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Original article

Adaptation of the crop model STICS to intercropping. Theoretical basis and parameterisation

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Abstract – Given the complexity of intercropping systems, models can be especially helpful to analyse them comprehensively. The present work puts forward a modelling approach based on an extension of sole crop models, considering the system to be composed of two species instead of one. The chosen sole crop model is STICS and its adaptation to intercropping relies first on a simplified definition of the complex agronomic system, which is subdivided into three sub-systems: the dominant canopy, and the shaded and sunlit parts of the understorey canopy. It is assumed that no inversion of dominancy occurs during the cycle of the shorter duration crop. Each of the sub-systems is embedded in a different light microclimate, estimated from a radiative balance module, assuming that a simple geometric shape can represent the dominant canopy. This radiative balance pilots the differential behaviours of the sub-systems in terms of growth, LAI dynamics, water and nitrogen uptakes and stress indices. The estimation of the water requirements for both crops relies on light partitioning coupled to a resistive scheme and applied at a daily time-step. In the soil, the horizontal differentiation is neglected in favour of the vertical one. As far as below-ground competition for water and nitrogen is concerned, it is assumed that the interactions between the two root systems result from the influence of the soil on each crop root profile through its water content dynamics. Data sets from three different intercrops, two annual and one perennial systems grown in French Antilles, were used for parameterisation of the model and verification of its consistency. The intercrop-specific modules of the model are described and discussed in comparison with the other existing models.

crop model / intercropping / radiative transfer / water requirement / rain interception / root competition

1. INTRODUCTION

Intercropping and agroforestry consists of growing several crops (annual or perennial) simultaneously, each crop developing and growing with its own rhythm resulting from the resource partitioning. This practice is traditional in the tropics and is starting to be used under temperate climates for environmental purposes. Intercropping can aim to take advantage of the association between leguminous and non-leguminous to optimise the available resources, covering the bare-soil spaces in-between trees to limit erosion, modifying the main crop microclimate or extending the period of soil cover to limit nitrate lixiviation. Various arrangements of intercrops exist: strip intercrops, alley crops, mixed intercrops or even windbreaks, which exhibit more or less spatial heterogeneity.

Given the complexity of the system, models can be especially helpful to analyse comprehensively intercropping [17]. The intercrop modelling framework can be summarised in three approaches. The first approach, consistent with de Wit's initial principles [19, 20] is an extension of sole *crop modelling*, considering the system to be composed of two species instead of one, simply organised within a kind of elementary pixel supposed to represent the whole field. Actually this is the oldest and more operational approach [16, 23], concentrating more on the dynamics of the system than on its spatial heterogeneity. The second approach relies on a description of the intercrop or agroforestry system as a series of discrete crop-based or tree-based points with flow of mass or energy between each. This *spatial discretised* approach allows one to account for large space variations, each point being generally simulated under the above-mentioned crop modelling principle and the field response results from a spatially integrated calculation [21]. The last possible approach derives from *architecture modelling*, putting emphasis on a realistic description of the 3D structure of the complex bi-species canopy, which leads to fine-scaled descriptions of processes [39] at the organ level. In that approach it is more difficult to account for the system dynamics because of the complexity of organ dynamics in interaction with the whole plant behaviour. The present work corresponds to the first approach, based on the STICS crop model [9], aiming to produce an operational tool to help with management of intercrops, while trying to overcome the problems of oversimplification of the approach in order to be truthful.

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Basically STICS (Simulateur mulTIdisciplinaire pour les Cultures Standard) is a monocrop model which has been developed at INRA (France) since 1996, the features of which correspond to those of a large number of existing models [49]. It is a daily time-step crop model with input variables relating to climate, soil and the crop system. Its output variables relate to yield (quantity and quality), the environment and the evolution of soil characteristics affected by the crop. The simulated object is the crop situation for which a physical medium and a crop management schedule can be determined. The main simulated processes are crop growth and development as well as the water and nitrogen balances. From a conceptual point of view, STICS is made up of a number of original parts but most of the remaining parts are based on conventional formalisms or have been taken from existing models [9]. Its novelty is its capability to adapt to various crops [14] (wheat, maize, soybean, sorghum, flax, grassland, tomato, sugar beet, sunflower, pea, rapeseed, banana, sugarcane, carrot, lettuce, etc.).

This work describes the adaptation of the model STICS to intercropping, making the model simulate two interacting crops simultaneously. This adaptation relies first on a simplified definition of the complex agronomic system of intercropping, second on the adaptation of the modules calculating the capture of the resources (light, water and nitrogen) and third on data sets from three different intercrops for parameterisation and testing of the model. One by one, those adapted modules are described and discussed in comparison with the other existing models.

2. MATERIALS AND METHODS

2.1. The monocrop STICS model

STICS simulates the behaviour of the soil-crop system over one or several crop cycles. The upper threshold of the system is the atmosphere characterised by standard climatic variables (radiation, minimum and maximum temperatures, rainfall, reference evapotranspiration and possibly wind and humidity) and the lower threshold corresponds to the soil/sub-soil interface.

Crops are perceived in terms of their above-ground biomass and nitrogen content, their leaf area index and also the number and biomass (and nitrogen content) of harvested organs. Vegetative organs (leaves, branches or tillers) are thereby not individualised. Soil is likened to a succession of horizontal layers, each of which is characterised in terms of its water content, mineral nitrogen content and organic nitrogen content. Interactions between the soil and the crop are undertaken by the roots, and these roots are defined with respect to root density distribution in the soil profile.

STICS simulates the biomass accumulation in the canopy, as well as the water and nitrogen balances in the system and makes it possible to calculate both agricultural variables (yield, fertilisation and irrigation requirements) and environmental variables (water and nitrate losses) in various agricultural situations.

Crop growth is led by the plants' carbon functioning [19]: solar radiation interception by the foliage and then transformation into above-ground biomass that is directed to the harvested organs during the final phase of the cycle. The crop's nitrogen balance is simulated together with the carbon balance on which it partly depends. According to the plant type, crop development is driven either by a thermal index (degree-days), a photothermal index or a photothermal index taking vernalisation phenomena into account. The development model is used to (i) make the leaf area index evolve, and (ii) define the harvested organ-filling phase. The possible existence of water stress and nitrogen stress is taken into account with indices that can reduce leaf growth and biomass accumulation under water- and nutrient-limiting conditions. These indices are calculated in the water and nitrogen balance modules.

Particular emphasis is placed on the effect of cropping techniques on how the soil-crop-climate system functions, in the knowledge that crop specificity is based both on how crops function physiologically and also on the crop management sequences applied to them.

The STICS model is organised into modules, each module dealing with specific mechanisms. In Figure 1 modules which required a specific adaptation for intercropping have been individualised.

2.2. Representation of the intercropping system

The soil-plant-atmosphere system is divided into three subsystems at the canopy level (Fig. 1). There is the dominant canopy (D) and the understorey canopy (U) divided into two parts: its shaded part (SU) and its sunlit part (LU), each of them being defined by a light microclimate. Those light microclimates, estimated from a radiative balance, drive the differential behaviours of the sub-systems in terms of growth (dry matter accumulation and LAI) and water and nitrogen budgets (transpiration, nitrogen uptake and stress index). The estimation of the water requirements for both crops relies on light partitioning coupled to a resistive scheme and applied at a daily time-step. The phasic development is considered to be the same for both parts of the understorey crop. Also, the soil environment is assumed to be the same for both crops, that is to say, that the horizontal differentiation within the soil profile is neglected in favour of the vertical one. It is assumed that the interactions between the two root systems result from the influence of the soil on each crop root profile through its penetrability and water content dynamics (mineral nitrogen dynamics is supposed not to influence root profile).

The application of this theory within the code of the model STICS is done by multiple calls to the elementary sub-routines and re-affectation of the state variables as a function of the considered sub-system. The specific modules which were added to the version documented in Brisson et al. [9] concern radiation interception, energy budget driving water requirements and microclimate and dynamics of the root system as influenced by soil status. The shoot growth was slightly modified to account for the understorey shaded crop growing under limiting radiation.

2.3. The experiments

Three experiments, representing a range of additive intercropping systems, were used in the study for parameterisation

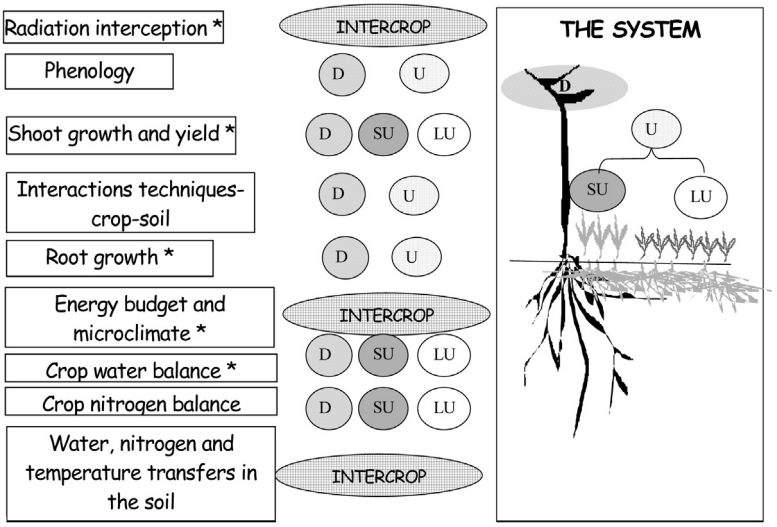

Figure 1. Simplified representation of the model with at the left side the modules (gathered as a function of their modality of call within the code), and at the rightside the system with its three sub-systems (D: dominant crop; U: understorey crop divided into a shaded part: SU and a sunlit part: LU) and in the centre the number of calls of each module devoted to a particular part of the system. * corresponds to the modules modified for the adaptation to intercropping.

and testing of concepts. They were all conducted in Guadeloupe (French Antilles 16° N, 61° W).

The Gliricidia/Dichanthium experiment (GD) was located on a chromic vertisol, in the eastern part of the island under a dry tropical climate. The canopy was made of rows of *Gliricidia sepium*, a perennial C3 legume shrub, on a natural pasture of C4 grass, *Dichanthium aristatum*. They were set in a North-South row direction every 0.3 m along the row, with a 2 m row spacing (a density of 16 600 plants ha^{-1}). The grass was mowed about once a month and the shrubs clipped every 2 months. The Maize-Canavalia (MC) and Maize-Sorghum (MS) experiments were located on a ferralitic soil in the western part of the island under a humid tropical climate.

In addition to standard meteorological (temperature, global radiation, air humidity, wind speed and rainfall) and crop measurements (Leaf Area Index), specific measurements were completed: canopy radiative budget in the PAR domain (GD), plant transpiration by the sap flow method (on G, M and S plants in the GD and MS experiments), total evapotranspiration (GD) or soil evaporation (MS), stemflow and wettability (MC and GD).

Plant samples of 0.15 m^2 were collected to measure leaf area index with a Li-Cor 3100 LAI meter (Li-Cor, Lincoln, USA). Incident radiation in the PAR waveband was measured with a quantum sensor (Delta-T, Cambridge, UK) serving as a reference, and amorphous silicon cells (ASC) (SOLEMS, Palaiseau, F). Reflected PAR was registered above the whole mixture and above the grass by a set of six ASC connected in series and evenly located in-between the rows, while transmitted PAR was measured below the shrubs by a set of six ASC connected individually and placed perpendicularly to the row. The evapotranspiration rate of the (soil+D) component of the GD canopy was estimated from the increase in air humidity in a closed chamber [34], measured 10 times a day on areas evenly spaced in the interrow and integrated over the day by assuming a linear evolution between two measurements. Sap flow measurements were based on the heating method [35], which has proved to be relevant for intercrop studies [31]; it consists of heating a part of the stem and measuring the different ways in which this energy is disseminated or stored. In the MS experiment, soil evaporation was measured by micro-lysimeters [7] consisting of open PVC cylinders located in the soil and excavated and weighed daily.

3. THE RADIATION INTERCEPTED BY THE DOMINANT CROP

3.1. Theory

The objective is to estimate, at a daily time-step, the proportion of the radiation intercepted by the dominant crop (or RD) and the part transmitted to both components of the understorey crop: the shaded (ROMBRE) and the sunlit (RSOLEIL). At a daily time-step, the shaded part corresponds to the vertical projection of the dominant foliage at the soil surface. The available daily variables are the Leaf Area Index of the dominant crop (LAI), calculated by the growth module and the global daily radiation (RG).

Then the radiation intercepted by both components of the understorey crop is derived from the use of the simpler global Beer's law analogy [9] applied to ROMBRE and RSOLEIL as incident radiations.

3.1.1. The radiative transfers

The simplest method of calculating the radiation received by a given point X (in order to simplify the explanation, X is located on the soil in the interrow: Figure 2, but in the case of intercropping the basic level of calculation is not the soil but the top of the understorey canopy) is to calculate angles h1 and h2 corresponding to the critical angles above and below which, respectively, point X receives the total radiation directly. At angles below h1 and above h2, point X receives an amount of radiation below the total radiation value, due to interception by the dominant crop. Within those angle windows, a Beer law is used to estimate the ratio of transmitted radiation.

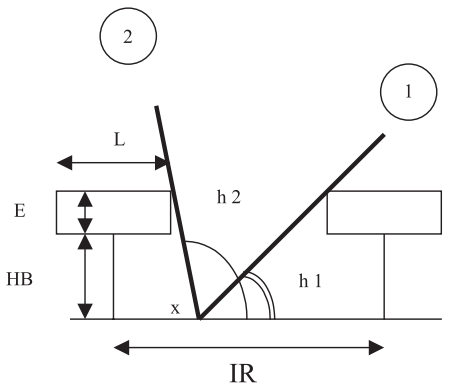

Figure 2. Simplified representation of the plant canopy and the principles used for calculating daily radiation received by the interrow (IR): HB is the base height of the canopy, E its thickness, L its width, X is any point located in the interrow and h1 and h2 are the two sun height angles corresponding to the daily positions 1 and 2 of the sun in-between which X is lighted directly.

It is assumed that a canopy can be represented by a simple geometric shape (rectangle or triangle) and that it is isotropically infinite. We can therefore partition the daily radiation received at point X in a proportion of the radiation not intercepted (*RDROIT*) by the dominant crop (sun at a height of between h1 and h2) and its complementary proportion corresponding to the radiation transmitted (*RTRANSMIS*). The "infinite canopy" hypothesis allows us to assume that when the sun is at a height of below h1 and above h2, all the radiation passes through the dominant crop.

Each part of the received radiation in X includes a direct component and a diffuse component. Let us hypothesise that, for the transmitted part, the same extinction coefficient (*KTROU*) applies to both components (which is generally accepted to be the case when the general Beer law is used with a daily timescale):

$$RTRANSMIS = (1 - RDROIT) \times \exp(-KTROU \times LAI). \quad (1)$$

In contrast, for *RDROIT*, direct and diffuse components should be separated because of the directional character of the direct component, which requires the calculation of the separated proportion of radiation reaching the soil. If *RDIFFUS* is the proportion of diffuse radiation in RG, *RDIRECT* the proportion of direct radiation in RG, and *KGDIFFUS* and *KGDIRECT* are, respectively, the proportion of *RDIFFUS* and *RDIRECT* reaching the soil, then *RDROIT* can be written as follows:

$$RDROIT = KGDIFFUS \times RDIFFUS + KGDIRECT \times RDIRECT. \quad (2)$$

All global radiation partitionings are expressed in proportions, so that:

$$RD + ROMBRE + RSOLEIL = 1.0 \quad (3)$$

$$RDIFFUS + RDIRECT = 1.0. \quad (4)$$

- The case of direct components.

If θ1 and θ2 are the hourly angles (the actual angles that are zero at 12 h TSV) corresponding to h1 and h2, and assuming sinusoidal variation in the direct radiation during the day, we can write that:

$$KGDIRECT = 0.5(\cos(\pi/2 + \theta 1) + \cos(\pi/2 + \theta 2)). \quad (5)$$

In order to calculate the θ angles, it is necessary to solve the following set of equations:

$$\sin(h) = \sin(lat)\sin(dec) + \cos(lat)\cos(dec)\cos(\theta) \quad (6)$$

$$\cos(A) = \left[-\cos(lat)\sin(dec) + \sin(lat)\cos(dec)\cos(\theta)\right]/\cos(h) \quad (7)$$

$$\tan(h) = G\sin(A + \alpha) \quad (8)$$

where h is the height of the sun (h1 or h2), A its azimuth, *lat* is the latitude of the location and *dec* the declination angle which depends on the day, and α is the azimuth angle of the rows (relative to the north). G depends on canopy geometry (L, E and HB defined in Fig. 2), the considered sun height (h1 or h2) and the position of the given point within the interrow (X), for example:

assuming X>L/2 and for the angle h2, G = (HB + E)/(X-L/2). (9)

The borderline between sun and shade is arbitrarily taken to be L/2.

The above set of equations cannot be solved by analytical methods. It therefore has to be solved by simple numerics (loop over θ with a basic variation of 3 degrees followed by linear interpolation).

- The case of diffuse components.

We take 46 directions (azimuth and height) and the corresponding percentage of diffuse radiation (SOC standard). For each direction, the point X is checked to see if it is under light, depending on the canopy geometry. The variable *KGDIFFUS* corresponds to the cumulative proportion of radiation received by point X for the 46 directions.

The diffuse to total radiation ratio (*RDIF*) is calculated according to Spitters et al. [40] on the basis of the total to extraterrestrial radiation ratio (*RSRSO*).

$$\left.\begin{array}{ll} if & RSRSO < 0.07 \quad RDIF = 1 \\ if & RSRSO \geq 0.07 \quad RDIF = 1 - 2.3 \times (RSRSO - 0.7)^2 \\ if & RSRSO > 0.35 \quad RDIF = 1.33 - 1.46\ RSRSO \end{array}\right\} \quad (10)$$

$$if \quad RSRSO > 0.75 \quad RDIF = 0.23.$$

The above equations are applied to 20 points spread equally along the inter-interrow, and the transmitted radiation values are then averaged for the shaded part (*ROMBRE*) and the sunlit part (*RSOLEIL*) and represent the RG proportion applied to the LU and SU sub-systems, respectively. The complementary part

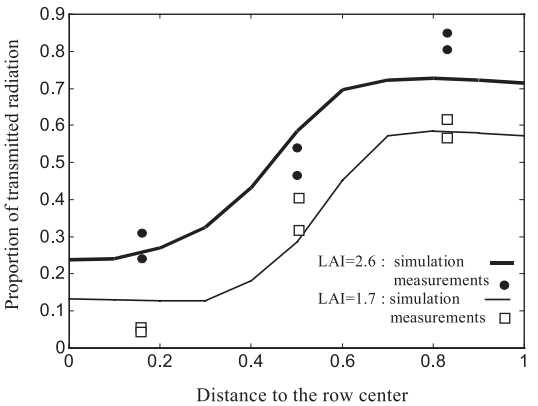

Figure 3. Comparison between calculations and measurements of transmitted radiation.

relative to the global radiation corresponds to the radiation intercepted by the dominant crop (RD, Eq. (3)).

3.1.2. Crop geometry

L and E are calculated assuming the following hypotheses:

- The volume of the crown (or the group of crop leaves) has a simple shape. We assume that its cross-section is rectangular or triangular.
- This volume can be evaluated on the basis of *LAI*, the inter-row value *IR*, the leaf density within the volume which is assumed to be constant (*DFOL*), and the *RAP* = *E/L* ratio (thickness/width) of the shape.

$$L = \sqrt{\frac{LAI \times IR}{DFOL \times RAP}} \text{ for the rectangle and } L = \sqrt{\frac{2 \times LAI \times IR}{DFOL \times RAP}}$$

for the triangle. (11)

- There is a choice of two triangle shapes: "right way up" or "upside-down".
- A maximal limit is imposed on the plant height value. Thereby, in the first stage, the shape of the plant evolves isotropically. Once the maximal limit is reached, the only way in which the shape can evolve is in terms of width.
- When both canopies (dominant and understorey) are vertically mixed, the sole superior part of the dominant crop, located above the understorey crop, is accounted for in the radiative transfer calculations. Thereby, an efficient shape is defined for the dominant crop; in the case of the "upside-down" triangle, the efficient shape is trapezoidal but it is assumed to be rectangular to simplify the geometrical calculations.

3.2. Parameterisation

The data set of radiation measurements collected in the GD experiment was used; two days' measurements were selected in order to have different levels of Gliricidia *LAI* (day 143, *LAI* = 1.7 and day 177, *LAI* = 2.6). Average geometrical values were: *HB* = 0.24, *E/L* = 0.75. We tested two hypotheses of efficient shape: rectangular and triangular, and for both, we fitted the parameter *KTROU* on a mean square error basis. Although externally the trees appear as rectangular or even as "upside-down" triangles, the "right way up" triangles appear more satisfactory (Tab. I) to simulate the radiative transfers graphed in Figure 3.

Table I. Test of the radiative optimal shape for the Gliricidia canopy.

Shape	rectangular	triangular
Calculated DFOL	5.4	10.9
Fitted KTROU	0.77	1.00
RMSE	0.0372	0.0216

3.3. Discussion

As in most "crop modelling" approaches [17], competition for light is simulated by a hedgerow model suitable for strip and row intercrops. It is based on the turbid medium principles and uses the Beer-Lambert analogy within each canopy. To avoid the hourly time-step, the model calculates shadow boundaries and related solar positions in order to partition daytime radiation in-between the two canopies. This method has been previously used by Caldwell and Hansen [16] but in our case the splitting between direct and diffuse radiations allows a better representation of the effect of row orientation, as in more mechanistic models [38]. Contrarily to "layered" models [26], the volume occupied by each canopy is globally accounted for. Though mixture between the two canopies is possible, thanks to the plant height and associated geometrical dynamics, relying on the *LAI* course, an inversion of dominance during the crop cycle cannot be simulated by STICS.

The fact that the appropriate shape for radiative transfer is "right way up" triangles suggests that the low leaf density (in the classical sense: leaf area per m^3) measured in the upper parts [45] allows more radiation to be transmitted than in the lower parts where the leaf density is higher. With our simple model based on a constant leaf density within the shape, this can be accounted for only by a triangle. Thus the shape required as a parameter in the model is far more linked to the leaf density profile than to the external shape of the plant foliage. There is also a strong correlation between the chosen shape and the fitted extinction coefficient, both of them translating the foliage gap fractions. The resulting values of *KTROU* are consistent with measurements reported in the literature for full covered canopies [6].

4. ENERGY BUDGET AND MICROCLIMATE

In the model STICS, the energy budget is used to estimate the crop water requirement [12]. Then actual soil evaporation and plant transpiration are calculated independently by the means of a soil water balance [8, 11]. These fluxes are then reintroduced into the energy budget to calculate crop temperature, which is a driving variable for growth and development

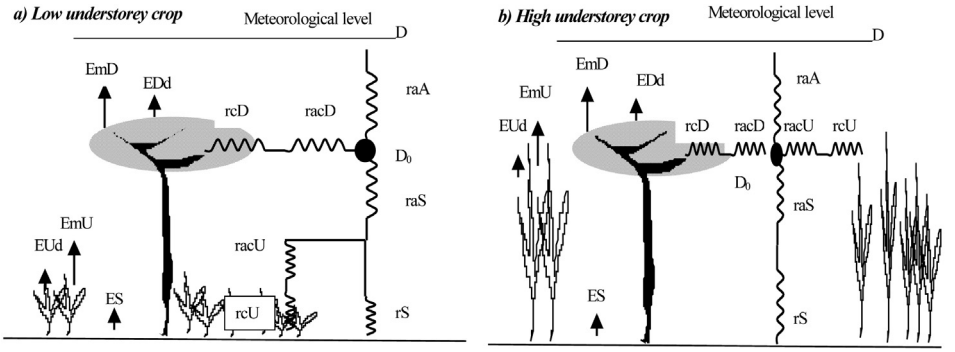

Figure 4. The two possible schemes of resistance networks used to estimate water requirement for intercrops (right side of the schemes) and the fluxes (left side of the schemes). (a) the understorey crop is near to the ground, (b) the understorey crop is nearly as high as the dominant crop.

of the plant (see [9], Sect. 3). The required adaptations for intercrops concern the first stage.

4.1. Theoretical basis

Following the relative position of the dominant and the understorey crops, the energy budget calculations rely on slightly different resistance networks (Fig. 4). This simplification aims at limiting to 2 the number of sites playing the role of water vapour sources. The resistance scheme for a low understorey crop is an extrapolation of the original model by Shuttleworth and Wallace [36] and the resistance scheme for a high understorey crop is an extrapolation of the model proposed by Wallace [48] for intercrops. Those two schemes are applied at a daily time-step relying on Monteith's [30] theory and its consequences [5] and on a previous study [12], in which full details in definitions and formulations are given.

The calculations involve five evaporative fluxes: soil evaporation (*ES*), maximal plant transpiration for the dominant crop (*EmD*), maximal plant transpiration for the understorey crop (*EmU*), direct evaporation of the water intercepted by the "dominant" leaves (*EDd*) or by the "understorey" leaves (*EUd*), three net radiation budgets: *RnetS, RnetD* and *RnetU* for, respectively, the soil, the dominant crop and the understorey crop and three types of resistance (eddy diffusion resistances: *raS* and *raA*, bulk boundary layer resistances of both crops: *racD* and *racU* and surface resistances: *rS, rcD,* and *rcU*). Each flux is calculated using a formula such as:

$$\lambda E_i = \frac{\Delta Rnet_j + \rho C_p D_0 / ra_j}{\Delta + \gamma(1 + r_j / ra_j)} \qquad (12)$$

where

E_i (mm d^{-1}) is one of the five evaporating fluxes (i = *S, mD, mU, Dd* or *Ud*),

λ (2.5 MJ kg^{-1}) the latent heat of vaporisation,

Δ (mb $°C^{-1}$) the gradient of the relationship between temperature and saturation vapour pressure,

$Rnet_j$ ($MJm^{-2}d^{-1}$) is one of the three net radiation budgets (j = S, D or U)

γ (0.65 mb $°C^{-1}$) the psychometric constant,

ρ (1.2 kg m^{-3}) air density,

Cp (1.013 10^{-3} MJ kg^{-1} $°C^{-1}$) its calorific capacity,

D_0 (mb) the saturation deficit within the vegetation,

rj (sm^{-1}) is a surface resistance for soil evaporation and plant transpiration fluxes (j = *S, cD or cU*) and 0 for direct evaporation fluxes of the water intercepted by leaves.

raj (sm^{-1}) is an aerodynamic resistance where j = *S, cD* for the soil and dominant crop, respectively, and is specific for the configuration (Fig. 4a or b) for the understorey crop (*racU* for the high understorey crop and *racU* + *raS* for the low understorey crop in order to account for convective phenomena in-between the two crops).

These flows are linked together by the relationship of Shuttleworth and Wallace:

$$D_0 = D + [\Delta Rnet - (\Delta + \gamma)\lambda E]\frac{raA}{\rho C_p} \qquad (13)$$

where D (mb) is the vapour pressure deficit at the meteorological level and E and $Rnet$ refer to the sum of E_i and $Rnet_j$, respectively.

In our case, the *EmD* and *EmU* fluxes are maximal fluxes which represent the climatic requirements of both crops. The accumulation of *ES, EDd* and *EUd* is referred to as direct evaporation (*Ed*). It is the Ed value which affects D_0 and can cause the climatic requirements of the crops to fluctuate. The three components of *Ed* are calculated from an intermediate value of the saturation deficit D_{0s} based on the hypothesis that, at complete saturation of the surfaces, E can be approached using a formalism of the Priestley-Taylor type [12].

Several points have to be dealt with in such a context: the distribution of the energy sources between the soil and both crops, water retention on the foliage, calculating the eddy diffusion resistances: *raA* and *raS*, calculating the surface resistance values: *rcD, rcU* and *racD, racU*, and calculating soil evaporation or *rS*.

4.2. Available energy and its distribution

The estimation of net radiation is described in Brisson et al. [12]. In order to evaluate the distribution of available energy between the soil and both crops, we base our method on the hypothesis that we know the proportion of global radiation intercepted by the crops (see Sect. 3). These values are calculated in the radiative transfers module. Thornley [44] inferred

the net radiation extinction coefficient from the extinction coefficient of the total radiation by applying a coefficient of 0.83 (which corresponds to the range of measurements taken under a soybean canopy: [12]).

$$\left.\begin{array}{l} RnetD = 083 fD\ Rnet \\ RnetU = 083 fU\ Rnet \end{array}\right\} RnetS = Rnet - RnetD - RnetU. \quad (14)$$

The amount of energy required for the direct evaporation of water on leaves, *EmDd* and *EmUd*, will be inferred from *RnetD* and *RnetU* before the *EmD* and *EmU* fluxes are calculated. Climatic demand distribution between the shaded part and the sunlight part is the same as the radiation interception.

4.3. Water persistence on foliage

Water persistence on foliage, which is directly subjected to the evaporative demand of the surrounding atmosphere, can evaporate, thereby significantly reducing the saturation deficit within the canopy and modifying the crop water requirements. In humid tropical environments, rainfall frequency combined with high evaporative demand (mainly radiation), means that this phenomenon can have a considerable effect on water balance, decreasing rainfall efficiency. The extent of the stemflow phenomenon (water flow along the stems) should be assessed so as to avoid overestimating water retention in the leaves [15]. In the model, the stemflow (*stemflow* variable in mm) is considered to have priority and is estimated in proportion to incident rainfall (*precip*), as an increasing function of leaf area index (*LAI*), with a maximum proportion allowed corresponding to the *stemflowmax* parameter.

$$stemflow = precip \times stemflow\max (1 - \exp(-kstemflow \times LAI)). \quad (15)$$

The *stemflowmax* parameter can vary between 0.2 and 0.5 [15]; the *kstemflow* parameter is less well known: it can initially be taken to be equal to the solar radiation extinction coefficient. The water which does not flow away via stemflow is partly retained on the foliage, up to a maximum value which is proportional to the *LAI* (*wettability* in mm LAI^{-1}). The wettability of leaves depends on leaf surface properties: shape, texture and pilosity. The water retained on leaves is then evaporated like free water.

4.4. Specificity in the calculation of the eddy diffusion resistance (raA and raS)

We adopted the formalisms suggested by Shuttleworth and Wallace [36], fully described in [12]. The particularity of their application in this study concerns the roughness for crop and soil (z0 and z0s) and displacement height (d), which are evaluated as follows:

For the high understorey crop

$$d = 0.66\ [hautU + (hautD - hautU)/2]$$
$$z0 = 0.10\ [hautU + (hautD - hautU)/2]$$
$$z0s = 0.10. \quad (16)$$

For the low understorey crop

$$d = 0.66\ hautD$$
$$z0 = 0.10\ hautD$$
$$z0s = 0.10\ hautU \quad (17)$$

where *hautD* and *hautU* are the heights (in m) of, respectively, the dominant and the understorey crops. The threshold height for the "low" understorey crop is arbitrary fixed to 0.2 m. The reference height taken from meteorological data is 2 m. If the plant canopy height exceeds this threshold, a wind speed value is recalculated at a reference height of over 2 m by applying a logarithmic profile. The other meteorological values are not recalculated.

4.5. Surface resistances

In order to simplify the formulae, the resistances of the boundary layer *(racD and racU)* are solely functions of the leaf area index of the covers:

$$rac = \frac{rb}{2LAI} \text{ et } rb = 50\,\mathrm{sm}^{-1} \text{ with a lower threshold of } rac = \frac{rb}{8}. \quad (18)$$

Canopy resistances (*rcD and rcU*) are the product of 4 factors:

$$rc = rsmin\left(\frac{0.5LAI + 1}{LAI}\right)\ (0.039\ D + 0.45)\ \left(\frac{28}{2.5 + Rg}\right) \quad (19)$$

with *D*, the saturation deficit in mbars, and *Rg*, the global radiation in MJ m^{-2} day^{-1}.

Minimum stomatal resistance of leaves (*rsmin*): due to the daily time-step, this parameter cannot be inferred from the instantaneous values of measurements made with a porometer [33, 45] but must be calculated or adjusted by a "top-down" approach [22]. The scale factor from leaf to canopy is the one used by Taconet et al. [43] and tested on a soybean crop [12]. The "saturation deficit" and "radiation" components are taken from research by Stockle and Kjelgaard [41]. With regard to the conditions for applying the proposed formulae, the saturation deficit is calculated at the meteorological level and the radiation is the incident radiation above each crop: *Rg* for the dominant crop and *fD Rg* for the understorey crop.

4.6. Calculating soil evaporation

Soil evaporation [10] is calculated from a potential evaporation value calculated from an intermediate value of the saturation deficit D_{0s} based on the hypothesis that, at complete saturation of the surfaces, E can be approached using a formalism such as that of Priestley-Taylor [12].

4.7. Parameterisation and testing

The maïze-sorghum and the gliricidia-dichanthium data sets of plant transpiration measurements were used to test the model by fitting the minimum stomatal resistance and the wettability,

Table II. Fitted values of minimum stomatal resistance and wettability.

	Gliricidia	Dicanthium	Maize	Sorghum
Minimum stomatal resistance (cm^{-1})	200	226	215	220
wettability (mm LAI^{-1})	0.23	0.27	0.27	0.28

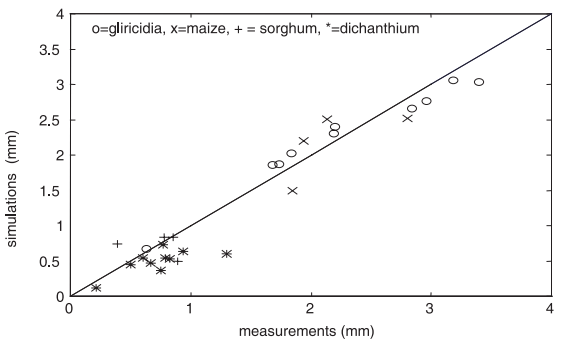

Figure 5. Verification of the simulated values of transpiration after fitting.

considered as plant characters. In this phase of parameterisation, the soil evaporation was imposed by in situ measurements. We used the measurements of leaf water potential measurements to choose the days when the intercrops could be considered without water stress. The stemflow parameters were given the following values for, respectively, gliricidia and maize: 0.5 and 0.7 for *kstemflow* and 0.2 and 0.5 for *stemflowmax*, according to rainfall interception measurements. The results of the fitting, using a Quasi-Newton mathematical procedure, are given in Table II and Figure 5, showing that stomatal resistances range from 200 to 226 sm^{-1} and wettabilities range from 0.23 to 0.28 mm LAI^{-1}. As a complement, direct measurements of wettability by branch weighing, done on Gliricidia leaves, gave a value of 0.17 ± 0.03 mm LAI^{-1}.

4.8. Discussion

This microclimate component of the model is probably the more complete and complex, as compared with other intercrop models of the "crop modelling" approach. In those models, climatic demand partitioning between the two canopies either mimics light partitioning or relies on transpiration efficiency and vapour pressure deficit [2].

The present approach is more mechanistic though remaining at a daily time-step. It relies on Shuttleworth and Wallace's [36] and Wallace's [48] works and allows the accounting for of microclimatic effects on water requirements: convection underneath the dominant canopy, decrease in the vapour pressure deficit due to transpiration from the understorey plants.

Rainfall interception is not usually included in crop models, while it is an important process in forestry models [15]. A common idea is that evaporation of intercepted water compensates exactly the decrease in climatic demand, especially for herbaceous canopies [29]. As far as intercrops are concerned, the processes are more complex and the above-mentioned compensation is not so compulsory, depending on rainy events, climatic demand and intercrop structure. Including those processes in an intercrop model looks worthwhile to correctly predict water use by the canopies, especially under a humid tropical climate (high climatic demand combined with frequent rainfalls). Through the simulation of stemflow and direct water evaporation from leaf surfaces, the objective is rather to correctly evaluate the amount of water that will reach the soil than to partition water between the two crops. Indeed, once in the soil the water is supposed to be evenly available for both root systems, neglecting horizontal variability of soil water content.

The values of the mean daily stomatal resistance (between 200 and 226 sm^{-1}) do not discriminate a lot between plants, but they are in a correct order of magnitude [12]. The same remark can be made for the wettability values that range between 0.23 and 0.28 mm LAI^{-1}, knowing that direct measurements are slightly inferior. Those figures are consistent with measurements made by various methods, reported in the literature [25, 28].

5. LEAF GROWTH OF THE UNDERSTOREY CROP

5.1. Adaptation of the existent STICS formalisms

In the model STICS, gross growth and senescence of the leaf area index (*LAI*) are not considered separately. *LAI* evolves through various phases: increase, stability and decrease. A first step of calculation of the net leaf growth rate (in m^2 $plant^{-1}$ $degree\text{-}day^{-1}$) is related to phenological stages; and represented by a logistic curve using development units on the x-axe. In a second step this value is multiplied by the effective crop temperature, the planting density combined with an interplant competition factor (*efdensity* that gathers quality light and trophic competition effects on canopy foliage expansion) that is characteristic for the variety, and the water and nitrogen stress indices [9]. Thus, the *LAI* calculation is independent of biomass accumulation, in a direct way.

In the case of pure crops strong correlation between intercepted radiation and temperature implicitly links those two fundamental growth processes, which makes the separate calculation of LAI and biomass accumulation realistic. In the case of an understorey crop, this correlation no longer exists because of the shade of the dominant crop. It is therefore important to limit leaf expansion when not enough structural biomass is available to expand leaves at the rate predicted by temperature and also to account for quality light effects. This is done thanks to:

- a trophic limitation of leaf expansion by the means of the parameter *sbv*, analogous to a specific leaf area (cm^2 g^{-1}): *sbv* is the maximal leaf expansion (in cm^2) allowed per g of accumulated plant biomass. The value of this parameter was fitted on the data from the Maize-Canavalia experiment at 300 cm^2g^{-1}. and was active in the simulation only for the shaded part of the Canavalia crop.
- the calculation of an equivalent plant density for the understorey crop ($densU_{eq}$), which accounts for the presence of

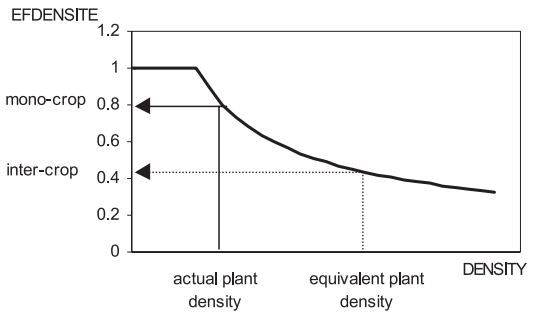

Figure 6. Illustration of the calculation of an equivalent planting density for the understorey crop.

the dominant crop. The interplant competition is synthetically represented in the monocrop model by a density effect applied to a per-plant-basis leaf area daily increase [9]. This density effect (*efdensite*, Eq. (20)), assumes that competition between plants does not exist at a density (*densite* in Eq. (20)) below *bdens*: plant leaf surface is independent of density. Beyond this density value, leaf surface per plant decreases exponentially. The parameter of the exponential (*adens*) represents the ability of a species (or genotype) to withstand increasing densities.

$$\left.\begin{array}{l}\text{If densite} > \text{bdens } efdensite = \left(\dfrac{densite}{bdens}\right)^{adens} \\ \text{with } adens < 0,\\ \text{if densite} < \text{bdens} \quad efdensite = 1.0.\end{array}\right\} \qquad (20)$$

In order to apply the same formalisation within the intercrop model, we introduced the notion of equivalent plant density for the understorey crop ($densU_{eq}$). If *densD* and *densU* are the planting densities of, respectively, the dominant and the understorey crops, and *bdensD* and *bdensU* the threshold densities for interplant competition, the equivalent density is calculated as:

$$densU_{eq} = densU + densD\frac{bdensU}{bdensD}. \qquad (21)$$

This empirical relationship allows an increase in the interplant competition compared with the monocrop situation (Fig. 6). Yet this relationship just accounts for the competition due to light quality while the trophic, mineral and water competitions are accounted for by other formalisms detailed in this paper.

5.2. Discussion

On the contrary to some sole crop models' effects [42], intercrop models require the simulation of interplant competition and planting density effects. The actual processes governing interplant competition are complex, including light quality [47] and competition for radiation, water and nitrogen resources at organ level. We can expect "architecture models" to be able to simulate such a complexity. As far as "crop models" are concerned, the approaches are generally more empirical. For example, Adiku et al. [2] use a trophic factor, depending on the amount of assimilates available to the plant, to limit leaf area index. Kiniry and Williams [24] make use of experimental *LAI* reduction/density relationships, which is a similar approach to ours.

6. ROOT PROFILES

6.1. Need for a new root density module

In STICS, root growth is not considered in terms of biomass but directly in terms of length. The rate of the root front growth depends on the species, the crop temperature and the soil water status. In the monocrop model, the root profile, effective for the absorption, is determined by the maximum depth reached and the root density, which always has the same distribution with the depth (notion of standard root profile) assuming an optimal density in the upper soil horizon. The hypotheses underlying the "standard profile" formalism may pose a certain number of problems for intercrops. For woody canopies arranged in widely-spaced rows, the maximal root densities measured are about 0.2 cm cm^{-3} [32], lower than the optimal density of 0.5 cm cm^{-3} (supposed to be valid for any crop: [8]). Moreover, the soil volume occupied by each crop is different in a monocrop and intercrop. Adiku et al. [3] showed that root systems of component plants in a mixture may intermingle considerably in well-watered situations whereas a tendency for the root systems to cluster within their 'own' zones may be observed under water-stressed conditions. These behaviours do not match the notion of a standard root profile. In this intercrop-adapted version we made the hypothesis that the influence of the crops' root systems on each other results from the influence of the soil status over the root distribution. Consequently, a new module of actual root distribution was developed (keeping the same simulation of the root front) based on three components: the daily production of root length, its distribution in the soil profile and the daily senescence of aged roots. Yet, as for monocrops, the horizontal variability in soil water content and root density is neglected in favour of the vertical one, which is based on experimental results from various intercrop situations [18, 37] and we assume (also as for monocrops) that the clustering of the root system can be accounted for by proper parameterisation.

6.2. Choice of modelling

6.2.1. Daily production of root length for both crops

For questions concerning internal coherence, we adopted a similar formulation to that used for leaf surface area growth [9].

$$rlj = \frac{draclong}{1+\exp[5.5(2.2-urac)]} \times densite \times efdensite \times (tcult - tcmin) + lvfront \times 10^4 \times deltaz \qquad (22)$$

where *rlj* is the daily production of root length (cm m^{-2} soil d^{-1}), *draclong* defines the maximal root growth rate in cm $plant^{-1}$

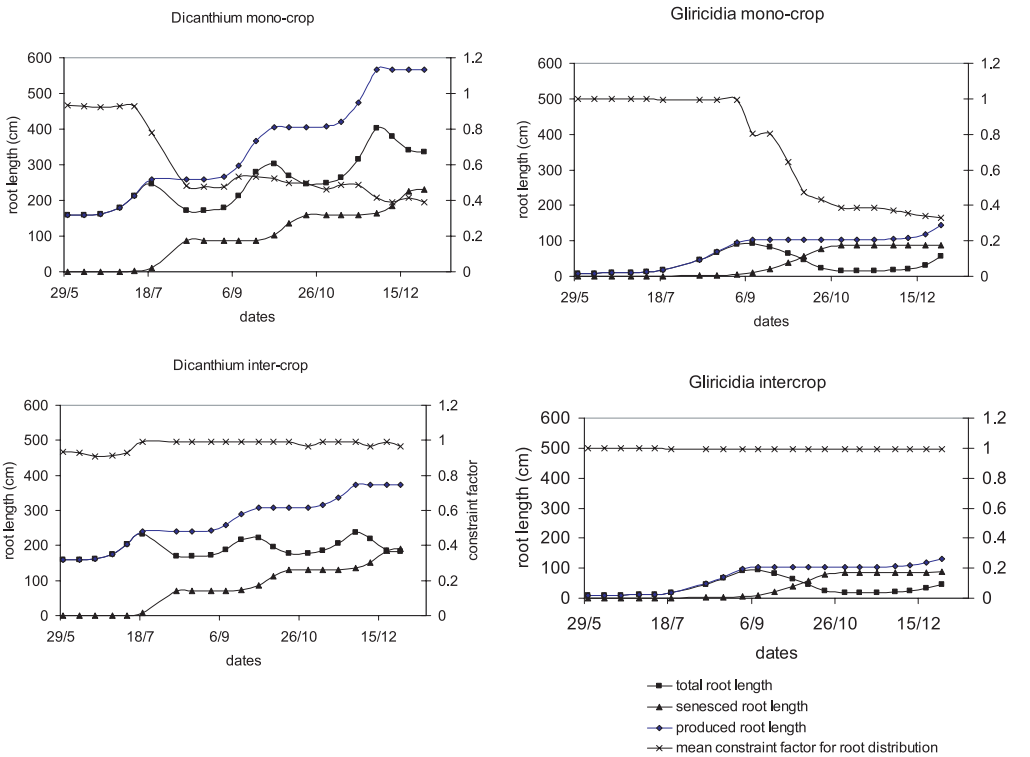

Figure 7. Simulation of root length production and a mean indicator of the constraint exerted by the soil on root distribution, in the case study of a Gliricidia-Dicanthium intercrop: monocrops above and intercrops below for both components.

degree-day $^{-1}$, and *urac* is an arbitrary root growth unit varying between 1 and 3 which depends only on soil temperature (even when the plant has vernalisation or photoperiodic requirements). *densite, efdensite, tcult* and *tcmin* are the same as for the leaf area index (density in plant m^{-2}, interplant competition effect as a function of density, crop temperature and minimum growth temperature: [9]. The first component of *rlj* is distributed throughout the existing root profile; for the root front component (*deltaz* being the daily increase, in cm, in the root system depth), and the second one, the density, is set at a fixed value: *lvfront* in cm cm^{-3} (standard value is 0.05 cm cm^{-3}). As opposed to the leaf area index, the plant stress indicators (water and nitrogen) are not involved.

6.2.2. Distribution of the root growth length in the profile

➢ At the pro rata of the existing roots

A "root sink strength" value is defined for each 1-cm layer as the proportion of roots within the layer. This does not concern the root front where *lvfront* defines the root density to be applied at the root front level. For sown crops, this system is only activated at emergence: between germination and emergence it is assumed that only the root front develops. For "planted" crops, or "set" crops, there is an initial root density profile to begin with (mean density defined for each soil horizon).

➢ Depending on soil environmental stresses

Each type of stress is defined in terms of an index between 0 and 1 (1 = no stress) and assumed to be independent of the others. The resulting index (*poussrac(z),* calculated at each depth (z) of the soil profile, is the product of the following basic indices:

$$poussrac\ (z) = efpfz(z) \times efda(z) \times (1 - anox(z)) \quad (21)$$

efpfz(z) defines the soil dryness effect: it is equal to 1 if the water content of the layer is above the wilting point, and 0 if not. *efda(z)* defines the soil compaction effect on the basis of soil bulk density (the density thresholds used are 1.4 and 2). The water excess variable (*anox(z)* is 1 when the layer is saturated (porosity completely full) and 0 when it is not.

6.2.3. Senescence

The thermal duration *stdebsenrac* defines the lifetime of the roots. Thereby, on day *j+stdebsenrac*, the roots established on day j in layer z are destroyed.

6.3. Examples of simulations

In order to verify that the choice of modelling allows the simulation of the differential behaviours between monocrops and intercrops, we simulated both systems for the Gliricidia/Dichanthium over one growth cycle of the Gliricidia corresponding to three cuts of the grass, from initial observed root

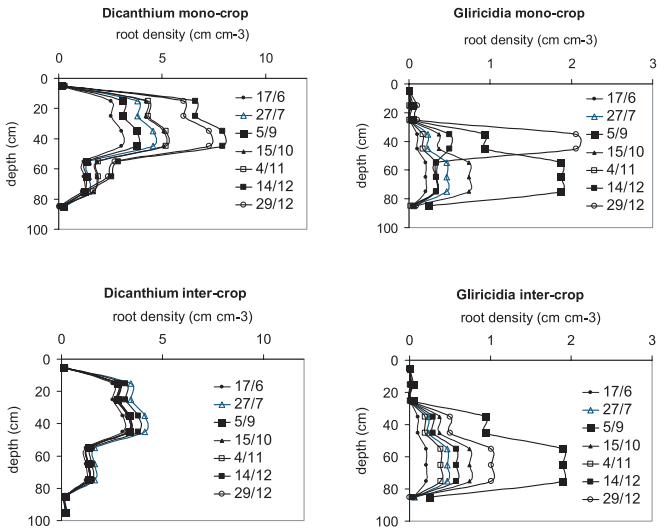

Figure 8. Simulation of root profile dynamics in the case study of Gliricidia-Dicanthium intercrop: monocrops above and intercrops below for both components.

profiles (they correspond to the 17 June profiles in Figure 8, taken from [37]).

The global production is given in Figure 7 as well as an averaged indicator of the soil constraints. Both monocrops are submitted to more severe soil constraints than intercrops as attested by the soil constraint factor. The grass monocrop produces more roots, resulting from the effects of higher density and elevated crop temperature.

Concerning the distribution of roots in the soil profile (Fig. 8), there is a modification of the strategy of the monocrop Gliricidia at the beginning of the wet season illustrated by a preferential colonisation of the 30–40-cm layer.

6.4. Discussion

Simulations of crop productivity and environmental quality depend mainly on the root activity model used [1]. Since root activity is strongly affected by soil state variables and strongly affects soil state variables, there is a need for flexible and generic root system modules that allow the testing of various hypotheses about how root systems of different component crops modify their environment and interact with each other.

Previous intercrop models, assuming that roots of the component crops are either completely separate [23], or completely mixed [2] (of course this does not concern a spatial discretised approach), did not explicitly take into account the retroactions between root systems' activity and soil state variables. Unlike these approaches, the plasticity of the proposed root model is illustrated (i) in the case of a Dichantium intercrop by the limitation of root growth with the decrease in temperature induced by the shade effect of the shrub, and (ii) with the lower capacity of a Gliricidia intercrop to colonise the upper layers at the end of the cycle, compared with the monocrop situation, where competition is less. Noteworthy is the evolution of the constraint factor, with a severe decrease during the monocrop cycles of Gliricidia and Dichantium, whereas it evolves to close to one for the intercrop situations. This behaviour is typical of the 'facilitation effect' mentioned by Vandermeer [46], for resource partitioning in intercrops.

In its current state of development, the root model is close to 'continuum models' for monocrop situations [1, 2], that attempt to overcome some of the shortcomings of earlier models by including soil state variables as environmental modifiers of root growth and distribution.

It is worth noting that the present root model, even if not taking into account dry matter partitioning from shoots to roots and nitrogen control of root growth, includes four of the main control parameters of root growth and distribution: water availability [4], soil temperature, soil strength and soil water excess. As a weakness of the current version, we can reproach the independency of the mentioned stress factors. For instance, it is obvious that soil strength is mainly related to soil water content (see [27]). Hence, future improvements will lie in the introduction of other stress factors such as nitrogen, salinity or aluminum toxicity, and their dependency on other soil state variables, such as temperature and water, particularly, to make the simulations more realistic and process-related. It could also be interesting to test the weight of the assumption of neglecting horizontal variability by comparing this 1D model with a 2D model such as the one described in [37].

7. CONCLUSION

In this paper are explained the concepts for developing an intercrop model by extrapolation of a sole crop model. Simplifying assumptions are required to provide an operational tool: simple shapes for dominant crops, no horizontal variability in water and nitrogen soil contents, and the root profile influenced by soil state variables. Those simplifications result from a hierarchy in the main limiting factors of the complex system of intercrops. Yet, the parameter values are derived from experimental data and the general behaviour of the model is consistent with the general knowledge about those agrosystems [13]. A thorough validation on many data sets, independent from those used in this paper for parameterisation, is still required and will be presented in a forthcoming paper.

In the future, such a tool could be useful to evaluate agronomic strategies. Its flexibility coupled to the generic character of the STICS model allow the testing of various combinations of crops, including arable crops, forage and perennial crops. Yet the explanatory capability is less than that of more sophisticated models, based on spatial distributed or architecture approaches. Some limitations could be improved in the future such as allowing an inversion in the crop dominance, which is very common for replacement intercropping systems, or connecting root length growth to above-ground carbon functioning.

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