

Intrinsic soil properties shape water availability under changing land-use in contrasting soil textures

Luís Fernando Stone^{a,*}, Márcia Thaís de Melo Carvalho^a, Mellissa Ananias Soler da Silva^a, Francine Neves Calil^b, Matheus Mentone de Britto Siqueira^b, Thamires Marques Moura^c, Emerson Trogello^d, Pedro Luiz Oliveira de Almeida Machado^a, Alexandre Bryan Heinemann^a, Alessandra da Cunha Moraes Rangel^a, Beáta Eموke Madari^a

^a Embrapa Rice & Beans, Rodovia GO 462 km 12, Zona Rural, Santo Antônio de Goiás, GO 75375-000, Brazil

^b Federal University of Goiás (UFG), Av. Esperança s/n, Campus Samambaia, Goiânia, GO 74690-900, Brazil

^c Federal Institute of Education, Science and Technology Goiano (IF Goiano), Av. Oeste, 350 - Parque União, Iporá, GO 76200-000, Brazil

^d Federal Institute of Education, Science and Technology Goiano (IF Goiano), Rodovia BR-153 km 633, Zona Rural, Morrinhos, GO 75650-000, Brazil

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ABSTRACT

Understanding how intrinsic soil properties modulate water retention under land-use change is critical for sustainable soil management in tropical regions. This study investigated how clay and soil organic matter (SOM) contents, along with bulk density (BD), influence the soil water retention curve (SWRC) and plant available water (PAW) following transitions from native forest (NF) to pasture (PAST) and crop-livestock-forestry systems (CLF). The study was conducted across four sites in Goiás State, Brazil, spanning sandy and clayey Ferralsols and Cambisols. Soil samples were collected from 0.0–0.2 and 0.2–0.4 m layers under each land use. SWRCs were modeled using the Van Genuchten equation. Principal component and correlation analyses were performed to evaluate relationships among soil properties and water retention parameters. Results showed that in sandy soils, moderate increases in BD and SOM under CLF and PAST enhanced water retention at field capacity, increasing PAW. In contrast, in highly clayey soils, increased BD and SOM often reduced PAW due to higher water retention at wilting point. Clay content improved water retention, especially in sandy soils, but its effect was more variable in clay-rich soils, where mineralogical differences influenced pore structure. These findings emphasize the context-dependent role of texture, SOM, and BD in regulating PAW. While CLF systems showed potential to restore PAW in sandy soils, their effect in clayey soils was limited by structural and mineralogical constraints. Tailored land management strategies that account for intrinsic soil characteristics are essential to optimize water availability in tropical agroecosystems.

1. Introduction

The conversion of large areas of the original Brazilian savanna biome (Cerrado) into productive land through deforestation and burning has led to a reduction of approximately 48 % in native vegetation and the release of significant amounts of C into the atmosphere (Soares et al., 2024).

When Cerrado native forests are converted, especially to pasture, profound impacts on soil carbon and nutrient dynamics are triggered,

with cascading effects on ecosystem function. Conversion to extensive cattle pasture often results in soil degradation, nutrient depletion, and erosion. Brazil has 151–160 million hectares of pastures and two-thirds of this area shows some level of degradation (Madari et al., 2024), mainly due to poor soil fertility, excessive grazing, and, in certain cases, physical constraints. The degradation of agricultural soils in pasture areas favors weed proliferation, which progressively reduces the pasture's carrying capacity (Assis et al., 2017).

Emerging integrated land-use systems offer a promising pathway to

* Corresponding author.

E-mail addresses: luisstone@gmail.com, luis.stone@embrapa.br (L.F. Stone), marcia.carvalho@embrapa.br (M.T.M. Carvalho), mellissa.soler@embrapa.br (M.A.S. da Silva), francine@ufg.br (F.N. Calil), matheusmentone@discente.ufg.br (M.M.B. Siqueira), thamires.moura@ifgoiano.edu.br (T.M. Moura), emerson.trogello@ifgoiano.edu.br (E. Trogello), pedro.machado@embrapa.br (P.L.O.A. Machado), alexandre.heinemann@embrapa.br (A.B. Heinemann), alessandra.moraes@embrapa.br (A.C.M. Rangel), beata.madari@embrapa.br (B.E. Madari).

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mitigate these negative impacts. In Brazil, integrated systems, including crop–livestock–forestry (CLF), contribute to increased soil carbon storage (Madari et al., 2024), stabilize animal and crop production, and improve water and nutrient use efficiency (Monteiro et al., 2024).

For example, in the Brazilian Cerrado, the CLF system promoted faster recovery of soil C and N stocks at 0–0.3 m depth compared with low-productivity pasture of signal grass (*Brachiaria decumbens*). The C content of the free light fraction of soil organic matter (SOM) under the CLF increased, reaching values similar to native vegetation up to 0.2 m (Freitas et al., 2020). In Southern Goiás, CLF systems showed positive soil organic carbon accumulation rates (0.23–0.56 Mg ha⁻¹ yr⁻¹) in the topsoil, compared with declines under pasture, and greater SOC stocks down to 1 m depth (Madari et al., 2024).

CLF systems are recognized for their societal and environmental benefits due to their positive effects on the physical, chemical, and biological properties of soils. These systems help mitigate soil degradation compared to simplified land-use strategies and align with Target 2.4 of the Sustainable Development Goals, particularly regarding resilient agricultural practices (Lemaire et al., 2014; Alves et al., 2017). However, converting existing land uses into CLF can impact physical soil properties, plant-available water (PAW), and SOM, especially in soils with different texture types—an area that requires further investigation (Valani et al., 2021).

Soil use and management lead to changes in its physical properties, including bulk density (BD), total porosity, pore size distribution, aggregation, SOM content, and water retention (Oliveira et al., 2013; Reichert et al., 2016). Understanding these changes is critical for assessing ecosystem impacts and developing sustainable soil management strategies (Shah et al., 2017; Soinnie et al., 2023).

Soil texture plays a key role in determining the extent of these physical changes. It controls the internal geometry of the soil and influences compaction, water retention, aeration, nutrient availability, and aggregate stability (Blum et al., 2018). The clay fraction (particles $\leq 2 \mu\text{m}$), due to its colloidal nature, significantly contributes to the soil's physicochemical behavior, such as surface activity. Along with sand and silt, clay determines the distribution of pore sizes, which in turn affects the contact area between soil solids and water—directly influencing water infiltration and aeration and, thus, soil's water retention capacity (Hillel, 1998; Freitas et al., 2013).

Clay mineralogy also influences physical soil properties. Ferralsols with high kaolinite content tend to have higher BD, lower aggregate stability in water, reduced macroporosity, and lower permeability compared to those dominated by gibbsite. The macrostructure of kaolinitic Ferralsols, composed mostly of subangular blocks, leads to denser packing due to the face-to-face arrangement of kaolinite plates, resulting in higher BD (Maia et al., 2018). In contrast, Ferralsols rich in gibbsite or with higher concentrations of iron and aluminum oxides tend to have lower BD (Pedrotti et al., 2003; Ghidin et al., 2006; Nogueira et al., 2020). Aluminium-rich clay fractions promote aggregation and structural stability, generating a microgranular structure that enhances water retention—although this also increases the energy plants must expend for water uptake. These pedogenic oxides and hydroxides contribute significant surface area, increasing sorption capacity in the soil matrix (Maia et al., 2018).

Soils with high clay content also tend to have higher SOM concentrations, greater total porosity, and lower BD (Freitas et al., 2014). In contrast, sandy soils typically exhibit higher BD due to their quartz-rich composition, with a dominance of macropores over micropores. While clayey soils have microaggregates that enhance microporosity and water retention, sandy soils—comprising larger particles and pores—have better aeration and higher temperatures, which may accelerate SOM decomposition. SOM is vital for soil health and productivity, influencing structure, water retention, pH buffering, cation exchange capacity, and overall sustainability (Cogo et al., 2013). Agricultural management practices can significantly alter SOM stocks, composition, and distribution within the soil profile (Silva et al., 2018a; Freitas et al., 2020; Pavei

et al., 2021).

SOM can increase water retention at field capacity (FC) more than at the permanent wilting point (PWP), thereby improving PAW. However, the magnitude of this effect depends on both soil texture and initial SOM levels (Lal, 2020). Minasny and McBratney (2018) caution that the contribution of SOM to PAW may be overestimated. They suggest SOM's effect on water retention is more pronounced in sandy soils, followed by silty, and least in clayey soils. Beutler et al. (2002) reported no significant influence of SOM on water retention or BD in medium- to clay-textured kaolinitic Ferralsols. However, they observed greater water retention across all tensions—and a more gradual decline in water content with increasing suction—in kaolinitic-oxidic Ferralsols compared to coarser-textured dystrophic ones.

Because PAW is critical for understanding water and nutrient use efficiency in crops, it is essential to investigate how soil properties influence it. At higher water potentials (≥ -10 kPa), water retention is mainly influenced by macropores, which is affected by structure, BD, and texture. As moisture content declines, adsorption forces dominate, and water retention becomes increasingly dependent on specific surface-related properties such as texture, mineralogy, and SOM (Assad et al., 2001; Beutler et al., 2002).

The soil water retention curve (SWRC) is a key tool in soil physics to describe water movement and retention in the soil profile. It provides insights into pore size distribution and unsaturated hydraulic conductivity and is shaped by soil-specific features, including clay mineralogy, particle shape and arrangement, and solute composition and concentration (Silva et al., 2018b).

Modeling the SWRC allows exploration of the relationships among soil properties such as clay and SOM content, and BD. For example, Machado et al. (2008) found a negative relationship between gravimetric water content at saturation (θ_s) and BD, emphasizing the role of soil structure in water retention. They also found that higher clay and lower SOM contents influenced residual water content (θ_r), with the effect of SOM on θ_r being greater in sandy soils than in clayey ones.

Despite advances in understanding soil water dynamics under various land uses, important gaps remain in linking intrinsic soil properties to SWRC responses following land-use change. Many studies focus on either texture or SOM as the primary driver of water retention (Minasny and McBratney, 2018; Lal, 2020), but few consider their interactions with clay mineralogy and BD. Furthermore, most existing models are calibrated for temperate soils and lack validation for highly weathered tropical soils, such as Ferralsols, which predominate in Brazilian agriculture (Maia et al., 2018). Additionally, the transition from degraded pastures to CLF systems remains underexplored in terms of its effects on soil pore distribution and PAW restoration.

Therefore, integrative approaches are needed to evaluate the interactions among intrinsic and dynamic soil properties under land-use intensification in tropical regions. This study aims to determine how intrinsic soil properties—particularly clay and SOM contents, and BD—modulate the effects of land-use change and soil management transitions (from native forest to pasture and subsequently to CLF systems) on the SWRC and PAW. Understanding these changes is essential for evaluating ecosystem impacts and guiding sustainable soil management strategies. Specifically, the study seeks to: (i) evaluate the role of bulk density (BD) and soil organic matter (SOM) in shaping water retention; (ii) determine how soil texture mediate responses in PAW; and (iii) identify management strategies that optimize PAW in sandy and clay soils.

2. Material and methods

2.1. Study area

The study was conducted in Goiás State, located in the Midwest region of Brazil, within the Brazilian savanna biome (Cerrado). The climate is classified as Aw (tropical savanna with dry winter) according

to the Köppen-Geiger system (Kottek et al., 2006).

The Cerrado features a seasonal rainfall pattern, with annual precipitation ranging from 800 to 1800 mm, approximately 90 % of which occurs between October and April. Its landscape forms a mosaic of vegetation types—from grasslands to woodlands—depending on species composition and canopy density (Bustamante et al., 2012).

2.2. Experimental sites and land-use treatments

Four experimental sites were selected across Goiás State (Fig. 1) to evaluate the effects of land-use change on water retention and availability. Each site included three land-use treatments:

- Native forest (NF): considered the reference condition, representing the undisturbed Cerrado, including typical savanna and woodland vegetation. It was located in a nearby area to the other treatments.
- Pasture (PAST): an area similar to the NF, previously deforested and converted to cattle grazing (meat and dairy) for over 30 years, in part of which the CLF was established.
- Crop-livestock-forestry system (CLF): area under integrated production systems combining trees, crops, and livestock.

2.3. Site descriptions

Quirinópolis: experimental site located at Santa Bárbara Farm (18° 21' 54" S, 50° 45' 17" W). The soil is classified as Ferralsol (FAO, 2022), with a sandy-loam topsoil layer (0.0–0.2 m). Soil particle size distribution is presented in Table 1. The pasture consisted of planted Ruzigrass (*Urochloa ruziziensis*). The CLF system was established in February 2016 with four lines of eucalyptus (clone AEC 043 – *Corymbia citriodora* × *C. torelliana*) spaced 2.5 m within rows and 3 m between rows per set, with 22 m between tree sets. *Urochloa ruziziensis* was cultivated between tree sets and grazed by dairy cattle.

Iporá: experimental site located at the research station of the Federal Institute of Education, Science and Technology Goiano (IF Goiano) (16° 25' 17" S, 51° 09' 33" W). The soil is classified as Cambisol, with a sandy-

loam topsoil layer (0.0–0.2 m). The pasture was composed of low-input Palisade grass (*Urochloa brizantha* syn. *Brachiaria*). The CLF system was established in October 2018 with eucalyptus (clone I144 – *Eucalyptus urophylla* × *E. grandis*) spaced 10 m between rows and 2 m within rows. Soybean, corn, and forage crops were grown between the tree lines, and dairy cattle grazed the forage.

Morrinhos: this site was also located at an IF Goiano research station (17° 48' 51" S, 49° 12' 31" W). The soil is classified as Ferralsol, with a clayey topsoil layer (0.0–0.2 m). The pasture consisted of low-input Palisade grass (*Urochloa brizantha* syn. *Brachiaria*). The CLF system was implemented in January 2018 with eucalyptus (clone AEC 2034 – *Eucalyptus camaldulensis* × *E. grandis* × *E. urophylla*), spaced 10 m between rows and 4 m within rows. Soybean, corn, and forage crops were cultivated between the tree lines, and dairy cattle grazed the forage.

Cachoeira Dourada: experimental site located at Boa Vereda Farm (18° 27' 40" S, 49° 35' 53" W). The soil is classified as Ferralsol with a clayey topsoil (0.0–0.2 m). The pasture was composed of a low-input mixture of Kikuyu (*Pennisetum clandestinum*) and Signal grass (*Urochloa decumbens*). The CLF system was established in the 2009/2010 summer season. Three eucalyptus (*Eucalyptus urograndis*) rows were planted 2 m apart within rows and 3 m between rows per set, with 20 m between sets. Corn (*Zea mays*) was intercropped with *Urochloa brizantha*, followed by cattle grazing 70 days after corn harvest.

2.4. Soil sampling and analysis

Sampling was carried out as follows:

a) Sites: four locations – Quirinópolis, Iporá, Morrinhos, and Cachoeira Dourada. b) Land uses at each site: (i) Crop–Livestock–Forestry (CLF), (ii) Pasture (PAST), and (iii) Native Forest (NF).

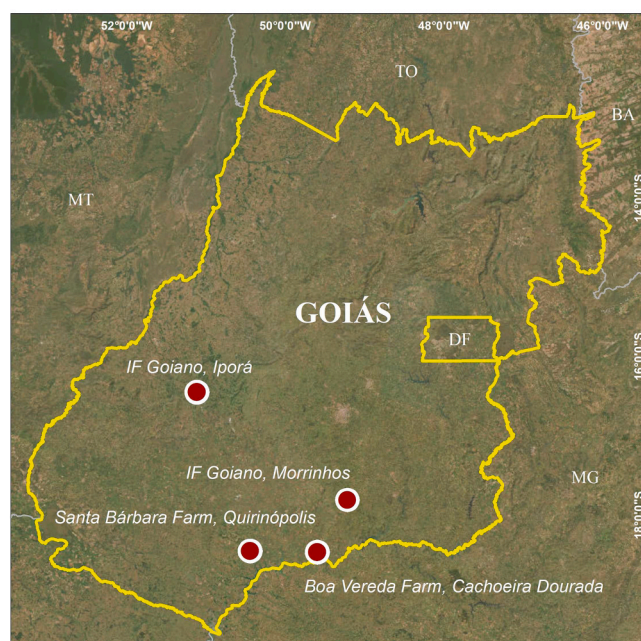
c) Depths: two soil layers – 0–0.2 m and 0.2–0.4 m.

This design resulted in 24 strata (4 sites × 3 land uses × 2 depths). A total of 96 samples were collected (24 strata × 4 replicates per stratum).

Sampling was carried out between November and December 2019 under eucalyptus rows (CLF), PAST, and NF (Fig. 2). At each site, four



(A)



(B)

Fig. 1. Geographic location of Goiás State within Brazil (A) and the four monitored sites (B): Iporá and Quirinópolis (sandy soil); Morrinhos and Cachoeira Dourada (clayey soil). Source: Adapted by A.C.M.R. (co-author) from © Google Earth.

Table 1

Particle size distribution (g kg^{-1}) in the 0.0–0.2 m and 0.2–0.4 m soil layers under crop-livestock-forestry systems (CLF), pastures (PAST), and native forests (NF) in Quirinópolis, Iporá, Morrinhos, and Cachoeira Dourada, Goiás State.

Site	Property	Land use			CLF	PAST	NF
		CLF	PAST	NF			
		0.0–0.2 m			0.2–0.4 m		
Quirinópolis	Clay (g kg^{-1})	193	192	193	222	235	208
Iporá		166	360	192	263	415	246
Morrinhos		441	461	513	536	521	536
C. Dourada	Silt (g kg^{-1})	665	744	433	655	772	589
Quirinópolis		30	58	33	27	55	50
Iporá		144	138	172	148	172	217
Morrinhos	Sand (g kg^{-1})	205	172	118	152	132	125
C. Dourada		146	144	185	144	138	192
Quirinópolis		777	750	774	751	710	742
Iporá	Texture	690	502	636	589	413	537
Morrinhos		354	367	369	312	347	339
C. Dourada		189	112	382	201	90	219
Quirinópolis	Texture	SCL	SCL	SCL	SCL	SCL	SCL
Iporá		SL	SC	SL	SCL	Clay	SCL
Morrinhos		Clay	Clay	Clay	Clay	Clay	Clay
C. Dourada	Clay	Clay	Clay	Clay	Clay	Clay	

SCL = sandy clay loam, SL = sandy loam, SC = sandy clay

trenches (Fig. 3) were dug at 20 m intervals under each land use. Both disturbed and undisturbed samples were collected from two layers (0.0–0.2 and 0.2–0.4 m) from trench walls for analysis of soil properties (BD, CLAY, SOM), soil water retention curve (SWRC) parameters (θ_r , θ_s , α , n), field capacity (FC), and plant available water (PAW).

Disturbed samples were air-dried and sieved to 2 mm. Particle size was determined by the pipette method (Bieganski and Ryżak, 2011), and SOM was estimated after determining soil organic carbon (SOC) by sulfochromic oxidation (Souza et al., 2016), both using 20 g of soil. The sulfochromic oxidation method measures SOC directly through a chemical reaction involving the digestion of the sample with potassium dichromate ($\text{K}_2\text{Cr}_2\text{O}_7$) in sulfuric acid (H_2SO_4), which oxidizes organic matter and reduces Cr^{6+} to Cr^{3+} , followed by titration with ferrous sulfate (FeSO_4) to quantify the oxidized carbon amount. SOM is estimated from SOC by assuming that it contains about 58 % carbon on average. Undisturbed cores (5 cm height \times 5 cm diameter rings) were used to determine BD and derive SWRCs via the centrifuge method (Nimmo et al., 2002), following the Van Genuchten (1980) model. Samples were saturated for 12 h and centrifuged using a Kokusan H-1400pF® unit at seven rotation speeds: 600, 700, 800, 1300, 1800, 2400 and 9100 rpm, corresponding to 0, -6, -8, -10, -33, -60, -100, and -1500 kPa. Water volume loss was used to determine SWRCs.

Bulk density was calculated as the oven-dried mass-to-volume ratio. Saturated moisture (θ_s) corresponds to 0 kPa. SWRCs were fitted using the Van Genuchten (1980) equation:

$$\theta(\Psi) = \theta_r + (\theta_s - \theta_r) \left[\frac{1}{1 + (\alpha\Psi)^n} \right]^m \quad (1)$$

Where:

$\theta(\Psi)$ = gravimetric soil moisture (kg kg^{-1}) at matric potential Ψ (kPa),

θ_r = residual moisture at $\Psi = -1500$ kPa,

θ_s = saturated moisture at 0 kPa,

α = inverse of air entry pressure (kPa^{-1}) (Van Genuchten, 1980),

n = pore size distribution parameter

$m = 1 - 1/n$ (per Mualem, 1976)

Field capacity (FC) was defined as water retention at -6 kPa, a value suitable for Cerrado soils (Andrade and Stone, 2011). Plant available water (PAW) was calculated as $\text{PAW} = \text{FC} - \theta_r$.

2.5. Statistical analysis

Principal component analysis (PCA) was performed to reduce the

dimensionality of soil properties and SWRC parameters by identifying major principal components. Biplots were generated to visualize relationships based on the first two components.

At each site and soil layer, mean values for CLF and PAST were compared using a *t*-test ($\alpha = 0.05$). Differences relative to NF were assessed using Dunnett's test at the 5 % significance level. Pearson correlation coefficients were calculated to evaluate pairwise associations among variables. All analyses were performed using R software version 4.4 (R Development Core Team, 2024).

3. Results

3.1. Quirinópolis site

Principal component analysis (PCA) of soil properties and SWRC parameters for the 0.0–0.2 m layer revealed that the first two components accounted for 74.4 % of the cumulative variance: PC1 explained 42.6 % and PC2 explained 31.8 % (Fig. 4A). Variables such as α , n , θ_s , FC, and PAW were more strongly correlated with PC1, whereas the remaining variables correlated more with PC2 (Table 2). The PCA distinguished three distinct land-use groups based on their relationships with soil and SWRC properties.

In PC1, negative loadings indicated that BD (-0.66) and the n parameter (-0.60) differentiated CLF from PAST, while θ_r (-0.58), FC (-0.75), and PAW (-0.84) distinguished PAST from NF. PAST exhibited higher θ_r , FC, and PAW values than NF, and higher SOM, θ_r , and FC than CLF (Table 3). Compared to NF, CLF had higher BD, n , θ_r , FC, and PAW, but lower α and θ_s . CLAY did not differ significantly among treatments. SOM was positively correlated with θ_s , whereas BD was negatively correlated with α and θ_s (Table 4).

At 0.2–0.4 m layer, the first two PCA components accounted for 76.8 % of total variance (PC1: 46.5 %, PC2: 30.3 %) (Fig. 5A). SOM, CLAY, θ_r , FC, and PAW were strongly associated with PC1, whereas the remaining variables correlated more with PC2 (Table 2). CLF was primarily associated with the n parameter; PAST with BD, SOM, CLAY, θ_r , and FC; and NF with θ_s . CLF exhibited higher SOM, n , FC, and PAW, and lower α than NF. Compared to NF, PAST had higher BD, SOM, CLAY, θ_r , FC, and PAW, and lower n and θ_s . Compared to CLF, PAST had higher θ_r and FC, but similar values for other parameters (Table 3). BD was negatively correlated with θ_s ; SOM was positively correlated with θ_r , FC, and PAW; and CLAY correlated positively with θ_r and FC (Table 4).

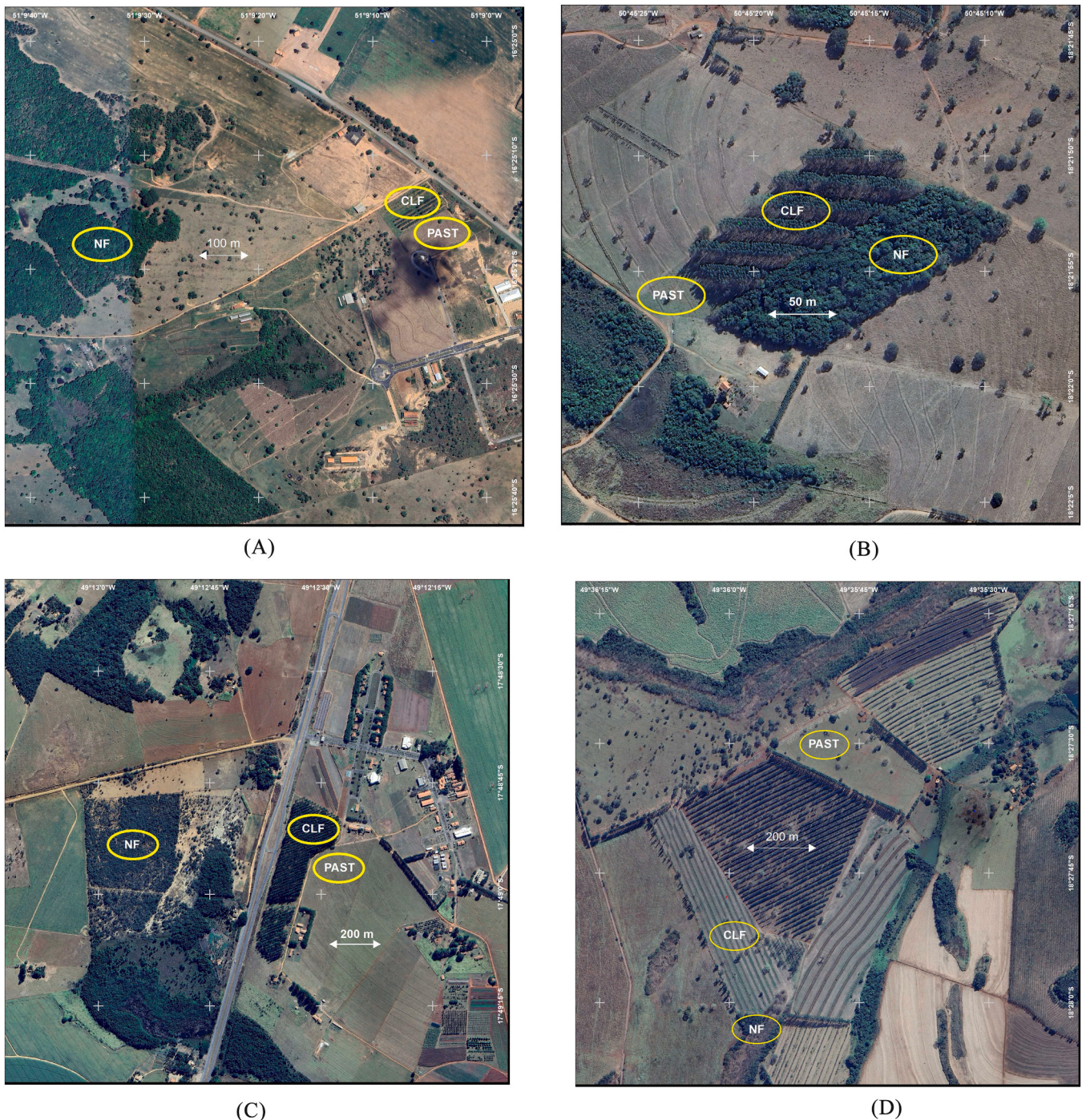


Fig. 2. Land-use systems - native forest (NF), pasture (PAST), and crop-livestock-forestry (CLF) - at each site: Iporá (A), Quirinópolis (B), Morrinhos (C), and Cachoeira Dourada (D). Source: Adapted by M.T.M.C. (co-author) from © Google Maps.

3.2. Iporá site

For the 0.0–0.2 m layer, PCA explained 79.7 % of the cumulative variability (PC1: 48.5 %, PC2: 31.2 %) (Fig. 4B). Most variables were strongly correlated with PC1, except for CLAY, θ_r , and FC, which were associated with PC2 (Table 2). CLF was linked to the n parameter; PAST to CLAY, θ_r , and FC; and NF to SOM, α , θ_s , and PAW. CLF had lower CLAY, θ_r , and FC than PAST. NF showed higher SOM, α , and θ_s , and lower BD, CLAY, and θ_r compared to PAST (Table 3). BD was negatively correlated with α , θ_s , and PAW, while SOM showed positive correlations with θ_s and PAW. CLAY positively correlated with θ_r (Table 4).

At 0.2–0.4 m layer, PCA explained 71.3 % of the variance (PC1:

48.8 %, PC2: 22.5 %) (Fig. 5B). SOM, CLAY, θ_r , FC, and PAW were correlated with PC1, while the remaining variables were more strongly correlated with PC2. CLF was associated with BD; PAST with CLAY, θ_r , FC, and PAW; and NF with SOM, α , and n . CLAY, θ_r , FC, and PAW were significantly higher in PAST than in CLF. Compared to NF, PAST had higher CLAY, θ_r , FC, and PAW, and lower α (Table 3). BD negatively correlated with θ_s , and CLAY was positively associated with θ_r , FC, and PAW (Table 4).

3.3. Morrinhos site

In the 0.0–0.2 m layer, PCA explained 83.0 % of the total variance



(A)



(B)



(C)

Fig. 3. Trenches under land uses in Quirinópolis: (A) native forest, (B) pasture, and (C) crop-livestock-forestry. Source: Photos by M.T.M.C. (Feb-Dec 2020).

(PC1: 69.5 %, PC2: 13.5 %) (Fig. 4C). All variables were more strongly correlated with PC1 (Table 2). CLF was associated with BD, θ_r , FC, and PAW; PAST with SOM and n ; and NF with CLAY, α , and θ_s . CLF showed higher BD, θ_r , FC, and PAW than PAST. Compared to NF, PAST exhibited higher BD, SOM, n , FC, and PAW, and lower α and θ_s (Table 3). BD negatively correlated with α and θ_s , and positively with θ_r , FC, and PAW. SOM correlated negatively with α , and positively with FC and PAW, while CLAY showed negative correlations with n and PAW (Table 4).

At 0.2–0.4 m layer, PCA explained 68.0 % of the variance (PC1: 40.4 %, PC2: 27.6 %) (Fig. 5C). Most variables correlated more strongly with PC1, except for BD, CLAY, and θ_s , which were associated with PC2 (Table 2). CLF was linked to θ_r , FC, and PAW; PAST to BD; and NF to α and θ_s . CLF showed higher FC, but lower SOM than PAST, with no other significant differences. Compared to NF, PAST had higher BD, SOM, FC, and PAW, and lower α and θ_s (Table 3). BD was negatively correlated with θ_s (Table 4).

3.4. Cachoeira Dourada site

At 0.0–0.2 m layer, PCA explained 82.4 % of the cumulative variance (PC1: 68.2 %, PC2: 14.2 %) (Fig. 4D). All variables were more closely associated with PC1, except CLAY, which was linked to PC2 (Table 2). CLF was associated with the n parameter and θ_s ; PAST with BD, SOM, CLAY, and α ; and NF with θ_r , FC, and PAW. Compared to PAST, CLF had higher n , θ_r , FC, and PAW, and lower CLAY and α . Compared to NF, PAST had lower n , θ_r , FC, and PAW, and higher SOM, CLAY, and α (Table 3). BD was positively correlated with α and negatively with θ_r , θ_s , FC, and PAW. SOM showed negative correlations with θ_r , FC, and PAW, and CLAY with FC and PAW (Table 4).

In the 0.2–0.4 m layer, PCA explained 69.5 % of the total variance

(PC1: 55.7 %, PC2: 13.8 %) (Fig. 5D). All variables were associated with PC1, except SOM and CLAY, which were more strongly correlated with PC2 (Table 2). CLF was associated with BD; PAST with CLAY and α ; and NF with n , θ_r , θ_s , FC, and PAW. Compared to PAST, CLF had higher n and FC, and lower CLAY. PAST showed lower n , θ_r , FC, and PAW, and higher CLAY than NF (Table 3). BD was negatively correlated with θ_r , θ_s , and FC (Table 4).

4. Discussion

4.1. Quirinópolis site

The transition from NF to PAST and CLF increased BD in both soil layers (0.0–0.2 and 0.2–0.4 m) of the sandy soil of Quirinópolis (Table 3) and is attributed to machine traffic during pasture implementation and ongoing livestock activity. This structural change decreased soil porosity and altered pore size distribution, modifying water retention and the shape of the SWRC (Machado et al., 2008; Silva et al., 2018b). The reduced porosity lowered the soil's water-holding capacity at higher potentials, as reflected in lower θ_s and α under PAST and CLF. Since α is inversely related to the air entry pressure, a reduction in α reflects a shift towards smaller dominant pore sizes, which is typically associated with a decline in soil macroporosity (Schaap and Leij, 2000).

The negative correlations between BD and both θ_r and α (Table 4) align with previous findings (Schaap and Leij, 2000; Michelon et al., 2010; Souza et al., 2014), emphasizing the influence of soil structure on water retention at higher water potentials (Assad et al., 2001).

CLF had higher values of the n parameter compared to NF (Table 3). Since n reflects the distribution of pore sizes, its increase suggests a narrower distribution dominated by mesopores—particularly medium

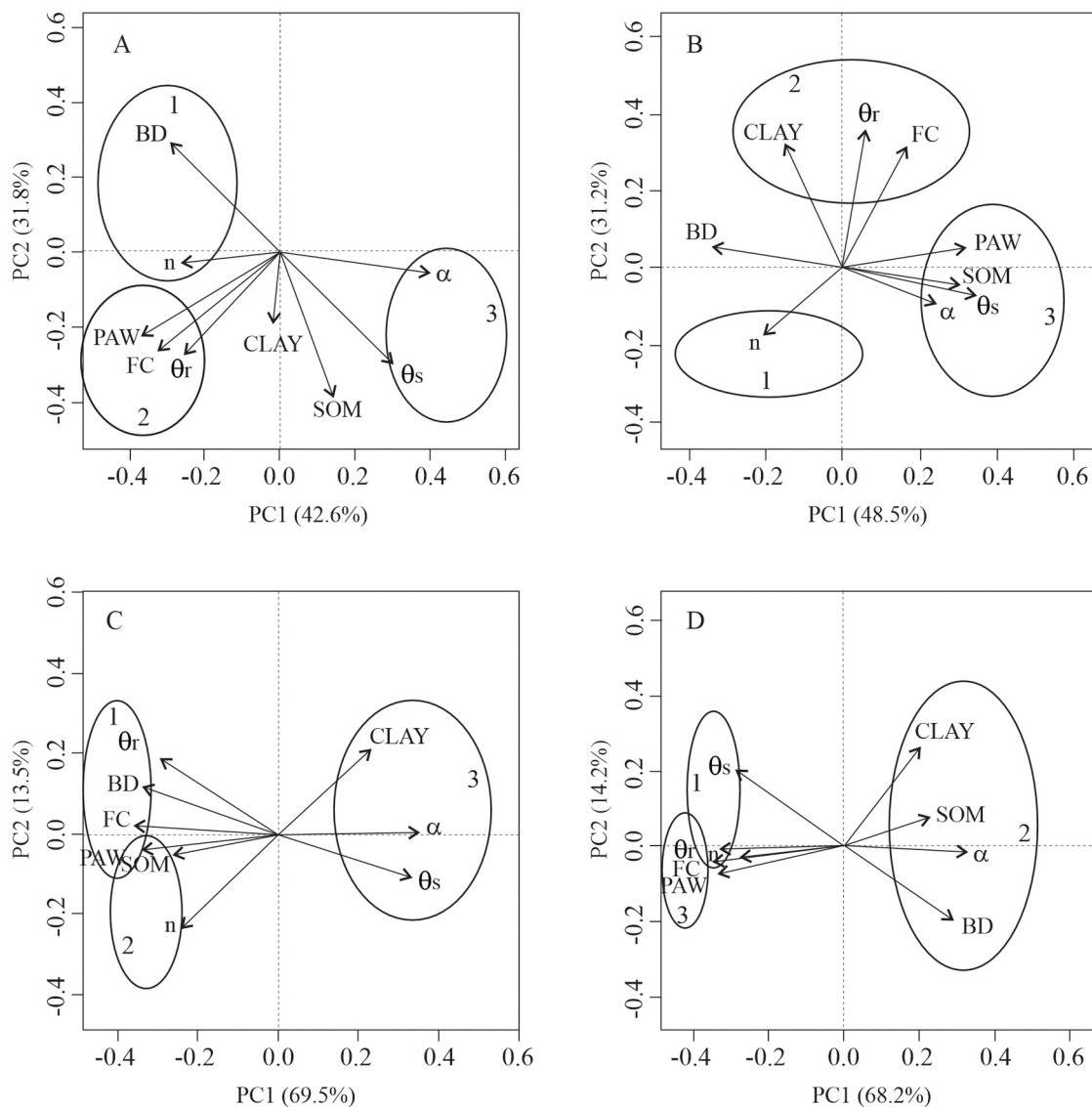


Fig. 4. Biplot generated from principal component analysis (PCA) of selected soil properties and soil water retention curve parameters in the 0.0–0.2 m soil layer under different land uses in Quirinópolis (A), Iporá (B), Morrinhos (C), and Cachoeira Dourada (D), Goiás State. 1, 2, and 3 = crop-livestock-forestry system, pasture, and native forest, respectively. BD = bulk density, SOM = soil organic matter, CLAY = clay content, α and n = empirical parameters of the Van Genuchten equation, θ_r = gravimetric soil moisture at the permanent wilting point (–1.5 MPa), θ_s = gravimetric soil moisture at saturation, FC: field capacity (gravimetric soil moisture at –0.006 MPa), PAW = plant available water.

(10–25 μm) and fine (2–10 μm) mesopores (Silva et al., 2020; Zhang et al., 2022). This configuration steepens the SWRC slope and can enhance PAW. Optimal water balance—combining minimal runoff, adequate infiltration, and sufficient drainage—requires a continuous network of variably sized pores (Soinnie et al., 2023).

Higher BD also led to increases in θ_r , FC, and ultimately PAW in CLF and PAST. CLF and PAST showed, respectively, PAW values 26 % and 40 % higher than those of NF in the 0.0–0.2 m layer, and 15 % and 17 % higher in the 0.2–0.4 m layer. At low water potentials, water retention becomes more dependent on surface area than on pore volume (Soinnie et al., 2023). Denser soils may have fewer adsorption sites due to reduced total porosity, causing water to be held with less energy, since reactivity or sorption of water molecules with the solid part of the soil diminishes (Maia et al., 2018). In Oxidic Ferralsols, slight compaction may convert macropores to micropores, improving water retention without compromising aeration (Severiano et al., 2011). However, Silva et al. (2006) cautioned that increases in both θ_r and FC may offset each other, leading to no net gain in PAW.

SOM was positively correlated with θ_s in the 0.0–0.2 m layer

(Table 4), likely due to its large specific surface area (Soinnie et al., 2023). Minasny and McBratney (2018) noted that SOM enhances water retention mainly at saturation, with limited effects at higher suctions. The effect is more pronounced in sandy soils. In the 0.2–0.4 m layer, SOM also improved θ_r , FC, and PAW, confirming its role in enhancing water retention in coarse-textured soils (Libohova et al., 2018). Higher SOM occurred under CLF and PAST, likely related to the deep root system of *Urochloa ruziziensis* (Ruzigrass) pasture. This, together with the slight compaction that occurs under CLF and PAST as mentioned earlier, contributes to higher PAW under these land uses.

Clay content positively influenced θ_r and FC at 0.2–0.4 m (Table 3). Clay particles, due to their large surface area and negative charge, adsorb water molecules efficiently (Souza et al., 2014; Silva et al., 2018b; Soinnie et al., 2023). Several studies have reported similar positive associations between clay and water retention (Giarola et al., 2002; Michelon et al., 2010; Nascimento et al., 2010; Carducci et al., 2011; Souza et al., 2014; Maia et al., 2018).

Table 2

Correlation coefficients between each principal component, soil water retention curve parameters, and soil properties in the 0.0–0.2 m and 0.2–0.4 m layers in Quirinópolis, Iporá, Morrinhos, and Cachoeira Dourada, Goiás State.

Property	Quirinópolis				Iporá			
	0.0–0.2 m		0.2–0.4 m		0.0–0.2 m		0.2–0.4 m	
BD (Mg m ⁻³)	-0.66	0.67	-0.50	-0.62	-0.93	0.14	-0.48	0.87
SOM (g kg ⁻¹)	0.32	-0.86	-0.82	0.23	0.84	-0.12	-0.35	-0.25
CLAY (g kg ⁻¹)	-0.04	-0.43	-0.83	-0.09	-0.40	0.86	0.81	0.17
α (kPa ⁻¹)	0.92	-0.12	0.29	-0.86	0.66	-0.26	-0.35	-0.38
n	-0.60	-0.07	0.12	0.84	-0.57	-0.48	-0.49	-0.50
θ_r (kg kg ⁻¹)	-0.58	-0.62	-0.91	-0.18	0.16	0.97	0.98	0.06
θ_s (kg kg ⁻¹)	0.68	-0.67	0.50	0.65	0.94	-0.19	0.49	-0.87
FC (kg kg ⁻¹)	-0.75	-0.60	-0.96	0.11	0.45	0.86	0.99	0.07
PAW (kg kg ⁻¹)	-0.84	-0.51	-0.70	0.61	0.87	0.14	0.92	0.11
	Morrinhos				Cachoeira Dourada			
	0.0–0.2 m		0.2–0.4 m		0.0–0.2 m		0.2–0.4 m	
BD (Mg m ⁻³)	-0.90	0.31	0.14	0.94	0.82	-0.55	-0.79	-0.25
SOM (g kg ⁻¹)	-0.71	-0.14	0.13	-0.19	0.65	0.22	0.21	0.65
CLAY (g kg ⁻¹)	0.63	0.57	-0.53	0.57	0.57	0.74	-0.46	-0.61
α (kPa ⁻¹)	0.94	0.01	-0.80	-0.47	0.92	-0.04	-0.70	0.37
n	-0.65	-0.64	0.50	-0.35	-0.76	-0.08	0.81	-0.27
θ_r (kg kg ⁻¹)	-0.79	0.50	0.83	-0.03	-0.91	-0.02	0.87	0.05
θ_s (kg kg ⁻¹)	0.91	-0.29	-0.15	-0.94	-0.80	0.57	0.78	0.24
FC (kg kg ⁻¹)	-0.96	0.05	0.96	-0.07	-0.98	-0.11	0.95	-0.12
PAW (kg kg ⁻¹)	-0.93	-0.12	0.88	-0.06	-0.93	-0.20	0.85	-0.30

BD = bulk density, SOM = soil organic matter, CLAY = clay content, α and n = empirical parameters of the Van Genuchten equation (significant at $p < 0.05$), θ_r = gravimetric soil moisture at the permanent wilting point (-1.5 MPa), θ_s = gravimetric soil moisture at saturation, FC = field capacity (gravimetric soil moisture at -0.006 MPa), PAW = plant available water, PC1 = first principal component, PC2 = second principal component.

4.2. Iporá site

Similar to Quirinópolis, the transition from NF to PAST and CLF increased BD in the 0.0–0.2 m layer (Table 3). This compaction reduced θ_s and α , and increased the n parameter in CLF. SOM positively influenced θ_s , consistent with earlier observations.

The higher SOM under NF helped offset lower BD, leading to increased PAW. This is supported by the negative correlation between PAW and BD, and the positive correlation between PAW and SOM (Table 4), in line with findings from Libohova et al. (2018) and Romaneckas et al. (2022). SOM's water-holding capacity is especially effective in sandy soils due to its macroaggregate formation and surface area. In the 0.0–0.2 m layer, PAW values under CLF and PAST were 28 % and 26 % lower, respectively, than under NF, whereas in the 0.2–0.4 m layer they were 3 % lower and 41 % higher. The higher PAW value in the soil under PAST can be explained by its higher clay content, which was unexpected given the proximity of the experimental areas (Fig. 2B).

Clay content improved water retention at θ_r in both layers and at FC in the 0.2–0.4 m layer, resulting in a positive correlation with PAW (Table 4). This again reflects clay's fundamental role in retaining water through its high specific surface area (Silva et al., 2018b).

4.3. Morrinhos site

In the clayey soil of Morrinhos, which has a high gibbsite content (D'Andréa et al., 2004), increased BD under CLF and PAST elevated θ_r and FC, resulting in higher PAW across both layers (Table 3). Gibbsite-rich soils are characterized by high macroporosity (Pedrotti et al., 2003), and the slight compaction that occurs under CLF and PAST—due to machine traffic during the cultivation of annual grain and forage crops and ongoing livestock activity—can convert macropores into micropores, thereby increasing water retention at low water potentials. CLF and PAST showed, respectively, PAW values 88 % and 46 % higher than those of NF in the 0.0–0.2 m layer, and 42 % and 24 % higher in the 0.2–0.4 m layer. In comparison with PAST, CLF resulted in greater PAW, mainly due to a better balance between macropores and micropores, as indicated by higher θ_r and FC, although a significant

difference was observed only in the 0.0–0.2 m layer. These positive correlations between BD and θ_r , FC, and PAW are consistent with results from Beutler et al. (2002), Souza et al. (2014), Maia et al. (2018), and Silva et al. (2018b). In clayey soils, denser packing may limit water-soil interactions, making water more plant-available (Maia et al., 2018).

SOM negatively correlated with α in the 0.0–0.2 m layer (Table 4), consistent with Rawls et al. (2003), who showed that SOM enhances aggregation in fine-textured soils and modifies water availability by influencing clay adsorption sites. Consequently, the combination of SOM and soil texture influences the “bound water” retained within the soil matrix, either through electrostatic forces at adsorption sites or via surface tension (capillary forces) in soil pores. According to Libohova et al. (2018), the relationship between PAW and SOM is complex, involving interactions among SOM, particle size, clay mineralogy, and bulk density.

Despite this, SOM was positively correlated with FC and PAW, possibly due to mineralogical influences. The influence of clay mineralogy on the soil porous media is mainly dependent on gibbsite content, and less dependent on kaolinite content (Silva et al., 2022). The dominant presence of gibbsite in Morrinhos' Ferralsols (D'Andréa et al., 2004) promotes strong aggregation and high macroporosity, mimicking sandy behavior (Pedrotti et al., 2003; Ghidin et al., 2006; Pessoa and Libardi, 2022).

Interestingly, CLAY negatively correlated with both n and PAW (Table 4), reflecting the broader pore size distribution and lower inflection slopes in highly clayey soils (Reatto et al., 2007; Zhang et al., 2022). The effect of clay on PAW is thus conditional upon the balance between macropores and micropores.

4.4. Cachoeira Dourada site

Cachoeira Dourada presented the highest clay content (~750 g kg⁻¹) and the longest-established CLF system (11 years), revealing distinct patterns in soil water dynamics. Under PAST, higher BD and clay content reduced n , θ_r , FC, and PAW, while increasing α compared to NF (Table 3). In highly clayey soils, connected large pores can produce low air-entry pressure and high α values (Zhang et al., 2022). The bimodal

Table 3

Soil properties and soil water retention curve parameters across soil layers and land-use types in Quirinópolis, Iporá, Morrinhos, and Cachoeira Dourada, Goiás State.

Site	Property	Land use							
		CLF	PAST	NF	SD	CLF	PAST	NF	SD
		0.0–0.2 m layer				0.2–0.4 m layer			
Quirinópolis	BD (Mg m ⁻³)	1.50a*	1.47a	1.40	0.07	1.43a	1.46a*	1.40	0.05
Iporá		1.42a	1.47a*	1.30	0.11	1.47a	1.42a	1.47	0.12
Morrinhos		1.26a*	1.20b*	1.14	0.03	1.25a	1.30a*	1.22	0.07
C. Dourada		1.13a	1.20a	1.17	0.08	1.13a*	1.12a	1.07	0.06
Quirinópolis	SOM (g kg ⁻¹)	13.3b	16.7a	16.3	1.8	9.3a*	10.4a*	8.2	1.0
Iporá		19.9a*	18.2a*	31.8	4.4	10.9a*	12.0a	15.6	1.8
Morrinhos		37.1a	37.3a*	34.2	1.4	24.1b	30.4a*	26.2	3.1
C. Dourada		39.6a	44.1a*	31.8	4.4	25.3a	24.7a	32.1	2.1
Quirinópolis	CLAY (g kg ⁻¹)	192.8a	192.1a	193.2	13.4	222.3a	234.6a*	208.2	10.4
Iporá		166.0b*	360.0a*	191.9	17.7	262.9b	415.1a*	245.9	43.4
Morrinhos		440.7a*	460.7a	513.2	46.9	535.7a	520.7a	535.7	46.5
C. Dourada		665.3b*	744.4a*	433.2	66.0	655.3b	772.4a*	588.7	95.0
Quirinópolis	α (kPa ⁻¹)	1.758a*	3.530a	9.018	3.349	1.442a*	2.797a	2.858	1.125
Iporá		20.221a	13.929a*	44.569	12.707	21.431a	6.347b*	37.570	6.221
Morrinhos		0.339b*	1.411a*	9.543	0.750	0.600a*	0.843a*	3.435	0.357
C. Dourada		1.294b*	22.021a*	0.622	13.457	2.216a	11.109a	1.294	11.332
Quirinópolis	n	1.554a*	1.517a	1.471	0.085	1.659a*	1.479b*	1.573	0.084
Iporá		1.445a*	1.361b	1.330	0.057	1.422a	1.357a	1.380	0.051
Morrinhos		1.438a*	1.457a*	1.388	0.033	1.470a	1.458a	1.441	0.046
C. Dourada		1.482a	1.318b*	1.429	0.077	1.431a*	1.348b*	1.486	0.055
Quirinópolis	θ_r (kg kg ⁻¹)	0.076b*	0.090a*	0.069	0.004	0.082b	0.098a*	0.077	0.002
Iporá		0.068b*	0.123a*	0.093	0.016	0.080b	0.148a*	0.081	0.016
Morrinhos		0.212a*	0.204b	0.197	0.007	0.207a*	0.197a	0.194	0.009
C. Dourada		0.253a	0.211b*	0.263	0.029	0.244a	0.217a*	0.252	0.027
Quirinópolis	θ_s (kg kg ⁻¹)	0.290a*	0.305a	0.342	0.032	0.324a	0.309a*	0.336	0.025
Iporá		0.338a	0.306a*	0.402	0.046	0.306a	0.330a	0.307	0.059
Morrinhos		0.419b*	0.457a*	0.505	0.021	0.426a	0.395a*	0.449	0.044
C. Dourada		0.505a	0.466a	0.478	0.059	0.506a*	0.519a	0.558	0.050
Quirinópolis	FC (kg kg ⁻¹)	0.129b*	0.149a*	0.111	0.007	0.135b*	0.152a*	0.123	0.006
Iporá		0.106b*	0.161a	0.146	0.022	0.111b	0.193a*	0.113	0.021
Morrinhos		0.338a*	0.302b*	0.264	0.008	0.308a*	0.286b*	0.266	0.016
C. Dourada		0.360a	0.281b*	0.381	0.040	0.342a*	0.300b*	0.367	0.036
Quirinópolis	PAW (kg kg ⁻¹)	0.053a*	0.059a*	0.042	0.006	0.053a*	0.054a*	0.046	0.005
Iporá		0.038a	0.039a	0.053	0.007	0.031b	0.045a*	0.032	0.006
Morrinhos		0.126a*	0.098b*	0.067	0.008	0.102a*	0.089a*	0.072	0.011
C. Dourada		0.108a	0.069b*	0.118	0.017	0.098a*	0.083a*	0.115	0.016

BD = bulk density, SOM = soil organic matter, CLAY = clay content, α and n = empirical parameters of the Van Genuchten equation (significant at $p < 0.05$), θ_r = gravimetric soil moisture at the permanent wilting point (–1.5 MPa), θ_s = gravimetric soil moisture at saturation, FC = field capacity (gravimetric soil moisture at –0.006 MPa), PAW = plant available water, CLF = crop-livestock-forestry system, PAST = pasture, NF = native forest, SD = standard deviation for the t test. Means in the rows followed by the same letter do not differ significantly by the t test at 5 % and those followed by an asterisk differ significantly from the NF by the Dunnett's test at 5 %, considering the NF as reference.

pore structure of tropical clayey Ferralsols—composed of very large and very small pores—also contributes to reduced PAW (Carducci et al., 2011; Amorim et al., 2022). CLF and PAST showed, respectively, PAW values 8 % and 42 % lower than those of NF in the 0.0–0.2 m layer, and 15 % and 28 % lower in the 0.2–0.4 m layer.

Negative correlations between BD and θ_r , θ_s , FC, and PAW (Table 4) in this site are consistent with previous findings (Machado et al., 2008; Libohova et al., 2018; Maia et al., 2018; Romanekas et al., 2022). In highly clayey soils, compaction can exacerbate pore discontinuity. Furthermore, the negative correlation between CLAY and both FC and PAW supports the idea that increased microporosity at the expense of macropores reduces water availability to plants (Severiano et al., 2011; Maia et al., 2018), since water retention at higher tensions, such as wilting point, is proportionally higher. Similar to what was observed in Morrinhos, CLF showed higher PAW than PAST, primarily due to a slightly lower clay content and a more balanced distribution of macropores and micropores, as reflected by higher θ_r and FC, although this difference was significant only in the 0.0–0.2 m layer.

Interestingly, PAST had higher SOM than NF in the 0.0–0.2 layer, yet lower water retention (Table 3). This reflects the complex interaction between SOM and soil texture, as SOM can increase aeration in fine soils while decreasing PAW (Rawls et al., 2003; Soinnie et al., 2023). The meta-analysis by Minasny and McBratney (2018) confirms that SOM has

minimal influence on PAW in clay-rich soils.

4.5. Contrasting effects of soil texture on water behavior

Soil texture strongly modulates the impact of land-use changes on soil water dynamics. In sandy soils (Quirinópolis and Iporá), increases in SOM improved water retention, particularly at saturation and FC, thereby increasing PAW. This is due to SOM's high surface area and macroaggregate formation (Giarola et al., 2002; Libohova et al., 2018; Minasny and McBratney, 2018; Soinnie et al., 2023). Moderate increases in BD also enhanced PAW by converting macropores into micropores, improving water storage (Severiano et al., 2011; Maia et al., 2018; Silva et al., 2018b).

In clayey soils (Morrinhos and Cachoeira Dourada), responses were more complex. While clay particles enhance retention at higher tensions (Carducci et al., 2011; Souza et al., 2014; Silva et al., 2018b), excessive clay content and compaction led to decreased PAW, often due to pore discontinuity and dominance of fine pores (Maia et al., 2018; Amorim et al., 2022; Zhang et al., 2022). In very clayey Ferralsols, the effects of BD and SOM on PAW were often neutral or negative, as water retained at wilting point offset increases at FC (Rawls et al., 2003; Minasny and McBratney, 2018; Soinnie et al., 2023).

These findings highlight the context-dependent nature of soil water

Table 4
Pearson correlation coefficients (r) between soil properties and water retention curve parameters in the 0.0–0.2 m and 0.2–0.4 m soil layers in Quirinópolis, Iporá, Morrinhos, and Cachoeira Dourada, Goiás State.

	0.0–0.2 m			0.2–0.4 m		
	BD	SOM	CLAY	BD	SOM	CLAY
Quirinópolis						
α	-0.63*	0.42	-0.18	0.21	-0.28	-0.14
n	0.20	-0.07	0.01	-0.34	-0.03	-0.06
θ_r	0.07	0.31	0.13	0.38	0.76**	0.75**
θ_s	-1.00**	0.75**	0.22	-1.00**	-0.09	-0.44
FC	0.15	0.25	0.16	0.30	0.80**	0.71**
PAW	0.21	0.16	0.17	0.05	0.60*	0.39
Iporá						
α	-0.61*	0.55	-0.31	-0.16	0.07	-0.25
n	0.44	-0.30	-0.30	-0.18	0.17	-0.30
θ_r	-0.02	0.00	0.75**	-0.40	-0.28	0.83**
θ_s	-0.99**	0.71**	-0.56	-1.00**	0.01	0.20
FC	-0.29	0.30	0.50	-0.40	-0.27	0.80**
PAW	-0.74**	0.81**	-0.34	-0.39	-0.20	0.58*
Morrinhos						
α	-0.85**	-0.62*	0.54	-0.49	0.07	0.18
n	0.39	0.45	-0.63*	-0.13	0.34	-0.40
θ_r	0.80**	0.51	-0.24	0.03	-0.03	-0.49
θ_s	-1.00**	-0.48	0.45	-1.00**	-0.11	-0.31
FC	0.84**	0.68*	-0.55	-0.01	-0.05	-0.42
PAW	0.78**	0.68*	-0.61*	-0.04	-0.05	-0.31
Cachoeira Dourada						
α	0.77**	0.41	0.53	0.40	-0.10	0.10
n	-0.50	-0.33	-0.36	-0.43	0.18	-0.28
θ_r	-0.72**	-0.58*	-0.54	-0.61*	0.18	-0.38
θ_s	-1.00**	-0.44	-0.09	-1.00**	0.11	-0.32
FC	-0.74**	-0.64*	-0.63*	-0.62*	0.13	-0.40
PAW	-0.64*	-0.62*	-0.65*	-0.47	0.03	-0.33

BD = bulk density, SOM = soil organic matter, CLAY = clay content; α and n = empirical parameters of the Van Genuchten equation (significant at $p < 0.05$), θ_r = gravimetric soil moisture at the permanent wilting point (-1.5 MPa), θ_s = gravimetric soil moisture at saturation, FC = field capacity (gravimetric soil moisture at -0.006 MPa), PAW = plant available water. Value of r followed by * and ** is significant at 5 and 1 % probability, respectively, ($n = 12$).

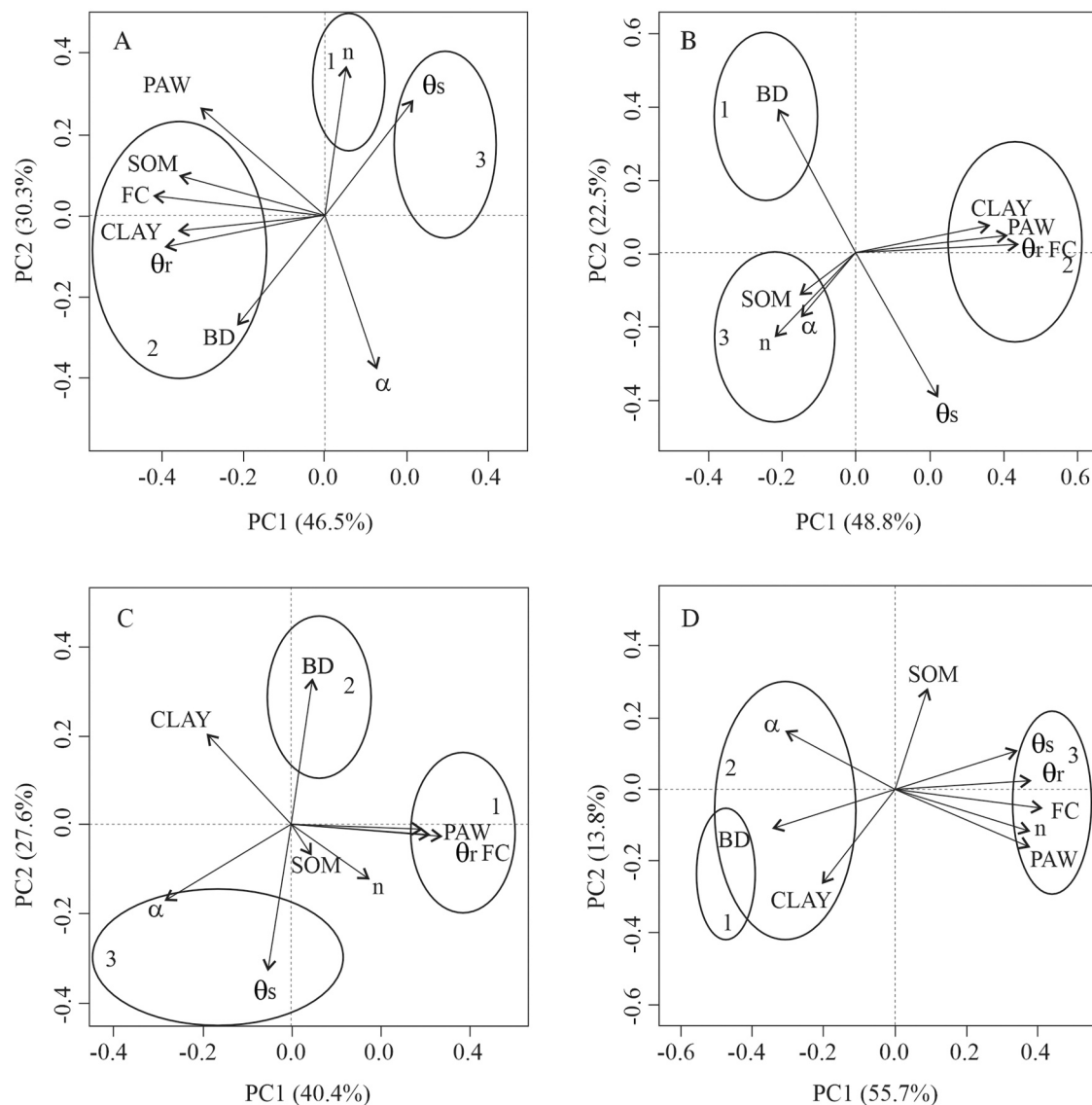


Fig. 5. Biplot generated from principal component analysis (PCA) of selected soil properties and soil water retention curve parameters in the 0.2–0.4 m soil layer under different land uses in Quirinópolis (A), Iporá (B), Morrinhos (C), and Cachoeira Dourada (D), Goiás State. 1, 2, and 3 = crop-livestock-forestry system, pasture, and native forest, respectively. BD = bulk density, SOM = soil organic matter, CLAY = clay content, α and n = empirical parameters of the Van Genuchten equation, θ_r = gravimetric soil moisture at the permanent wilting point (–1.5 MPa), θ_s = gravimetric soil moisture at saturation, FC: field capacity (gravimetric soil moisture at –0.006 MPa), PAW = plant available water.

dynamics, where the same property may produce divergent effects depending on texture, mineralogy, and structural characteristics.

4.6. Limitations of Pearson's correlation for explaining soil–water relationships

In Table 4, only a few Pearson's correlation coefficients are statistically significant. The lack of correlation in most cases likely reflects the complex, site-specific, and nonlinear interactions of soil properties with water retention, compounded by the limited sample size (12 per site/layer) and statistical power, which makes it difficult to detect moderate correlations.

SOM, CLAY, and BD each influence soil water differently depending on depth, texture, and mineralogy (Libohova et al., 2018; Maia et al., 2018; Minasny and McBratney, 2018), so simple linear correlations cannot fully explain the variability. For example, SOM is usually higher in the topsoil (0.0–0.2 m) but decreases sharply with depth; at 0.2–0.4 m, it may no longer be a strong driver of water retention,

weakening correlations. Moreover, soil properties often act in combination—for instance, SOM may improve aggregation only when sufficient CLAY is present (Soinnie et al., 2023) - so simple bivariate correlations fail to capture synergistic or antagonistic effects, leaving many real relationships hidden. In soils with strong textural control (e. g., very sandy or very clayey), BD or SOM may also have limited additional influence on water retention (Severiano et al., 2011; Minasny and McBratney, 2018).

Finally, many soil–water processes are nonlinear: a small increase in BD in sandy soils may increase PAW by filling medium pores (Severiano et al., 2011), but further compaction reduces it; similarly, SOM may improve PAW only up to a threshold, beyond which additional SOM has little effect (Libohova et al., 2018; Soinnie et al., 2023).

5. Conclusions

The intrinsic soil properties—particularly bulk density (BD), soil organic matter (SOM), and clay content—significantly modulate the

effects of land-use change and management transitions from native forest to pasture and subsequently to crop-livestock-forestry (CLF) systems on soil water retention characteristics and plant available water (PAW).

Across all sites, BD played a pivotal role in shaping the soil water retention curve (SWRC), influencing both the amount and distribution of pore sizes, which in turn affected PAW. While moderate increases in BD could improve water availability in sandy soils, the same effect was not consistently beneficial in clayey soils.

The impacts of land-use change on PAW were strongly dependent on soil texture:

- In sandy soils (e.g., Quirinópolis and Iporá), increases in SOM and moderate compaction under CLF and pasture systems enhanced water retention at field capacity more than at wilting point, thereby increasing PAW. These effects were attributed to SOM's contribution to aggregate stability and to the transformation of macropores into micropores through slight increases in BD.
- In clayey soils (e.g., Morrinhos and Cachoeira Dourada), responses were more complex. While high clay content increased total water retention, excessive compaction and the bimodal pore structure of highly weathered Ferralsols often led to reduced PAW. This occurred due to increased water retention at high tensions (e.g., wilting point), offsetting potential gains in field capacity. In these soils, SOM and BD sometimes had neutral or even negative effects on PAW.

These findings underscore the importance of considering soil texture and mineralogy when designing and managing land-use systems aimed at improving soil water availability. They also highlight the potential of CLF systems to enhance PAW in sandy soils, while pointing to the need for careful management of compaction and organic matter in clayey soils to avoid detrimental effects.

Ultimately, strategies to improve PAW and optimize water use efficiency must be site-specific, accounting for the intrinsic physical and mineralogical characteristics of each soil. In sandy soils, CLF adoption can be encouraged to enhance water availability, whereas in clayey soils, stricter control of compaction and organic matter dynamics is essential to avoid reductions in PAW.

CRedit authorship contribution statement

Melissa Ananias Soler da Silva: Funding acquisition, Data curation. **Márcia Thaís de Melo Carvalho:** Writing – original draft, Visualization, Project administration, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Stone Luis Fernando:** Writing – original draft, Visualization, Formal analysis, Data curation. **Beata Eموke Madari:** Writing – review & editing, Supervision, Funding acquisition. **Alessandra da Cunha Moraes Rangel:** Writing – review & editing. **Alexandre Bryan Heinemann:** Writing – review & editing. **Pedro Luiz Oliveira de Almeida Machado:** Writing – review & editing, Supervision, Funding acquisition. **Emerson Trogello:** Visualization, Conceptualization. **Thamires Marques Moura:** Investigation. **Siqueira Matheus Mentone de Brito:** Investigation. **Francine Neves Calil:** Supervision, Conceptualization.

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Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work the author Luís Fernando Stone used ChatGPT in order to improve the readability and language of the manuscript. After using this tool/service, the author reviewed and edited the content as needed and takes full responsibility for the content of the published article.

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.

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Data availability

Data will be made available on request.

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