

Annual Course of Matric Potential in Differently Used Savanna Oxisols in Brazil

Juliane Lilienfein,* Wolfgang Wilcke, Miguel Angelo Ayarza, Samuel do Carmo Lima, Lourival Vilela, and Wolfgang Zech

ABSTRACT

Sustainable land use in periodically dry Brazilian savannas requires a water-saving management. We hypothesized that the annual course of matric potentials (ψ_M) in very-fine, isohyperthermic Anionic Acrustoxes of *Pinus* plantations (PI), degraded (DP) and productive pastures (PP), no-till (NT) and conventional tillage (CT) cropping, and natural savanna (Cerrado, CE) differed significantly. On three plots in each of these land-use systems water input and ψ_M at the 0.15-, 0.30-, 0.80-, 1.2-, and 2.0-m depths was measured with tensiometers weekly between 27 Mar. 1997 and 28 Apr. 1998. Precipitation between 29 Apr. 1997 and 28 Apr. 1998 was 1562 mm, with only 210 mm in May to September, when ψ_M at the 0.15- and 0.30-m depths decreased to less than -80 kPa in all systems; the lowest ψ_M at 2-m depth was -57 kPa. During the monitored period, the PI soils had lower average ψ_M at the 0.8- to 2-m depths (-60 kPa) than those in CE (-46), indicating higher rainfall interception losses and higher transpiration. In CT, average ψ_M values at the 0.8- to 2-m depths (-29) were higher than in NT (-51) because of different crops and different soil management. Between June and November, ψ_M at the 2-m depth in CE decreased to a lower value (-42) than in vegetation-free CT (-22) and NT (-27). In DP and PP soils, ψ_M s were similar to those in CE soils at all depths. The estimated average water storage in the upper 2 m during the monitored period was: 565 mm (CT) > 553 (PP) > 541 (DP) > 537 (CE) > 526 (NT) > 479 (PI). Our results show that mainly the vegetation type and tillage practices control the annual course of matric potential in differently used savanna Oxisols.

IN THE LAST 30 YR, intensive agriculture developed on the nutrient-poor soils of the Brazilian savanna region (the Cerrados). Large parts of natural Cerrado were cleared and afforested or transformed to pasture and cropping systems (Goedert, 1983). Agriculture in this region is water-limited. In soils under native vegetation, matric potentials at 0.5-m soil depth decrease below the permanent wilting point, that is, the matric potential at which plants wilt, only one month after the end of the rainy season (Franco et al., 1996). If dry periods occur during critical stages of crop growth, such as flowering, water stress may result in severe yield losses (Goedert, 1983). Land-use practices which result in changed water budgets may therefore affect crop yields and, in the long run, may also have impacts on the groundwater level and storage.

The soil water content is influenced by the water consumption of plants and by soil management (McGowan and Williams, 1980a, 1980b; Azooz et al., 1996). In

Great Britain, McGowan and Williams (1980a, 1980b) found decreasing evapotranspiration along the line: woodland > pasture > barley. Because forests generally consume more water and have a greater interception capacity resulting in higher evaporation losses, lower soil water contents are often found in soils under forest than under cropping systems or pastures (Blume and Zimmermann, 1975; Hodnett et al., 1995). In a study by Lima (1983), conducted in the state of São Paulo, Brazil, the water content of the uppermost 2 m of soils under different *Pinus* species was significantly lower than under natural Cerrado vegetation. *Pinus* forests use up to 93% of the annual precipitation for transpiration (Schiller and Cohen, 1998). Lima et al. (1990) reported a higher annual evapotranspiration of 5-yr-old *Pinus caribaea* Morelet plantations (716 mm yr⁻¹) than of native Cerrado vegetation (576 mm yr⁻¹) in Brazil. Hodnett et al. (1995) compared evapotranspiration rates of Amazonian rain forest and pasture and found similar evapotranspiration rates of ≈ 4 mm d⁻¹ at high soil water contents. At low soil water contents, evapotranspiration rates in pasture were substantially reduced to a minimum of 1.2 mm d⁻¹, while those of the forest remained above 3.5 mm d⁻¹. In cropping systems transpiration rates depend on crop species and yield. The economically most important crops cultivated in the study region are corn (*Zea mays* L.) and soybean [*Glycine max* (L.) Merr.]. The transpiration coefficient (i.e., the ratio between dry biomass and transpiration water loss) of soybean is almost two times (>700 kg H₂O kg⁻¹ dry biomass) that of corn (300 – 400 kg kg⁻¹; Geisler, 1980).

In CT soils, pore continuity is reduced compared with NT soils, resulting in reduced evaporation (Lal et al., 1980; Logsdon et al., 1990; Azooz et al., 1996). Azooz and Arshad (1996) reported higher infiltration rates and a higher saturated hydraulic conductivity in NT than in CT soils. While the volume of macropores (>14 μ m) in the study of Azooz and Arshad (1996) was not significantly different between NT and CT soils, Hill (1990) found a higher macropore volume (>15 μ m) in CT than in NT soils and, in contrast to the conclusions of Azooz and Arshad (1996), inferred faster drainage in the former than in the latter. Furthermore, the pore space for plant-available water was greater in CT than in NT soils (Hill, 1990). The effects of tillage practices also depend on climatic conditions. For example, during humid winters in Great Britain, Goss et al. (1978) found no difference in water content between the tillage variants, whereas in dry winters more water was stored in NT systems than in the tilled ones.

Abbreviations: Al_o, oxalate-extractable Al; CE, Cerrado; CT, conventional tillage; DP, degraded pasture; Fe_d, dithionite-citrate-extractable Fe; NT, no-till; PI, *Pinus caribaea* plantation; PP, productive pasture; ψ_M , matric potential.

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The objective of this work was to compare the annual course of matric potentials in differently used Brazilian savanna Oxisols and to evaluate the systems with regard to water availability for plants and water storage in the rooting zone.

MATERIALS AND METHODS

Study Sites

The study area is located southeast of Uberlândia (State of Minas Gerais) ≈ 400 km south of Brasília (Fig. 1). Within an area of ≈ 100 km², three plots of each of the following six land-use and natural systems were selected: (i) *Pinus* plantations (PI), (ii) degraded (DP) and (iii) productive pastures (PP), (iv) no-till (NT) and (v) conventional tillage (CT) cropping, and (vi) natural savanna (Cerrado, CE). We considered these land-use systems the most important ones in the study region. To allow for statistical evaluation with variance analysis we aimed at selecting independent replicates of each system. As our objective was to conduct an on-farm experiment, we had to select the experimental plots in existing land-use systems. Thus, an entirely randomized plot selection was not possible. However, we only chose replicate plots of each land-use and natural system which were separated from each other by a distance of at least 300 m and, except for PI, by an area which was differently used between the replicate plots. The PI forest covered a large area without intermixed plots with different land-use. We assume that the prerequisites for variance analysis have been met by this experimental design.

The PI system consisted of *P. caribaea* planted in 1977 which received an initial fertilization of 25 kg P ha⁻¹ (80 g superphosphate per plant). In both, DP and PP *Brachiaria decumbens* Stapf, an imported grass species from Africa, was planted as a monoculture in 1985. The DP had vegetation-free spots and some invaded Cerrado plants, while PP was a pure grass pasture with a closed vegetation cover. Both pastures were fertilized with 40 kg P ha⁻¹, 65 kg K ha⁻¹, 32 kg N ha⁻¹, and 1 t dolomite ha⁻¹ when established; PP was further fertilized with 17 kg P ha⁻¹ and 33 kg K ha⁻¹ in 1996–1997. There were additional fertilizer applications to PP at unknown rates and application times prior to 1996. The CT soils have been plowed or loosened with a disk harrow two to three times per year for 12 yr and used for corn–soybean rotation. In 1996, soybean was harvested at the end of March, then corn was planted on 11 Nov. 1997 and harvested on 1 Apr. 1998. The NT systems had been established only between 1 and 3 yr prior to the beginning of our experiment in 1997 after the plots had been used as CT in the way described above for 9 to 11 yr. In the 1996–1997 rainy season, after the harvest of soybean in the end of March, corn was planted on 10 Feb. 1997 and harvested on 15 June 1997; then soybean was planted on 28 Nov. 1997 and harvested on 16 Apr. 1998. In 1998 the soil moisture did not support a second crop because of an unusual dryness due to the “El Niño” effect. Both cropping systems (CT, NT) were fertilized with an annual average of ≈ 70 kg N ha⁻¹, 100 kg P ha⁻¹, and 160 kg K ha⁻¹. The Cerrado vegetation was characterized by an open grassland with a 15 to 40% cover of 3- to 5-m-high trees and may be considered as typical (Sarmiento, 1984). The dominant tree species are *Pouteria torta* (Mart.) Radlk., *Kielmeyera coriacea* (Spreng.) Mart., *Caryocar brasiliense* Camb., *Ouatea hexasperma* (St. Hil.) Benth., and *Miconia albicans* (Sw.) Triana.

All study sites had slopes below 1°; they have been continuously used for the same purposes for 12 (DP, PP, NT, CT) or 20 (PI) yr and passed directly from natural vegetation to the current land-use system except for the NT soils. All study soils

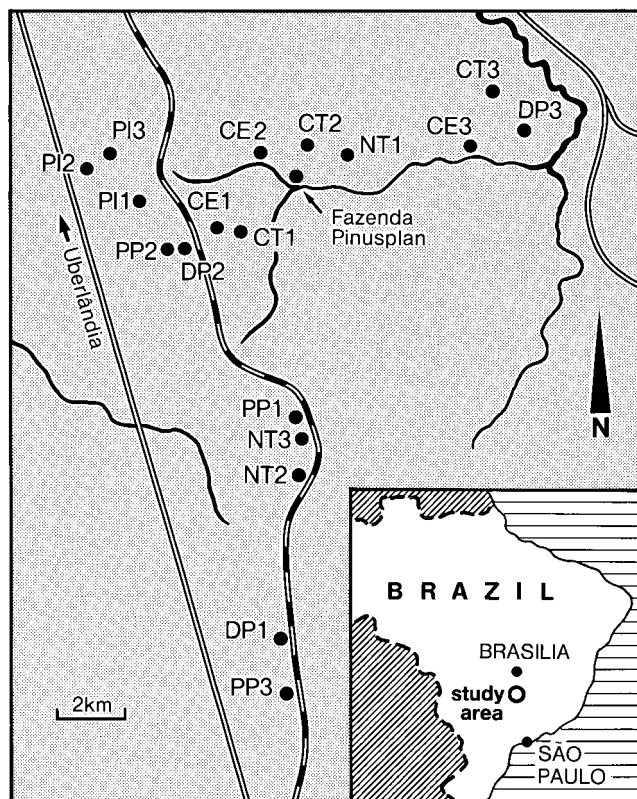


Fig. 1. Locations of the study sites (CE, native Cerrado; PI, *Pinus*; NT, no-till cropping; CT, conventional tillage; DP, degraded pasture; and PP, productive pasture).

developed from fine limnic sediments of the lower Tertiary. The soils were homogeneously weathered to a depth of several meters.

Equipment and Measurements

On each of the 18 plots a 10 by 10 m area was fenced and equipped with five replicate tensiometers at each of 0.15-, 0.3-, 0.8-, 1.2-, and 2-m depths. All plots were equipped with five rain collectors consisting of a sampling bottle and a funnel with a diameter of 115 mm at 0.3-m height above the soil surface to measure soil water input. Each sampling bottle was protected against larger particles and small animals with a polyethylene net (0.5-mm mesh width). A table-tennis ball was used to reduce evaporation. Tensiometers and rain collectors were placed within and between the crop rows in the cropping systems and near and between the trees in CE and PI. During the rainy season (March–April 1997 and October 1997–April 1998) and during the dry season (May–October 1997), ψ_{MS} were read and precipitation measured every 7 and 14 d, respectively. The soils in CT were hoed manually instead of plowing on 9 October and 21 Nov. 1997 within the fenced plots as tensiometers could not be removed. Weed in NT was controlled by the application of 1.2 kg ha⁻¹ glyphosate [*N*-(phosphonomethyl)glycine; Roundup, Monsanto, St. Louis, MO] on 27 Nov. 1997.

Meteorological Data

Precipitation data, and daily maximum and minimum temperatures were provided by the Fazenda Pinusplan, a commercial farm producing mainly corn, soybean, and *Pinus*. The meteorological station of the farm is located near Plot CE2 and CT2 (Fig. 1) in the study area.

Soil Physical Characterization

Particle-size distribution was determined in the 0- to 0.15-, 0.15- to 0.3-, 0.3- to 0.8-, 0.8- to 1.2-, 1.2- to 2-m layers after removal of the oxides with Na-dithionite and of organic matter with H_2O_2 at 90°C, following dispersion with hexametaphosphate. Coarse and fine sand were sieved to 250 to 2000 and 50 to 250 μm , respectively. Silt and clay concentrations were determined with the pipette method (Gee and Bauder, 1986). Soil density was determined gravimetrically by taking five undisturbed 100-mL soil cores.

To determine soil water characteristic curves, five undisturbed soil samples were taken from the 0- to 0.15-, 0.15- to 0.3-, 0.3- to 0.8-, 0.8- to 1.2-, 1.2- to 2-m soil layers with 100-mL steel rings from one selected soil in each of CE and NT (CE1 and CT2 in Fig. 1). The five replicate cores per layer were taken from various depths to account for the heterogeneity within one layer. The gravimetric soil water content was determined at ψ_{Ms} of -0.316 , -1.0 , -3.16 , -10.0 , and -31.6 kPa after equilibrating on ceramic plates. Water content at -1584.8 kPa was determined in a pressure pot using disturbed samples (Klute, 1986).

Soil Chemical Characterization

Soil organic carbon (SOC) was determined with a CHNS-analyzer (Vario EL, Elementar Analysensysteme GmbH, Hanau, Germany). Aluminum in poorly ordered Fe oxides was extracted with the oxalate-buffer method (Al_o ; Schwertmann, 1964), crystalline Fe oxides with the cold dithionite-citrate-buffer (DCB) method (Fe_d ; Holmgren, 1967). Aluminum and Fe were measured with flame atomic absorption spectrophotometry (Varian AA 400, Varian, Mulgrave, Australia).

Calculations and Statistical Evaluation

To fit soil water characteristic curves to the measured values, the Soil Hydraulic Properties Fitting (SHYPPFIT) program (Durner, 1994) was used. The soil water characteristic curves obtained for a specific layer of one soil in each of CE and NT were averaged to estimate water storage in the soil layers. Estimates were calculated for the dry season (May–October 1997) and the rainy season (November 1997–April 1998) separately:

$$WS_{sl} = \rho_{sl} l_{sl} \theta_{sl} \quad [1]$$

where WS_{sl} is the water storage in the soil layer (mm), ρ_{sl} the soil bulk density (Mg m^{-3}), l_{sl} the depth of the soil layer (m), and θ_{sl} average water content in the soil layer (g kg^{-1}).

Water storages of the soil layers were summed to get the water storage of the uppermost 2 m:

$$WS = WS_{0-0.15} + WS_{0.15-0.3} + WS_{0.3-0.8} + WS_{0.8-1.2} + WS_{1.2-2.0} \quad [2]$$

Main and interactive means of the soil water characteristic curves, Fe_d and Al_o concentrations, texture, and the calculated water contents were tested with Tukey's honestly significant difference (HSD) mean separation test (Hartung and Elpelt, 1989). Mean ψ_{Ms} were tested with the Wilcoxon matched pairs test. Significance was set at $P < 0.05$. Statistical analyses were performed with STATISTICA for Windows 5.1 (StatSoft, 1995, Hamburg, Germany).

RESULTS AND DISCUSSION

Comparability of the Soils

Differences in ψ_{Ms} between land-use systems can only be interpreted as caused by land-use practices if the

soils were similar prior to the beginning of land use. To test this prerequisite, we compared soil characteristics that are not or only little influenced by land use. Such characteristics include the soil classification, the particle-size distribution, and the mineralogical composition. As indicators of the mineralogical composition, we determined the concentration of Fe_d , which is a measure for the concentration of Fe oxides formed after the release of Fe from primary minerals (Mehra and Jackson, 1960). Additionally, we used the concentration of Al_o as a measure for the concentration of the Al that isomorphously substitutes for Fe in Fe oxides (Parfitt and Childs, 1988).

All studied soils were very-fine isohyperthermic Anionic Acrustoxes (Soil Survey Staff, 1997) with high clay concentrations ($615\text{--}885 \text{ g kg}^{-1}$). There was no significant change in clay content with increasing soil depth in any individual soil (data not shown). Clay, silt, coarse, and fine sand concentrations were not significantly different between the land-use systems within any individual soil layer (Table 1). The Al_o and Fe_d concentrations of the same depth layer were not significantly different between any of the studied soils of all land-use systems. Additionally, the average standard deviations of the Al_o and Fe_d concentrations between the replicate plots of one system (Fe_d : 9.1 g kg^{-1} , Al_o : 0.27 g kg^{-1}) were similar to those between all soils (Fe_d : 9.2, Al_o : 0.33). Thus, we assume that the soils had similar properties prior to land use, and differences in ψ_M and water storage can be interpreted as the result of land-use practices, which also are the reason for small but significant differences in SOC concentrations.

Climate and Soil Water Input

Between 29 Apr. 1997 and 28 Apr. 1998, the average maximum temperature was 29°C and the average minimum temperature was 16°C, with only small variations during the year. Total precipitation during that time was 1562 mm; 1342 mm fell between October 1997 and April 1998 and only 220 mm during the dry season between the end of April and September 1997 (Fig. 2). The cumulative precipitation between 29 Apr. 1997 and 28 Apr. 1998 is comparable with the mean annual precipitation between 1981 and 1990 of 1550 mm (Rosa et al., 1991). However, due to the El Niño effect, precipitation during the dry season in 1997 was higher (220 mm) compared with the average of 130 mm between 1981 and 1990.

The land-use systems with a noncontinuous canopy (CE, DP) received higher soil water inputs than the other land-use systems because of the smaller loss due to the evaporation of intercepted water (Table 2). Reduced soil water input on the PI plots are related to evaporation of water intercepted by the needles, which has been reported to be equivalent to ≈ 25 to 30% of above-canopy precipitation in evergreen coniferous forests (Bäumler and Zech, 1997; Parfitt et al., 1997). Smallest inputs were measured for CT where corn was planted in the 1997–1998 rainy season. Ellies and Huber (1991) showed that the proportion of stemflow in corn cultures can reach values of up to 50% of the precipitation. As

Table 1. Mean soil organic C (SOC), citrate-dithionite-extractable Fe (Fe_d), oxalate-extractable Al (Al_o), and particle-size distribution of native Cerrado (CE), Pinus (PI), no-till cropping (NT), conventional tillage (CT), degraded pasture (DP), and productive pasture (PP).

Soil depth	Plot	SOC	Fe_d	Al_o	Particle-size distribution				Bulk density
					Coarse sand	Fine sand	Silt	Clay	
m					g kg ⁻¹				Mg m ⁻³
0–0.15	CE	22.0ab†	32.1	2.8	139	68	88	705	0.88ab
	PI	21.9b	30.7	3.4	106	65	96	733	0.82b
	NT	21.7b	32.2	3.0	104	62	116	718	0.99a
	CT	20.8b	38.4	3.0	127	67	115	692	1.03a
	DP	22.4b	31.2	2.9	97	59	50	793	1.00a
	PP	26.7a	24.2	3.0	100	61	78	762	0.96ab
0.15–0.3	CE	17.7	33.3	2.9	138	70	83	708	0.99
	PI	15.8	31.1	3.1	104	65	76	755	0.95
	NT	19.0	32.4	3.1	104	62	133	702	0.92
	CT	17.4	39.9	3.2	121	64	110	705	1.10
	DP	18.4	32.1	2.9	97	51	55	797	0.94
	PP	18.5	25.9	2.9	102	61	47	790	0.94
0.3–0.8	CE	11.3	32.0	2.7	127	62	130	680	0.94
	PI	11.4	30.6	3.2	90	57	88	765	0.89
	NT	11.7	32.6	3.1	89	53	125	733	0.88
	CT	10.9	40.2	3.1	103	60	107	730	0.85
	DP	12.0	31.9	2.9	90	49	63	798	0.86
	PP	12.4	26.0	2.8	94	51	78	778	0.90
0.8–1.2	CE	8.4	31.8	2.6	121	62	129	688	0.84
	PI	8.3	30.5	2.6	90	59	105	746	0.84
	NT	8.9	32.3	3.1	88	53	130	729	0.85
	CT	7.4	40.0	3.1	101	58	141	700	0.86
	DP	8.2	31.5	2.6	84	49	45	821	0.85
	PP	8.5	25.4	2.8	87	48	102	763	0.86
1.2–2	CE	6.4	31.5	2.5	117	65	134	684	0.82
	PI	6.9	29.4	2.5	93	58	101	748	0.79
	NT	6.8	31.5	3.0	85	55	139	721	0.83
	CT	6.3	38.8	3.0	100	59	102	738	0.82
	DP	6.7	31.2	2.5	87	55	74	785	0.81
	PP	6.7	24.8	2.9	84	50	96	770	0.82

† Means followed by different letters are significantly different between the land-use systems at $P < 0.05$ (Tukey's honestly significant difference [HSD] test). Missing letters indicate that there were no significant differences between the land-use systems.

we did not measure the stemflow, the soil water input values in CT may be artificially low compared with the precipitation.

Matric Potentials

Matric potentials at the 0.15- and 0.3-m depths reflected the precipitation in all land-use systems (Fig. 3a and 3b). Missing values during the dry season indicate that ψ_M decreased to less than -80 kPa, and thus could no more be measured with the tensiometers that were used. At the 0.8- to 2-m depth, it took more time until ψ_M increased during a wet period (Fig. 3c–3e). At the 2-m depth, maximum ψ_M was only reached ≈ 2 mo after the first rain. This was a result of the low unsaturated

hydraulic conductivity of Oxisols due to the pseudosand and pseudosilt structure, that is, the formation of sand- and silt-sized aggregates stabilized by Fe oxides (Van Wambeke, 1992). After the soil had been rewetted at the 2-m depth, ψ_M remained almost constant around -5 kPa during the whole rainy season (December 1997–April 1998; Fig. 3e). During the whole dry season (June–November 1997), there was plant-available water at soil depths of 0.8 to 2 m in all land-use systems (Fig. 3c–3e).

The course of ψ_M in PI soils paralleled that in CE soils, but the average ψ_M of the whole monitored period at ≥ 0.3 -m soil depth under PI was significantly lower (Fig. 3b–3e). Differences in ψ_M between PI and CE increased with soil depth. During periods of little rain, differences between PI and CE became greater as a

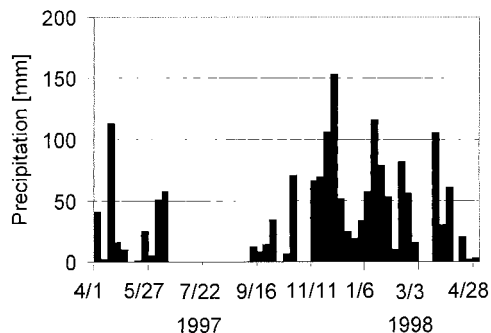


Fig. 2. Precipitation between 1 Apr. 1997 and 28 Apr. 1998 recorded at the Fazenda Pinusplan, a commercial farm.

Table 2. Mean soil water input (measured at 0.3 m above surface) into different land-use systems from 27 Mar. 1997 to 28 Apr. 1998.

Land-use system	Soil water input
	mm
Native Cerrado (CE)	1560a†
Pinus (PI)	1335ab
Degraded pasture (DP)	1503a
Productive pasture (PP)	1425a
No-till cropping (NT)	1366ab
Conventional tillage cropping (CT)	1103b

† Means followed by different letters are significantly different between the land-use systems at $P < 0.05$ (Tukey's honestly significant difference [HSD] test).

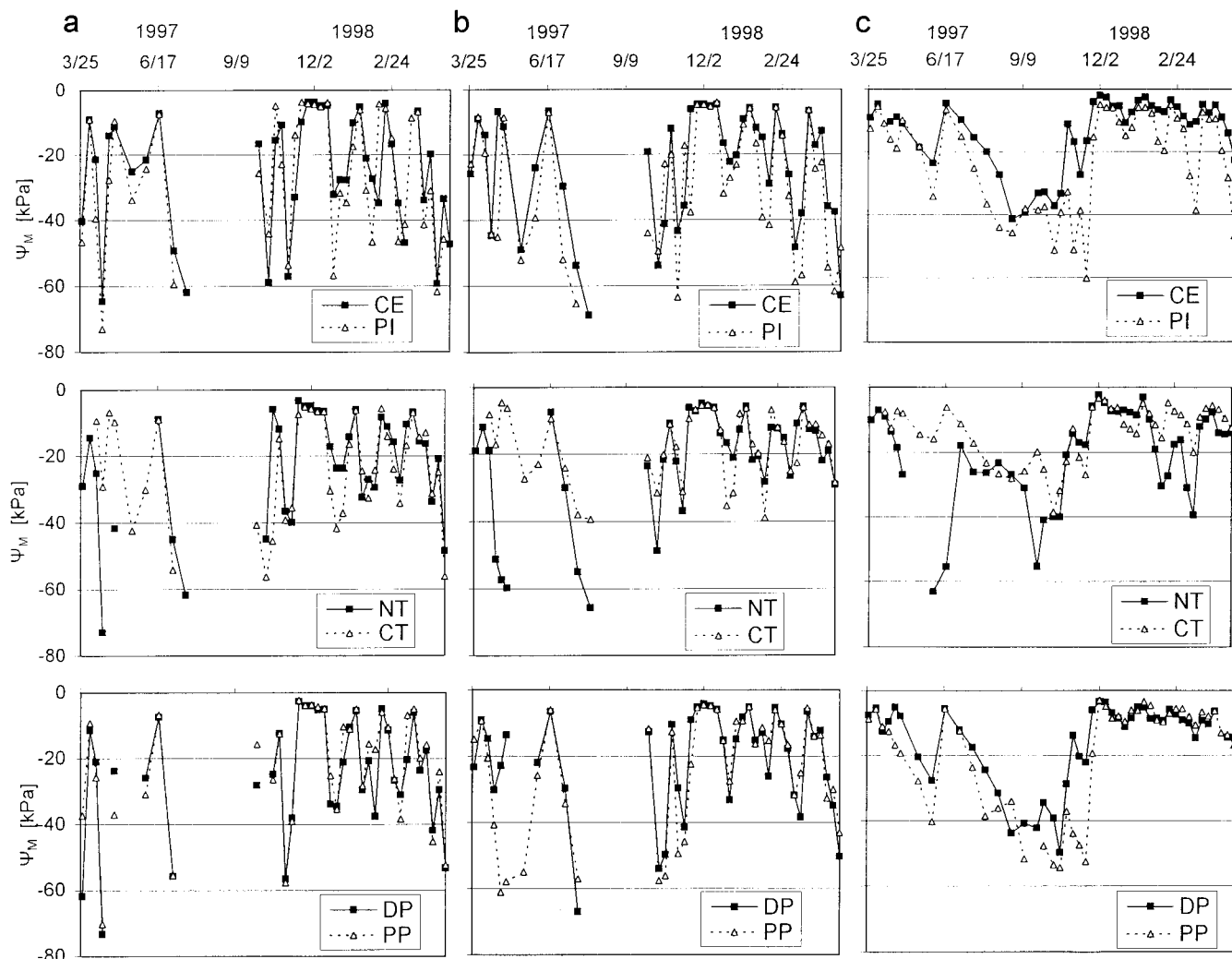


Fig. 3. Course of matric potentials (ψ_M) at (a) 0.15-, (b) 0.30-, (c) 0.80-, (d) 1.20-, and (e) 2.00-m depth in soils of native Cerrado (CE), Pinus (PI), no-till cropping (NT), conventional tillage cropping (CT), degraded pasture (DP), and productive pasture (PP) between 27 Mar. 1997 and 28 Apr. 1998. Shown values are averages of three replicates per treatment.

result of the higher evapotranspiration rates of PI (Lima et al., 1990). The greatest differences were recorded at the end of August ($\psi_{M,CE} - \psi_{M,PI} \approx 30$ kPa). During the rainy season, the differences were smaller. In December or later, during wet periods, ψ_M in both systems were nearly identical. During short dry periods from December to April, differences in ψ_M between CE and PI soils increased but were generally <10 kPa.

Average ψ_M of the whole monitored period at the 0.15-m depth were not significantly different between CT, NT, and CE (Fig. 3a). Average ψ_M in CT were significantly higher than in CE at the 0.3-, 1.2-, and 2-m depths (Fig. 3b, 3d, and 3e) and in NT at 0.3- to 2-m depths (Fig. 3b–3e). Average ψ_M in NT at the 0.8- and 1.2-m depths were significantly lower than in CE (Fig. 3c and 3d). However, differences in soil ψ_M between the cropping systems and CE varied in the course of the year.

The reasons for differences in ψ_M between CE, CT, and NT are related to different plant cover and different soil management. Between the 15 March and the end of June 1997, the NT soils were cropped with corn while

the CT soils were without crops. The water consumption of the corn probably lowered ψ_M . This may, in part, also be the reason for the lower ψ_M in NT than in CT at the 0.3- to 2-m depths during the dry season (June–November 1997; Fig. 3b–3e). However, evaporation from NT soils may also have been higher than from CT soils because plowing destroys the pore continuity and thus reduces evaporation (Azooz and Arshad, 1996). After the harvest in CT and in NT, the water consumption of the partly evergreen vegetation in CE was higher and ψ_M consequently decreased to a lower value than in the cropping systems.

Lower ψ_M at the 0.8- to 2-m depths in NT than in CT during the period of high biomass production (February–April 1998; Fig. 3c, 3d, and 3e) can be explained by higher transpiration coefficients of soybean than of corn (Geisler, 1980) and similar average biomass production (soybean: 11.3 Mg dry mass ha^{-1} , corn: 12.8 Mg ha^{-1}) on our plots during the 1997–1998 vegetation period. Lower ψ_M in NT than in CT soils could also be attributable to a lower infiltration rate and a lower saturated hydraulic water conductivity in NT than in

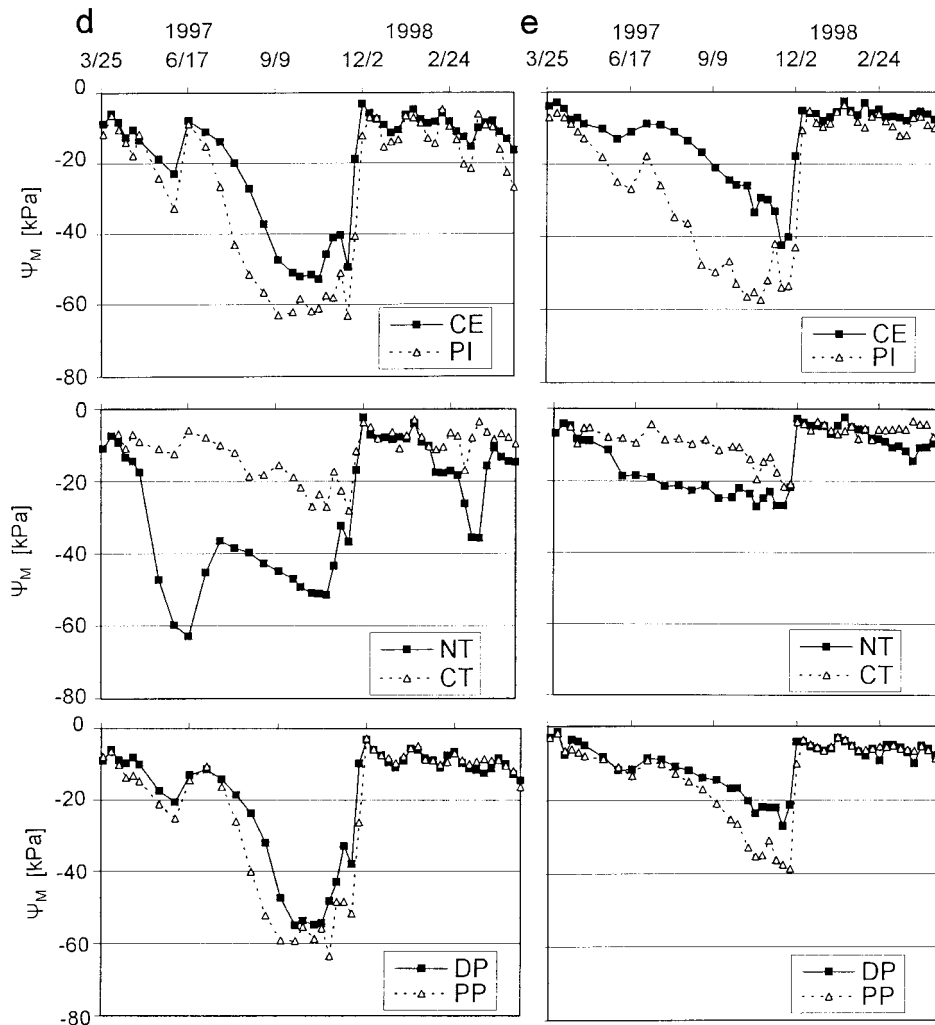


Fig. 3. Continued.

CT, and therefore to slower soil water refill, particularly at greater depth. However, infiltration in all study soils was rapid, and we never observed any surficial water even during strong rainfall events. Evaporation losses from surficial water may thus be excluded. Furthermore, NT soils should display a higher water conductivity than CT soils because of the higher pore continuity, and we measured a higher soil water input into NT soils than into CT soils (Table 2). An additional reason for lower ψ_M in NT than in CT between February and April 1998 may be the lower water storage in NT soils as a result of water consumption at the end of the preceding cropping period.

Differences in ψ_M between the pasture systems and CE were smaller than between the other systems and CE. There were no significant differences in average ψ_M of the monitored period at the 0.15- and 0.3-m depths between CE, PP, and DP (Fig. 3a and 3b). Between 0.8- and 1.2-m depths, small but significant differences between the three land-use systems were recorded (Fig. 3c and 3d). Between December 1997 and April 1998, the average ψ_M in DP at the 0.8- and 2-m depths were significantly lower than in PP and CE (Fig. 3c and 3e); at the 1.2-m depth, the average ψ_M in DP was significantly

lower than in PP (Fig. 3d). Between May and November 1997, average ψ_M at the 0.8- to 2-m depth in PP were significantly lower than in DP (Fig. 3c–3e) and also significantly lower than in CE (Fig. 3c and 3d). Lower ψ_M in DP than in PP at greater depth during the rainy season may be related to the water uptake of the invaded natural Cerrado brushes and trees, which may have a greater rooting depth than the grass in PP. In contrast, differences in ψ_M between the pasture systems during the dry season indicate a higher water consumption of the PP vegetation, which is denser and shows more intensive grass rooting.

Water Storage

The soil water content can be estimated from ψ_M with the help of the soil water characteristic curve. The shape of the soil water characteristic curve is influenced by soil texture and bulk density. We found that there were only small differences in texture between the studied soils and between the soil depths within one soil (Table 1). At the 0- to 0.15-m soil depth, the average soil density in PI was significantly smaller than in NT, CT, and DP. There was no other significant difference in soil density

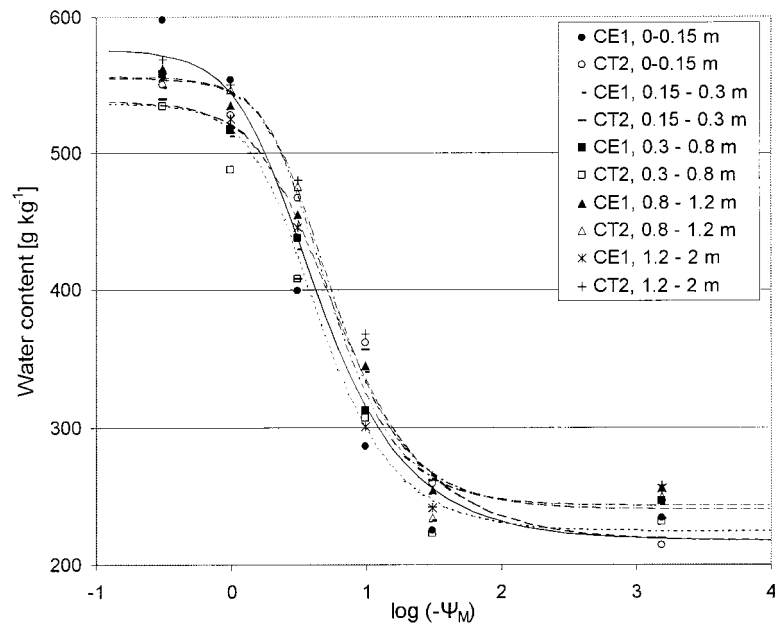


Fig. 4. Measured (data points) and fitted (lines) soil water characteristic curves in two selected soils in each of Cerrado (CE) and conventional tillage (CT) treatments (CE1 and CT2 in Fig. 1) at 0- to 0.15-, 0.15- to 0.30-, 0.30- to 0.80-, 0.80- to 1.20-, and 1.20- to 2.00-m depths.

between the various layers of the soils of the same land-use system and between the same layers among the different land-use systems. As a result of the great similarity in soil texture and bulk densities among the studied soils, we did not expect significant differences in the soil water characteristic curve. Therefore, we chose only one soil in each of the CE and CT treatments (at the plots CE1 and CT2 in Fig. 1) to determine the soil water characteristic curves for five soil layers of each of the selected two soils (Fig. 4).

The shape of the soil water characteristic curves was typical for Oxisols with kaolinitic and oxidic mineralogy. At high ψ_M , the soils retain water similarly to coarse-textured temperate soils, but at low ψ_M they retain water similarly to clayey-textured ones. (Sharma and Uehara, 1968; Tsuji et al., 1975). This is attributable to the strong pseudosand aggregation of Oxisols (Van Wambeke, 1992), consisting of positively charged oxyhydroxides and negatively charged kaolinite and organic matter.

The water content at the monitored ψ_M range was not significantly different between the selected CE and CT soils at the 0.8- to 1.2- and 1.2- to 2.0-m depths. For the layers above the 0.8-m depth, small but significant differences in water content at a given ψ_M between the selected CT and CE soils and between different layers within the same soil occurred at ψ_M above -3.16 kPa and below -1584.9 kPa but not between -10.0 and

-3.16 kPa, which covered the most frequently measured range of ψ_M in the field. We concluded that for this range of ψ_M , the water content at a given ψ_M was comparable between the two soils and differences in ψ_M measured with the tensiometers can directly be interpreted as differences in soil water contents. The lack of significant differences between the water characteristic curves of the selected CE and CT soils led us to the assumption that, at the range of ψ_M observed in the field, an appropriate estimate of the water content of the soils in all studied land-use systems is possible by using only one water characteristic curve (averaged from the two determined curves) for each individual soil layer. Because the tensiometers only work down to -80 kPa, we could not estimate plant-available water contents in soils at ψ_M s less than -80 kPa. However, the difference in water contents between -31.6 and -1584.9 kPa was only 20 to 46 g kg^{-1} for all studied soil samples, in the same range as those reported for Oxisols of northeastern Brazil (20–40 g kg^{-1} ; Bui et al., 1989). Therefore, the difference in water contents between -80 kPa and the permanent wilting point at -1584.9 kPa by which we underestimate the plant-available water contents in our study soils is small.

With the help of the averaged water characteristic curves and the soil densities of the five soil layers (0–0.15, 0.15–0.3, 0.3–0.8, 0.8–1.2, and 1.2–2 m) the average

Table 3. Mean water storage in the uppermost 2 m of native Cerrado (CE), Pinus (PI), no-till cropping (NT), conventional tillage (CT), degraded pasture (DP), and productive pasture (PP).

	Land-use system					
	CE	PI	NT	CT	DP	PP
	mm					
Dry season (May–Oct. 1997)	476b†	429c	460bc	523a	480b	479b
Rainy season (Nov. 1997–Apr. 1998)	587a	516b	578a	620a	586a	608a
Whole period (May 1997–Apr. 1998)	537a	479b	526ab	565a	541a	553a

† Means followed by different letters are significantly different between the land-use systems at $P < 0.05$ (Tukey's honestly significant difference [HSD] test).

water storage of each system in the uppermost 2 m was estimated using Eq. [1] and [2]. During the rainy season, the average water storages were not significantly different among all studied land-use systems, except for PI where the average water storage in the uppermost 2 m was significantly smaller than in all other land-use systems (Table 3). During the dry season differences were more pronounced; the water storage decreased along the line: CT > DP = PP > CE > NT > PI.

CONCLUSIONS

Our results indicate that it is mainly the type of vegetation that controls the annual course of ψ_M in differently used savanna Oxisols because it influences evapotranspiration, interception, and stemflow. In CT, plowing probably additionally results in reduced evaporation and thus increased ψ_M because the pore continuity is destroyed. Both pasture systems showed similar annual courses of ψ_M in soil as CE, indicating that the soil water budget under pasture is close to that of the natural system. In PI and NT soils, ψ_M was decreased and the average annual water storage was reduced compared with CE.

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