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Simulation of agroforestry systems with sugarcane in Piracicaba, Brazil

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Abstract

Sugarcane (*Saccharum officinarum*) occupies large areas of tropical regions as a single crop, and there is a lack of research on its cultivation in agroforestry systems (AFS). Thus, the use of simulation models to investigate its potentialities and restrictions is an important phase of evaluation. The Water, Nutrient and Light Capture in Agroforestry Systems (WaNuLCAS) model was used to investigate long-term biophysical interactions and system performance of sugarcane–rubber (*Hevea brasiliensis*) and sugarcane–eucalyptus (*Eucalyptus grandis*) alley cropping. Each system was simulated for 20 years in two soil types of Piracicaba, Brazil. The effects of light and soil water on plant growth were evaluated. Outputs of the mature phase of the system were compared to results of on-farm sugarcane-tree trials. Simulations showed a strong competition in the AFS and that light and soil water are limiting factors. Competition for these resources increased as the trees grew and it depended on tree biological characteristics and management of the systems. WaNuLCAS was an useful tool to speculate about the

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systems, to identify limiting factors, qualitative tendencies, and management strategies, but it presented limitations to quantitative analysis.

Keywords: Eucalyptus; Light; Model; Rubber; WaNulCAS; Water

1. Introduction

Sugarcane (*Saccharum officinarum*) cultivation is widespread in tropical areas worldwide in a total of 19.4 million ha as a single crop, and Brazil (4.9 million ha) and India (3.7 million ha) have the largest areas (FAO, 1999). Monocropping is the main production system, but technological and management levels vary from low to very high, being produced by small land holders and also in large farms.

Environmental and socioeconomic reasons have pressed for alternative production systems of high yields while conserving the natural resources (Pinto et al., 2003). There are some reports on intercropping sugarcane with smaller plants such as potato, maize, sunflower and beans in Asia, Africa and Brazil (Souza and Andrade, 1985; Govinden, 1990; Kwong et al., 1996; Sharma et al., 1997). Zarin et al. (1998) considered sugarcane as an alternative for slash and burn systems in the Amazon region. However, there is a lack of systematic research on the sugarcane production in agroforestry systems (AFS). Pinto et al. (2003) discussed its feasibility in contour hedgerows in Piracicaba, Brazil, indicating rubber *(Hevea brasiliensis*) and eucalyptus (*Eucalyptus grandis*) as potential tree species. Pinto (2002) measured yield and biometric indexes of plants in one sugarcane–rubber and one sugarcane–eucalyptus interfaces in Piracicaba, Brazil, but only for one crop harvest. Pinto et al. (in press) found that light was the most limiting factor for crop growth in a sugarcane–rubber interface. They also concluded that the relative importance of water competition increased in function of the proximity of the tree row, but a medium-term simulation suggested that eucalyptus higher growth would offset reduction in crop yield. Nevertheless, there is still a need for performance indicators of the whole system in the long-term prior to its recommendation as a commercial alternative.

Due to the lack of trials with sugarcane in AFS, the results of simulation models are then strategic to speculate about its potentialities and restrictions in the long-term (Lott et al., 2000). Besides, modeling may test and generate hypothesis, guide field experimentation and provide subsidies for public policies (Pereira, 1984; Sinclair and Lawson, 1997). Moreover, present agroforestry models, such as HyPAR (Mobbs et al., 1998) and Water, Nutrient and Light Capture in Agroforestry Systems (WaNuLCAS) (Van Noordwijk and Lusiana, 1999), are recent and there is a need to test them in different environmental conditions.

Thus, this paper has two objectives: (1) to use the WaNuLCAS model to investigate biophysical interactions and the performance of sugarcane–rubber and sugarcane–eucalyptus AFS in the longterm in the region of Piracicaba, Brazil; and (2) to verify the suitability of WaNuLCAS as a tool to assess AFS as a land use alternative.

2. Materials and methods

WaNuLCAS represents a four layers soil profile with four horizontal spatial zones with different intensity of interactions between the tree and the crop components (Fig. 1). It also includes a water and nitrogen balance and uptake by a crop and a tree. Belowground competition is based on sharing the potential uptake rate on the basis of relative root length multiplied by relative demand per crop and tree in the same soil compartment. Light capture is treated on the basis of Leaf Area Index of tree and crop and their relative heights in each zone. Plant growth is calculated on a daily basis by multiplying the potential growth by the minimum stress factor, regarding light, water or nitrogen. The growth daily cycle considers the following sequence of calculations: LAI, canopy height, relative light capture, potential growth rate (considering the light use efficiency of the plant stage), transpiration demand (considering the potential water use efficiency), actual water uptake and actual nitrogen uptake (Van Noordwijk and Lusiana, 1999). The option for WaNuLCAs instead of HyPAR was due to its potential flexibility to adapt the tree and the crop components to any possible species one intend to simulate and the possibility for users to modify assumptions and equations in the Stella modeling environment (Hannon and Rut, 1994).

Using WaNuLCAS version 2.06, an alley cropping system of 27.5 m in length was simulated. One row of trees grew in Zone 1, and sugarcane in Zones 2–4 (Fig. 1). The trees were either rubber (*H. brasiliensis*) or eucalyptus (*E. grandis*), and the simulation considered the interactions for 20 years using meteorological records from 1981 to 2000. Simulations were done without nutrient limitations in the two most representative soils of the sloping lands of Piracicaba, because these are priority for sugarcane cultivation in agroforestry systems (Pinto et al., 2003). According to the

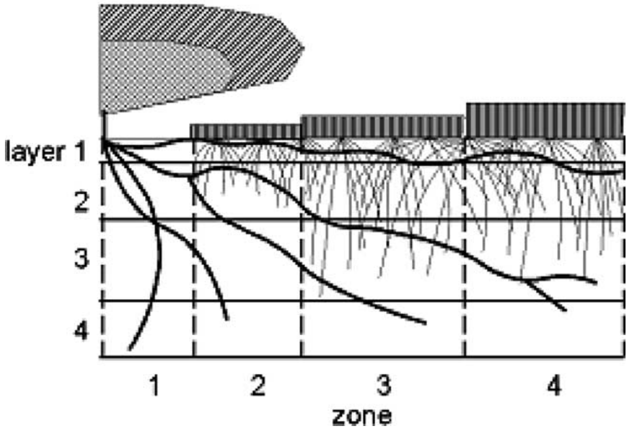

Fig. 1. General layout of spatial zones and soil layers in the WaNuLCAS model. In the simulations, Zone 1 had a tree (rubber or eucalyptus) and Zones 2–4 had sugarcane. Adapted from Van Noordwijk and Lusiana (2000).

Table 1
Values of soil properties used in the pedotransfer functions in the WaNulCAS model for simulations in Piracicaba (Brazil)

Depth (m)	Soil properties			
	Clay (%)	Silt (%)	Organic matter (%)	Bulk density (g cm^{-3})
Typic Kandiudul				
0.0–0.2	13	11	1.4	1.65
0.2–0.4	17	9	1.2	1.69
0.4–0.8	28	12	1.5	1.70
0.8–1.2	28	13	1.0	1.68
Lithic hapludoll				
0.0–0.2	37	39	2.3	1.60
0.2–0.4	29	43	1.8	1.55
0.4–0.6	29	33	0.8	1.45
0.6–0.8	32	35	1.3	1.30

previous authors, the soils were Typic Kandiudult (TK) and Lithic Hapludoll (LH), with physical characteristics shown in Table 1.

The simulation considered the following management for each species: the sugarcane field was initially planted on 01 March 1981 and harvested on 19 July 1982 (a 500 days cycle); the crop plant was followed by three ratoons (regrowth of the plant harvested). Each ratoon was simulated as a new planting and always planted on 23 July, with harvest one year later. The sequence of one planting followed by three ratoons was repeated four times, and ratoons were noted as $S_{11}, \ldots, S_{13}$, $S_{21}, \ldots, S_{23}, \ldots, S_{41}, \ldots, S_{43}$; where the first number refers to the planting that produced the ratoon. Rubber trees were planted on 30 January 1981, with a 3 m spacing between trees, and tapping began after the tree perimeter reached 50 cm (Bernardes, 2000), which usually occurs within 5–7 years after planting. As indicated by Paardekooper (1989), 10% of the carbohydrates reserves were allocated for rubber production. Eucalyptus trees were also planted on 30 January 1981, in a 2 m spacing. There were three harvests during the 20 years simulated, with the last two ones being from the regrowth of the first harvest. The regrowth was simulated as a new planting with different initial conditions of the seedlings and a lower tree density (80% for the first and 62% for the second regrowth). The first harvest was 7 years after planting, the second after 6 more years, and the third after another 6 years and 10 months. Local cycle for harvesting wood for paper and charcoal usually lasts from 6 to 7 years.

The model was adapted for simulations with sugarcane because its default crops are grain and tuber ones. For instance, the plant cycle was limited to the vegetative phase, without a biomass allocation for grains. As indicated by Robertson et al. (1996), the ratoon crop presented a light use efficiency 10% lower than the first planting. The model parameters were obtained from the literature (Table 2). These were selected as they better fitted within the range of expected outputs during the model calibration. The potential evapotranspiration was estimated by using the FAO-56 Penman-Monteith (Allen et al., 1998) for the 20 years of simulation (1981–2000).

Table 2
Main crop and tree parameters used as input for simulations with WaNuLCAS

Variables	Species					
	Sugarcane	Source	Rubber	Source	Eucalyptus	Source
Maximum daily growth rate ($\mathrm{t\,ha^{-1}\,d^{-1}}$)	0.26	Machado et al. (1982)	0.1	Templeton (1968)	0.08	Cromer et al. (1993)
Specific leaf area ($\mathrm{m^2\,kg^{-1}}$)	10	Machado et al. (1982)	10	Conceição et al. (1986)	15	Cromer et al. (1993)
Leaf weight ratio	0.7–0.1	Machado et al. (1982)	0.1	Templeton (1968)	0.45	Leite et al. (1997)
Light extinction coefficient	0.5	Van Den Berg (2000)	0.7	Bernardes (2000)	0.8	Default
Water consumption for dry matter production (1 H_2O $\mathrm{kg^{-1}}$ of DM)	80	Barbieri (1981)	400	Bernardes, personal communication	430	Lima (1993)
Root length density	Variable	Alvarez et al. (2000)	Variable	Bernardes et al. (1998)		Gonçalves and Mello (2000)
Harvest index	0.8	Miocque (1999)	–	–		

All crop parameters were obtained in experiments done in Piracicaba, Brazil.

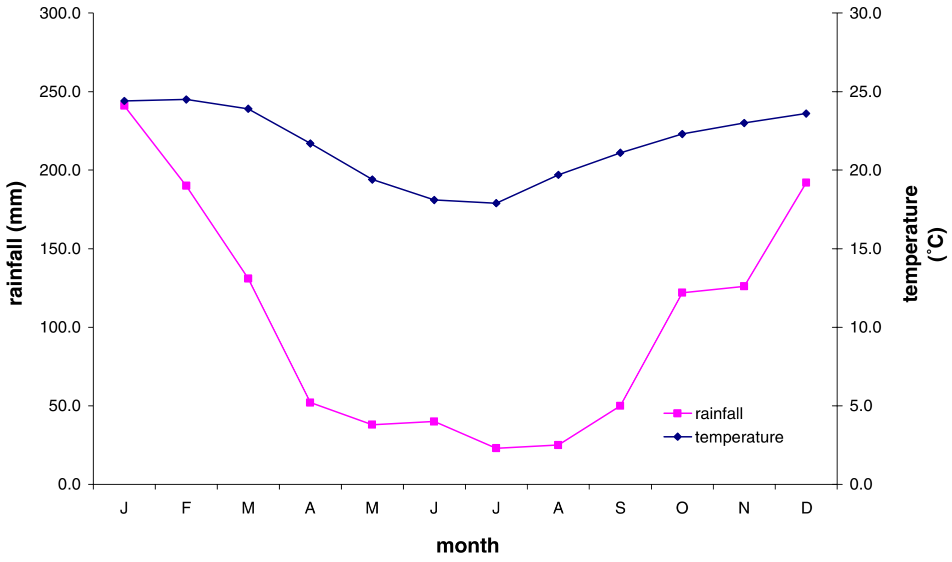

Fig. 2. Mean monthly rainfall and temperature of Piracicaba, Brazil.

The simulation outputs were compared to the data obtained by Pinto (2002) in the sugarcane–rubber and sugarcane–eucalyptus interfaces and other growth controlled experiments in monocropping for the species in the same region (Piracicaba, Brazil). In both interface trials, trees were mature for the systems they were planned. Eucalyptus was planned to be harvested in a 7 years cycle – as in the simulation. Rubber trees were 19 years old and eucalyptus trees were 5 years old. Based on crop dry matter production, three homogenous zones across the transect with six positions where measurements were done were identified. Measured data and crop simulated outputs were compared to the system mature phase. The 20 years simulation outputs were used to investigate biophysical interactions and the system performance in the long-term.

Both tree–crop interface studies were conducted in two on-farm sites (one with eucalyptus and another with rubber plantation) in Piracicaba, Brazil, in 2001. In the sites, the plant crop and the trees were cultivated in monocrops, but with an interface between the tree plantations and the crop fields. Both sites were in a flat area of Typic hapludox soil (well-drained and moderately deep with sandy loam texture). Piracicaba (Brazil) is located at 22°42′ S, 47°38′ W, altitude 554 m. The local climate is Cwa (wet sub-tropical, with rainy summer and dry winter) Fig. 2.

3. Results and discussion

3.1. Plant growth

As seen from Fig. 1, Crop roots in Zones 2–4 did not compete with tree roots in Zone 1. The crop in Zone 4 has no aboveground and weak belowground interaction with trees. In Zone 4, the crop plant (first of each sequence) produced an average of 83.8 t of DM ha^{-1}, with maximum of 90.9 t ha^{-1}. For the LH soil, the average and maximum values were 52.5 and 59.4 t DM ha^{-1}. For the ratoon crop, the average and maximum values were 49.6 and 60.6 t DM ha^{-1} for TK, and 28.1 and 40.1 t DM ha^{-1} for LH. Such values are in the range of potential growth described in literature, but are higher than measured and expected for the region. Irvine (1983) estimated DM potential production to be around 130 t DM ha^{-1} year^{-1} and Machado et al. (1982) reported 53 t DM ha^{-1} for two varieties after 500 days in a growth controlled trial in Piracicaba, Brazil. Pinto (2002) measured 51.5 and 35.1 t DM ha^{-1} in the control positions (without tree effect) of the on-farm trials with rubber and eucalyptus interfaces.

The simulated tree growth was also in the range of estimated potential growth, but it also produced higher values than measured in the on-farm trials and field experiments in the region (comparisons in Figs. 3 and 4).

3.2. Tree–crop interactions and system performance

Regarding overgrowth of plants in simulations, comparisons of crop growth of the system mature phase were done on a relative basis, assuming growth values of Zone 4 as free of tree effect (Table 3). Both for simulated outputs and measured data,

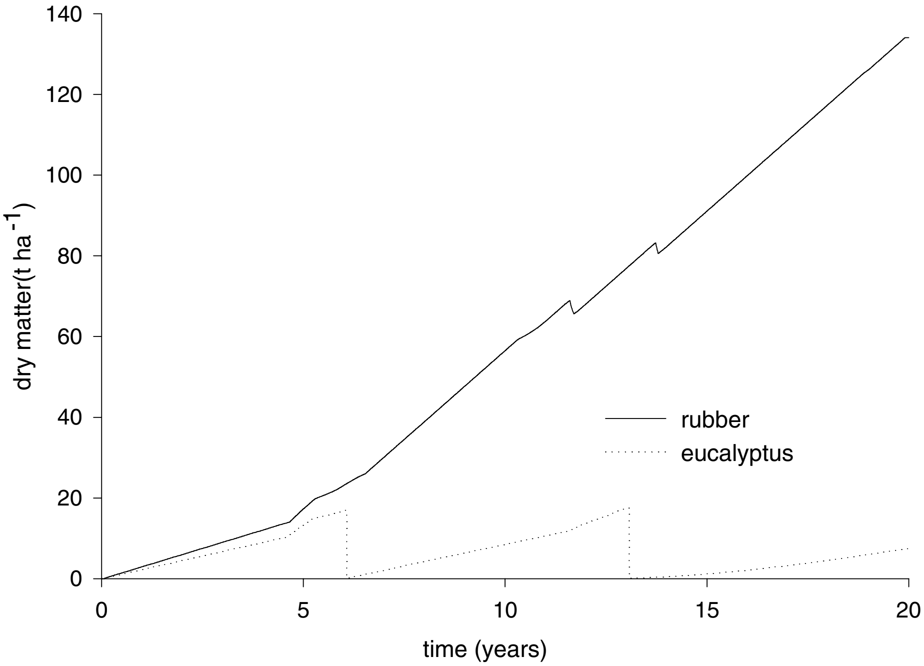

Fig. 3. Accumulated tree dry matter simulated for a Typic Kandiudult soil for 20 years in Piracicaba, Brazil.

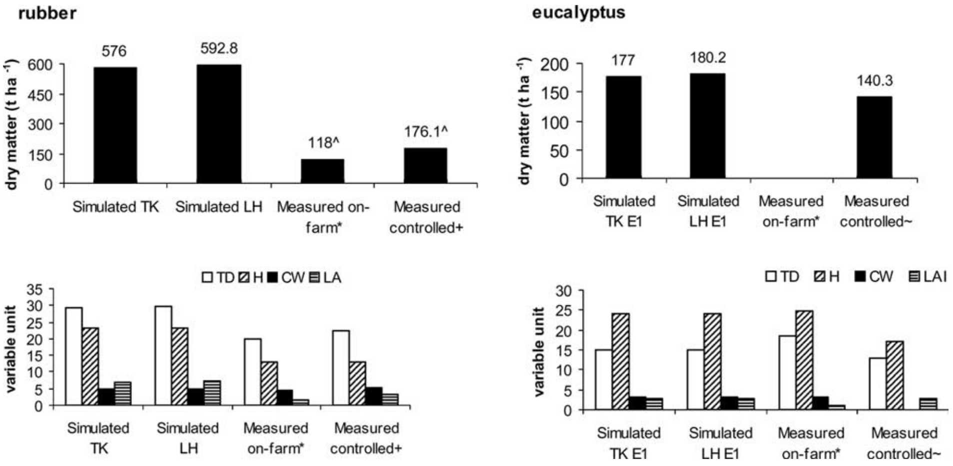

Fig. 4. Final output values of tree growth in two soils (TK – Typic Kandiudult and LH – Lithic hapludoll) and measured tree values in on-farm interfaces and monocropping growth trials in Piracicaba, Brazil. TD: trunk diameter; H: tree height; CW: canopy width; LAI: leaf area index. E1 refers to the first eucalyptus planting. * – Pinto (2002); + – Righi (2000); ~ – Gonçalves et al. (1999); except LAI, from Leite et al. (1997); ∧ – estimated by allometric equation (Shorrocks et al., 1965).

Table 3
Simulated and measured relative sugarcane dry matter in function of tree distance in Piracicaba, Brazil

	Simulated zone			Measured zone		
	2	3	4	2	3	4
Rubber						
Relative tree distance[a]	0.11–0.35	0.35–0.87	0.87–1.30	0.58–0.96	0.96–1.23	1.23–2.82
Relative dry matter	0.02	0.47	1.00	0.36	0.70	1.00
Eucalyptus						
Relative tree distance[a]	0.10–0.33	0.33–0.83	0.83–1.25	0.24–0.47	0.47–0.64	0.64–1.15
Relative dry matter	0.29	0.85	1.00	0.26	0.50	1.00

Mean considering trees in mature phase and output simulations from Typic Kandiudult soil.

[a] Distance/tree height.

the tree influence was evident in a distance equal or higher to tree height. For similar relative tree distances, outputs of relative crop growth in simulations presented a lower effect of tree competition. This difference increased further away from trees. Righi (2000) reported similar negative effect of rubber trees over growth and yield of beans in a distance equal to tree height in Brazil. Khan and Ehrenreich (1994) found that wheat yield was reduced in a distance up to 8.5 m from *A. nilotica* trees in Pakistan. The yield was 58% lower at one meter and 22% lower at 8.5 m from trees. Gillespie et al. (2000) found that maize yield was up to 50% lower close to trees in a temperate alley cropping system. Thus, the relative effect of rubber trees over sugarcane next to tree rows in simulations were higher than measured and described in similar trials. Nevertheless, eucalyptus outputs were similar to the measured data.

For the long-term sugarcane performance, outputs of the ratoon crop were assessed because there are more scenarios to analyze than in the crop plant. Results from one soil (TK) were chosen because differences in crop growth between soils are only quantitative, but with similar pattern (as discussed later). As expected, there was a reduction of growth from Zones 4 to 2 (Figs. 5 and 6a). The reduction refers to a combination of competition for radiation and soil water. In order to separate these effects, the same systems were simulated without tree root system in Zones 2–4 (Figs. 5 and 6b). Competition for radiation occurred only in Zone 2, being strong in the rubber system and weak and sporadic in the eucalyptus one. Differences between the species were due to the larger canopy of rubber (with higher width and LAI) and management of the eucalyptus system, where trees were cut and their canopies were removed twice during the simulations.

Competition for soil water was more relevant in Zones 2 and 3, being stronger in the rubber combination, despite its root system being defined as slightly less dense than eucalyptus one. From the total amount of water used, rubber took up 53% from Zone 1, 36% from Zone 2, 10% from Zone 3, and 1% from Zone 4. Eucalyptus presented a similar pattern (51%, 32%, 14% and 3%), but the main reason of higher competition for rubber was the absolute amount of water uptake. Rubber used three times more soil water than eucalyptus as it grew continuously and presented higher biomass and water consumption during most of the simulation. Similar to light competition, management played a major role in defining competition for water as growth rates and water demand for dry matter production presented close values for both species. Fig. 6 indicates that eucalyptus had stronger water competition with sugarcane close to tree harvest, when it had higher biomass and water consumption (S_{13} and S_{31}) and that there was an opposite situation in the beginning of eucalyptus growth (ratoons S_{22} and S_{33}). This scenario is in accordance with the results of Ong et al. (2000) and Lott et al. (2000) in a long-term experiment with Grevilea in Kenya, where the rainfall was around 50% of the region studied in Brazil. Both authors verified that intensity of tree–crop competition for water progressively increased as trees grew and the system became more mature.

A stronger negative effect of light than water in agroforestry systems for C_4 understorey crops like sugarcane is expected as C_4 may capture more of the available water in the system due to its high water use ratio, but shade may significantly damage its growth (Black and Ong, 2000). In contrast to this hypothesis, Gillespie et al. (2000) reported that not light, but water competition seemed to be critical in defining maize productivity in a temperate alley cropping system with *Juglans nigra* L. and *Quercus rubra* L. trees. The tree function in the system is also crucial to define competition and crop yield. Agus et al. (1999) reported that maize and rice yields tended to be lower than monocropping in hedgerow systems with nitrogen fixing trees for the first two years, but exceeded monocropping in the third and fourth years. Suprayogo (2000) used WaNuLCAS to simulate hedgerow systems and reported that simulations suggested that light and water rather than nitrogen competition limited groundnut and that light, water and nitrogen limited maize performance. Cannell

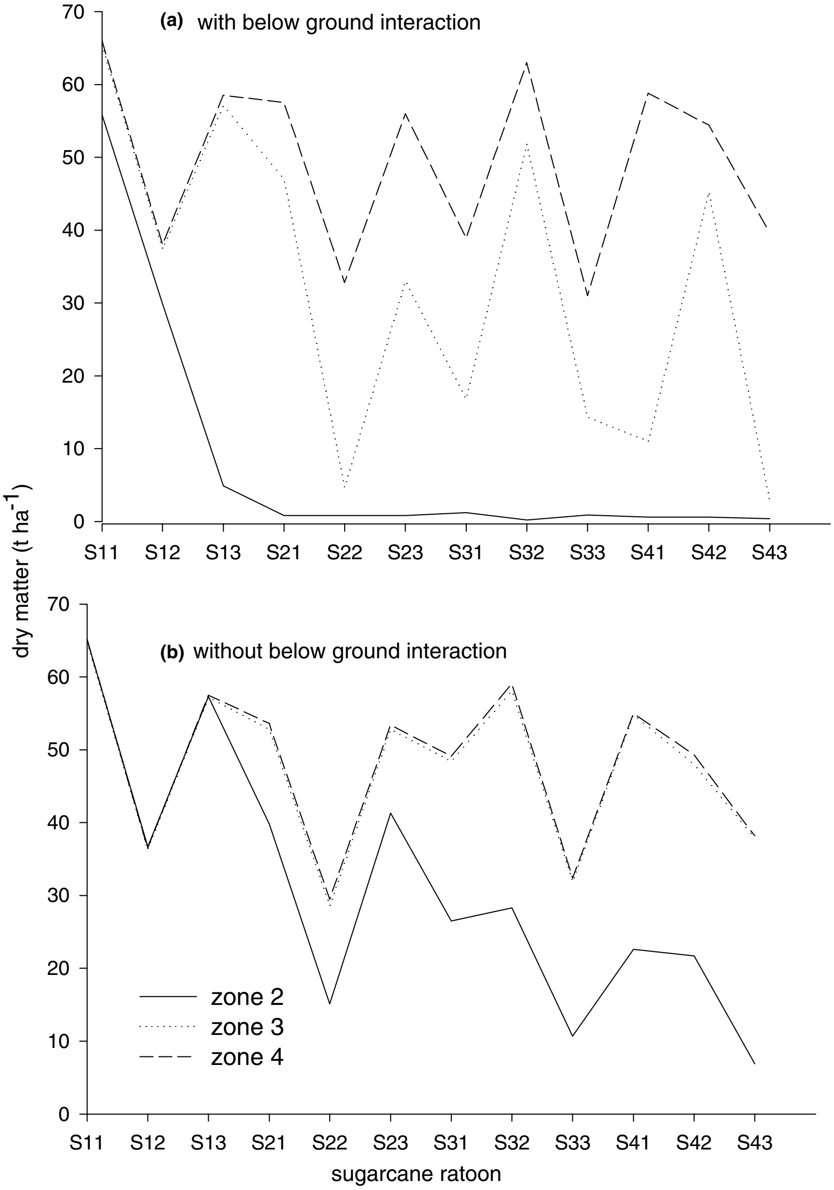

Fig. 5. Final dry matter of ratoons in the rubber system for Typic Kandiudult soil in Piracicaba, Brazil.

et al. (1998) simulated sorghum with a generic tree in a range from arid to humid climates with HyPAR and concluded that low water use efficiency of trees at dry sites and sensitivity of C_4 crops to shading limited possibilities of increasing the site productivity.

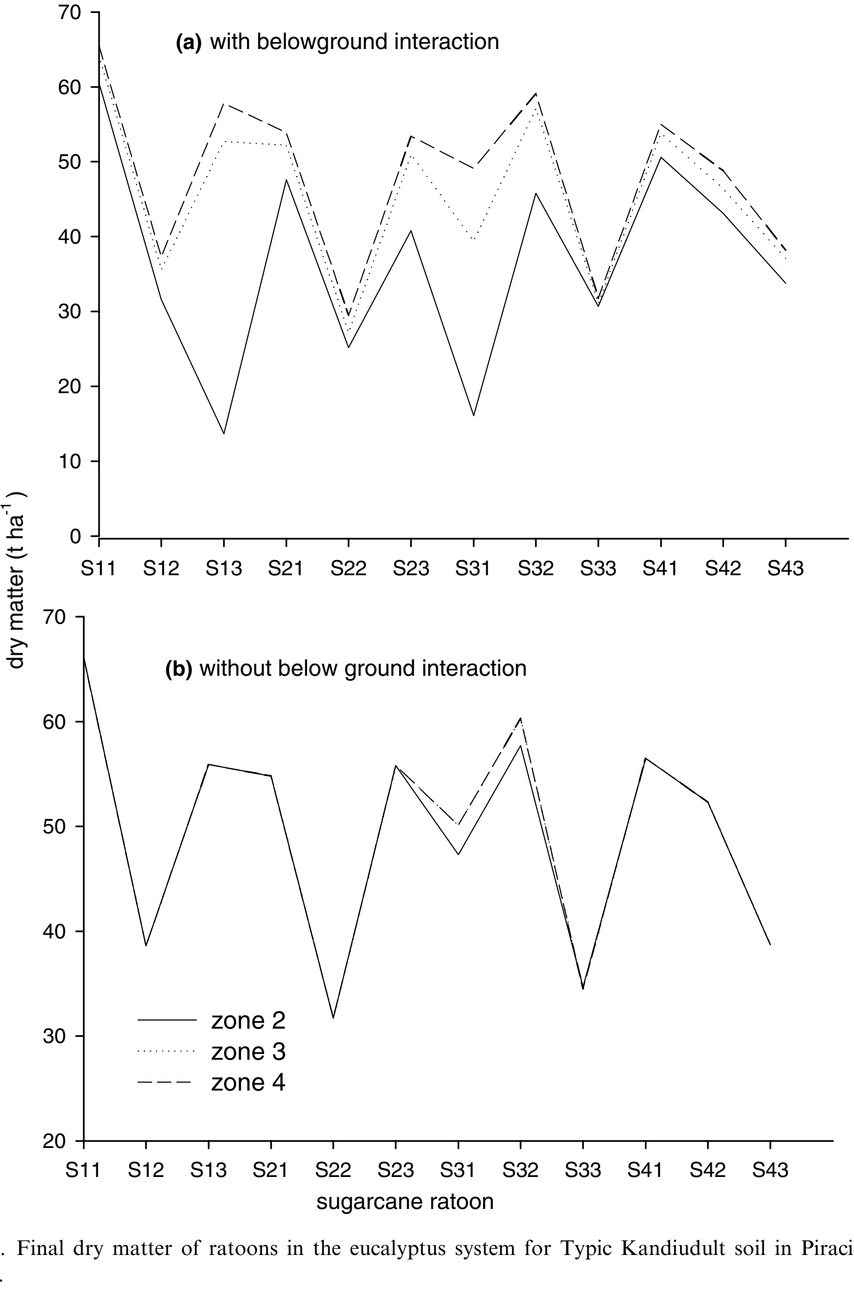

Fig. 6. Final dry matter of ratoons in the eucalyptus system for Typic Kandiudult soil in Piracicaba, Brazil.

The other variations among sugarcane performance were caused by the quantity and distribution of precipitation. To better illustrate competition in simulations, four sugarcane ratoons of the rubber system for the TK soil were sampled (Table 4).

Table 4
Simulated sugarcane dry matter and water use by plants in rubber system for Typic Kandiudult soil Piracicaba, Brazil

Ratoon	Rain (mm)	Sugarcane dry matter (t ha^{-1})	Sugarcane transpiration (l m^{-2})	Water uptake by tree (l m^{-2})
Zone 2				
S11	2176.07	55.8	475.53	257.65
S13	1265.61	4.9	39.31	303.23
S41	1462.10	0.6	2.98	973.70
S42	1617.90	0.6	2.93	914.81
Zone 3				
S11	2176.07	65.4	552.91	9.87
S13	1265.61	57.1	479.85	20.50
S41	1462.10	11.0	91.47	268.42
S42	1617.90	45.2	384.35	267.29
Zone 4				
Sll	2176.07	66.0	558.41	0.00
S13	1265.61	58.5	493.12	0.02
S41	1462.10	58.8	495.74	14.92
S42	1617.90	54.4	455.80	2.90

Trees took up significant amounts of water from Zones 2 and 3 and this uptake increased with their growth. At Zones 2 and 3 of ratoons S_{11} and S_{13} and in Zone 3 of ratoons S_{41} and S_{42}, a decrease in crop transpiration and consequent growth reduction were exclusively due to water competition as there is no shade from trees. In Zone 2 of ratoons S_{41} and S_{42}, the reduction was due to below and aboveground interactions. In Zone 3 of ratoons S_{41} and S_{42}, the trees took up similar amounts of water, but higher precipitation in ratoon S_{42} provided higher water availability for the crop. However, it was not enough to compensate the combination of negative effects of below and above competition of crop growth in Zone 2. In accordance with outputs, Jose et al. (2000) reported that soil moisture, maize water uptake and growth increased directly in function of distance from tree rows of *J. nigra* L. and *Q. rubra* L. and the end of crop season. They also found that variation of soil moisture in the topsoil followed local precipitation pattern, but moisture depletion in deeper soils layers was not correlated with rainfall events. Lefroy et al. (2001) showed that tagaste trees (*Chamaecytisus proliferus* Link.) depleted soil water 2, 4 and 8 m laterally from tree rows in the first, second and third years after coppice regrowth and reduced yield of a cereal legume alley.

Typic Kandiudult was a deeper soil with different physical properties than Lithic Hapludoll, and this is possible to distinguish in WaNuLCAS by Pedotransfer Functions (parameters shown in Table 1). Therefore, the first soil presented a higher water retention capacity which caused higher crop water uptake and growth as previously presented, presenting higher losses by evaporation of water intercepted by the plant canopy. Crop in LH presented a lower water uptake and sugarcane growth and higher losses by drainage, run-off and soil surface evaporation. Thus, sugarcane biomass was around 60% higher at TK. On the other hand, at LH there was a slightly higher water uptake and growth by the trees (Fig. 4) due to the use of water drained from the soil layer of crop roots and taken up in deeper layers by tree roots. For sugarcane, there was a lower relative reduction of growth in Zones 2 and 3 at TK for both tree species (Fig. 7). The differences were stronger in Zone 3 of the rubber system and Zone 2 of eucalyptus, where the isolated effect of water competition is more intense for each tree. The outputs agree with Young (1997), who stated that soil physical properties play an important role to define the intensity of tree–crop interactions and competition in an agroforestry system. Additionally, Rao et al. (1998) stated that crop yield increases are rare in infertile acid soils because fertility improvements do not offset the large competitive effect of hedgerows with crops for water and/or nutrients. Soil comparisons indicated higher complementarity of water use for TK as reduction in tree growth (2–3% lower) would be compensated by a significantly higher sugarcane yield, when water competition is more severe. It indicated that LER (land equivalent ratio, Ong, 1996) would be higher in TK than in LH.

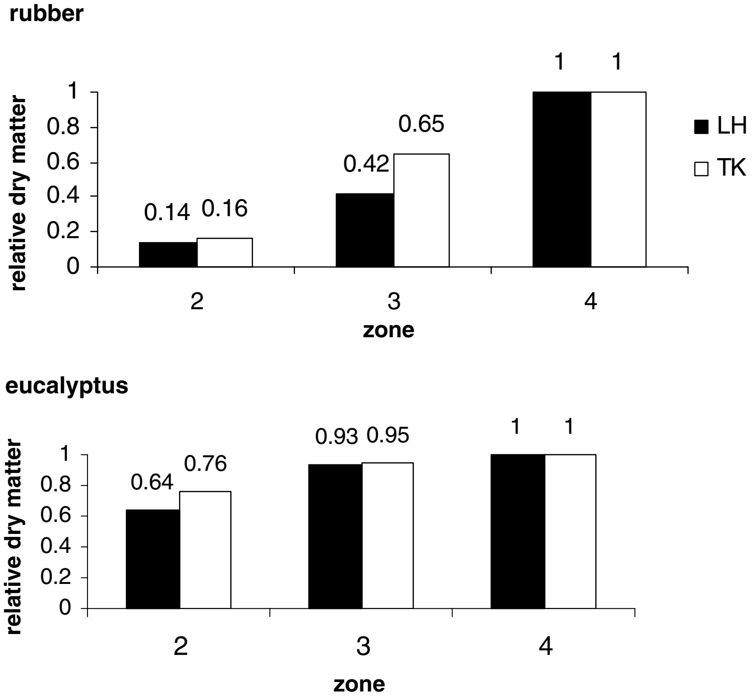

Fig. 7. Relative sugarcane dry matter in each system simulated as a function of values obtained in Zone 4. Values are an average of the 20 years simulated in Piracicaba, Brazil.

4. Evaluation of the model performance

The overestimation of crop growth in monocropping was attributed to the combination of the following assumptions about the model crop module. It does not consider air temperature as a plant growth factor, and this is relevant for sugarcane (Mongelard and Mimura, 1971). The inconsideration of air temperature seemed to be a major limitation of the model for application in sub-tropical and temperate conditions, where this factor influences growth more severely during a cropping season. Dry matter accumulation started immediately after planting in the simulation, but the emergence of sugarcane may take up to 30 days in the field (Casagrande, 1991), as crop emergence depends on soil temperature and moisture (Loomis and Connor, 1992). Therefore, crop emergence in the field may be delayed compared to simulations. Pedotransfer functions are based on temperate soils and have a moderate performance to predict water retention in Brazilian tropical soils (Tomasella et al., 2003). This performance may cause higher or lower water availability to crops and the consequent under or overestimation of their growth. Mobbs et al. (1998) also identified limitations predicting sorghum yield in agroforestry systems in simulations with HyPAr and stated that outputs should be regarded as potential values. Simulations of Suprayogo (2000) with WaNuLCAS showed a close fit between groundnut and maize biomass simulated and measured in monocropping. However, in agroforestry systems, crop growth was underestimated and grain yield was overestimated compared to field measurements.

The main reasons for tree overgrowth were low sensitivity to water stress and consequently to reproduce annual leaf senescence, besides not taking into account air temperature as a growth factor. Additionally, the model did not include maintenance respiration, causing overestimation of growth. It limited the use of the model for continuous long periods of tree growth because the error caused by this assumption accumulated in time and resulted in a much higher tree growth. Eucalyptus had lower overestimation as it was cut every 7 years, interrupting growth and accumulation of this error. It is also possible to speculate that the initial parameters used for potential daily growth of trees were not appropriate for Piracicaba, as the rubber value was determined in Malaysia (Templeton, 1968), and the eucalyptus value was measured in Australia by Cromer et al. (1993). Vermeulen et al. (1993) also found problems in long-term simulations of agroforestry systems with the Soil Changes Under Agroforestry (SCUAF) model and reported that the model was unable to accurately simulate miombo woodland productivity because it was unable to attenuate biomass increase as the woodland approached steady-state maturity.

Regarding tree–crop interactions, the main problem of simulations was inconsideration of lateral shading by the model. It overestimated shading in Zone 2 and underestimated it in Zones 3 and 4, specially for such systems with tall trees. Weak response to leaf senescence also had impacts on defining the intensity of tree-crop competition for light. Rubber presents leaf senescence in the relatively dry winter of Piracicaba and makes more light available for understorey crops during this period. This was not possible to reproduce in the model and it contributed to lower growth of sugarcane below rubber canopy. Besides, overgrowth of rubber overestimated the effect of light and water competition over sugarcane. These limitations reduced the quality of quantitative outputs and the application of simulations to orientate potential productivity of the systems tested.

On the other hand, WaNuLCAS presented flexibility enough to simulate the system to be tested by this research. Despite being a generic agroforestry model, it was possible to adapt the crop module to simulate the behavior of sugarcane, which has complex specific models (O'Leary, 2000). Adaptations made possible to harvest stalks instead of grains and new plantings with lower light use efficiency reasonably reproduced ratoon behavior. Root system of ratoon was not possible to be simulated, but the simplification of a new planting had a minor role in determining interactions to the purpose of simulations. Tree module also allowed imposing different management strategies to the trees, including tapping and rubber production and harvesting of eucalyptus wood. Changing initial conditions of new eucalyptus seedlings (planting density, biomass and seedling eight) also reproduced satisfactorily the system to the aim of the simulation. The majority of the key parameters required for the model were available in the literature and others were calibrated from generic tree and crop literature. Stella modeling environment also allowed to easily changing routines of the model, including simulating the system with and without belowground interactions and systems without nutrient competition. Calibration was also facilitated by the option of simulating the system without water competition. However, quantitative results of simulations needed to be interpreted with caution due to the cited model limitations regarding the type of simulation done (in sub-tropical climate, with tall trees growing in the long term). The model also did not incorporate microclimatic modifications resulting from association of trees and crops. These modifications are frequently responsible for complementarity of aboveground resource use and relative advantages of AFS compared to monocropping (Wallace, 1996). For instance, Jonsson et al. (1999) found that positive changes in air temperature exceeded negative shade effects of scattered trees over millet yield in Burkina Faso. Therefore, simulations tended towards emphasizing competitive aboveground interactions and the results produced were probably conservative and represented the worse crop performance that would happen in the field. Mobbs et al. (1998) had similar conclusions with HyPAR, because it assumes the same temperatures for understorey crops and overstorey trees and it lead to an underestimation of crop yield to less than 20% and overestimation could occur in hot, dry climates. Thus, these considerations should be understood as a challenge for future development of agroforestry models.

For the indication of AFS as a land use alternative, compared to monocropping, the model was important to indicate qualitative aspects of the system and to indicate that agroforestry systems should remain as an option to sugarcane production, but it requires field studies, combined with economic evaluation prior to its recommendation. Future studies should test if the economic value of tree products would compensate the decrease of sugarcane due to tree competition, besides accounting environmental benefits of adopting AFS to replace sugarcane monocropping systems. However, this study provided subsidies to orientate hypothesis for field trials as well as the design and selection of variables for field experiments.

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