Seasonal changes in tree–grass complementarity and competition for water in a subhumid tropical silvopastoral system

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Abstract

Previous studies have shown that silvopastoral systems are sometimes unsuitable in the subhumid tropics because strong competition for water between species reduces grass growth and production. The work described in this paper was carried out in order to analyse the microclimate inside a silvopastoral system and to assess how it modifies the evaporative demand and soil water availability. The study was conducted on plots of 11-year leguminous tree (Gliricidia sepium (Jacq.) Walp.)–grass (Dichanthium aristatum (Poir.) C.E. Hubbard) association (SS treatment), and of an open grassland with the grass only (OG treatment), cultivated on a vertisol. Both plots were managed as cut-and-carry systems where residues of tree pruning (every 2–6 months, tree height <2 m) and cut grass (every 42 days) were removed from the site and animals were excluded. A three compartment model of soil porosity was constructed to interpret the results of water dynamics in both grasslands. The three compartments corresponded to the structural water (easily available), the matric water (not easily available), and the cracks (bypass flow); i.e. three levels of soil porosity. The incoming photosynthetically active radiation at the grass level (PARi) varied from 4.5 to 9.5 MJ m$^{-2}$ per day in OG, and from 2.5 to 7.5 MJ m$^{-2}$ per day in SS. Although windspeed was lower under the trees, air temperature (average 25°C) and air humidity (>70% even in the dry season) at the grass level were similar in both treatments. Therefore, evapotranspiration from the grass was always lower in SS because it depended principally on PARi. During the rainy season, soil water content was lower in SS due to a higher water uptake by the association, and the simulations performed with the model indicated that the structural porosity was an important water reserve for the crops. In the dry season, when the matric reserve was the major water source, water uptake was reduced by the low hydraulic conductivity of the soil, and then water content was similar in both treatments. These results suggested that the tree component was relatively less competitive for water in the dry season, and it provided a microclimate which reduced grass evapotranspiration compared with OG. This was supported by the results of grass production in the dry season which was similar in both treatments. Conversely, grass production in the wet season was higher in OG because the lower PARi limited grass growth in SS. The model satisfactorily described the changes in soil water content in both treatments. However, some discrepancies between model and experimental data were observed when the soil was rewatered following heavy rainfall (>90 mm per day). This was due to the assumption concerning bypass flow within the soil cracks, which needs to be improved in future work.

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Keywords: Alley cropping; Evapotranspiration; Gliricidia sepium; Tropical grass; Vertisol; Water reserve

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1. Introduction

The association of leguminous trees and forage grasses in silvopastoral systems is an interesting alternative for livestock production in tropical regions because it increases land-use efficiency and offers a balanced diet for animals (Archimède et al., 2001). In the last ten years, considerable attention has been focused on improved silvopastoral systems where leguminous trees or shrubs are cultivated on natural grasslands (Kass et al., 1997). This system may be used as a protein bank and is generally managed as alley cropping in which the grass grows between tree hedgerows. The trees are periodically pruned to prevent excessive shading for the grass and tree pruning residues may be used as forage. In subhumid tropics, the suitability of this system depends on the complementary and competitive relationships between trees and grass for limited resources, principally water (McIntyre et al., 1997). The presence of trees in an agricultural system influences the hydrologic cycle by affecting rainfall interception, runoff, evapotranspiration and water uptake from the soil profile. Deep tree rooting is currently cited as the main reason for the low risk of water competition when grasses have a shallow root system (Breman and Kessler, 1997; Lehmann et al., 1998). However, some trees have a dual root system, which should allow the plant to take up water from the topsoil as well as from the deep layers (Cavagnaro and Passera, 1991). Hence, some authors have shown that the benefits of silvopastoral systems, including the improvement of soil fertility, may be outweighed by the adverse effect of competition for water (Cavagnaro and Passera, 1991; Smith et al., 1997). Another aspect associated with the presence of trees is the change of the microclimate inside the system. This principally concerns the incoming radiation, wind speed, air temperature and air humidity (Tournebize, 1994). As a general rule, these changes reduce the evaporative demand under a tree canopy and may improve the water status of the grass, especially during the dry season. Several authors reported that in subhumid regions, the lower evapotranspiration was the main factor inducing an increased biomass production of the grass growing under the trees compared with the same grass species in open grasslands (Ovalle and Avendaño, 1988; Belsky et al., 1993). These results imply that the improvement of grass water status may compensate for the effect of a lower incoming radiation level in silvopastoral systems. From the available knowledge of these systems, it seems that controversy as to the advantage of silvopastoral systems in subhumid regions may be attributed to differences in length of the dry season, tree density, and soil characteristics.

The soil of the silvopastoral system analysed in the present study is a cracking clay (vertisol), typical of subhumid regions with a long dry season, and characterised by physical constraints to water uptake by plants. This soil characteristic may enhance water competition between trees and grass and affect the suitability of the system in subhumid regions. The assessment of the water balance in vertisols is extremely difficult because drying and wetting cause large spatial and temporal variation in soil water content, and water redistribution after rainfall varies widely depending upon the water status of the crack porosity (Ozier-Lafontaine and Cabidoche, 1995). Some mechanistic models of water flux have been proposed to describe water redistribution in these soils (e.g. Ruy et al., 1999). These models work at small spatial (e.g. soil peds delimited by cracks) and temporal (e.g. hours) scales, and therefore have not yet been adapted to assess the water balance at the plot level.

The present study was carried out to analyse the changes in the microclimate and the soil water balance inside a tropical silvopastoral system compared with an open grassland. The aim was to assess the impact of these changes on the water use and the productivity of the grass in the wet and dry seasons. We also tested a simple compartment model of soil water balance in order to describe and interpret the experimental data.

2. Materials and methods

2.1. Experimental site and treatments

The study was carried out at the Godet Experimental Station of the Institut National de la Recherche Agronomique in Guadeloupe (French Antilles) (16°25'N, 61°30'W). The climate is warm and subhumid, the annual mean air temperature being 26°C and the annual mean rainfall 1300 mm, with a dry season from February to July, during which there is 30% of the annual rainfall. The soil is a vertisol (Chromic...
Table 1: Soil depth and chemical and physical properties of the 0–0.2 m soil layer in the silvopastoral (SS) and in the open grassland (OG) plots

<table>
<thead>
<tr>
<th>Plot</th>
<th>Soil depth (m)</th>
<th>Organic (g kg⁻¹)</th>
<th>pH</th>
<th>CEC (cmol (+) kg⁻¹)</th>
<th>Ca (cmol (+) kg⁻¹)</th>
<th>Particle size (kg kg⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>C</td>
<td>N</td>
<td></td>
<td></td>
<td>&lt;2 μm</td>
</tr>
<tr>
<td>SS</td>
<td>0.5</td>
<td>31.6</td>
<td>2.8</td>
<td>7.4</td>
<td>52.2</td>
<td>0.78</td>
</tr>
<tr>
<td>OG</td>
<td>0.6</td>
<td>27.1</td>
<td>2.2</td>
<td>7.8</td>
<td>51.5</td>
<td>0.79</td>
</tr>
</tbody>
</table>

Hapludert, USDA taxonomy) with 80% clay rich in smectite, developed over coral reef limestone. In this region, the depth of this limestone is very irregular and soil depth varies abruptly within a few meters. For this study we selected two 20 m × 13 m plots located 20 m apart, which had similar and relatively homogeneous soil depth (i.e. 0.5–0.6 m) and similar soil chemical and physical characteristics (Table 1). One of the plots had been cultivated with a leguminous tree (*Gliricidia sepium* (Jacq.) Walp)–grass (*Dichanthium aristatum* (Poir.) C.E. Hubbard) intercrop (the silvopastoral system, or SS treatment) since 1989, and the other one had been kept under a natural grassland of *Dichanthium aristatum* since the same date (open grassland, or OG treatment). The SS plot was established by planting stakes cut from *Gliricidia sepium* in a natural grassland of *Dichanthium aristatum*. *Gliricidia sepium* is a multipurpose tree, which is frequently used as a forage crop in many parts of the tropics (Cruz et al., 1999). The trees were planted in rows in a N–S direction with 2 m between rows and 0.3 m between trees within the rows. Because of mortality, actual tree density was about 12,000 plants ha⁻¹. Both treatments were managed as cut-and-carry systems where grass cutting and tree pruning residues were removed from the plot, and animals were excluded. In this study, the trees were pruned every 2–6 months, depending on the season, when the level of the incoming photosynthetically active radiation (PAR) on the associated grass was about 50% of PAR in the open grassland. The height of the trees never exceeded 2 m. In both treatments, grass was cut every 42 days. The sampling of the grass was done using an electric hand mower to cut the grass in three 0.2 m × 1 m quadrats at 1 cm height. In SS the quadrats were placed perpendicular to the tree row. Fertilisers (100, 150 kg K ha⁻¹) was applied in March 1989, May 1991, March 1995 and February 1998. No N fertiliser was applied. The experiment was run from July 1998 to February 2000.

2.2. Microclimatic measurements

In the OG treatment, the PAR, was measured with a quantum sensor (PAR-CBE, Solems, Palaiseau, France) placed in the middle of the plot. The PAR transmitted (PARt) below the tree in the SS treatment was measured with two 1 m sticks of six amorphous silicon cells (PAR-IR, Solems, Palaiseau, France). The sticks were placed horizontally on the two adjacent interrows of the innermost tree row, and perpendicularly to the row. Calibration of each individual amorphous silicon cell was made prior to the experiment and twice more during the experiment by comparing with a quantum sensor (Delta T, LI-COR, Stanmore, UK). The measurements were carried out just above the grass, i.e. 0.15 m from the soil surface. Therefore, the PARt below the trees corresponded to the PAR of the associated grass in the SS treatment. Air temperature (thermocouple type T copper-constantan), air humidity (HMP 35A, Vaisala, Helsinki, Finland) and windspeed (anemometer, CIMEL, Paris, France) were also measured at 0.15 m above the soil surface in both treatments; in SS the measurements were taken in the middle of the innermost interrow. All of the sensors were connected to a datalogger (CR10, Campbell Scientific, Shepshed, UK). Data was recorded every 10 s and averaged hourly. Daily rainfall was recorded at a weather station located 500 m from the plots.

2.3. Soil water content

Because commonly used devices such as tensiometers cannot be used in vertisols, the measurements of soil water content in the matric porosity were performed using THERESA transducers (AquaVert, Capesterre, Guadeloupe, France). This transducer measures the changes in the thickness of a given soil layer due to the shrinkage-swelling processes, which are related to the changes in the water content of the clay matrix of the layer. A detailed description of the
transducer is given in Cabidoche and Ozier-Lafontaine (1995). Measurements were made in triplicate in each treatment by inserting the THERESA transducers in the middle of the three innermost interrows in SS and in the middle of the OG plot, at 0–0.2, 0.2–0.4, 0.4 m profile bottom (i.e. 0.5 m in SS and 0.6 m in OG; Table 1). Changes in the thickness of soil layers were monitored once a week with a calliper rule (10⁻³ m precision).

The thickness of a soil layer on day \( t \) (\( \delta t \), in m) is related to the soil matric water content (\( W(t) \), in mg mg⁻¹) by the following equation:

\[
W(t) = (W_{AE} + \nu_s \rho_w) \times \frac{\delta t}{\rho_{w}} - \nu_s \rho_w \tag{1}
\]

where \( W_{AE} \) (mg mg⁻¹) is the gravimetric water content at the air entry point for cracks, \( \nu_s \) (m³ mg⁻¹) the specific volume of solid, and \( \rho_w \) (mg m⁻³) the density of water, assumed to be equal to 1 mg m⁻³.

For each layer, the matric water storage on day \( t \) (\( Sm(t) \), in m) was calculated as

\[
Sm(t) = W_{AE} \times \frac{\nu_s}{\rho_{w}} \tag{2}
\]

where \( W_{AE} \) (m³ mg⁻¹) is the total specific volume of soil at the air entry point for cracks. The values of \( \nu_s \) used in this study were those reported by Cabidoche and Ozier-Lafontaine (1995). We estimated \( W_{AE} \), \( \nu_s \) and \( \rho_{w} \) by measuring the shrinkage curve of each soil layer of each plot using the method proposed by Cabidoche and Ozier-Lafontaine (1995). In Table 2 we present the estimated values of these parameters.

<table>
<thead>
<tr>
<th>Plot</th>
<th>Layer (m)</th>
<th>( W_{AE} ) (mg mg⁻¹)</th>
<th>( \nu_s ) (m³ mg⁻¹)</th>
<th>( \rho_{w} ) (mg m⁻³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SS</td>
<td>0–0.2</td>
<td>0.35</td>
<td>0.209</td>
<td>0.375</td>
</tr>
<tr>
<td></td>
<td>0.2–0.4</td>
<td>0.45</td>
<td>0.205</td>
<td>0.375</td>
</tr>
<tr>
<td></td>
<td>0.4–0.5</td>
<td>0.39</td>
<td>0.100</td>
<td>0.370</td>
</tr>
<tr>
<td>OG</td>
<td>0–0.2</td>
<td>0.54</td>
<td>0.206</td>
<td>0.375</td>
</tr>
<tr>
<td></td>
<td>0.2–0.4</td>
<td>0.49</td>
<td>0.208</td>
<td>0.373</td>
</tr>
<tr>
<td></td>
<td>0.4–0.6</td>
<td>0.40</td>
<td>0.205</td>
<td>0.370</td>
</tr>
</tbody>
</table>

SS: Silvopastoral plot; OG: Open grassland. \( W_{AE} \): gravimetric water content at the air entry point for cracks; \( \nu_s \): thickness of the soil layer at the air entry point for cracks; \( \rho_w \): specific volume of solid.

For each layer, the matric water reserve on day \( t \) (\( Rm(t) \), in m) was calculated as the difference between \( Sm(t) \) of the layer and a minimum \( Sm \), named \( Sm_{min} \). We assumed that water in the matric reserve is unavailable for plants when \( Sm < Sm_{min} \). The \( Sm_{min} \) was estimated from the lowest water content observed in the dry season. In both treatments, the minimum water content for the 0–0.2 m soil layer was observed on 24 April 1999, the values being 0.254 mg mg⁻¹ in the OG treatment and 0.264 mg mg⁻¹ in the SS treatment. We assumed that the water content corresponding to \( Sm_{min} \) was the same for the three analysed layers of each plot. This assumption is supported by the small differences observed in the retention curve of the three soil layers of each plot (Dulormne, 2001). These values were similar to those reported by Maertens (1988).

2.4. Model of soil water balance

Several authors (e.g. Ruy et al., 1999; Dulormne, 2001) reported that classical soil water balance, which takes into account water inputs (rainfall, irrigation) and outputs (evapotranspiration, drainage) was not suitable for analysing the changes in soil water content in vertisols, principally when the soil was rewatered at the beginning of the rainy season. This was due to the bimodal water reserve distribution in these soils which makes it difficult to establish a simple relationship between water inputs and outputs and soil water content. For this reason, we constructed a model of soil water balance in order to explain the experimental data obtained in this study. The model calculates the daily water reserve of the soil as a whole (0–0.6 m in OG and 0–0.5 m in SS). Rainfall is the only water input. Runoff and foliage interception were not described in this model. The model takes into account three classes of soil porosity: the structural porosity, the matric porosity, and the crack porosity. The water reserve in the structural porosity (\( Rs \), in m) is easily available for plants; the water reserve in the matric porosity (\( Rm \), in m) is not easily available, and water in the crack porosity is lost by drainage. Note that it is not easy to express water availability in \( Rs \) and \( Rm \) in terms of water potential because drying and wetting cause changes in pore distribution of vertisols. In this way, the upper and lower water potential limit of each compartment of soil porosity vary with soil water content. However, it may be assumed that \( Rs \) represents...
water retained up to about −50 kPa, and Rm represents water retained from that suction to −1600 kPa.

For a cracking clay soil, Hoogmoed and Bouma (1980) found that horizontal flow of water from the cracks to the structural porosity was small in relation to by-passing within the cracks. So, we assumed that the fraction of rainfall entering the crack porosity is lost in the calcareous substrate of the soil. This assumption seems valid for our vertisol because the cracks reach the bottom of the soil profile (Ruy et al., 1999).

In our model, rainfall first fills Rs and then the crack porosity, and water may be transferred from Rs to Rm. Daily water output from Rs and Rm corresponds to the actual evapotranspiration on day t (ETR(t), in m).

In SS, ETR(t) is the total evapotranspiration of grass and tree considered together. The effective rainfall on day t (Pe(t), in m) entering in the structural porosity was calculated as

$$P(t) = \min(P(t), R_{\text{max}} - R_s(t - 1))$$

where Pe(t) (m) is the rainfall on day t, R_{\text{max}} (m) is the maximum structural reserve, and Rs(t − 1) (m) is the structural reserve on the previous day. Therefore, water entering in the crack porosity is equal to the difference between Pe(t) and P(t). Rs(t) was calculated from a daily water balance:

$$R_s(t) = R_s(t - 1) + P(t) - [R_s(t - 1) 	imes W_{\text{m,n}}]$$

$$- [E(T)(t) \times T_s]$$

where W_{\text{m,n}} is the fraction of Rs being transferred to Rm, and T_s is the fraction of ETR(t) coming from water uptake in Rs. In a similar way, Rm(t) was estimated as

$$R_m(t) = R_m(t - 1) + [R_s(t - 1) \times W_{\text{m,n}}]$$

$$- [E(T)(t) \times (1 - T_s)]$$

with 0 ≤ Rm(t) ≤ R_{\text{max}}, where Rm(t − 1) (m) is the matric reserve on the previous day, and R_{\text{max}} (m) is the maximum matric reserve.

If for a given day [E(T)(t) × T_s] is higher than the amount of water remaining in Rs, then Rs(t − 1) = 0 and the value of Eq. (4) is considered as water taken from Rm.

The ETR(t) was assumed to depend on soil water availability:

$$E(T)(t) = K_1 \times E(T)(t), \quad \text{for } R_s(t) > 0$$

and

$$E(T)(t) = K_2 \times E(T)(t), \quad \text{for } R_s(t) = 0$$

where E(T)(t) (m) is the reference evapotranspiration on day t, and K_1 and K_2 are coefficients according to the plant characteristics in each treatment. Eqs. (6) and (7) are simplifications of the complex process of evapotranspiration, and their suitability is discussed below. E(T)(t) was assessed as proposed by Bastergue (1988):

$$E(T)(t) = 0.24 \times R_g(t)$$

where R_g(t) (MJ m^{-2} per day) is the global radiation on day t, and 0.24 is an empirical coefficient determined for the conditions of the subhumid region of Guadeloupe. Eq. (8) is reliable to calculate E(T) in that region because the small seasonal differences in windspeed and the high air humidity, even in the dry season, induce a constant effect of the advective component on the evaporative demand (Bastergue, 1988; Bonhomme and Ometto, 1978). Eq. (8) may be expressed in terms of the daily PAR (MJ m^{-2} per day) by assuming that PAR = 0.48 × R_g (Varlet-Grancher et al., 1982). Therefore

$$E(T)(t) = 0.50 \times \text{PAR}_{\text{OG}}(t)$$

where PAR_{\text{OG}}(t) is the PAR measured in OG on day t.

The model was run using the ModelMaker 3.0 program (ModelKinetix, 2000). The initial value of Rs was set to 0 m because rainfall prior to the beginning of the experiment was small and lower than E(T). The initial value of Rm was the average of the two first measurements carried out with THERESA transducers; i.e. 0.06 m in both treatments. In OG, the parameters fitted were R_{\text{max}}, R_{\text{max}}, W_{\text{m,n}}, T_s, K_1, and K_2. Because soil depth was different in both plots (Table 1), R_{\text{max}} and R_{\text{max}} were also fitted in SS. The same was made for T_s, K_1, and K_2 which depend upon the plant characteristics of each treatment. Conversely, as soil physical properties were similar in both plots (Table 2), we assumed that the soil specific parameter W_{\text{m,n}} did not vary between plots and in SS it was set to the value fitted in OG. The fit was performed using the Marquardt method (ModelKinetix, 2000) included in the ModelMaker program and considering the entire data set; i.e. measurements of soil water content taken from July 1998 to February 2000, n = 72.
Although the variables soil water reserve, rainfall and evapotranspiration are expressed in m in the model, they will be expressed in mm in Sections 3 and 4 in order to simplify the presentation.

2.5. Statistical analysis: assumptions and methods

High spatial variation in soil depth within the experimental site, which may affect soil water balance, did not allow us to replicate each treatment. This makes the validity of the statistical analysis dependent on there being no other confounding effects affecting the differences between treatments. As the plots were only 20 m apart, topography was homogeneous within the experimental site, and physical soil properties were similar between plots (Tables 1 and 2), we reasonably assumed that the soils of both plots were sufficiently similar in terms of the factors affecting water transport and uptake. However, the slight difference between plots in soil depth (Table 1) might induce differences in soil water content between treatments by affecting the size of the water reserve compartments, and hence water uptake, principally in the dry season. This constraint is less important to compare estimates of the model parameters, since this involves mechanisms where some of that confounding effect has been eliminated. The effect of this constraint on the reliability of our analysis is discussed in Section 4.2.

For soil water content, differences between treatments were analysed using the mixed model procedure of the SAS software (i.e. longitudinal data analysis; Littell et al., 1996). For the microclimatic variables and grass production, differences were analysed using classical t-tests. The comparison of the fitted parameters of the model of water balance was performed with F-tests by considering the root mean square error (RMSE) of the respective fits. These statistical tests were carried out using the GLM procedure of the SAS statistical analysis system (SAS Institute, 1994). The level of probability was fixed at $P < 0.05$ for all the tests.

3. Results

3.1. Microclimate and grass production

For the overall study period, the daily PAR$_i$ at the grass level varied from 4.5 to 9.5 MJ m$^{-2}$ per day in OG, and from 2.5 to 7.5 MJ m$^{-2}$ per day in SS. In OG, the maximum and the minimum PAR$_i$ were found in July and December, respectively, which correspond to the months with maximum and minimum daily global radiation in Guadeloupe. In SS, PAR$_i$ depended principally upon tree growth and was higher just after pruning (Fig. 1A). The PAR$_i$(SS)/PAR$_i$(OG) ratio var-

![Fig. 1. Ten-day averages of weather variables during a six month period following tree pruning in the silvopastoral plot. All the factors were measured at the grass level (0.15 m above ground): (A) PAR. (B) air temperature and humidity. (C) windspeed. OG, open grassland plot; SS, silvopastoral plot. Vertical bars indicate the standard deviation.](image-url)
ied from 0.8 at the beginning of the period of tree regrowth period to 0.5 at the end of the period. The latter value was observed for tree above-ground biomass varying from 2.5 to 4 mg DM ha$^{-1}$, depending on the season. Some measurements made along one interrow in SS (i.e. 13 m) indicated that the spatial variation of the daily PAR$_i$ was relatively high (coefficient of variation 25%; data not shown). This was associated with the heterogeneity of the tree canopy within the row. In addition, although PAR$_i$ in the middle of the interrow was always higher than PAR$_i$ near the tree row, these differences varied with tree growth. For example, PAR$_i$ was 20% lower near the tree row just after pruning, and 66% lower at the end of the regrowth period.

There were no significant differences between treatments in air temperature and humidity just above the grass for the duration of the experiment (Fig. 1B) which indicates that tree growth did not affect these variables. The mean daily air temperature ranged from 23$^\circ$C (December) to 30$^\circ$C (July), and the air humidity ranged from 70% (May, dry season) to 95% (December, wet season). Windspeed was significantly higher in the open grassland (Fig. 1C), and differences between treatments averaged 0.5 m s$^{-1}$. These differences were smaller just after tree pruning.
Although in the wet season grass dry matter production was significantly different between treatments (e.g. mean and standard deviation of nine 42-day regrowth periods: 2.1 ± 0.5 mg ha\(^{-1}\) for OG and 1.7 ± 0.3 mg ha\(^{-1}\) for SS), no significant differences were observed in the dry season (e.g. mean and standard deviation of five 42-day regrowth periods: 1.6 ± 0.3 mg ha\(^{-1}\) for OG and 1.5 ± 0.4 mg ha\(^{-1}\) for SS).

### 3.2. Soil water content

Although the general pattern of the changes in water content in the soil matric porosity (\(W_m\) in Eq. (1)) was similar in both treatments, \(W_m\) was generally higher in OG especially in the 0–0.2 m layer during the wet seasons (Fig. 2). In these seasons, \(W_m\) varied around 0.50 mg mg\(^{-1}\) in OG and 0.45 mg mg\(^{-1}\) in SS for the top soil layer. In the beginning of the dry season (February 1999), \(W_m\) decreased simultaneously in all layers and both treatments. The lowest values were observed in the middle of the dry season (May 1998), and \(W_m\) was about 0.25 mg mg\(^{-1}\) in the 0–0.2 m layer and 0.30 mg mg\(^{-1}\) in the deeper layers of both plots. The spatial variation of \(W_m\) was relatively high in the three layers and both treatments (coefficient of variation ≈ 30%, \(n = 3\)); the standard deviation was not plotted in Fig. 2 in order to simplify its presentation.

Significant differences between treatments were found for the 0–0.2 m soil layers in both wet seasons. Conversely, differences between treatments were not significant for the two deeper layers in the wet seasons nor for the three layers in the dry season.

The model described the changes of \(R_m\) reasonably well, particularly in the OG treatment (Fig. 3, Table 3). The model simulated the regular decrease in \(R_m\) quite accurately at the beginning of the dry period (March to April 1999), as well as its regular increase at the beginning of the rainy season (September to October 1999). The major discrepancies between simulated and experimental data were observed at the beginning of the first wet season in the SS treatment, when \(R_m\) was sometimes overestimated by the model. In addition, rapid changes in \(R_m\) following high rainfall in the middle of the dry season were generally underestimated by the model; e.g. on 11 May 1999, rainfall 92 mm. The same was observed in the wet season following high rainfall in November 1999; e.g. on

![Figure 3](image-url)

**Fig. 3.** Observed and simulated data of matric water reserve (\(R_m\)) in the silvopastoral and the open grassland plots. Values correspond to the entire soil profile. Vertical bars indicate the standard deviation.

<table>
<thead>
<tr>
<th>Table 3</th>
<th>Estimated values for the parameters of the model of water dynamics</th>
</tr>
</thead>
<tbody>
<tr>
<td>SS</td>
<td>OG</td>
</tr>
<tr>
<td>(R_{max} (\text{mm}))</td>
<td>53a</td>
</tr>
<tr>
<td>(R_{max} (\text{mm}))</td>
<td>87a</td>
</tr>
<tr>
<td>(K_1)</td>
<td>1.27a</td>
</tr>
<tr>
<td>(K_2)</td>
<td>0.40a</td>
</tr>
<tr>
<td>(\eta_{max})</td>
<td>0.57</td>
</tr>
<tr>
<td>(\chi)</td>
<td>0.46a</td>
</tr>
<tr>
<td>(R^2)</td>
<td>0.77</td>
</tr>
<tr>
<td>RMSE (\text{mm})</td>
<td>11.1</td>
</tr>
</tbody>
</table>

For a given parameter, values followed by the same letter are not statistically different at \(P < 0.05\). SS, silvopastoral plot; OG, open grassland plot; \(R_{max}\), maximum structural reserve; \(R_{max}\), maximum matric reserve; \(K_1\) and \(K_2\), plant coefficients affecting water in the structural and in the matric reserve, respectively; \(\eta_{max}\), fraction of \(R_s\) being transferred daily to \(R_m\); \(\chi\), fraction of the evapotranspiration coming from water in \(R_s\); \(R^2\), the multiple regression coefficient; RMSE, the root mean square error of the model.

The value was set to that fitted in OG.
18 November 1999, rainfall 204 mm (Fig. 2; note that in this figure rainfall is expressed as cumulated values over 10-day periods).

Significant differences between treatments were found for the fitted values of $R_{m_{\text{max}}}$, $K_1$ and $T_s$ (Table 3). The difference in $R_{m_{\text{max}}}$ was associated with the differences in soil depth between the plots (Table 1), but it only slightly affected the estimated $R_{s_{\text{max}}}$. Whilst no differences between treatments were observed for water consumption from the matric reserve ($K_2$ in Eq. (7)), the higher values of $K_1$ and $T_s$ in SS indicates that there was an increase in water uptake from the easily available reserve $R_s$ in the alley cropping system compared with the open grassland. When $R_s$ was filled with water, the actual evapotranspiration estimated by the model (Eq. (6)) was 26% higher in SS and water consumed from $R_s$ (i.e. $E_{\text{TR}}(t)$ in Eq. (4)) was 92% higher in this treatment. However, the value of $W_{s\rightarrow m}$ was relatively high which indicates that $R_s$ was only a transient water reserve for plants in the dry season. For example, for a PAR$_i$ (OG) (Eq. (9)) of 7 MJ m$^{-2}$ per day, $R_s$ in SS was 53 mm just after rain sufficient to fill the reserve (Table 3), 19.3 mm on the first day following that rainfall, 4.7 mm on the second day and 0 mm on the third day. It should be noted that the $K_1$ value in SS was higher than 1 indicating that $E_{\text{TR}} > E_{\text{TPR}}$ (Eq. (6)).

4. Discussion

4.1. Effect of the trees on the microclimate

Only PAR$_i$ and windspeed were modified by the trees in SS. Monteith et al. (1991) also found no significant differences in air temperature and air humidity inside a *Leucaena leucocephala*—pearl millet alley cropping system compared with a pure pearl millet stand, although the windspeed was lower in the alley cropping. Conversely, in the same SS plot used in the present study, Tournebize (1994) observed that air temperature and air humidity were higher under the trees than outside the plot. The tree canopy in the Tournebize’s study was considerably larger than in our study, and completely covered the interrow, inducing a strong windbreak effect. In our study, it seems that air turbulence under the trees was sufficient to ensure heat and mass exchange with the air outside the plot. This confirms the reliability of the estimation of $E_{\text{TPR}}$ based only on the incoming radiation (Eq. (9)).

4.2. Relationship between soil water content and water consumption

The lower value of $R_{m_{\text{max}}}$ in SS compared with OG corresponded well to the differences in soil depth between plots; e.g. soil depth and $R_{m_{\text{max}}}$ were 17% and 19% lower in SS than in OG, respectively. The $R_{s_{\text{max}}}$ values were similar in both treatments because the difference in soil depth corresponded to the lowest layer where the structural porosity is small (Cabiacoche and Ozier-Lafontaine, 1995). The differences between plots in $R_{m_{\text{max}}}$ did not cause great differences in water use between treatments. For example, the model estimated that $R_m$ was empty during 11 days in SS and 2 days in OG in the dry period, but observed $R_m$ values always were >0 mm in both treatments (Fig. 3). This implies that the size of $R_m$ did not limit water uptake. This result, together with the lack of significant differences found for $R_{s_{\text{max}}}$, suggest that differences in soil depth between plots had a minor effect in our study, and we assumed that the confounding effect discussed in Section 2.5. was small in our statistical analysis.

Rainfall in the dry season did not saturate the matric porosity and this was correctly described by the model, which indicates that the assumption of effective rainfall ($P_{e}(t)$ in Eq. (3)) was reasonable in our study. However, our model failed when high rainfall occurred and a fraction of the water was transferred towards $R_m$ in both treatments. It is possible that under these conditions the model overestimated water transfer within the cracks or lost it in the bottom of the soil profile. This would be the case when fast soil swelling closed the cracks after heavy rain and caused some of the water on the soil surface to enter the matric porosity.

By definition, $E_{\text{TR}}$ might be lower or equal to $E_{\text{TPR}}$, which implies that $K_1$ and $K_2$ might be lower or equal to 1. In fact, $E_{\text{TPR}}$ is a reference value generally calculated from the evapotranspiration data obtained on grasses (e.g. *Paspalum notatum* in Bastergue, 1988). But plant systems with a heterogeneous canopy, such as shelter belts or alley crops, sometimes present $K$ values >1, as in our SS treatment (Table 3). This is generally attributed to a complex modification of the
convective exchanges in such systems (McNaughton, 1989; Wallace, 1995). Note that $K_2$ was $<1$ (Table 3) because ETR was limited by water availability as assumed in Eq. (7).

The lower soil water content in SS during the wet season indicated that water consumption by evapotranspiration in the intercrop was greater than in the pure grassland. This agrees with the results reported by Tournebize (1994) who found that although transpiration of the grass in SS was generally 15–20% lower than in OG, the whole system transpiration was 2–2.5 times higher in the SS treatment. As the structural reserve was frequently filled with water in the wet season, the higher water consumption in SS may be linked to its greater $K_1$ and $T_s$ values (Table 3). This preferential water uptake from the structural water reserve agrees with direct measurements carried out by Ozier-Lafontaine and Cabidoche (1995) for a vertisol cultivated with sugar cane in Guadeloupe.

Although water consumption affected soil water content in the entire profile, it was particularly noticeable in the top layer of both plots (Fig. 2). This implies that roots were concentrated in that layer even if they reached 0.5–0.6 m depth. In a simultaneous study carried out in the same plots, Dulormne (2001) found that 65% of the root biomass of the grass in both treatments was located in the top 0.25 m of the soil. Similar results were obtained by other authors for tropical grasses growing in subhumid regions (e.g. Mordelet et al., 1997). In addition, the works of Ozier-Lafontaine et al. (1999) and Rowe et al. (2001) showed that *Gliricidia sepium* planted from stakes have a superficial root system, and only some secondary roots may reach 0.6 m depth. These results and our observations of soil water content suggest that water competition between species in SS occurred principally in the first soil layer during the wet season, the 0.2–0.4 m layer was only slightly concerned by water competition (Fig. 2). This disagrees with the proposal of Knoop and Walter (1985) whose model is based on a weak water competition between the associated species due to their different root system pattern; i.e. deep for the tree and shallow for the grass. Conversely, Lehmann et al. (1998), working with a Kenyan alley crop, found great water competition between *Acacia* sp. and sorghum in the first 0.45 m of the soil, even though the tree roots reached 1.5 m depth. Suresh and Rao (1999) found similar results in semiarid areas for intercrops with sorghum and nitrogen fixing trees such as *Acacia ferruginea* and *Albizia lebbeck*.

The pattern of water consumption in the dry season was different from that discussed for the wet season. In the dry season, the structural reserve was generally empty and water was taken from the matric porosity. In this way, water uptake was strongly limited by water availability and, as discussed above, this was reflected by the low $K_2$ value and also by the high $K_1/K_2$ ratio in both treatments; i.e. 2.5 in OG and to 3.2 in SS (Table 3). The low $K_2$ values were probably associated with the very low hydraulic conductivity of the matric porosity of vertisols (often below $10^{-3}$ m per day, Ruy and Cabidoche, 1998). As water uptake was principally limited by soil properties and not by evaporative demand, the rate of evapotranspiration $K_2$ and soil water content were similar in both treatments in that season (Table 3, Fig. 2). Some authors have proposed that silvopastoral systems are not useful in tropical subhumid regions due to the great water competition between species, especially in the dry season (Cavagnaro and Passera, 1991; McIntyre et al., 1997). Our observations showed that tree growth was drastically reduced in the dry season but leaf loss was small (Dulormne, 2001). This could represent an advantage for the grass in SS because trees are relatively less competitive for water in the dry season, and the microclimate under the trees reduces grass transpiration compared with the open grassland. The results of grass production in the dry season are in agreement with this hypotheses, and suggest that grass growth in SS in the dry season was more affected by water transfer from the soil than by water competition with the tree. Conversely, differences between treatments in grass production in the wet season reflected the different incoming radiation (Dulormne, 2001).

5. Conclusions

Our results showed that the water status of the intercropped grass in the dry season resulted from the balance between reduced evapotranspiration and reduced soil water availability, and water competition with the tree was less important. From a practical point of view, this result indicates that tree pruning has to be avoided just before the beginning of the dry season.
in order to ensure a favourable microclimate for the grass.

The compartment model proposed in this study was a useful tool to understand the major features of soil water dynamics and water consumption for crops grown in a cracking clay soil. However, some improvements will be necessary to describe water dynamics in deeper soils. In this case the assumption than water is lost by passing through the cracks is not reliable, and horizontal water flow from the bottom of the crack to the structural porosity should be considered.

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References


Gliricidia sepium

Digitaria decumbens

Peltophorum pterocarpum

Chloris gayana


References


