

Agrometeorological soil water balance for crop simulation models

Nadine Brisson^a, Bernard Seguin^a and Patrick Bertuzzi^b

^aStation de Bioclimatologie, ^bStation de Science du Sol, INRA BP 91, 84143 Montfavet, France

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ABSTRACT

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The use of crop simulation models on a large scale for agrometeorological purposes is often limited by their inputs being non-routinely collected data, especially with regard to their soil water balance compartment. The objective of this study is to develop a water balance sub-model which can be run with readily available inputs. The model predicts water use, soil evaporation and crop transpiration throughout the growing season. Physiological reduction factors, as influenced by water stress, are derived from the soil water availability. This is achieved by using empirical relationships such as the reservoir analogy to assess water availability in relation to root development. The framework of applicable conditions is assessed by sensitivity analyses performed on inputs: the model can be run with a time step of ten days and using soil information given by soil maps, i.e. soil texture and depth, which fit agrometeorological purposes. Moreover, the model is shown to describe realistically soil water depletion, crop evapotranspiration and rooting depth. However, wetting processes are not correctly simulated, especially when large amounts of water are supplied. This limitation is emphasized for ten day time steps. Therefore incorporating effective rainfall simulation, i.e. both runoff and rainfall interception by the canopy, would improve the model.

NOTATION

D	drainage between the root zone and the drainage zone (mm day ⁻¹)
E_a	actual soil evaporation (mm day ⁻¹)
E_p	potential soil evaporation (mm day ⁻¹)
ET_c	potential crop evapotranspiration (mm day ⁻¹)
ET_r	reference climatic potential evapotranspiration (mm day ⁻¹)
$F(z)$	root water extraction function (% θ_{mav})
I	irrigation supply (mm day ⁻¹)
LAI	leaf area index
R	rainfall (mm day ⁻¹)
S_t, S_l, S_r	stress factors for transpiration, leaf expansion and roots (dimensionless)

Correspondence to: N. Brisson, Station de Bioclimatologie, INRA, BP91, 84143 Montfavet, France.

T_a	actual plant transpiration (mm day^{-1})
T_p	potential plant transpiration (mm day^{-1})
W	water amount in the two upper reservoirs (mm)
W_{av}	actual available water (mm)
W_b	biological available water (mm)
W_p	physical available water (mm)
z	depth (cm)
z_m	mulch thickness (cm)
z_r	maximum rooting depth (cm)
(input data notation is reported in Tables 1 and 2)	

Greek letters

$\overline{\theta}_{fc}$	average field capacity moisture (cm cm^{-1} soil)
$\overline{\theta}_i$	average initial soil moisture (cm cm^{-1} soil)
$\overline{\theta}_i(z)$	initial soil moisture profile (cm cm^{-1} soil)
$\overline{\theta}_{mav}$	$\overline{\theta}_{fc} - \overline{\theta}_{wp}$ (cm cm^{-1} soil)
$\overline{\theta}_r$	residual moisture of dry soil (cm cm^{-1} soil)
$\overline{\theta}_{wp}$	average wilting point moisture (cm cm^{-1} soil)

INTRODUCTION

Basically, crop simulation models work from two modules describing growth and development of the canopy (Baker, 1980; Whisler et al., 1986). When water supply becomes limiting, a water module interferes to reduce the main physiological processes such as photosynthesis or leaf expansion, according to the stress intensity (Ritchie, 1981; McCree and Fernandez, 1989). Water stress is generally computed on a daily basis, and is generally expressed as a function of transpiration flux (Ritchie, 1985a; Jagtap and Jones, 1986; Van Keulen and Seligman, 1987). However, the literature reports some attempts to use leaf water potential (Childs et al., 1977) or soil water availability (Sinclair, 1986; McCree and Fernandez, 1989) as simulated descriptors for water stress.

Most of those models describe water soil-plant relations in terms of fluxes, using Darcy's law for soils and the electrical analogy for evapotranspiration; this approach requires a detailed knowledge of soil physical and hydrodynamic properties. These data are not readily available for operational use on an agrometeorological scale. The objective of this study is to develop a water balance sub-model (which will be referred to as the model BYM) which is simple in operation, yet allows a proper prediction of the crop response to a water deficit.

The model BYM is a representation of the soil-plant-atmosphere system

composed of simply defined sub-systems: soil is considered as a set of three reservoirs, plants are considered as a large transpiring leaf and water-extracting roots, and the atmosphere is characterized at the climatic scale.

MODEL DEVELOPMENT

The objective of the water balance sub-model (BYM) is to compute reduction factors related to water stress. Within the crop model, each of these factors will act on physiological functions through their water stress sensitivity (Bradford and Hsiao, 1982). The link with the growth module is carried out by a single state variable: the LAI.

The calculation of plant water requirement (potential transpiration) on the one hand and of the soil water available to the root system on the other hand allows the assessment of the stress factors. In the following detailed description of BYM, the reader should refer to Fig. 1, which shows the main functions schematically.

Soil evaporation

The potential soil evaporation ratio, i.e. the ratio between potential soil evaporation and potential evapotranspiration, is assessed as an extinction function of LAI by analogy with the penetration of net radiation within the canopy (Uchijima, 1976; Belmans et al., 1983; Ragab et al., 1990):

$$\frac{E_p}{ET_r} = \exp(-\delta \text{LAI}) \quad (1)$$

where ET_r is the reference climatic potential evapotranspiration (Penman formula or another formula correctly adjusted to the studied location) and δ is an extinction coefficient for a whole day time step. This coefficient is considered as an input parameter because it characterizes the canopy structure. According to Uchijima (1976), δ is nearly equal to the extinction coefficient for net radiation and subsequently can vary between 0.45 and 0.65.

The actual soil evaporation, E_a , is simulated in two stages after a rainy sequence. The first stage lasts until cumulative evaporation reaches a given threshold, depending on the soil texture; we have adopted the values given by Ritchie (1972), i.e. 6 mm for sandy soils, 9 mm for loamy soils and 12 mm for clayey soils. During this stage, soil evaporation depends on climatic demand only ($E_a = E_p$). During the second stage, actual evaporation is reduced with respect to the potential reference ($E_a < E_p$). The extent of this reduction depends on the water content of the surface layer as well as on the hydrodynamic properties of the soil. To simulate this drying stage of evaporation, we have developed a semi-empirical model (Brisson and Perrier, 1991) based on the daily mass balance of the dry surface layer, which leads to the formula

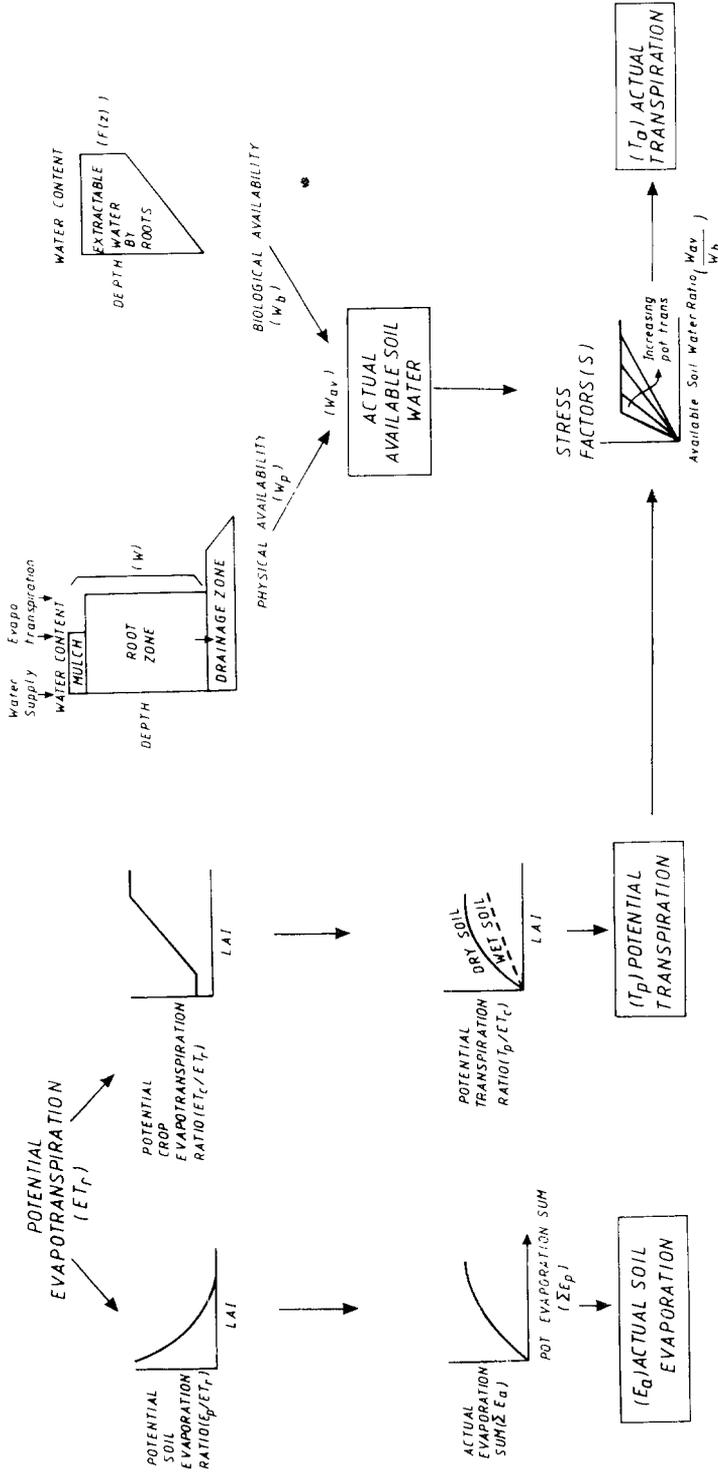


Fig. 1. Flow-chart of the sub-model BYM. Symbols of variables are shown in brackets.

TABLE 1

Sensitivity to invariant parameters and values

Sub-system		
Soil	Plant/croup	Climate
<i>Sensitive parameters</i> (error of estimation within the ranging interval may lead to more than 10% variations in stress factors)		
	Maximal crop coefficient (<i>k</i>)	
	[1; 1.5]	1.4*
	Maximal available water capacity ratio (m)	
	[100; 120]% θ_{max}	110%*
<i>Moderately sensitive parameters</i> (error of estimation may lead to a variation in stress factors ranging between 5 and 10%)		
	Slope of <i>F</i> penetration (<i>l_f</i>)	
	[0.8; 1.1]% θ_{max} cm ⁻¹	0.9*
	Critical leaf potential (Ψ_{cr})	
	[-8; -12]bars	-10*
<i>Non-sensitive parameters</i> (error of estimation may lead to a variation in stress factors of less than 5%)		
Depth of tillage (<i>z_i</i>)	Genetic maximal root depth (<i>z_f</i>)	Climatic parameter for soil evaporation
[30; 50]cm	50* [150; 200]cm	150* (<i>a_c</i> , increasing when wind speed decreases)
	Sowing depth (<i>z_i</i>)	
	[2; 5]cm	3* [9; 21]mm
	Extinction coefficient (δ)	
	[0.45; 0.65]	0.6*

[], Reasonable ranging interval.

*Values used for validation (soybean crop).

$$\sum E_a = \sqrt{(2a \sum E_p + a^2)^{\frac{1}{2}}} - a \tag{2}$$

where *a* is a function of soil texture and climate. The climatic component of *a* (*a_c*) is introduced as an input parameter (see Table 1), whereas the soil component is calculated as a function of the soil texture. This model gives an additional item of information: the thickness of the dried surface layer, also called mulch, which allows us to model a surface storage solely affected by evaporation and water supply (see the section on ‘Soil water availability’ below).

Plant water requirement

The estimation of potential transpiration requires a definition of the potential crop evapotranspiration.

Potential crop evapotranspiration, ET_c

ET_c gives the evaporation rate which would occur if the total surfaces, i.e. soil and leaves, were brought to saturation (Perrier, 1975; Granger, 1989). It depends upon the climatic demand, the crop structure and the minimum leaf stomatal resistance (Katerji and Perrier, 1985; Lynn and Carlson, 1990). Subsequently, ET_c may be larger than the grass referenced Penman ET_r ; this is the case for maize, sunflower or soybean crops when these are fully developed. For operational purposes of estimating irrigation requirement, this effect is generally introduced by means of a crop coefficient greater than one. Actually, the ET_c/ET_r ratio can be considered as a crop coefficient measured from everyday irrigations (Jagtap and Jones, 1989) so that soil water evaporates at a potential rate to respect the following split: $ET_c/ET_r = E_p/ET_r + T_p/ET_r$. Crop coefficients are usually measured with less frequent irrigations: E_p is replaced by E_a , which leads to values less than one at the beginning of the growing season. ET_c/ET_r is expressed as a function of LAI, which seems more realistic than the usual phenological stages (Al-Kaisi et al., 1989):

$$\begin{aligned} \text{if } LAI \leq 1.5 \quad & ET_c/ET_r = 1 \\ \text{if } LAI \geq 5 \quad & ET_c/ET_r = k \\ \text{if } 1.5 < LAI < 5 \quad & ET_c/ET_r = \frac{(k-1)LAI + 5 - 1.5k}{3.5} \end{aligned} \quad (3)$$

where k is the maximal crop coefficient, which may reach 1.5 for some crops.

Potential transpiration of plants, T_p

With a moist soil, T_p can be taken as $ET_c - E_p$. However, several workers have pointed out the effect of drying of the soil surface (Denmead, 1973; Ritchie, 1985b; Feddes, 1987), because of the micro-convective process that occurs beneath the canopy. To account for this process, we propose the following formula:

$$T_p = (ET_c - E_p) \left[\beta + (1 - \beta) \frac{E_a}{E_p} \right] \quad (4)$$

We have adopted a value of 1.1 for β , according to Denmead's results, which simulates a 10% increase in T_p/ET_c (reported in Fig. 1) between wet soil conditions ($E_a = E_p$) and dry soil conditions ($E_a = 0$).

Soil water availability

Soil is considered as a set of three reservoirs of variable size (see Fig. 1) as follows.

(1) The first reservoir corresponds to the mulch zone. Its thickness (z_m) is

a function of the cumulative soil evaporation since the last rainy event (Brisson and Perrier, 1991).

(2) The second reservoir is the root zone, which extends from the base of the mulch down to the maximum rooting depth (z_r). Consequently, its depth increases as it follows root penetration.

(3) The third reservoir is the complementary reservoir between the maximum rooting depth and the total soil depth given as an input. In the case of initial soil moisture being less than field capacity, this last reservoir can be filled by drainage from the upper reservoir.

The water available for plants in the second reservoir depends upon: (1) the water amount present in this soil storage, named the physical availability (W_p); (2) the water amount which the plant can extract, limited by its root system development (W_b), named the biological availability.

Therefore, the actual water available for plants, W_{av} , can be defined as the lower of the two quantities W_p and W_b . This reservoir analogy implicitly assumes that capillary flow could occur through the soil space colonized by roots.

Physical availability, W_p

BYM evaluates the soil water budget using the equation

$$W_t = W_{t-1} + (R+I)_t + 10 \int_{z_{n-1}}^{z_n} \Theta_i(z) dz - T_{at-1} - E_{at} - D_{t-1} \quad (5)$$

where $t-1$ and t are two consecutive time steps.

The quantity of soil water (W) in the two upper reservoirs is the result of the inputs of rain + irrigation and additional supply from the root zone and of the outputs of evaporation, transpiration and drainage. As far as water supply is concerned, BYM does not take into account runoff, rainfall interception by foliage and capillary flow from a possible water table. When a rainy sequence occurs, the mulch zone is first affected, i.e. rain is first consumed by soil water evaporation before it provides the root system with water (this is why the variables $R+I$ and E_a are evaluated at time step t). The water amount exceeding the field capacity (Θ_{fc}) is computed as drainage.

Determination of the contribution of increasing root depth to the water balance requires knowledge of the initial moisture profile, $\Theta_i(z)$, computed with a parabolic type formula:

$$\Theta_i(z) = a(z^4) + b \quad (6)$$

To solve this equation, we assume that the initial average soil moisture ($\overline{\Theta}_i$) is given as an input variable and that at the maximum soil depth (d_x) the moisture is equal to $\overline{\Theta}_{fc}$, which can be written

$$\Theta_i(d_x) = \overline{\Theta}_{fc}$$

and

$$\overline{\Theta}_i = \frac{1}{d_x} \int_{z=0}^{d_x} \Theta_i(z) dz$$

This calculation simply considers that when $\overline{\Theta}_i$ is less than field capacity, soil moisture is lower close to the surface and higher at depth, as a result of drying processes before sowing.

In eqn. (5), the two reservoirs involved enclose water that is held too tightly for the extraction ability of the root system. Moreover, no water is available for plants in the dry surface layer, and the water storage can be solely addressed to the root reservoir (accounted for by the term $z_r/(z_r - z_m)$ in eqn. (7)). Consequently, the physical availability (W_p) is expressed as follows:

$$[W_p = W - (z_r - z_m)10\overline{\Theta}_{wp} - z_m10\overline{\Theta}_r] \frac{z_r}{(z_r - z_m)} \quad (7)$$

where $\overline{\Theta}_r$ is the dry soil moisture assessed from the soil clay content (Brisson and Perrier, 1991).

$\overline{\Theta}_{fc}$ and $\overline{\Theta}_{wp}$ are average values for the whole soil profile, given as inputs. Many workers have pointed out the differences between these definitions as measured in the laboratory and their actual equivalent values measured in field conditions (Ratliff et al., 1983). The most usual explanation is that crops can extract water held more tightly than pF 4.2 especially in the first 30–40 cm (Maertens, 1988). This aspect is integrated in the assessment of biological availability.

Biological availability, W_b

W_b aims at integrating, with an empirical approach, the two components of root growth: depth and density.

The increase of maximum rooting depth (z_r), from the sowing depth (z_i), is assessed as a function of temperature and water stress:

$$z_r = \sum T \times g_r \times s_r \quad (8)$$

where $\sum T$ is the cumulative degree-days since sowing, g_r is the root growth rate (generally equal to $0.15 \text{ cm } ^\circ\text{C}^{-1} \text{ day}^{-1}$ for common herbaceous species Ritchie, 1985a; Masse et al., 1988) and s_r is a root stress factor (see the next section). Additionally, roots cannot exceed a given depth which is characteristic of the plant species (z_f).

An average value of maximum available water capacity ($\overline{\Theta}_{mav}$) is computed as follows: $\overline{\Theta}_{mav} = \overline{\Theta}_{fc} - \overline{\Theta}_{wp}$. A root water extraction factor (F) is then calculated and gives, for each depth between the surface and z_r , the $\overline{\Theta}_{mav}$ proportion extractable by the root system. Assuming that $\overline{\Theta}_{mav}$ is constant for the whole profile, W_b is assessed as a simple integral of this factor:

$$W_b = \int_{z=0}^{z_r} F(z) dz \tag{9}$$

The parameterization of F depends on the architecture of the root system influenced by the soil tillage. We suggest a simple bilinear function, with a limited number of parameters. Above the depth of tillage (z_t), the plant root system is supposed to be able to extract a water amount that can exceed Θ_{max} (the introduction of the parameter m is reported in Fig. 2 and Table 1). This option is consistent with previous observations (Grimes et al., 1975; Tardieu, 1988).

Actually, to simulate correctly the evolution of the root system, we have to make $F(z)$ progress with z_r , as represented in Fig. 2, which implies the need for an additional input parameter, namely, the slope of the function $F(z)$ (l_F expressed as percent $\Theta_{\text{max}} \text{ cm}^{-1}$). Root senescence, as a consequence of severe water stress, is accounted for by the root stress factor. This simple description of root evolution is also able to simulate an increase in root growth density above a pedological obstacle.

Stress factors

As suggested by Ritchie (1981), or more recently by McCree and Fernandez (1989), we use simple bilinear functions giving stress factors (values ranging between zero for maximum stress and one for absence of stress) vs. relative soil water availability. According to the model options, relative soil water availability is assessed as the W_{av}/W_b ratio. If S is a stress factor, then

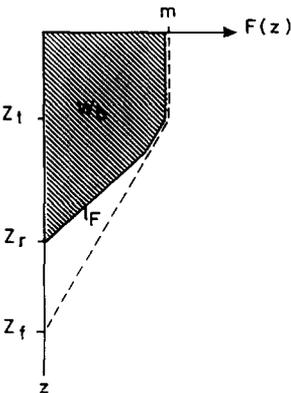


Fig. 2. Scheme of the evolution of the root system. $F(z)$ is the root water extraction function, W_b is the biological available water, z_r is the maximum rooting depth, z_f is the genetic maximal root depth, l_F is the slope of $F(z)$ penetration and m is the maximum water availability ratio.

$$S = 1 \quad \text{if } \frac{W_{av}}{W_b} > s$$

$$S = \frac{1}{s} \times \frac{W_{av}}{W_b} \quad \text{if } \frac{W_{av}}{W_b} \leq s$$
(10)

The threshold, s , depends on the kind of physiological function and on the evaporative climatic demand (Hallaire, 1964). To account for this last phenomenon, we introduce Slabber's function (1980) set up for the transpiration stress factor, s_t :

$$s_t = 0.94 + \left(0.26 \times \frac{\Psi_{cr}}{T_p} \right) \quad (\text{dimensionless})$$
(11)

where Ψ_{cr} is the critical leaf potential (see Table 1), which is specific for each crop. The other stress factors (leaf expansion and root stress) are derived from s_t as follows:

$$s_l = 1.5s_t \quad \text{and} \quad s_r = 0.5s_t$$
(12)

Equations (12) account for an increase in water stress sensitivity from root growth to leaf expansion, as has been established by several workers (see, e.g. Bradford and Hsiao, 1982).

Actual transpiration, T_a , is derived from the transpiration stress factor:

$$T_a = T_p \times S_t$$

MODEL INPUTS: REQUIREMENT AND SENSITIVITY

The objective of this section is to point out the sensitivity to the inputs, to give the framework of conditions in which the model may be used. By inputs we mean here the characteristics of the sub-systems required to run the model. They can be divided in two groups: the driving variables which govern the time step of the model and the input parameters.

Driving variables

Meteorological driving variables are: potential evapotranspiration (mm day⁻¹); rainfall (mm day⁻¹); mean temperature (°C). Crop driving variables are: irrigation amounts (mm day⁻¹); leaf area index. As daily values are not always available on an agrometeorological scale, it can be useful for the model to be run with a larger time step. Thus we have compared the model outputs on two time bases: a daily basis and a ten day period. The loss of accuracy between them was assessed by considering the soil water content in

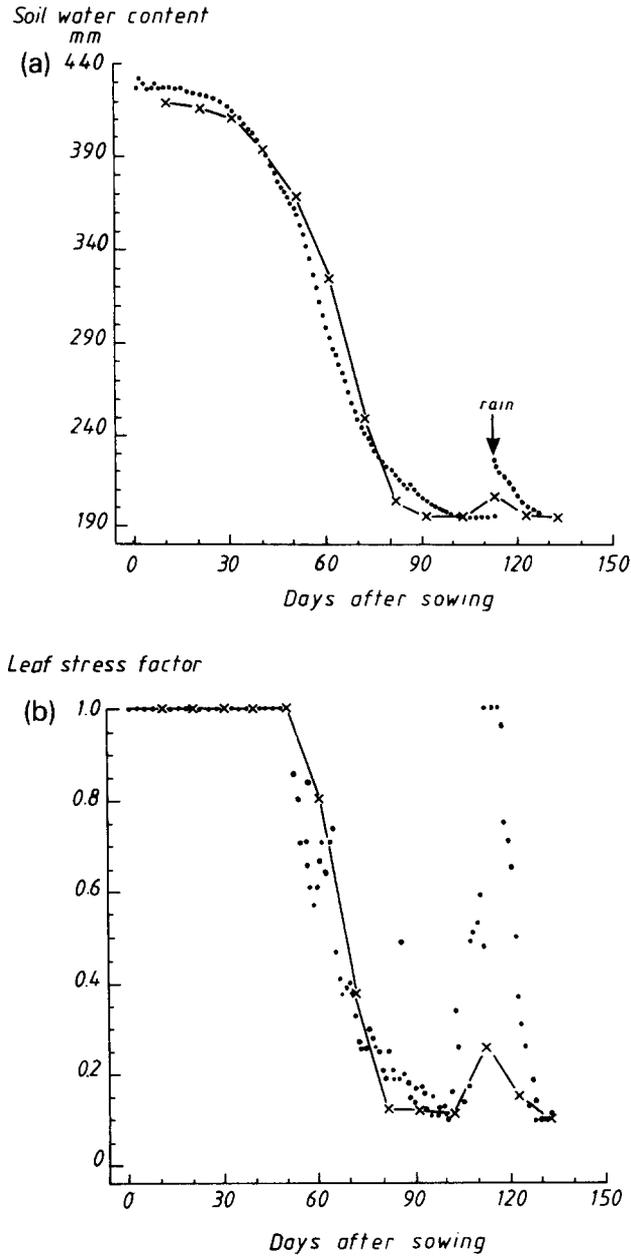


Fig. 3. Comparison between a daily simulation (.....) and a simulation with a ten-day period (—x—) performed with the same set of input data, for Avignon, 1988. The daily LAI was provided by the model SOYGRO and averaged for the 10 day time basis. (a) Results of prediction of the soil water content in the 0–150 cm layer; (b) results of assessment of the leaf stress factor.

a 0–150 cm layer (Fig. 3(a)) and the stress factor, which affects leaf expansion (Fig. 3(b)).

We note that the ten day period curve is a good estimator of the phenomenon as long as a drying process occurs. In contrast, the effects of water income cannot be properly simulated by the ten day period version, which acts as if the water supply was equally divided over the period and counterbalanced by the crop evapotranspiration. Consequently, a great discrepancy may appear in the stress factor simulation (Fig. 3(b)), and the simplified version is likely to miss some of the beneficial effects of isolated rainy events.

Parameters

The required accuracy in parameter assessment depends on the sensitivity of the model to those parameters. We have thus performed two sensitivity analyses. The first concerns the soil descriptive parameters which depend on the soil variability, and the second concerns the parameters which can be considered as invariant temporally and spatially at a regional scale.

Sensitivity to soil spatial variability

The parameters involved are: initial soil moisture (cm cm^{-1} soil); soil depth (cm); soil texture. Texture is used as a synthetic parameter, relying on the results of workers who have established connections between textural estimates and characteristic soil variables, namely wilting point, field capacity and bulk density (Hall et al., 1977; Jamagne et al., 1977; Rawls et al., 1982). A multivariable variance analysis was performed to determine the respective weights of those parameters, and texture was quantified by Θ_{mav} . The parameters were varied within the following intervals: initial moisture, [60–100% Θ_{fc}]; depth, 40–180 cm; Θ_{mav} , 0.109–0.20 cm cm^{-1} soil. Repetitions were obtained using a data set of 10 climatic years from Montpellier (south of France) and two water supply levels (irrigation or no irrigation). LAI was simulated by the crop growth model SOYGRO (Wilkerson et al., 1983) in which BYM was inserted. The analysed variable was the reduction of soybean yield simulated by SOYGRO/BYM and the resulting classification was as follows: 1, depth; 2, initial water content; 3, texture. The analysis underlines the role of depth in providing water to the plants, which cannot be entirely counterbalanced by the maximal available water capacity (Fig. 4). In addition, the initial water content, resulting from the previous winter's rain supply, appears as an important limiting factor.

Sensitivity to invariant parameters

The test for sensitivity to the invariant parameters was carried out by considering extreme values of each and running the model in various conditions of water supply. The parameters were then classified (Table 1) according to

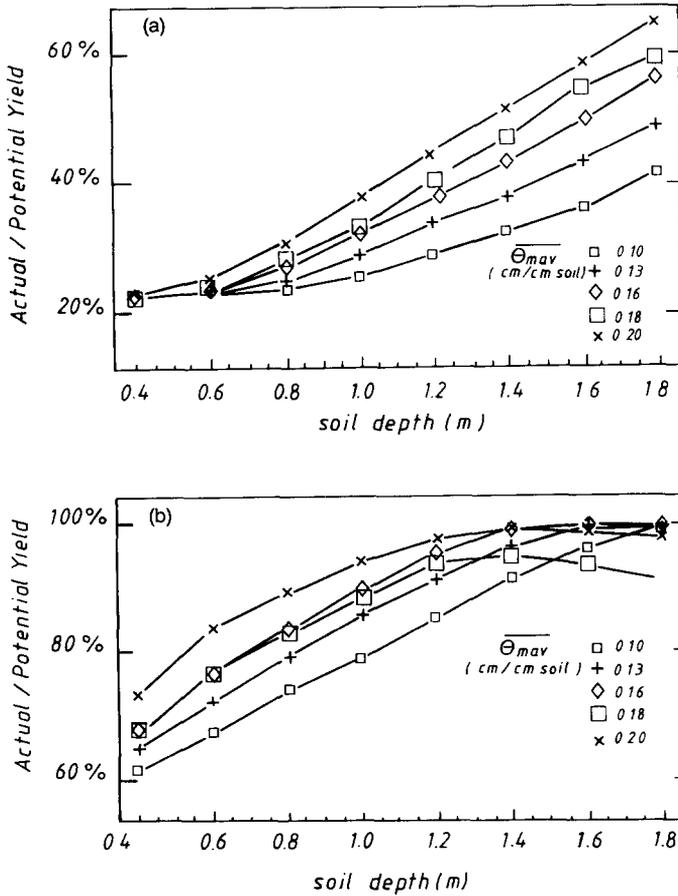


Fig. 4. BYM sensitivity to soil parameters, i.e. soil depth and maximal available water content. Results are expressed in yield reduction as influenced by water stress, and yield is computed by the coupled growth model SOYGRO. (a) Rain-fed conditions; (b) irrigated conditions.

the resulting variations on stress factors, which are directly related to physiological functions, and with respect to the sub-system they characterize. This classification underlines the specific role of plant/crop parameters and especially the parameters that define water requirement.

MODEL VALIDATION

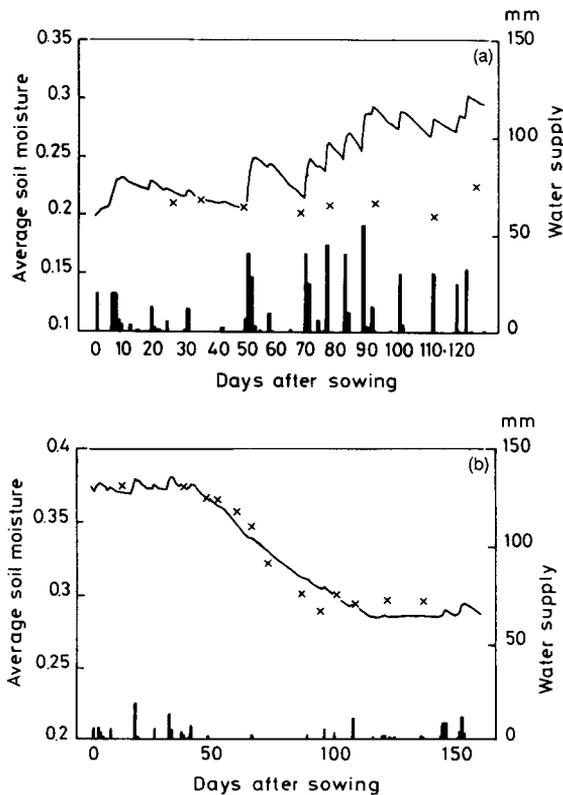
The validation phase is conducted in two steps. The first step is a multilo-cated validation and tests the model with various pedo-climatic environments. The second step is a field validation and aims at comparing more precisely some state variables simulated by the model with their field measurements. The experimental crop is soybean and the associated crop

growth model required to simulate LAI is SOYGRO. Calibration and validation of the growth compartment of SOYGRO for cultivars commonly grown in the south of France were performed before this study (Brisson et al., 1989). Input parameters are given in Table 1. The chosen values come from the literature or technical knowledge.

TABLE 2

Data sets used for multilocated validation

Location	Year	Soil type	Measured initial soil moisture (% θ_{i0})	Water supply
Montelimar	1987	Silty	60	Irrigated
Toulouse	1986	Clayey	90	Rain-fed
Toulouse	1988	Clayey	100	Rain-fed
Avignon	1988	Silty loam	97	Irrigated



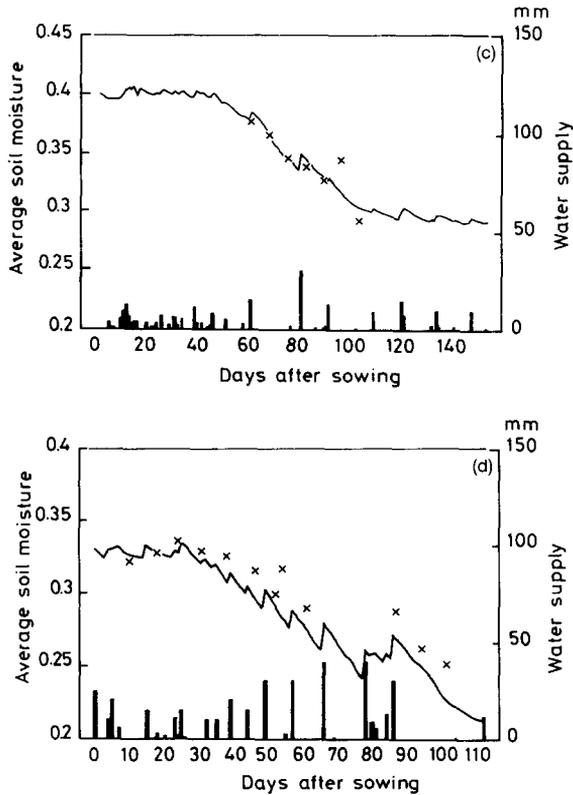


Fig. 5. Multilocated validation for a soybean crop. Evolution of the simulated average soil moisture (—) as compared with field measurements (×) various locations: (a) Montelimar, 1987; (b) Toulouse, 1986; (c) Toulouse, 1988; (d) Avignon, 1988.

Multilocated validation

Three soil types and three years are investigated (Table 2). Agricultural techniques and the chosen cultivar correspond to common regional practices and are introduced in SOYGRO for a proper simulation of the LAI. On each site, neutron probe data have been collected about 10 times throughout the growing season, with two or three replicates per site. Subsequently, the chosen variable for validation is total soil moisture.

The two rain-fed crops (Figs. 5(b) and 5(c)) give very satisfactory results and indicate that the consumption term from either plants or soil is correctly simulated, at least in a cumulative expression. Although the crop at Avignon is grown in irrigated conditions (Fig. 5(d)), the soil moisture follows a pattern similar to the previous ones, which is fairly well simulated. By contrast, the crop at Montelimar (Fig. 5(a)), which differs from the others because the initial soil moisture was depleted with regard to field capacity, shows an

important discrepancy in the second half of the growing season. It is obvious that the model disagrees with the experimental data in accounting for water which is filling up the soil storage. The problem may appear as site specific: the soil type is sensitive to slaking, which reduces the infiltration capacity and consequently increases runoff (not accounted for in the model). Another possibility is that the problem is masked in the other cases by the initial conditions of high soil water content.

From this analysis emerges the notion of effective rainfall, which integrates runoff and rain interception by the foliage. In flat cropped field conditions the second component is the more important (Butler and Huband, 1985) but is not easy to incorporate. Indeed, the water intercepted by the foliage is evaporated at a potential rate and thus contributes to decrease the climatic evaporative demand. However, some attempts have been reported in the literature (Reid, 1990; Ragab et al., 1990) and could be used to improve the model.

Field validation

The following results rely on an experiment which was conducted in 1989 on the site of INRA–Avignon (France). This experiment aimed at characterizing in situ the water status of a soybean crop (*Glycine max*, cv. 'Weber') throughout the growing season. Consequently, daily measurements of the soil water budget (using neutron probe and tensiometers to a depth of 155 cm, with four replicates) and the energy balance above the canopy (using the eddy correlation method to estimate the sensible heat flux) were performed. In

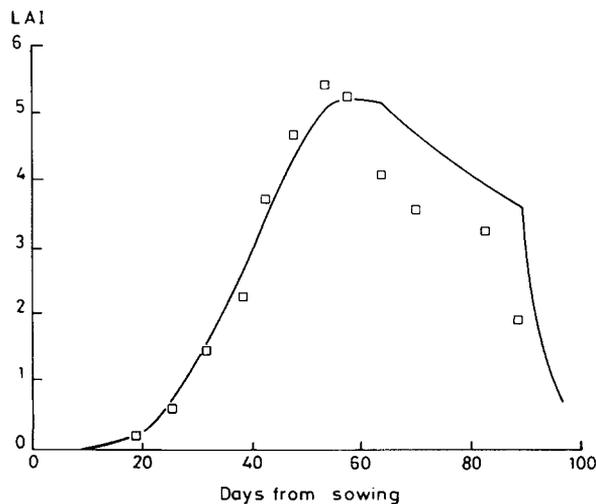


Fig. 6. Leaf area index for field validation. □, Measurements; —, simulated by SOYGRO and used as an input in BYM.

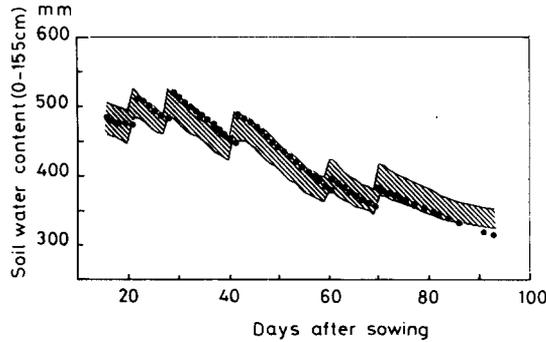


Fig. 7. Field validation of soil water content. ▨, Confidence interval (95%) of the measured values; ···, results from simulation.

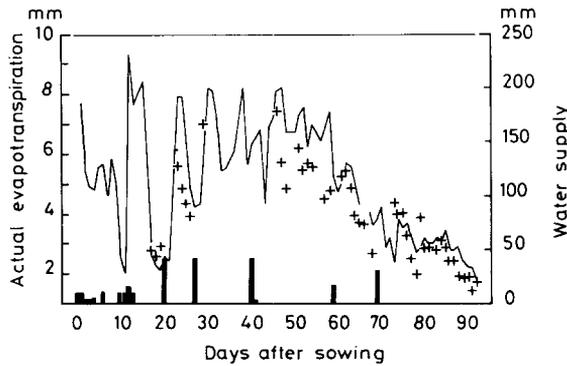


Fig. 8. field validation of evapotranspiration. +, Measurements by the energy budget method; —, results from simulation.

addition, the root system was characterized by two methods: grid observations (Tardieu and Manichon, 1986) and root sampling, both to a depth of 150 cm, with two or three replicates.

Weekly controls of the leaf area index allow us to check whether the LAI input from the SOYGRO growth model was reliable. We find a slight over-estimation during the senescence phase, i.e. later than 50 days after sowing (DAS), of about 1 LAI unit (Fig. 6). Concerning water supply inputs, daily measurements of soil water content on the one hand and of evaporative flux on the other hand allow us to assess the runoff–canopy interception term of the water budget. It is found that this term was negligible when irrigation was less than 45 mm, i.e. in most cases (no rain occurred during the growing season and water was supplied by irrigation). However, for two irrigations of 70 and 56 mm the interception term was non-negligible and was therefore subtracted from rain + irrigation measurements.

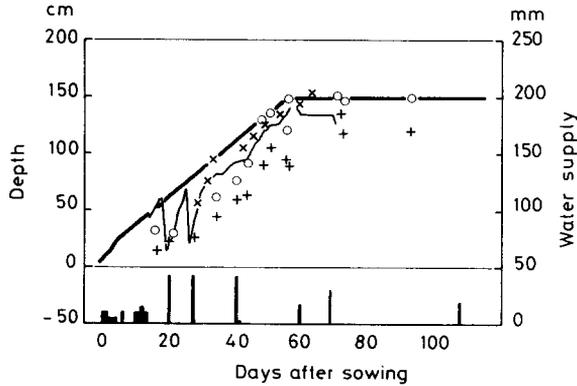


Fig. 9. Field validation of rooting depth. Results of direct observations: +, depth limit above which 95% roots occur; O, maximum rooting depth. Results of indirect assessments: —, depth of the zero flux plan; X, effective depth from neutron probe data. Results from simulation: z_r .

The validation of the average soil moisture (Fig. 7) confirms the previous results. For direct estimates of evapotranspiration (Fig. 8) we find that the model respects the crop short-term behaviour: increase of evapotranspiration after a rainy event (e.g. around 20 DAS) as well as the long-term behaviour related to the LAI progression. Around 50 DAS, i.e. when LAI values are maximum, a discrepancy appears between simulated and measured values, which may be attributed to an excessive simulation of water requirement by the combination of overestimations of LAI and k .

To validate the simulation of root progression in the soil, various methods of root growth estimation have been tested with the model results. We use both direct methods (grid observation and root sampling), and indirect methods (zero flux plan and effective rooting depth calculated from the neutron probe data (Gregory, 1991)). As the direct methods give similar values, we do not distinguish between the two on the graph in Fig. 9. It appears that the root depth as defined in the model for computing the depth of the active reservoir is more closely comparable with the indirect calculations from soil water measurements than with root observations. Concerning these observations, the graph shows that the efficiency of the 5% deepest roots (difference between 100% and 95%) is significant.

CONCLUSION

Although the model uses empirical relationships to describe the crop water behaviour, the results are in reasonable agreement with measured values as long as drying processes occur. However, disagreement on soil water content may appear when a large amount of water is supplied. In that sense, some improvement could be made in accounting for rainfall efficiency.

The present study provides a tool for simulation of water aspects of crop growing available for agrometeorological studies. Indeed, when compared with other water balance compartments of crop models (Brisson and Voltz, 1992), the model BYM appears to be the simplest in operation. It is characterized by its analogical approach to crop water processes and by the use of readily available inputs. Moreover, it can be coupled with various types of growth simulator giving basic information on the leaf area index. Attempts to insert this water component within various models have given good results (Brisson, 1989; Brisson et al., 1990). However, the LAI variable can also be supplied by field observations or estimation from remote sensing data. In those cases, the 10 day version of the model fits well the data availability.

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