covers 10 million hectares, predominantly concentrated (92%) in the central-south region of Brazil [1]. Growing global bioenergy demand has driven a substantial increment of the sugarcane cultivated area since the early 2000s. In the last decade only, the Brazilian sugarcane area increased by 50% [1]. Despite the economic challenges that many countries face nowadays, Brazil is committed to promoting sugarcane production in the next years, having projections for expanding the current sugarcane area by 30% [2,3]. This expansion has occurred in the central-southern region [1], mainly in areas previously covered with pasture [4,5]. The Brazilian large-scale sugarcane production system is predominantly based on conventional tillage and intensive machinery traffic during the cultivation cycle [6]. Therefore, soil physical degradation as soil compaction induced by field traffic has become one of the major concern among sugarcane farmers, consultants, and researchers [7].

Recent studies have shown that land-use change (LUC) for sugarcane cultivation can negatively affect several soil physical properties such as pore size [8] and shape [9], bulk density and penetration resistance [10], and soil structural stability [11]. Those changes in soil physical properties inevitably can alter hydraulic conductivity [10] and retention in the soil. Moreover, physically degraded soils may reduce the water availability to plants and soil biota, compromising not only provisioning ecosystem services expressed by crop yield, but also other related ecosystem services, such as C sequestration, erosion control, and water purification.

Nevertheless, there is a paucity of studies that focused on soil water changes induced by LUC to sugarcane expansion. For example, Cherubin et al. [10] conducted a comprehensive evaluation of LUC effects on soil physical quality, but they only measured soil hydraulic conductivity to infer about potential changes in soil water dynamics. In addition, the authors highlighted that these modifications could depend on the elapsed time since the LUC, tillage, and other management practices adopted on sugarcane cultivation. Conventional tillage increases soil hydraulic conductivity [10]; besides this soil physical benefit, conventional tillage causes negative effects on soil (e.g., inversion of soil horizons, breakdown of macro-aggregates, aggregate slaking, clay dispersion, accelerated oxidation of soil organic carbon, and accelerated decomposition of plant root and shoot), as well as are no longer noticeable after successive cycles including heavy mechanization [8,12]. Therefore, the initial impact of conversion from pasture to sugarcane (i.e., first time impact) over water dynamics in soil remains poorly explored, representing an important research gap for broader sustainability assessment of sugarcane expansion and production in Brazil [13] and elsewhere.

Soil water management is an environmental and socio-technical challenge to sugarcane expansion in tropical regions [14]. Monitoring the water resources is essential to ensure that sugarcane expansion will not compromise them [15], not only in soils more resistant to degradation (i.e., clayey soils, as a consequence of higher aggregate stability and lower susceptibility to erosion) but also in soils more susceptible to degradation (i.e., sandy soils, as a consequence of poor soil structure, lower aggregate stability, and higher susceptibility to erosion) [16,17], which are prevalent in most regions of sugarcane expansion in Brazil. Besides that, it is estimated that 70–80% of the yield gap in sugarcane fields is caused by water deficit throughout the crop cycle in different regions of Brazil [18], which can be associated with degraded soil structure, poor soil aeration, and reduced water storage [19].

Soil hydraulic properties, which are useful for describing the patterns of water in the soil, can be extracted from the soil water retention curve. The soil water retention curve is described as the relationship between soil water content and matric potential [20]. From this relationship, some physical indicators associated to pore-size distribution [21], water and air capacity, drainage time [22], field capacity, permanent wilting point, and hydraulic conductivity [23], can be obtained. Additionally, soil physical quality can be linked to water dynamics and pore-size distribution through the S-index derived from the soil water retention curve [23,24]. The use of those indicators may provide better comprehension about the impacts of LUC on soil water and air fluxes [25], as well as its impact on soil functions and ecosystem services related to water dynamics regulation and soil erosion control [26].

Comprehensive in-field studies are fundamental to design more sustainable management practices that increase water retention, plant-available water content, and soil porosity, optimizing the landscape management in the current climate change age [27]. For that purpose, the study objective was to evaluate the effects of a typical LUC sequence (native vegetation–pasture–sugarcane) for sugarcane expansion on soil water dynamics in contrasting soil textures in central-southern Brazil. Our hypothesis is that soil hydro-physical properties are negatively affected as a consequence of this LUC sequence, and successive sugarcane cultivation, regardless of soil texture, negatively affects soil water processes and associated functions.

2. Materials and Methods

2.1. Experimental Site and LUC Sequence

The study was conducted in two sites with contrasting soil textures located in Brotas (22°17′ S and 48°07′ W) and Manduri (23°00′ S and 49°19′ W), São Paulo (SP) state, central-south region of Brazil, the main site of sugarcane expansion of the country. The soil classification and texture and climate information for each site can be found in Table 1 and Figure 1, respectively. To facilitate the presentation and interpretation of results, we named the sites as Sandy soil (site 1) and Clayey soil (site 2) and have used them throughout the manuscript. The LUC soil sampled sequence in both sites represents the most ordinary LUC's convention in central-southern Brazil (i.e., native vegetation (NV)—pasture (PA)—sugarcane (SC)). Sugarcane fields were further analyzed shortly after the conversion, during the plant cane cycle (SCplant) and for a longer period after the conversion, during ratoon cycles (SCratoon). The sugarcane cycle is about five years with annual harvestings. The first year after planting is considered the plant cane cycle. After the first harvest (i.e., 12–18 months after the planting) the ratoon cycles start, which represent the interval between following annual harvesting from the second to the fifth year. After the fifth year, the sugarcane is replanting using soil tillage practices. In our study, SCratoon was in the first ratoon cycle in the Sandy soil and the second ratoon cycle in the Clayey soil, therefore soil conditions were similar between the two sites, even the age of LUC was different. The land-use history and the management practices for both places are shown in Table 2.

Table 1. Location and soil particle-size distribution at the Sandy and Clayey soil in the State of São Paulo, Brazil.

Site identification		Sandy soil			
Geographical location		Brotas-SP (22°17′ S and 48°07′ W)			
Soil classification		Arenosol [28], Quartzipsamments [29]			
		Soil particle-size distribution (%)			
depth (cm)		NV *	PA	SCplant	SCratoon
	clay	05	05	07	08
0–20	silt	01	02	01	00
	sand	94	93	92	92
	clay	07	10	12	15
20–40	silt	02	02	02	00
	sand	91	88	86	85
Site identification		Clayey soil			
Geographical location		Manduri-SP (23°00′ S and 49°19′ W)			
Soil classification		Ferralsol [28], Oxisol [29]			
		Soil particle size-distribution (%)			
depth (cm)		NV	PA	SCplant	SCratoon
	clay	59	47	62	58
0–20	silt	31	27	29	32
	sand	10	26	09	10
	clay	61	50	65	58
20–40	silt	30	25	29	31
	sand	09	25	06	11

* NV = native vegetation, PA = pasture, SCplant = sugarcane plant, SCratoon = sugarcane ratoon.

Sandy soil
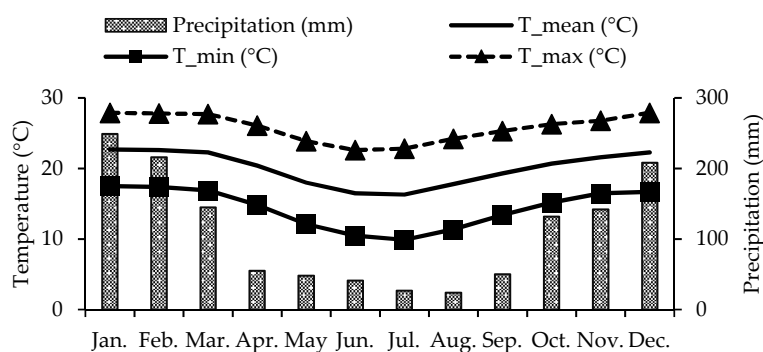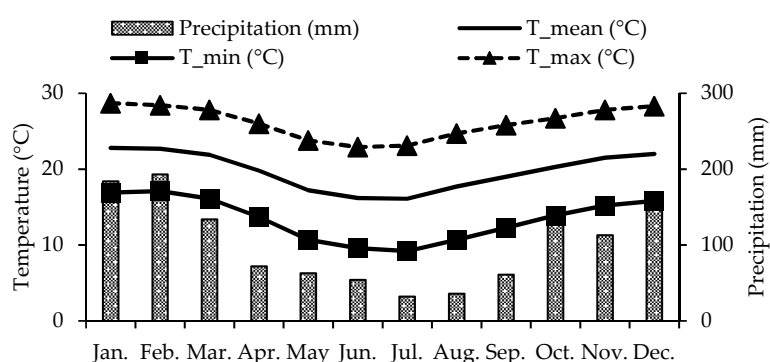

Clayey soil

Figure 1. Mean monthly temperature (maximum, mean, and minimum) (°C) and mean annual precipitation (mm) for Sandy soil (near the city of Brotas-SP) and Clayey soil (near the city of Manduri-SP). Source: climate-date.org (https://pt.climate-data.org/).

Table 2. History of land use and description of management practices conducted in each study area.

Site	Use *	Description
Sandy soil	NV	Secondary vegetation and seasonal semi-deciduous forest composed of *Trichillia clausenii*, *Euterpe edulis,* and *Aspidosperma polyneuron* as dominant species.
	PA	The land-use change (LUC) from NV to PA occurred in 1975. The PA was cultivated with brachiaria grass (*Brachiaria decumbens)* cv. Basilik, without mineral fertilizer inputs, and with an average stocking rate of ~7 animal units (AU) (7 AU ha^{-1}) until 2018. The *B. decumbens* was replaced by *Brachiaria brizanta* cv. Marandu in 2018. During this process, 2 Mg ha^{-1} of lime, fertilizer inputs of 200, 135, and 115 kg ha^{-1} of nitrogen, phosphorus, and potassium, respectively, were applied on the soil surface. The stocking rate was kept the same as in the previous period. Cattle grazing is continuous, without a resting period for the pasture.
	SCplant	The LUC from PA to SCplant occurred in 2018. The conversion occurred with conventional tillage by plowing and disking. In this area, 2 Mg ha^{-1} of lime was applied on the soil surface. Fertilizer inputs of 60, 150, and 120 kg ha^{-1} of nitrogen, phosphorus, and potassium, respectively, were applied in planting furrows. The sugarcane cultivar planted was IAC SP 97-4039.
	SCratoon	The LUC from pasture to SCratoon occurred in 2002. In the following years, harvesting was done mechanically without burning or straw removal. The sugarcane renewal (replanting) was done every five years when the soil was tilled by plowing and disking. The last sugarcane planting was in 2017 with cultivar IAC SP 97-4039. After the last harvesting in 2018, 155, 41, and 86 kg ha^{-1} of nitrogen, phosphorus, and potassium, respectively, were applied, as mineral fertilizers.

Table 2. *Cont.*

Site	Use *	Description
Clayey soil	NV	Similar description as for Sandy soil.
	PA	The LUC from NV to PA occurred in 1970. This PA was composed of *Brachiaria decumbens* and poorly managed without mineral fertilizer. Cattle grazing is continuous, with an average stocking rate of 1.2 AU ha^{-1}.
	SCplant	The LUC from PA to SCplant occurred in 2018. This conversion occurred with conventional tillage, by plowing and disking. In this area, 2 Mg ha^{-1} of lime was applied on the soil surface, and 50, 150, and 50 kg ha^{-1} of nitrogen, phosphorus, and potassium, respectively, were applied in planting furrows.
	SCratoon	The LUC from pasture to SCratoon occurred in 2016. Mechanical harvesting without burning or straw removal was performed in 2017 and 2018. Every year, 90 and 80 kg ha^{-1} of nitrogen and potassium, respectively, were applied.

* NV = native vegetation, PA = pasture, SCplant = sugarcane plant, SCratoon = sugarcane ratoon.

2.2. Soil Sampling

Undisturbed soil cores were sampled in both sites during the summer in February 2019. The samplings consisted of four sample points spaced 50 m apart in each land-use area to represent LUC. Samples were taken from the center of soil layers 0–10, 10–20, and 20–30 cm using cylindrical rings of ~100 cm^3 (5 cm in diameter by 5 cm in height). In sugarcane fields, the samples were taken from the crop inter-row position five months after conversion and planting in SCplant in both places, in the first ratoon in the Sandy soil and the second ratoon cycle in the Clayey soil in SCratoon. A total of 96 samples were taken and then forwarded to the laboratory for analysis.

2.3. Soil Water Retention Curve Determination

To avoid any confusion in signals and for the mathematical formulation, the matric potential (Ψ) will be described in terms of water tension (h), which can be given as h = $|\Psi|$. The undisturbed soil cores were saturated with distilled water by capillarity for 48 h and subjected to the *h* of 10, 30, 60, 100, 330, and 1000 hPa, whereas disturbed soil samples previously sieved through a 2 mm sieve, saturated in small rings of known volume and subjected to the h of 5000, 10,000, and 15,000 hPa. Both undisturbed and disturbed soil sampled were equilibrated using a pressure plate apparatus. After reaching the hydraulic equilibrium, the samples were weighed and oven-dried at 105 °C for 24 h to determine the water content and bulk density. Bulk density was calculated as the ratio between oven-dried soil mass and the total volume of the soil, whereas the gravimetric water content was calculated as the difference between the mass of the samples at each water tension and that at oven-dried conditions.

Soil water retention data were fitted to the van Genuchten model [30], Equation (1):

$$\theta(h) = \theta_r + \left[\frac{(\theta_s - \theta_r)}{\left[1 + (\alpha h)^n \right]^{(1-1/n)}} \right] \tag{1}$$

where θ and h are the volumetric water content (m^3 m^{-3}) and soil water tension (hPa), respectively; θ_s and θ_r are the fitted saturated and residual water contents (m^3 m^{-3}); and α and n are fitting parameters (Table S1).

The van Genuchten-based approach given by Assouline and Or [31] was used for calculation of the h at field capacity (h$_{FC}$) (Equation (2)), which was used to calculation of the volumetric water content at field capacity (θ_{FC}) (using Equation (1)):

$$h_{FC} = \frac{1}{\alpha} \left(\frac{n-1}{n} \right)^{(1-2n)/n} \tag{2}$$

The saturated hydraulic conductivity was estimated using the θ_s and α van Genuchten parameters, as described by Guarracino [32]. From the saturated and unsaturated soil hydraulic conductivities, we calculated the time to reach the field capacity (t_{FC}) using the procedure given by Assouline and Or [31] and Meskini-Vishkaee et al. [33] (Equation (3)):

$$t_{FC} = -\frac{[z(\theta_s - \theta_r)]}{K_s} \ln\left[\frac{K(\theta_{FC})}{K_s}\right]$$ (3)

where z is the soil depth (cm), K_s is saturated hydraulic conductivity (cm d^{-1}), and $K(\theta_{FC})$ is the unsaturated hydraulic conductivity at the volumetric water content at the field capacity (cm d^{-1}), which was calculated by the van Genuchten [30] procedure.

Plant-available water (PAW) was then calculated using the water content available between the θ_{FC} and that measured at −15,000 hPa. Pore-size distribution was determined using the soil pore volume fractions for the h values <30 hPa, 30–100 hPa, and >100 hPa, which were used as thresholds for calculation of the macro-, meso-, and micropores, following Cavalcanti et al. [8]. The soil pore volume correspondent to the macro-, meso-, and microporosity were extracted from the fitted water retention curve (applying Equation (1)) for each land use. Finally, S-index was calculated using the van Genuchten parameters by applying the expression given by Dexter [24] (Equation (4)):

$$S = -n\left(\frac{\theta_s - \theta_r}{BD}\right)\left[\frac{2n - 1}{n - 1}\right]^{\left[\frac{1}{n} - 2\right]}$$ (4)

where S is the S-index, n, θ_s, and θ_r (volumetric water contents) are van Genuchten parameters; and BD is soil bulk density.

The S-index has been used as a sensitive indicator of soil physical quality. According to Dexter and Czyz [34], based on S-index values, the soil physical quality can be classified as very poor (S-index < 0.020), poor (0.020 > S-index < 0.035), good (0.035 > S-index < 0.050), and very good (S-index > 0.05).

2.4. Data Analysis

The analysis of variance (ANOVA) was calculated through the PROC GLM routine to test LUC effects on soil pores size distribution, bulk density, and parameters from the soil water retention curve (SWRC) within each site. When the values of the ANOVA results were significant ($p < 0.05$), the means were separated using Tukey test ($p < 0.05$). All statistical procedures were performed using Statistical Analysis System—SAS 9.3 software (SAS Inc., Cary, NC, USA). Moreover, a canonical discriminant analysis was used to examine variables relationships and treatment differences in a multivariate approach. Biplot graphs were used to examine the dispersion of the canonical scores associated with original variables, as well as the impact of these variables on the discrimination of the treatments. The mean values of the canonical variables for each treatment were compared by 95% confidence spheres. The graphs and statistical procedures were performed using the R Software [35].

3. Results

3.1. Soil Pores Size Distribution and Bulk Density

The pore-size distribution was altered due to conversion from NV to PA in both soils, although the magnitude of changes varied between soils (Figure 2a,c). While microporosity increased in the PA of the Sandy soil, no changes were observed in the Clayey soil. The mesoporosity was reduced in both soils (Figure 2), but macroporosity was reduced only in the surface layer of the Sandy soil, reaching a value lower than 0.10 m^3 m^{-3} (Figure 2a). Furthermore, this land transition from NV to PA reduced total porosity in the surface layer of the Sandy soil, and in the subsurface layers (10–20 and 20–30 cm) of the Clayey soil. The reduction in mesopores increased micropores in the Sandy soil but did not

increase it in the Clayey soil (Figure 2c). In addition, the reduction in mesopores was responsible for the reduction in total porosity in the Clayey soil (e.g., 10–20 and 20–30 cm layers).
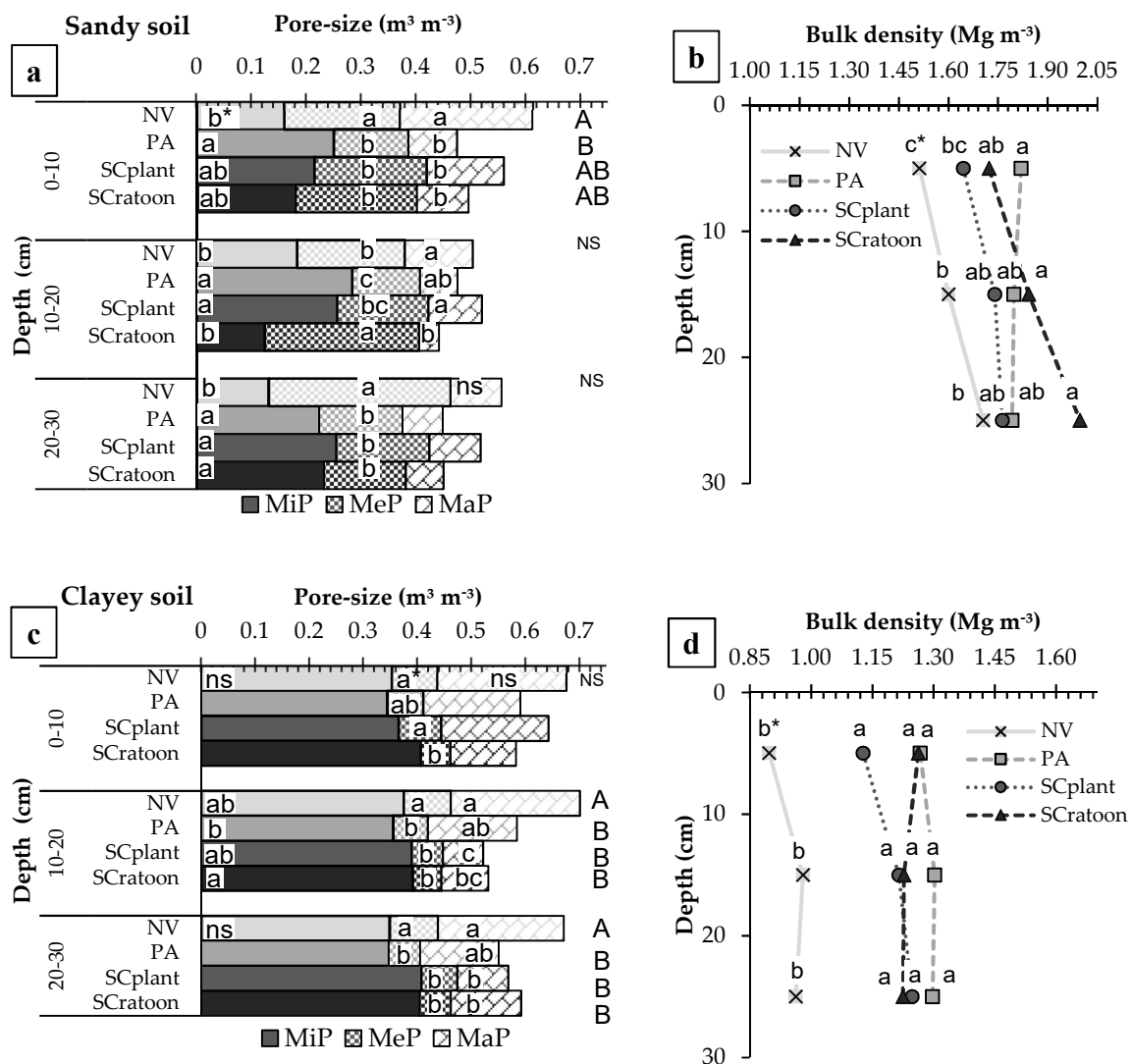

Figure 2. Soil pore-size distribution (microporosity (MiP) ≤15 μm, mesoporosity (MeP) = 15–50 μm, macroporosity (MaP) ≥50 μm), total porosity (**a**,**c**), and bulk density (**b**,**d**) from 0–10, 10–20, and 20–30 cm layers under native vegetation (NV), pasture (PA), sugarcane plant (SCplant), and sugarcane ratoon (SCratoon) at Sandy soil (**a**,**b**) and Clayey soil (**c**,**d**). * Mean values within each site and each pore-size distribution in the same depth followed by the same letter do not differ among themselves according to Tukey's test (*p* < 0.05). ᶰˢ Not significant.

Short-term conversion from PA to SCplant did not change the microporosity of both soils. On the other hand, conversion from PA to SCratoon altered the microporosity in the 10–20 cm layer of both soils. Microporosity was reduced in the Sandy soil and increased in the Clayey soil. Consequently, this conversion increased mesoporosity in this same layer in the Sandy soil. Microporosity and macroporosity were also reduced in SCratoon in comparison to SCplant in the 10–20 cm layer in the Sandy soil. However, in both soils, total porosity was not altered due to conversion from PA to sugarcane.

The alterations in pores size distribution, e.g., total porosity and mesoporosity were reflected in an increment of bulk density when NV was converted to PA. Bulk density increased by 17% in the surface layer of the Sandy soil (Figure 2b) and about 27% in all layers of the Clayey soil (Figure 2d). Conversion from PA to SCplant reduced bulk density by 10%, but only in the surface layer in the Sandy

soil. Moreover, sugarcane cultivation (SCratoon) did not induce changes in bulk density in comparison to PA. In SCratoon, bulk density values were lower than 1.30 Mg m^{-3} (Figure 2d) in the Clayey soil and varied between 1.74 Mg m^{-3} and 2.0 Mg m^{-3} in the Sandy soil (Figure 2b).

3.2. Field Capacity (θ_{FC}, h_{FC}, t_{FC}) and Soil Water Retention Curve (SWRC)

The conversion from NV to PA did not alter θ_{FC} in the Sandy soil, where it varied from 0.17 to 0.23 m^3 m^{-3} (Figure 3a). Besides that, this conversion reduced soil water content at field capacity in the 10–20 cm layer from 0.47 to 0.43 m^3 m^{-3} in the Clayey soil (Figure 3b). The conversion from PA to SCplant did not alter the θ_{FC} in both soils at all layers. However, the SCratoon reduced the θ_{FC} by 50% when compared to PA and SCplant in the 10–20 cm soil depth, but it was not altered in other layers in the Sandy soil (Figure 3a). Therefore, the higher limit of plant-available water was altered in the 10–20 cm layer in both soils.

The h_{FC} was increased by 50% after the conversion from NV to PA in the Sandy soil. In the Clayey soil, whose h_{FC} varied from 30 to 100 hPa (Figure 2d), no change was observed after conversion. However, the conversion from PA to SCplant and SCratoon reduced h_{FC} from 169 to 120 and 90 hPa, respectively, in the 10–20 cm layer of the Sandy soil (Figure 2c). Furthermore, conversion from NV to PA increased t_{FC} in the soil surface, but the conversion from PA to SCplant and SCratoon did not alter t_{FC} in this soil when compared to PA. In the Clayey soil, t_{FC} varied from 1 to 22 h and was not altered in the LUC sequence (Figure 3f). Therefore, neither h_{FC} nor t_{FC} were sensitive indicators to detect alterations due to LUC in the Clayey soil. It shows then that h_{FC} and t_{FC} are sensitive to alterations in soil structure mainly in the Sandy soil.

The SCratoon reduced θ_{FC} in the 10–20 cm layer in the Sandy soil but did not alter other layers nor differed as to SCplant in the Clayey soil. Furthermore, the t_{FC} and h_{FC} did not differ between SCratoon and SCplant in both soils (Figure 3).

The SWRCs for both soils are shown in Figure 4. The total porosity was responsible for higher water retention in the NV at lower h in the Clayey soil as well as in the NV and SCplant in the Sandy soil. Therefore, the alterations on θ_{FC} can be seen in the SWRC. The higher θ_{FC} in NV related to PA, SCplant, and SCratoon in the 10–20 cm layer in the Clayey soil reflected on the difference observed in the SWRC close to t_{FC} (i.e., 30–90 hPa) (Figure 4d). However, a higher proportion of mesopores corresponds to lower water retention, as shown in the Sandy soil when compared to the Clayey soil. The higher mesoporosity in the Sandy soil also affected t_{FC} in function of depth (Figure 3e). This higher mesoporosity effected the SWRC due to the higher decline of the curve in SCratoon (Figure 4c) and in NV (Figure 4e).

The S-index derived from the SWRC was sensitive to detecting alterations in soil structure due to LUC. Conversion from NV to PA reduced S-index from 0.13 to 0.06 in the Sandy soil (Figure 5c) and from 0.10 to 0.05 in the Clayey soil (Figure 5d). In contrast, the conversion from PA to SCplant did not have a negative impact on S-index and even promoted improvement in the surface layer of Sandy soil. Similarly, SCratoon also presented close or higher S-index values as compared to PA, reaching similar values to NV in the Sandy soil (Figure 5c). Lastly, based on S-index values, soil physical quality was classified as very good in all land uses in the Sandy soil, very good in NV, and good in PA, SCplant, and SCratoon in the Clayey soil.
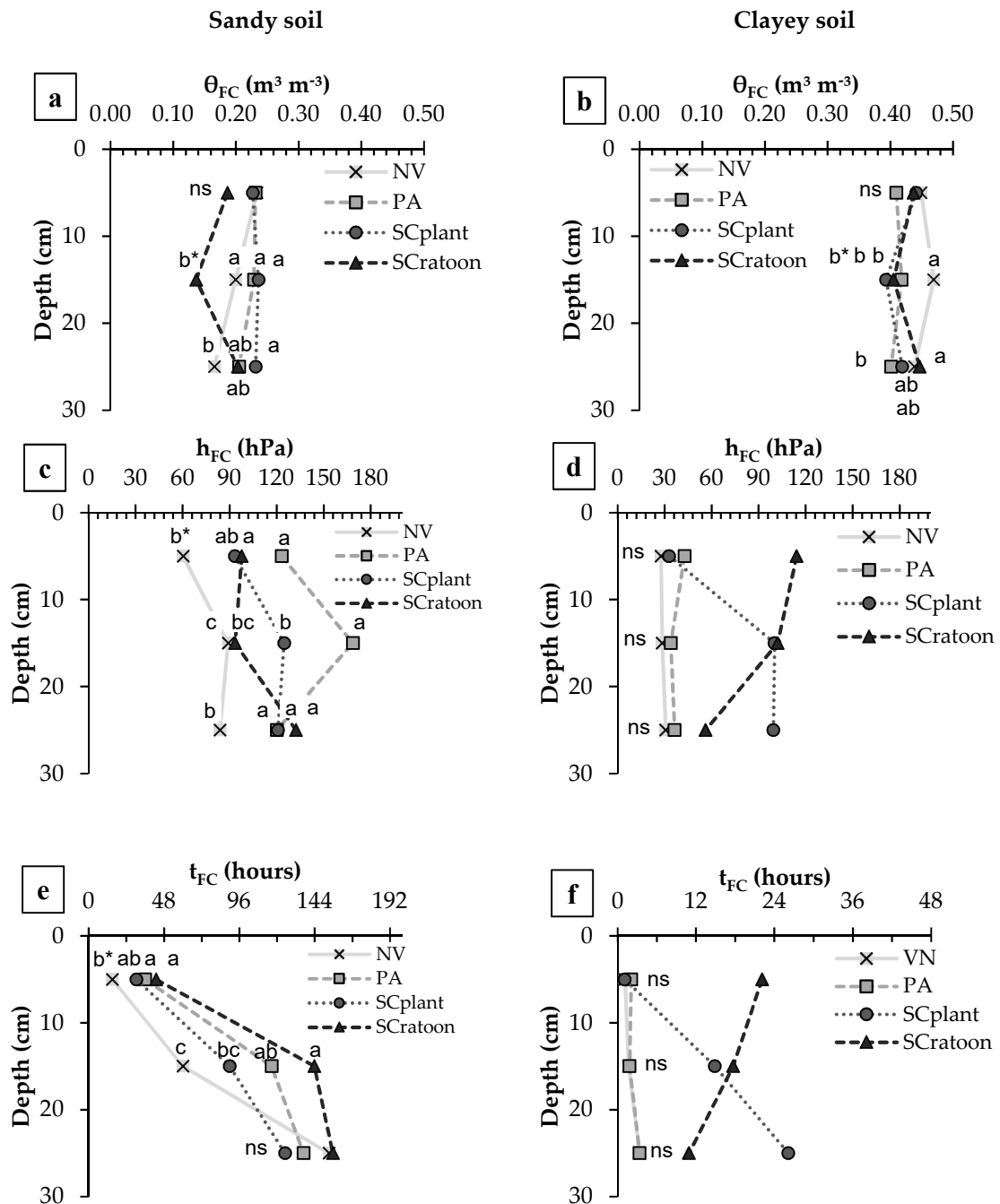
Sandy soil　　　　　　　　　　　　　　**Clayey soil**

Figure 3. Water content at field capacity (θ_{FC}) (**a,b**), water tension at field capacity (h_{FC}) (**c,d**), drainage time to reach the field capacity (t_{FC}) (**e,f**) from 0–10, 10–20, and 20–30 cm layers under native vegetation (NV), pasture (PA), sugarcane plant (SCplant), and sugarcane ratoon (SCratoon) at Sandy and Clayey soil. * Mean values within each site in the same depth followed by the same letter do not differ among themselves according to Tukey's test ($p < 0.05$). [ns] Not significant.

Sandy soil　　　　　　　　Clayey soil
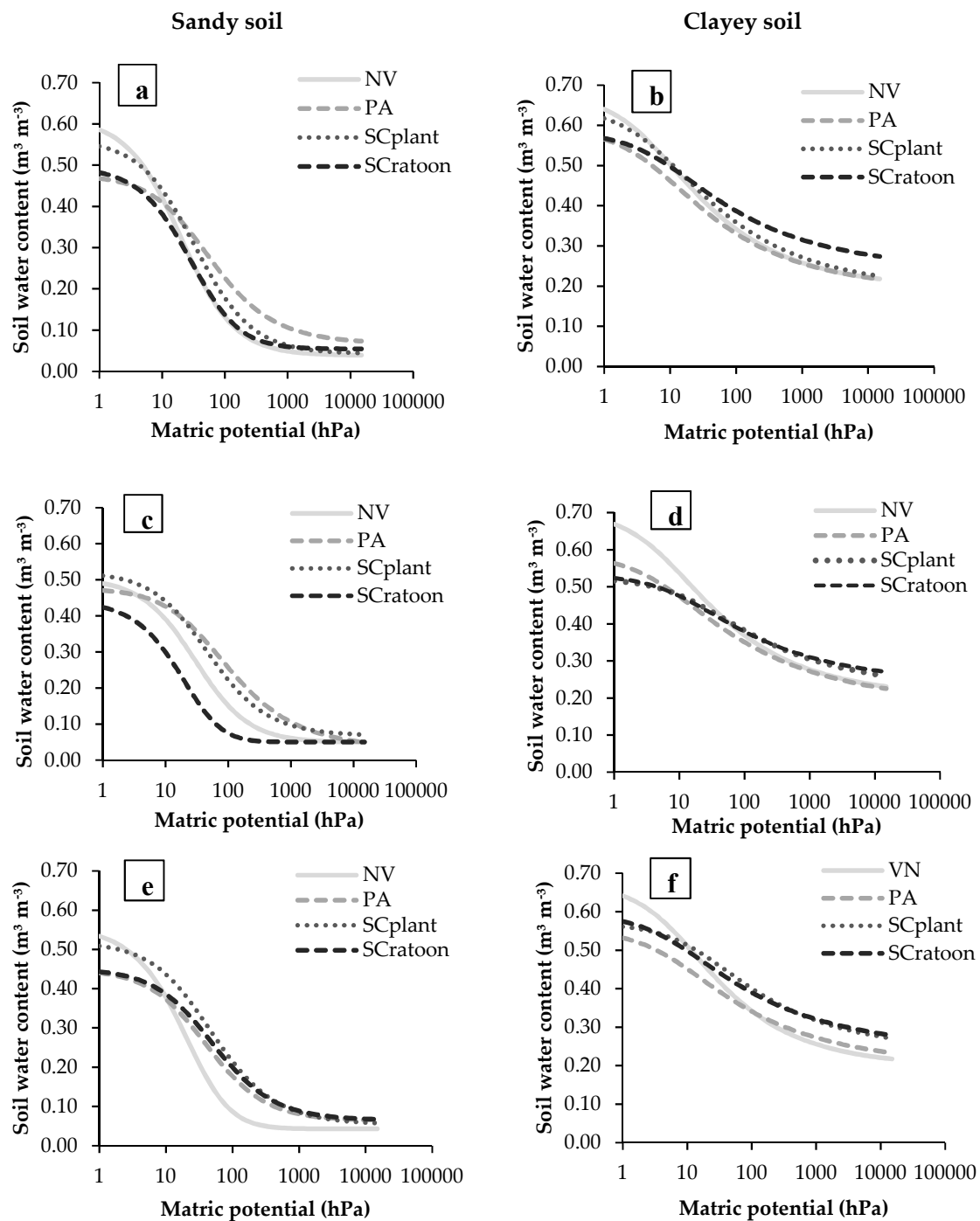
Figure 4. Average soil water retention curve (SWRC) from 0–10 (**a**,**b**), 10–20 (**c**,**d**), and 20–30 cm (**e**,**f**) layers under native vegetation (NV), pasture (PA), sugarcane plant (SCplant), and sugarcane ratoon (SCratoon) at Sandy soil (**a**,**c**,**e**) and Clayey soil (**b**,**d**,**f**).

3.3. Plant-Available Water Content (PAW) and S-Index

PAW varied from 0.09 to 0.20 m^3 m^{-3} in the Sandy soil (Figure 5a) and from 0.17 to 0.27 m^3 m^{-3} in the Clayey soil (Figure 5b). For both soils, the conversion from NV to PA did not alter PAW. The main alteration in this parameter was a reduction observed in SCratoon compared to PA in the 10–20 cm layer in both soils. The pattern of PAW was different in SCratoon and SCplant in the 10–20 cm layer in each soil. While PAW was lower in the SCratoon in comparison to SCplant (Figure 5a) in the Sandy soil, SCratoon and SCplant presented similar PAW in that layer of the Clayey soil (Figure 5b).
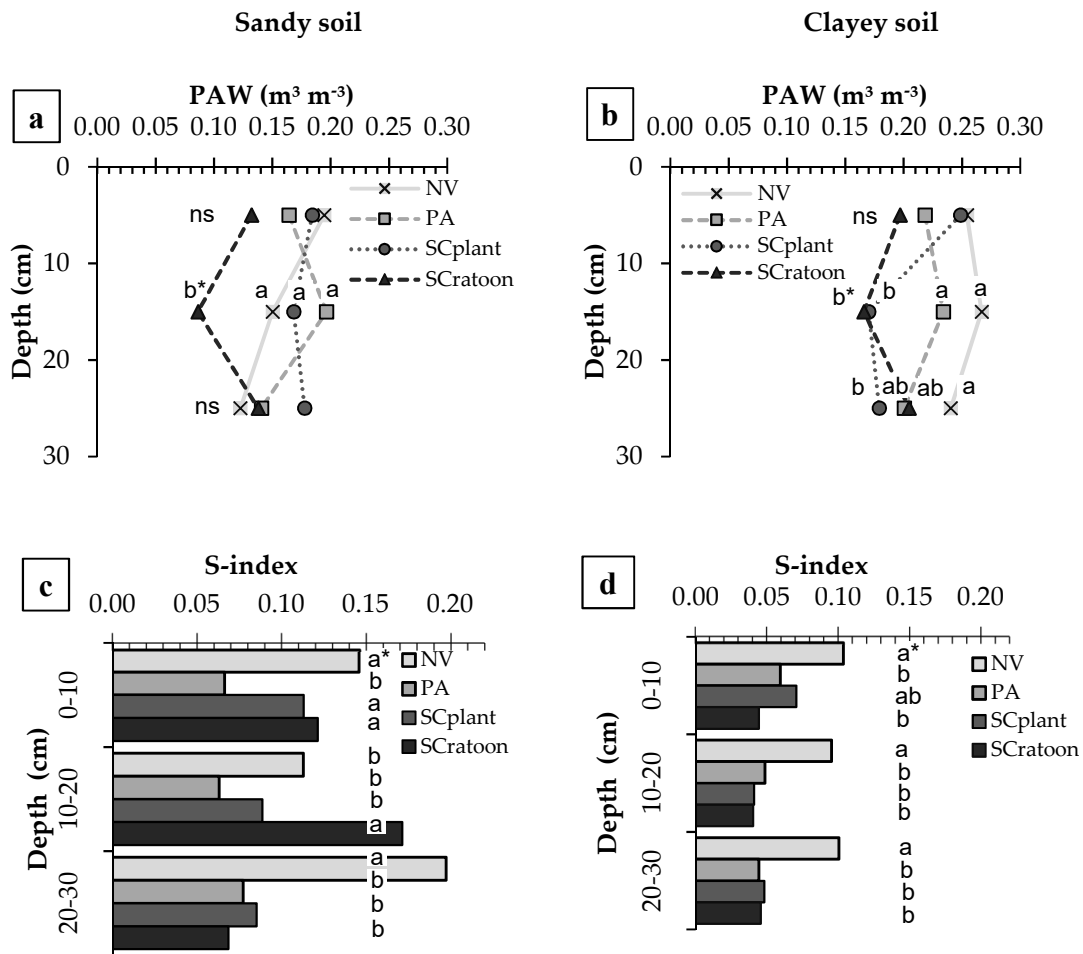
Figure 5. Plant-available water (PAW) content (**a**,**b**) and S-index (**c**,**d**) from 0–10, 10–20, and 20–30 cm layers under native vegetation (NV), pasture (PA), sugarcane plant (SCplant), and sugarcane ratoon (SCratoon) at Sandy soil (**a**,**c**) and Clayey soil (**b**,**d**). * Mean values within each site in the same depth followed by the same letter do not differ among themselves according to Tukey's test ($p < 0.05$). ns Not significant.

3.4. Relationships among Hydro-Physical Indicators and Land Use

Figure 6 shows the distribution of land use with soil water indicators as explanatory variables in the dispersion of the canonical scores in each soil. The two axes together explained 85% and 93% of the variance for the Sandy and Clayey soil, respectively. In both soils, S-index, mesoporosity, and macroporosity were associated with NV, whereas bulk density, microporosity, h_{FC}, and t_{FC} were not associated with NV. Therefore, the CAN_1 (Figure 6), which explained most of the total data variance, showed better soil physical quality in NV when compared to PA, SCplant, and SCratoon in both soils.
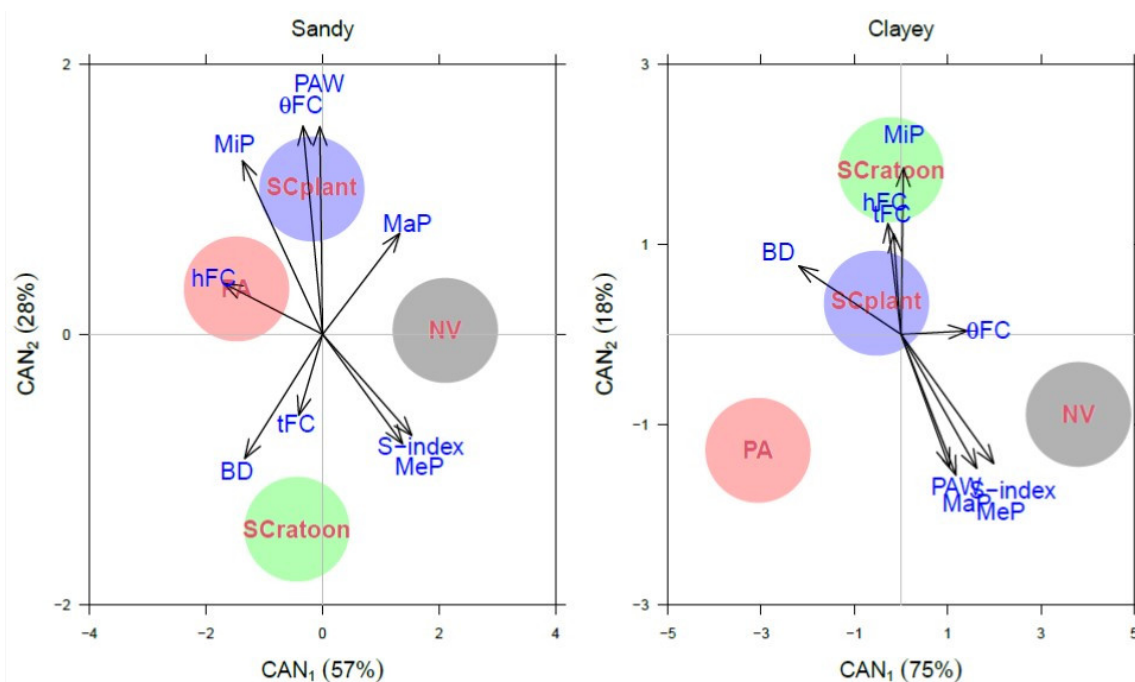
Figure 6. Dispersion of the canonical scores associated with soil porosity (MaP = macroporosity, MeP = mesoporosity, MiP = microporosity), bulk density (BD), parameters from soil water retention curve (θFC = soil water content at field capacity, hFC = water tension at field capacity, tFC = drainage time to reach the field capacity, PAW = plant-available water content, S-index) in four land uses: (NV= native vegetation, PA = pasture, SCplant = sugarcane plant, SCratoon = sugarcane ratoon). n = 48.

In addition, PAW had a positive correlation with θ_{FC} and microporosity in the Sandy soil and with macroporosity, mesoporosity, and S-index in the Clayey soil. On the other hand, the higher h_{FC} and t_{FC} were associated with higher bulk density and microporosity.

4. Discussions

4.1. LUC Impacts on Soil Physical Quality and Water Dynamics

4.1.1. Land Transition from Native Vegetation to Pasture

The conversion from NV to PA substantially altered the soil physical properties and, consequently, the soil water dynamics. The reduction in soil macropores and mesopores due to the conversion from NV to PA (Figure 2) reduced soil water retention at lower h (e.g., <10 hPa) (Figure 4). While PA reduced soil water retention in lower h, this conversion had positive effects on soil water retention in higher h (e.g., >10 hPa) due to the transition from mesopores to micropores, as well as an increase in bulk density. As a consequence, the h_{FC} (Figure 3c) and t_{FC} (Figure 3e) were higher at PA in the Sandy soil. These results of h_{FC} and t_{FC} reflected the increment on soil compaction and agree with Cherubin et al. [10], who observed a reduction in field-saturated hydraulic conductivity in pasture areas. Although a higher bulk density in PA in comparison to NV was observed, this increase did not reflect in alterations in h_{FC} and t_{FC} in the Clayey soil. However, the lower stocking rate during grazing in the Clayey soil when compared to the Sandy soil (Table 2) can be an important aspect [36] that attenuated water dynamic changes in this soil. In addition, it should be noted that excessive soil water retention at higher h in PA can impair grass growth, due to a limited supply of oxygen to plants, since macropores were <0.10 m^3 m^{-3}, which is considered critical for air fluxes in the soil [37]. In addition, the association between h_{FC} and t_{FC} (Figure 6) showed that land uses with higher h_{FC} will have higher t_{FC} (e.g., PA in comparison to NV), which might negatively affect air fluxes.

Furthermore, the increase in bulk density reached critical values in the Sandy soil (i.e., 1.60 Mg m^{-3}), according to Reynolds et al. [23], and did not reach critical values in the Clayey soil (i.e., 1.33 Mg m^{-3}), according to Reichert et al. [38]. Nevertheless, mesoporosity and macroporosity were reduced in the PA in the Clayey soil, which indicates alterations in soil structure due to LUC, as can be seen in Figure 6 by the association of these parameters with NV. The alterations in soil structure by LUC from NV to PA in tropical regions were described by several authors. First, conventional soil tillage used at land conversion breaks soil aggregates [39], leading to increased soil C oxidation to the atmosphere [38,40]. Secondly, after conversion of external drivers such as soil compaction due to continuous cattle trampling, this negatively influences the soil structure [9,17], water movement [10], and consequently, important ecosystem services, such as grass productivity, soil biodiversity and C sequestration [11], and erosion control. Therefore, the poor soil structure in PA and reduced vegetation cover in poorly managed pastures make the soil more susceptible to runoff [41] and soil erosion [39], mainly in months with higher precipitation, i.e., from October to March in the studied region (Figure 1).

In addition, the S-index was able to confirm alterations in soil water dynamics where conversion from NV to PA reduced soil structure quality by about 50% (Figure 5c,d), and θ_{FC} was reduced in Clayey soil. Despite those reductions, PAW was not altered in this scenario being considered ideal (>0.20 m^3 m^{-3}) for maximum root growth in the Clayey soil and good ($\geq$0.15, $\leq$0.20 m^3 m^{-3}) in the Sandy soil, according to Reynolds [20].

Our findings showing soil physical degradation and its consequent negative implications on water dynamics in extensive PA soils confirm what previous studies with a broader scope have reported, namely that those areas are characterized by poor overall soil quality [42] and provision of soil-related ecosystem services [13], low productivity and stocking rate [5], and low economic developments to farmers, workers, and the surrounding urban centers [13]. Due to all these environmental and socio-economic aspects, the prevalent scenario of sugarcane and other annual crops expansion has been, and will continue to be, over areas previously occupied with extensive pasture [4,13]. The full monitoring of PA soil conditions is fundamental to evaluate if sugarcane cultivation is degrading, sustaining, or even enhancing soil quality compared to the pasture baseline.

4.1.2. Conversion from Pasture to Sugarcane Cultivation

The transition from PA to sugarcane cultivation did not negatively impact water dynamics in both soils, refuting our initial hypothesis. Conventional tillage by plowing and disking (Table 2) break up soil structure [8], which sometimes reduces bulk density and increases soil porosity as compared to the previous use [43]. Therefore, in the Sandy soil, where bulk density was considered critical in PA, the conversion to SCplant alleviated soil compaction mainly on the soil surface making the soil structure in SCplant similar to the one observed in NV. As a consequence of that, an increase in soil water retention at lower h (Figure 4a,c,e), coupled with an increase in S-index (e.g., 0–10 cm layer), reduction in h$_{FC}$ (e.g., 10–20 cm layer) and t$_{FC}$, and association with PAW and θ_{FC} (Figure 6) were observed. In a previous study by Cherubin et al. [10], conversion from pasture to sugarcane was able to increase the field-saturated hydraulic conductivity and decrease bulk density.

In the clayey soil, where PA did not reach the critical bulk density, the conversion from PA to SCplant negatively affected soil porosity and reduced PAW only in the 10–20 cm layer. In that case, soil macropores were reduced to lower than 0.10 m^3 m^{-3} (Figure 2c); consequently, PAW decreased from 0.23 to 0.17 m^3 m^{-3} (Figure 5b). Similar results were observed by Cavalcanti et al. [8] when soil tillage at the sugarcane replanting degraded soil structure and altered soil porosity. Despite the critical value of macroporosity (<0.10 m^3 m^{-3}) [37] being reached in SCplant, no limitation was observed for available water content [20], as shown in Figure 5b. Furthermore, the initial impact after conversion from PA did not cause substantial alterations in soil structure and soil water dynamics, as previously expected.

A negative impact induced by conversion from pasture to sugarcane was found by Youlton et al. [44] in a Quartzipsamments with 12% clay, who reported that runoff was increased in sugarcane just after the conversion due to soil disturbance and absence of soil cover. However, results from soil porosity and

bulk density in SCplant showed a higher potential of water infiltration in comparison to PA, considering that about 3% of the amount of total rainfall might cause runoff near the city of Brotas-SP [41]. Besides, during sugarcane ratoon cultivation, there is no additional soil disturbance, and plant canopy plus crop residues could substantially reduce the risks of soil erosion and soil losses [41,44].

Results from SCratoon showed that sugarcane cultivation altered the soil structure mainly in 10–20 cm layer where the observed θ_{FC} values were lower t*h*an PA (Figure 3a), and the PAW values were limited (Figure 5a) [20] in the Sandy soil. After soil disturbance by conversion from pasture to sugarcane, machinery traffic by harvesters, tractors, and loaded trailers during harvesting intensifies soil compaction [6,45,46], mainly in the subsurface layer [47]. Soil compaction induced by machinery traffic likely explains the reduction in the PAW, of the soil water retention at lower h (Figure 4c), and alterations in soil porosity in the 10–20 cm layer in SCratoon in both soils (Figure 2a,c). Despite that, SCratoon not only did not display altered bulk density in comparison to PA (Figure 2) but showed an increased S-index in this soil layer (Figure 5c). These results alleviate the negative impacts related to θ_{FC} in SCratoon and concur to the findings of Cherubin et al. [10] and Luz et al. [16], who did not find increases in bulk density due to conversion from pasture to sugarcane.

Soil compaction by traffic can positively affect soil water retention due to rearrangement of pore-size distribution in sandy soils, as reported by Moraes et al. [48] in a Typic Paleudult with 25% of clay and 55% of sand. However, our findings indicated an inverse pattern in the Sandy soil, in which there was a reduction in PAW in SCratoon that has experienced successive machinery traffic. In this case, the soil with a lower amount of clay and a higher amount of sand (Table 1) responded differently to machinery traffic, when compared to the results reported by Moraes et al. [48], and tillage followed by traffic altered soil pore-size distribution in SCratoon (e.g., 10–20 cm layer) (Figure 2a). Nonetheless, a positive effect on soil water retention due to compaction could be confirmed when macroporosity does not reach critical values. Macroporosity reached critical values not only in sugarcane fields but also in pasture soils (Figure 2a). This compaction reinforces the poor structural stability of sandy soils, mainly in deeper layers [49].

Despite alteration in the 10–20 cm layer, conversion from PA to sugarcane did not change PAW and soil pore-size distribution in the soil surface and the lowest layer. In addition, about 60–90% of the sugarcane root system is distributed in the 0–40 cm layers [49,50], which allows sugarcane to explore soil layers with no limited water uptake. This means that no alterations in the soil water uptake by plants is expected as a result of the conversion from PA to sugarcane during the annual cycle, especially in periods of high-water deficit (Figure 1). Besides, our data showed that the management adopted in sugarcane cultivation (SCplant and SCratoon) did not induce water (PAW) and mechanical (bulk density) limiting conditions to plant growth in the Clayey soil. The S-index values corroborate it, indicating that those soils present good physical quality. Additionally, the principal component analysis demonstrated a positive correlation between S-index and mesoporosity (Figure 6), which was not altered in sugarcane fields.

As a result of the previous conditions of extensive pasture characterized by compacted soils, conventional tillage for planting sugarcane did not induce additional degradation on soil structure and soil water dynamics. During the sugarcane cycle, comparing SCplant and SCratoon, soil water retention was reduced in the Sandy soil, but only in the 10–20 cm layer, and it was not altered in the Clayey soil. In addition, t_{FC} and PAW were increased and reduced, respectively, in the 10–20 cm layer in the Sandy soil. Thus, the Sandy soil was shown to be more prone to physical degradation by machinery traffic than the Clayey soil. On the other hand, the increased water retention promoted by SCratoon in the 0–10 cm layer (Figure 4b) did not change bulk density, soil porosity, and water dynamics when compared to SCplant.

4.2. Sustainable Management Practice to Enhance Water Dynamics in Sugarcane Fields

Despite the similar conditions observed in SCplant and SCratoon related to soil water dynamics, sugarcane fields are still susceptible to soil compaction [51,52], mainly in the 10–20 cm layer. The risk of

compaction in sugarcane fields is dependent not only on machinery traffic but also on the management system [46]. Therefore, soil management such as a no-tillage system [12] and reduced tillage [53] can be promising strategies for reducing tension transmission through the soil profile [54] and, consequently, reduce the negative impact on soil structure. Additionally, keeping sugarcane straw on the soil surface after harvesting increases soil carbon content [55], reduces the negative impact of the raindrop splash effect, and reduces the negative impact on soil structure caused by traffic [50,56]. Therefore, these practices have the potential to improve soil water retention, field capacity, and PAW and make the soil more resistant to soil erosion processes.

The benefits of soil management practices, which reduce soil disturbance, keep the soil surface covered, and promoted balanced water and air contents in the soil, should be accompanied by other important conservation practices such as crop rotation or cover crops during sugarcane planting [57] and controlled traffic in sugarcane fields [58]. The latter is fundamental to minimize soil compaction [47] preserving appropriated soil hydro-physical conditions to sugarcane growth [58], and reducing sugarcane yield losses [18].

We expect that our findings can be useful for a better understanding of the impacts of sugarcane expansion in contrasting soils in the central-southern region of Brazil. Furthermore, this information can serve as a scientific basis to design better soil management practices, that increase soil water conservation by reducing runoff and soil erosion. Finally, our findings can also be valuable for an array of modeling purposes, such as prediction of plant growth, hydrological processes, and broader ecosystem services assessments.

5. Conclusions

Long-term LUC from native vegetation to extensive pasture induced the degradation of the soil physical quality and soil water dynamics. This leads pasture soils into a vicious cycle, in which poor soil hydro-physical functioning leads to pasture degradation, and then consequently, pasture degradation and continuous grazing lead to further degradation of soil properties, functions, and services.

One strategy to reincorporate those pasturelands into a productive system is through converting those areas for sugarcane cultivation. Our data showed that even conventional tillage used during such conversion did not cause additional degradation to soil structure and soil water dynamics. Over time, sugarcane cultivation slightly impaired soil water and physical conditions, but only in the 10–20 cm layer in both soils. We highlight that sustainable management practices to enhance soil physical quality and water dynamics in sugarcane fields are needed to prevent limiting conditions to plant growth and synergistically contribute to delivering other ecosystem services.

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