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# SEASONAL AND DEPTH VARIATION OF SOIL MOISTURE IN A BURNED OPEN SAVANNA (CAMPO SUJO) IN CENTRAL BRAZIL

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*Abstract.* The soil water regimes of two areas of open savanna (campo sujo) near Brasilia, Brazil, were monitored between August 1999 and November 2000. Each area was subjected to a different fire regime. Soil water content was measured to a depth of 3.6 m, using a neutron probe. The profile storage at the end of the 1999 and 2000 dry seasons was very similar despite a difference in dry season duration and large differences in rainfall in the preceding wet seasons, indicating that the vegetation is conservative in its water use. In the last two months of the dry season, the water content of the upper 0.6 m of the soil profile did not decrease further, suggesting that the vegetation had used all of the available water in this layer. The seasonal variation in soil water storage to a depth of 3.6 m was 403 mm, 65% of which occurred below 1 m. The wet and dry season evaporation rates were estimated to be 2.4 mm/d and 1.6 mm/d, respectively, but for a month after fire, before regrowth started, the evaporation rate was less than 0.5 mm/d.

*Key words: savannas; soil water; water balance.*

## Introduction

The savannas of central Brazil, known as cerrado, occupy an area of $2.0 \times 10^6$ km$^2$ and are the second major ecosystem in South America. The cerrado vegetation is usually divided into five principal forms according to the proportion of tree and grasses: campo limpo, open grassland with few shrubs or trees; campo sujo, open savanna with scattered small trees and shrubs over a continuous herbaceous layer; campo cerrado, open scrub formed by a denser woody layer and grasses; cerrado sensu stricto, closed scrub with tall trees, a dense woody underlayer, and grasses; and the cerradão, a closed-canopy forest with dense woody underlayer and sparse grasses. Ratter (1992) and Eiten (1972, 1994) have given extensive descriptions of the cerrado vegetation.

The cerrado area has a tropical climate with monthly average temperature above 18°C and mean annual rainfall of 1436 mm (Pereira et al. 1993). Seasonality is an important characteristic of the cerrado region, where the dry season is typically five to six months long. This extended dry season leads to seasonal vegetation changes where the herbaceous component dries almost totally in the mid dry season and become dormant until the onset of the next wet season. However, even during the dry season, the woody vegetation still shows a capacity to maintain its physiological activities. Leaf expansion, flowering, and frutification occur mainly during the dry season (Oliveira and Gibbs 2000), suggesting that this vegetation component has access to soil water, probably at great depths.

The capacity of the Cerrado woody plants to absorb water from deeper layers of the soil has been known for some time. Rawitscher (1948) working in a cerrado sensu stricto near São Paulo, reported that the soil moisture decreased during the dry season from the surface to a depth of 3 m. Variations of soil moisture were negligible in deeper layers. In the same work, the author observed the occurrence of roots to a depth of 18 m, and concluded that water may not be a limiting resource for woody plants with deep root systems. However, there are few reports in the literature on the behavior of the soil water in Cerrado. Rawitscher (1948), Dunin et al. (1997), and Oliveira (1999) have reported soil water behavior, but with the exception of Oliveira (1999), these studies are without long-term measurements and/or without information on moisture variation with depth. This work present here shows soil water data for areas of campo sujo with two different fire regimes. It examines the patterns of soil water uptake, soil water recharge, and general water balance of this form of cerrado, and the impact of fire on the soil water regime. Fire is taken into account in this study since it is a common event in the cerrado region and is used to manage campo sujo areas for cattle ranching.

## Materials and Methods

### Site description

The study was carried from August 1999 to November 2000 in two adjacent campo sujo plots located within the Ecological Reserve of the Brazilian Institute of

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Geography and Statistics (IBGE), 35 km south of the city of Brasilia (15°56′41″ S, 47°51′02″ W), within the cerrado core area. The Ecological Reserve has an area of 1360 ha, and the altitude varies from 1048 to 1160 m. The climate in the region is tropical (Cwa in the Köppen classification) with a mean annual temperature of 21°C. The mean annual rainfall for the Cerrado area is 1436 mm (Pereira et al. 1993). In the last 20 years at the experimental site, the rainfall ranged from 1000 to 1900 mm per year, with an average of 1500 mm (weather station, IBGE). Rainfall is highly seasonal, with about 90% occurring in the wet season, between October and April. The soil is a very deep well-drained yellowish red Oxisol with a clay texture (60% clay). The dry bulk density is very low, typically $<0.8$ $Mg/m^3$ in the first meter and $\sim 1.1$ $Mg/m^3$ deeper in the soil, which results in a very high porosity (Kato 2001). Plant available water capacity is relatively low, $\sim 130$ mm/m (Reatto et al. 1998). The water table is at a depth of $\sim 40$ m. The soil type at the study site is very widespread in Brazil and particularly in the cerrado regions, occupying 46% of the cerrado area (Reatto et al. 1998).

The IBGE reserve presents the most common physiognomic forms of cerrado vegetation. Campo sujo was chosen for this study since it is often used for cattle ranching and is managed with fire during the dry season (Coutinho 1990). The study plots were located in the area of a long-term research project (Projeto Fogo) to investigate the effects of different fire regimes on the physiognomic forms of cerrado vegetation. The vegetation had been protected from fire for 19 yr before this project began in 1991.

Two campo sujo plots were studied, each subjected to a different fire regime. In the 4Y regime, plots burned every 4 yr in mid dry season (August); in the 2Y regime, plots were burned every 2 yr, at end of dry season (September). Both plots were burned during the study period; the 4Y plot in mid-August 1999 and the 2Y plot in mid-September 2000.

The study plots were contiguous and separated by a 4.0-m firebreak. Each plot was 200 $\times$ 200 m (4 ha) and had a slope of $<2°$. In August 1999, the 4Y plot presented 360 trees/ha, of which 75 trees/ha were dead as a consequence of the 1991 and 1995 fires (Rocha e Silva 1999). The herbaceous layer had a biomass of 8.7 Mg/ha and the grasses represented 64% of the total biomass (Castro Neves 2000). The 2Y plot presented 357 trees/ha, of which 137 trees/ha were dead as consequence of the four preceding prescribed burns. The herbaceous layer had a total biomass of 7.2 Mg/ha and the grasses represented 60% of the total biomass. In both areas, *Erythroxylum suberosum* and *Roupala montana* were the most frequent woody species and *Echinolaena inflexa* (a $C_3$ grass common in the cerrado region); *Axonopus* spp., and *Trachypogon* spp. were the most common grasses.

The root distribution in campo sujo areas has been studied by Oliveira (1999) and Castro and Kauffman (1998). Both reported that more than 80% of the roots are in the first 30 cm of the soil and fine roots represent almost 50% of the total root biomass. Nevertheless, fine roots can be found in the whole soil profile until 4 m depth, with root density decreasing with depth. Coarse roots are found mainly in the upper meter. Castro and Kauffman (1998) also reported a root:shoot ratio of 7.7 for campo sujo vegetation.

### *Measurements*

Soil water content was measured with a neutron probe (model IH II; Institute of Hydrology, Wallingford, UK). Two access tubes were installed to a depth of 3.6 m in the 4Y plot and one tube was installed to the same depth in the 2Y plot. The tubes were located 20 m apart to account for the heterogeneity of the vegetation and were never less than 50 m from the edges of the plots. The measurements depths were 0.1 and 0.2 m, and then at 0.2-m intervals until 3.6 m. The counting time was 16 s. Neutron probe calibration was based on the neutron capture model calibration method described by Couchat et al. (1975) and a special gravimetric calibration was used for the depth of 0.1 m. Neutron probe readings were taken monthly with weekly readings at: the end of the dry season 1999/2000, the middle of the wet season and the onset of both wet seasons (September 1999 and August 2000). Measurements of soil moisture were started in the 4Y plot in August 1999, one week before the prescribed fire for that year. Measurements began in the 2Y plot in October 1999.

Rainfall was measured daily at the Ecological Reserve weather station, $\sim 700$ m from the study plots. The water balance was used to estimate evapotranspiration losses from the plots as follows:

$$P - I = E + D + \Delta S + Q \qquad (1)$$

where $P$ is the rainfall, $I$ is the interception loss, $E$ is the evapotranspiration, $D$ is the deep drainage (below 3.6 m), $\Delta S$ is the soil water storage changes, and $Q$ is the surface runoff, all expressed in units of millimeters over the period between soil moisture measurements.

Interception was calculated from daily rainfall using the interception coefficient of 22% measured by Seyffarth (1995) for campo sujo. The use of this figure to calculate the interception loss for each period between soil moisture measurements is inevitably an approximation, as interception values will vary depending on storm size and duration, but the value of 22% is the only figure for the interception coefficient currently available for campo sujo vegetation.

Evapotranspiration was estimated from the water balance during periods when the drainage could be assumed to be negligible. Oxisols are very free draining (Sanchez 1976, Tomasella and Hodnett 1996). Drainage from the 3.6-m profile was assumed to be negligible from the mid dry season into the wet season, until the wetting front reached 3.6 m. During the early wet season, before the profile had become wetted to 3.6 m, there was no measurable decrease in water content in the lower profile, indicating no drainage. After the profile had become wetted to 3.6 m, drainage from the microaggregated, low-density, upper horizons was assumed to have virtually ceased within a day of heavy rainfall. Peaks of soil water storage after heavy rainfall were not observed because drainage is so rapid. Soil water storage was calculated from the layer water contents measured using the neutron probe. Runoff was considered to be negligible as the soil surface is highly permeable.

The available water capacity (AWC) of the 0–1-m layer was calculated as the difference between the profile storage at field capacity, and the minimum value of water storage measured in this layer. The minimum storage was taken to be close to wilting point as there were no further changes in water content in the late dry season. The profile water storage on 2 March 2000 was taken as field capacity. It was measured after the whole profile had been thoroughly wetted but there had been no rain during the previous 24 h.

### *Errors, spatial variability, and uncertainties on calculations*

The possible sources of errors on neutron probe measurements are calibration bias, human errors during the readings, instrumental errors, and spatial variability of the soils.

Neutron moisture meters are very reliable equipments and the associated errors are small (Bell 1973). The instrumental error related to the natural decay of the radioactive source is minimized using a large drum of water as standard to correct for any instrumental drift (Hodnett and Bell 1991). To avoid human errors in this study, the observations were always done by the same person, and the transcription of the readings to the computer were checked twice by the SWIPS program (Soil Water Information Processing System; Institute of Hydrology, Wallingford, UK).

Regarding the calibration errors, one source of bias is the amount of bound water (still retained by the soil after drying at 105°C). This varies with clay content and influences the intercept of the calibration, but has little influence on the slope. This affects the measurement of the absolute water content, but has little influence on the measurement of the changes of water content. Calibration biases are also much more important when absolute values are desired. In this study, all calculations are based on changes of soil water content. These are much more accurate than absolute soil water values (Bell 1973).

In this study, the soils are Oxisols, which are very homogenous in clay content and structure. The calibration curve used in this study gave similar values of soil water changes to those estimated using soil water retention curves derived for soils in the same area. The neutron probe based water balance also gave very similar evaporation values to those measured by an eddy covariance system operated at the same site during the same period, indicating that the calibration curves were well defined. Spatial variability of soil water in cerrado soils is also small. Personal observations by the author in cerrado sensu stricto areas indicate that the soil profiles are very similar, and showed almost identical behavior of soil water changes at 12 access tube sites, with little spatial variability.

The results presented here also show that the spatial variability of soil water storage is small and that the differences in soil water storage changes between tubes is even less (see Fig. 1). This indicates that the soil system has a very similar behavior in relation to soil water.

## RESULTS

### *Soil water behavior and water balance*

Fig. 1 shows the changes in profile storage to a depth of 3.6 m in the 2Y and 4Y plots during the study period. For the campo sujo in general, the soil moisture storage during the study period was markedly seasonal. The mean change in profile storage for the two tubes in the 4Y plot between the wettest and driest days was 403.3 $\pm$ 7.7 mm (mean $\pm$ 1 SD). During August 1999, the changes in storage in the profile were very small, both before and after the prescribed burn, indicating very low rates of water loss (by drainage or evapotranspiration). The minimum profile storage observed in the 2000 dry season (August) was almost as low as that observed in 1999, even though the 1999–2000 wet season rainfall total (1547.8 mm) was much greater than in the previous wet season (1010 mm).

Fig. 2 shows the changes in storage in the profile throughout the study period by successive 0.6-m layers. Fig. 3 shows a sequence of profiles of soil moisture in the 2000 season, from the wettest profile through to the driest, but also includes the driest profile from the extended 1999 dry season for comparison. The upper layers (0–180 cm) showed greater variation in water storage than the lower layers due to greater water uptake from the surface layers. By 20 June 2000, after 88 d without rain, storage in the top 0.6 m had stopped decreasing, and remained constant for a further 58 d, until end of the 2000 dry season. This suggests that the vegetation had already used all of the available water from the top layer of soil (Figs. 2 and 3). However, during the same period the vegetation still showed a capacity to absorb water from deeper layers in the soil, with a total uptake of 124 mm and 127 mm from the 4Y and 2Y plots, respectively. In the last two weeks of the dry season, the zone in which no further drying was occurring extended down to a depth of 0.8 m and

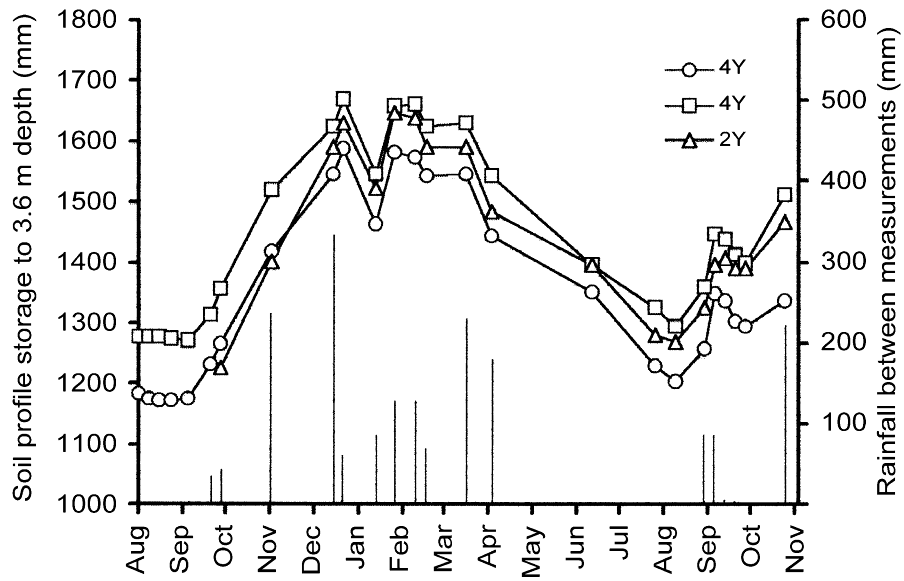


FIG. 1. Soil water storage variations to a depth of 3.6 m and rainfall (vertical bars; right-hand axis scale) between moisture measurements from three locations in an area of Brazilian campo sujo subjected to fire. The two locations designated 4Y are in an area burned once every 4 yr. The location designated 2Y is in an area burned once every 2 yr. Measurements were made from August 1999 to November 2000.

uptake was restricted to the zone between 0.8 m and 3.0 m. The water uptake from each of the 0.6 m soil layers during this period is summarized in Table 1. The soil available water content (AWC) in both plots was estimated to be 120 mm/m.

The soil water content profiles (Fig. 3) show that the changes of water content become smaller with depth, implying a decrease in uptake with depth with only a small amount of uptake from below 3.6 m in 2000. The soil water content profile from the end of the 1999 dry season showed evidence of slightly greater uptake from depth. The 1999 dry season was 1 mo longer than the 2000 dry season, and followed a wet season with very low rainfall.

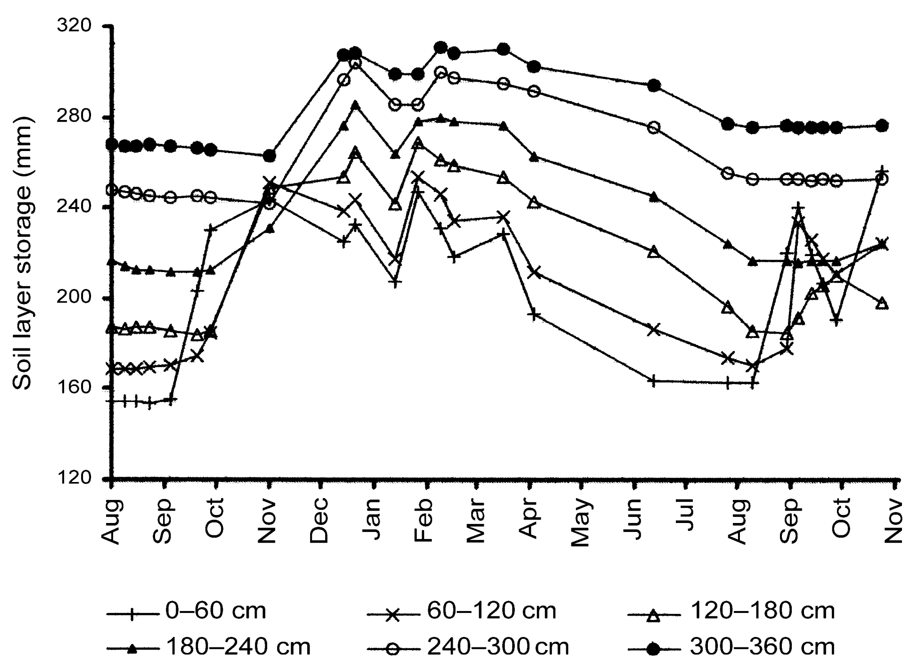


FIG. 2. Variation of mean soil water storage (1999–2000) for the two locations in the 4Y plot, shown for successive 0.6 m thick layers to a depth of 3.6 m.

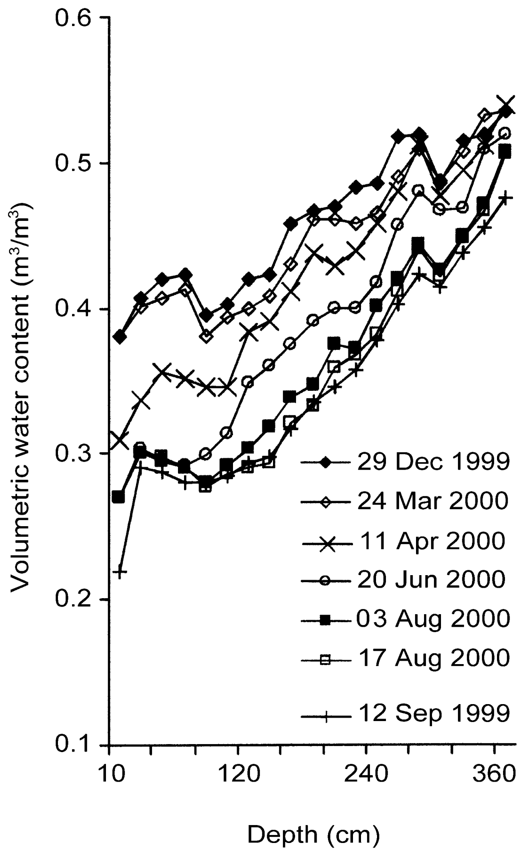


FIG. 3. Profiles of mean water content from the two locations in the 4Y plot, from 29 December 1999 (wettest) to 17 August 2000 (driest). The driest profile from 1999 (12 September) is also shown.

Fig. 4 shows the driest water content profile in August 1999 and successive profiles after the onset of the rainy season until the profile had been rewetted to below 3.6 m depth. In the season studied, 85 mm of rain were needed for the wetting front to reach 1 m in the soil and 323.2 mm to reach 2 m. For the wetting front to reach 3.6 m (108 d after the onset of the rainy season), the amount of rain needed was 719.4 mm. All profiles show a well-defined wetting front, with no evidence of bypass flow wetting the lower profile before the layers above had wetted up. In addition, once the rainy season had begun, the water content below the wetting front changed very little, indicating that there was almost no uptake or drainage occurring. This is apparent at the start of both of the two wet seasons shown. Uptake at depth must cease soon after the upper layers are wetted.

Fig. 5 shows the evapotranspiration rates calculated from the water balance for the periods when drainage could be considered to be negligible. Also shown is the water content at a depth of 0.2 m.

Evapotranspiration rates ranged from <0.5 mm/d immediately after the fire in the 4Y plot (August 1999) to a maximum of 2.8 mm/d. The mean evapotranspiration rate calculated for the periods when the upper part of the soil profile was well wetted was 2.4 mm/d. In the latter part of the 2000 dry season, the mean evapotranspiration rate was 1.6 mm/d.

TABLE 1. Soil moisture variations during the late dry season, summarized by layer.

| | Soil moisture variation | | | |
|---|---|---|---|---|
| | 20 Jun–17 Aug 2000† | | 3–17 Aug 2000‡ | |
| Soil depth (m) | Variation (mm/d) | Variation (%) | Variation (mm/d) | Variation (%) |
| 0.0–0.6 | 1.8 | 1.6 | 0 | 0 |
| 0.6–1.2 | 16.5 | 14.6 | 3.2 | 14.4 |
| 1.2–1.8 | 22.5 | 19.9 | 9.3 | 42.2 |
| 1.8–2.4 | 28.4 | 25.3 | 6.5 | 29.4 |
| 2.4–3.0 | 25.1 | 22.3 | 1.7 | 7.7 |
| 3.0–3.6 | 18.4 | 16.3 | 1.4 | 6.3 |
| Total | 112.8 | | 22.1 | |

† Evaporation rate = 1.9 mm/d; rainfall = 0 mm.
‡ Evaporation rate = 1.6 mm/d; rainfall = 0 mm.

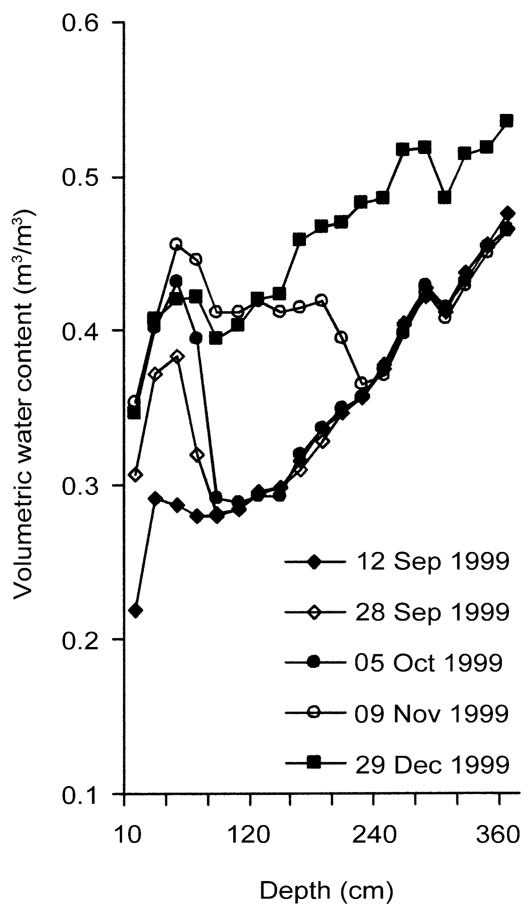


FIG. 4. Profiles of mean water content from the two locations in the 4Y plot, from 12 September 1999 to 29 December 1999, showing the progressive wetting of the soil profile.

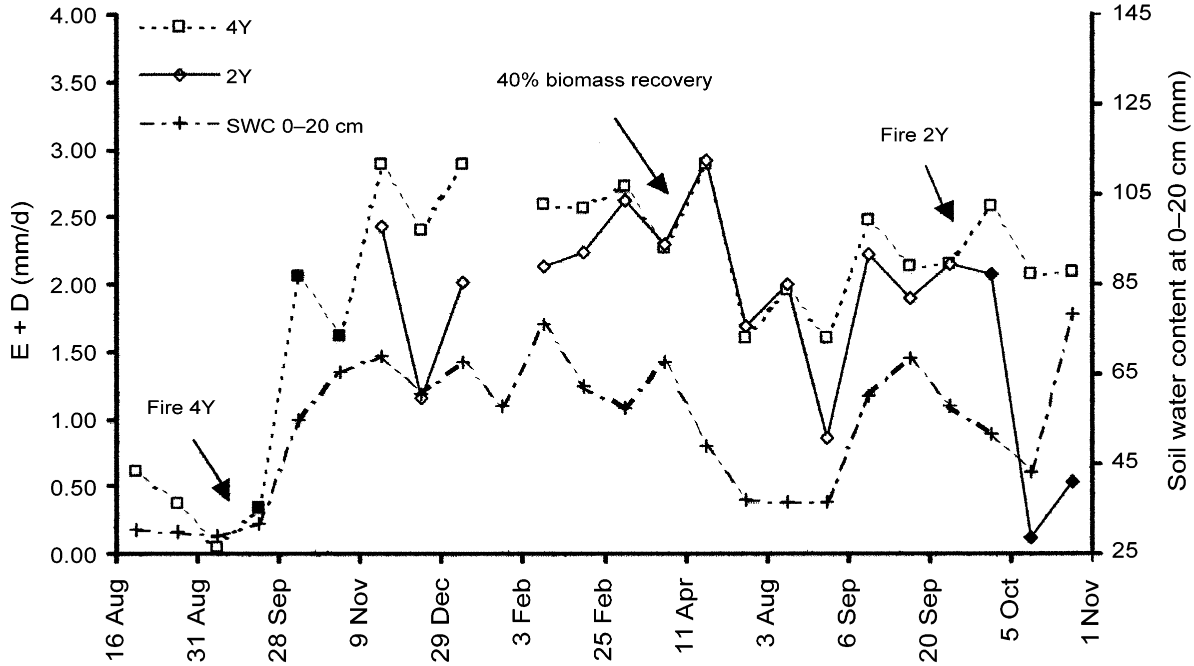


FIG. 5. Evapotranspiration plus drainage rates (mm/d) derived from the water balance of the soil profile. The closed symbols indicate the evapotranspiration rates that were mainly the result of soil evaporation, when the soil was bare after the fires. Changes in soil water content (SWC) in the top soil layer (0–20 cm) are also shown.

The components of the annual water balance for the hydrological year 1999/2000 were 1548 mm of precipitation, 847 mm (55%) of evapotranspiration and changes in soil water storage, 340 mm of interception and 360 mm of deep drainage. The interception was calculated from the annual rainfall using the figure of 22% of annual rainfall determined for campo sujo vegetation in the same area by Seyffarth (1995).

### *Fire and soil water*

After the fires, when the soil was bare, both areas showed high values of evapotranspiration after rain events. On these occasions, the overall evapotranspiration loss must have been dominated by soil evaporation. These points are shown shaded in Fig. 5 and showed a maximum value of 2.1 mm/d. These high soil evaporation rates only occur when the top soil was well wetted. No similar rates occur with low moisture levels at the top 0.2 m, even whether high volumetric water contents occur below this depth.

Once the vegetation had regrown, the mean evapotranspiration rate from the 4Y plot was 2.6 mm/d, compared to 2.2 mm/d for the 2Y plot that had not been burned for 18 mo. In the following year, 7 mo after the fire and with 40% of biomass recovered, the mean evapotranspiration rate from the 4Y plot became very similar to the 2Y plot in its second season after burning (see Fig. 5). This very similar pattern of evapotranspiration after the vegetation recover will not appear only in late August (last days of the dry season), when there was a difference of 0.8 mm/d between 4Y and 2Y plots.

As the vegetation recovery after fire was not the subject of this study, further information about the biomass recovery patterns in campo sujo is required. Andrade (1998) presented biomass data after fire for campo sujo areas subjected to the same fire regime as the experimental plots in this study. Biomass recovery was 5% after 1 mo, 25% after 4 mo, 50% after 6 mo, and 73% after 9 mo. It is important to note that differences in the date of onset of the rains and the rainfall distribution will alter the values somewhat, but not the pattern. The author reported that productivity after fire is strongly linked with rainfall.

## DISCUSSION

Water use by the campo sujo vegetation was concentrated at shallow depths (Figs. 2 and 3), and this is likely to be a consequence of the root distribution of this ecosystem. The root densities of both grasses and shrubs range from 16.4 Mg/ha to 30.1 Mg/ha and are generally found in the top layers of soil (95% in the first 1 m and about 80% in the top 0.3 m) and fine roots represent about 50% of the total root biomass (Castro and Kauffman 1998, Oliveira 1999). The slower rate of moisture changes from greater depth (0.8–3.6 m), is also in accordance with the campo sujo root distribution, where previous studies report 5% of total root biomass between 1 m and 4 m depth. However, 65% of the storage change in the profile to a depth of 3.6

m was below 1 m depth, indicating the high efficiency of the deep fine roots in sustaining the woody component of campo sujo.

Different strategies of conservative water use can be found in the campo sujo vegetation. Grasses are dormant in the dry season, and new growth occurs only after the onset of the rainy season. Some of the shrubs are deciduous and others are evergreen. Deep root systems, deep water uptake and osmotic adjustment, are additional important characteristics of the vegetation (Rawistcher 1948, Lüttge 1997, Oliveira 1999).

Evergreen species and some of the deciduous (small palms and some small trees and shrubs), were probably responsible for the deep water uptake (0.8–3.0 m) shown in Fig. 2 between 3 and 17 August 2000, as the grasses are dormant and some deciduous species have already lost their leaves in the late dry season. Jackson et al. (1995) working in a lowland tropical forest in Panama, report that evergreen species had access to the more abundant soil water at greater depth than deciduous species. The authors also show that species using deep soil water had both higher rates of water use and more favorable leaf water status. Meinzer et al. (1999) reported that evergreen campo sujo species in Brazil show high evapotranspiration rates ranging from 1.5 to 4.0 $mmol \cdot m^{-2} \cdot s^{-1}$, even during the dry season.

However, deciduous species also have ready access to soil water at greater depths. Pinto (1999) reported leaf growth, floration, and frutification in brevideciduos campo sujo species independent of season, which suggests that they have access to available soil water throughout the year. The author also reported high predawn leaf water potentials from deciduous species during dry season, also confirming access to deep soil water. Jackson et al. (1999) used stable isotopes of hydrogen to investigate the zonation of root uptake with depth for a range of woody cerrado species. In this study, they report that deciduous wood species explore water resources at greater depths than evergreen species. They also were able to identify three different uptake zones in the upper 1.7 m of the profile, used by five of the species studied. Four other species took up water from below 2.5 m, and the abstraction zone of one species overlapped the others, ranging from 0.5 m to 2.3 m. This confirms deep water uptake by woody species and reveals a strong optimization of the use of the soil water resources. Thus, the leaf abscission from cerrado woody plants may occur due to high evaporative demand in the dry season (Pinto 1999) as well as due to hydraulic restrictions caused by the internal architecture of the plants (Meinzer et al. 1999).

In this study, the evapotranspiration rates obtained from the water balance agree with results from other studies that have been carried out in the same area, using different methodologies. Santos (1999) using an eddy covariance system, measured a mean evapotranspiration rate of 2.3 mm/d during the wet season and 1.4 mm/d during the dry season. Using a similar system, Dunin et al. (1997), reported a mean evapotranspiration rate of 2.9 mm/d during the wet season from an area that had been burned three years before. The low evapotranspiration rates even when atmospheric demand is high and soil water is readily available, is a characteristic of the vegetation and reveals the conservative water use of the plants. It should be caused by stomata control as well as by plant architecture restrictions on the soil/leaf pathway (Meinzer et al. 1999).

The reduction in the evapotranspiration rates from 2.4 mm/d during the wet season to 1.6 mm/d during the late dry season is explained by the herbaceous layer dormancy and by the abscission of leaves from some woody plants. Thus, during the late dry season, only some of the vegetation is still releasing water to the atmosphere. Andrade (1998) showed that the percentage of live biomass in campo sujo areas reduced from 50.2% in the wet season to 19.8% in the dry season. This would led to a reduction of 33.3% in the evapotranspiration rates. Miranda et al. (1996) found a similar pattern in a cerrado sensu stricto (woodland) area, where the herbaceous layer dormancy and leaf abscission changed the surface conductance from 0.4 $mol \cdot m^{-2} \cdot s^{-1}$ in the wet season to less than 0.2 $mol \cdot m^{-2} \cdot s^{-1}$ in the dry season. Santos (1999) also related the reduction in the surface conductance during the dry season to the dormancy of the herbaceous layer.

The estimated AWC (120 mm/m) is close to literature values. Reatto et al. (1998) report AWC for clay Oxisols to be 260–330 mm in the top 2 m. These values are slightly higher than the values estimated in this work, but for these soils, clay content cannot be considered to be the only determinant factor of features such as water availability, infiltration capacity, or cation exchange capacity once the basic clay minerals are 1:1 type and the biggest part of the clay fraction are iron and aluminum oxides. Strong small granular structure along the profile leads these soils to behave like coarse textured soils (Haridasan 1994). Hodnett et al. (1995) present AWC of 89.5 mm in the first meter and 65.5 mm to the second meter for a clay Oxisol at the Brazilian Amazon. Sanchez (1976) reported that Oxisols ''act like sands in terms of water movements at lower tensions but hold water like clays at higher tensions. Therefore they have a narrower available water range than most clays. Most of these well aggregated soils have drought problems completely out of proportion to their clay and water contents.'' Low soil AWC implies that deep root system is an essential strategy to overcome the extended cerrado dry season.

The soil water storage data presented here extend from the late dry season of 1999 to the early part of the 2000–2001 wet season. The 1998–1999 wet season was the driest for 20 years, with a total of only 1010 mm, which was 537 mm less than in the 1999–2000 wet season. The 1999 dry season (at the end of which the observations began) was also 1 mo longer than the 2000 dry season. However, despite this, and the low rainfall, the minimum value of soil water storage at the end of the two dry seasons studied was very similar. This suggests that, despite the low rainfall during the 1998–1999 wet season, there was sufficient moisture recharge to provide for the water requirements of campo sujo. The similar profile storage at the end of the following, shorter, dry season, which was preceded by a wet season with 50% more rainfall, clearly shows the conservative water use of this ecosystem, and its adaptation to drought years. The conservative water use occurs because the vegetation is dominated by grasses and deep uptake is limited by the low woody plant density (Meinzer et al. 1999). The deep rooting of the woody plants means that they should be able to survive seasons with much lower rainfall, by accessing still available soil water from greater depths.

Although the soil water recharge in the 1998–1999 wet season was sufficient to sustain the campo sujo vegetation, the deep drainage, or groundwater recharge, must have been very low. This will have led to much reduced base flow in the streams draining the area. The soil moisture profiles in Fig. 4 show the progressive wetting of the soil profile, with a well-defined wetting front, with no evidence of bypass flow wetting the lower profile before the layers above had wetted up. In 1999, the time for the wetting front to reach a depth of 3.6 m was 108 d. This delay must have an important influence on water table response and the generation of stream flow (base flow) in the cerrado region. In addition, once the rainy season had begun, the water content below the wetting front changed very little, indicating that there was almost no uptake or drainage occurring. This is apparent at the start of both of the two wet seasons shown. Uptake at depth must cease soon after the upper layers are wetted. This provides water that is more readily available to the vegetation than that in the deeper layers.

Following fire, soil evaporation was enhanced in periods when the profile was well wetted. This may occur because fire removes the dead biomass, which serves as an effective mulch, reducing soil evaporation. Dunin et al. (1997) reported that preservation of dead material as a mulch is critical to soil water conservation. The authors found short-lived soil evaporation rates of 3.0 mm/d in a burnt area after rainfall events, and differences in soil evaporation between burnt and unburned areas were as much as threefold. Fig. 5 shows the soil water storage in the soil surface plotted against evaporation. Short-lived soil evaporation appears only when the soil surface is well wet. Dry conditions at the soil surface reduce the soil conductance not allowing high evaporation rates from the deeper soil water.

The increase of evapotranspiration rates after fire may be the result of two complementary phenomena: an increase in soil evaporation following the loss of the dead biomass ''mulch,'' and the increment in the leaf area index related with the regrowth. The decrease of the evapotranspiration to the previous rates 7 mo after the fire can be explained by the return of the biomass cover and the reduction of live material in the total biomass (Andrade 1998). The difference of 0.8 mm/d of evapotranspiration (Fig. 5) in late August (2000) is probably due to the different composition of the vegetation between the plots. The 2Y plot has much less woody vegetation than the 4Y plot and during the late dry season woody vegetation is basically the only source of evapotranspiration to the atmosphere.

The frequent occurrence of fire leads to a reduction in the amount of woody species and consequent increase in the herbaceous layer (Coutinho 1990). Dawson (1996) report that woody component is the most important route for water transport to the atmosphere. Thus, the reduction in the woody component by frequent burns, may lead to a reduction in the regional evapotranspiration rates, particularly during dry periods when the herbaceous layer is dormant. Deep water uptake would be reduced by removal of the woody component and this would change the soil water behavior and the water balance. Interception would also be reduced and the net effect of these two factors would be an increase in groundwater recharge. Part of that reduction of the water losses to the atmosphere could be compensated by the increased transpiration and evaporation after the fire, but that increased rate will only occur during the first year following the burn. In contrast, the effect of the reduction in the woody layer will remain for many years altering the regional water balance.

## Conclusions

Water uptake by campo sujo vegetation is concentrated at shallow depths (0–0.8 m), but the shrub component continues to take up water from lower depths during the dry season, at rates of ~1.6 mm/d.

The campo sujo vegetation is conservative in its use of water through strategies such as dormancy, leaf abscission, and deep water uptake. The low evapotranspiration rates even when the soil profile storage is high, is a characteristic of the vegetation and it is in accordance with the conservative water use.

Short-lived soil evaporation was stimulated by fire under well-wet soil conditions. The occurrence of fire in the campo sujo vegetation enhanced the evapotranspiration during the first 7 mo after the fire.

Frequent fires may alter the shrub/grass composition of the vegetation, reducing evapotranspiration and interception losses, changing the regional water balance.

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