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Comparison of root water uptake modules using either the surface energy balance or potential transpiration

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Abstract

Numerical models simulating changes in soil water content with time rely on accurate estimation of root water uptake. This paper considers two root water uptake modules that have a compensation mechanism allowing for increased root uptake under conditions of water stress. These modules, proposed by Lai and Katul and Li et al. [Adv. Water Resour. 23 (2000) 427 and J. Hydrol. 252 (2001) 189] use potential transpiration weighted, for each soil layer, by a water stress and a compensation function in order to estimate actual transpiration. The first objective of the paper was to assess the accuracy of the proposed root extraction modules against two existing data sets, acquired under dry conditions for a winter wheat and a soybean crop. In order to perform a fair comparison, both modules were included as possible root water extraction modules within the Simple Soil Plant Atmosphere Transfer (SiSPAT) model. In this first set of simulations, actual transpiration was calculated using the solution of the surface energy budget as implemented in the SiSPAT model. Under such conditions, both root extraction modules were able to reproduce accurately the time evolution of soil moisture at various depths, soil water storage and daily evaporation. Results were generally improved when we activated the compensation mechanisms. However, we showed that Lai and Katul [Adv. Water Resour. 23 (2000) 427] module was sensitive to soil hydraulic properties through its water stress function, whereas the Li et al. [J. Hydrol. 252 (2001) 189] module was not very sensitive to the specification of its parameter. The latter module is therefore recommended for inclusion into a larger scale hydrological model, due to its robustness.

When water balance models are run at larger scales or on areas with scarce data, actual transpiration is often calculated using models based on potential transpiration without solving the surface energy balance. The second objective of the paper was to assess the loss of accuracy in such conditions for the Lai and Katul and Li et al. [Adv. Water Resour. 23 (2000) 427 and J. Hydrol. 252 (2001) 189] modules. For this purpose we compared results from the SiSPAT model solving the surface energy balance with those of a degraded version where only potential evapotranspiration was imposed as input data. We found that actual transpiration and evapotranspiration were in general underestimated, especially for the Lai and Katul [Adv. Water Resour. 23 (2000) 427] module, when we used the potential evapotranspiration as calculated from FAO standards. The use of crop coefficients improved the simulation although standard values proposed by the FAO were too small. The definition of

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the potential evapotranspiration was the major source of error in simulating soil moisture and daily evaporation rather than the choice of the root extraction modules or the inclusion of a compensation mechanism. When used for water management studies, a sensitivity to the definition of potential evapotranspiration used to run the models is therefore advisable.

Keywords: Compensation; Root extraction; Water stress; SVAT; Potential evapotranspiration; Energy balance

1. Introduction

In the context of sustainable agriculture and environmental management, there is a need for modelling tools able to assess the influence of management practices, changes in land use and climate on crop yield and/or water resources. In order to be applied over large areas and long temporal sequences, these models need to be simple enough to remain computationally tractable, although keeping enough realism to represent the main physical processes. One of these processes is transpiration by plants, as reviewed by Molz (1981). In the so-called Soil Vegetation Atmosphere Transfer (SVAT) models, transpiration, assumed to be equal to root water uptake, is modelled based on the water—and energy balance approach. In an analogy with Ohm's law, the driving force for water uptake is the water potential gradient between the soil and the leaves, with resistances along the flow path, including a soil resistance, a soil-root resistance, and resistances within the plant. This approach is used, among others by Lynn and Carlson (1990), Daamen and Simmonds (1994), Braud et al. (1995) and De Ridder and Schayes (1997). These models are often used when diurnal information on surface fluxes is required or in the context of remote sensing data assimilation.

A simpler group of SVAT models deals only with the water balance and ignores the vegetation energy balance equation. In the latter models, root water extraction is incorporated as a sink term in the mass conservation equation. Generally, root water uptake from each soil layer is modelled as a function of potential transpiration, vertical root distribution and soil water availability, with or without a water stress function accounting for increased water uptake from deeper, more moist soil layers. The water balance models are easier to use and require less information on root geometry, soil characteristics and weather conditions than the fully comprehensive SVAT models. Their use is consequently favoured in hydrological and management-oriented water simulation models. However, there is a need to assess which type of root extraction module is better suited for inclusion into such less comprehensive models and to quantify the errors associated with their simplifications.

The study focuses on models where root water uptake is represented as a sink term within the soil water transfer equation (for instance Richards (1931) equation), assumed to be proportional to a 'potential' transpiration rate and an effective root distribution function. This approach, pioneered by Feddes et al. (1978) for water balance studies was used in recent studies of crop modelling (e.g. Green and Clothier, 1999; Wu et al., 1999) and chemicals transport (e.g. Vogeler et al., 2001). Limited root water uptake due to soil dryness can be accounted for by a weighting function. Feddes et al. (1978) proposed a module related to soil water potential, accounting for a reduction of transpiration for very wet soil and for drying soils, down to the wilting point. Homaee et al. (2002) recently compared alternative formulations for this reduction function. The root distribution function was originally uniform with depth. Various authors proposed improvements based on linear and non-linear functions, generally decreasing with depth (e.g. Hoogland et al., 1981; Prasad, 1988; Li et al., 1999). In most models, with the exception of the SOIL model (Jansson, 1998), water stress occurring in one layer cannot be compensated through increasing the water uptake from other layers. In recent papers by Lai and Katul (2000) and Li et al. (2001) root uptake modules accounting for compensation between dry and wet layers were proposed. In each of these papers, compensation improved the simulation of soil moisture.

The first objective of this paper was the evaluation of these two modules against measured data sets. We selected two data sets, covering a full growing cycle of a winter wheat crop and a soybean crop, respectively. Both data sets were collected under dry conditions, generating water stress for the plants. The use of these data sets allowed a full evaluation of the compensation mechanisms as the latter were expected to be more active under dry conditions. This evaluation was performed using the Simple Soil Plant Atmsophere Transfer (SiSPAT) model, which solves both the water and the surface energy balance. A second objective of the study was to assess the performance of the Lai and Katul (2000) and Li et al. (2001) modules with potential transpiration as direct input. For this purpose, we used a degraded version of the SiSPAT model where the surface energy balance was not solved. The results of this assessment were used to select a root extraction module with enough physical realism but requiring a limited set of input data for inclusion into a larger scale hydrological model.

2. Materials and methods

2.1. The SiSPAT model

An extensive description of the SiSPAT model can be found in Braud et al. (1995) and Braud (2000) and only a brief summary is presented here. SiSPAT is a vertical 1D model that deals with heterogeneous soils. The driving forces are climatic time series of air temperature and humidity, wind speed, incoming solar and long-wave radiation and rainfall. In the soil, coupled heat and mass transfer equations (Philip and De Vries, 1957; Milly, 1982) are solved for temperature T and soil matric potential ψ. The required upper boundary conditions are obtained form the soil–plant–atmosphere interface module which considers one vegetation layer with two energy budgets: one for the bare soil fraction and one for the vegetated fraction.

Root water uptake is modelled using an electrical analogue scheme (Ohm's law) with various resistances in series. Moisture extraction from layer j is proportional to the difference between the soil water potential in layer j and the leaf water potential. The latter is calculated by assuming that the total moisture extraction equals the transpiration calculated from the atmospheric conditions. The leaf water potential, along with the incoming radiation and vapour pressure deficit, controls the water stress function of the stomatal resistance.

Finally, when rainfall exceeds the infiltration capacity of the soil, saturation of the soil surface occurs. The matric potential is then set to zero, and surface runoff is calculated form the mass budget equation. Iterative procedures are used to solve the various modules of SiSPAT (Braud, 2000).

2.2. Description of the root extraction modules of Lai and Katul (2000) and Li et al. (2001)

The root extraction modules considered in this paper are designed to represent the sink term $S(z,t)$ (s^{-1}) in the equation describing vertical water movement within the soil:***

$$\frac{\partial\theta(z,t)}{\partial t} = -\frac{\partial q(z,t)}{\partial z} - S(z,t) \qquad (1)$$

where θ($m^3\ m^{-3}$) is the volumetric water content, t(s) is time, z(m) is the vertical coordinate (positively oriented downward) and q($m\ s^{-1}$) is the soil water flux. The root water uptake is related to the actual transpiration rate T($m\ s^{-1}$) through:

$$T(t) = \int_z S(z,t)\mathrm{d}z \qquad (2)$$

where it is assumed that no water storage can occur within the plant and that water extracted by roots is instantaneously transpired by the leaves. In the modules of Lai and Katul (2000) and Li et al. (2001) referred to as LK00 and LI01, respectively, $S(z,t)$ can be written:

$$S(z,t) = \beta(\theta,z)T_p \qquad (3)$$

where T_p($m\ s^{-1}$) is the 'potential' transpiration and $\beta(\theta,z)\in[0,1]$ is an empirical function depending on the soil water content and depth. It can be further decomposed into:

$$\beta(\theta,z) = \alpha(\theta,z)g(z) \qquad (4)$$

where $g(z)$ depends on the root density distribution with depth and $\alpha(\theta,z)$ accounts for restriction to transpiration caused by soil moisture limitations. In the paper by LK00, linear root distribution was used, whereas LI01 used an exponential function. In order to compare the soil moisture compensation mechanism of both modules, an exponential distribution was used for both of them.

$$g(z) = g_o \frac{\exp(-bz)[1.5 + 0.5\exp(-bz)]}{1 + \exp(-bz)} \tag{5}$$

where g_o is the root density at the soil surface and b a parameter characterising the exponential decrease of the root density distribution. In the following the relationship proposed by LI01 was used for the b parameter

$$b = \frac{24.66(F_{10})^{1.59}}{z_R} \tag{6}$$

where z_R is the maximum rooting depth and F_{10} is the fraction of root length density per unit length area (m m^{-2}) between depth 0 and 0.1*z_R. Consequently, the LK00 and LI01 modules only differ in the way they represent the water stress and water compensation mechanisms.

LK00 further decomposed the $\alpha(\theta)$ function as the product of two functions $\alpha_1(\theta,z)$ and $\alpha_2(\theta,z)$ accounting for the compensation and water stress mechanisms, respectively. The LI01 function can also be decomposed in the same way. They are written:

$$\alpha^{LK}(\theta,z) = \alpha_1^{LK}(\theta,z)\alpha_2^{LK}(\theta,z) \tag{7}$$

$$\alpha^{LI}(\theta,z) = \alpha_1^{LI}(\theta,z)\alpha_2^{LI}(\theta,z) \tag{8}$$

where the superscripts LK and LI refer to the LK00 and LI01 modules, respectively.

LK00 proposed the following formulation for the $\alpha_1(\theta,z)$ and $\alpha_2(\theta,z)$ functions:

$$\alpha_1^{LK}(\theta,z) = \mathrm{Max}\left(\frac{\theta(z,t)}{\theta_s - \theta_{wilt}}, \frac{\int_0^z \theta(y,t)\mathrm{d}y}{\int_0^{z_R} \theta(y,t)\mathrm{d}y}\right) \tag{9}$$

$$\alpha_2^{LK}(\theta,z) = \left(\frac{\theta(z,t) - \theta_{wilt}}{\theta_s}\right)^{(\gamma/\theta(z,t) - \theta_{wilt})} \tag{10}$$

where θ_s is the saturated water content, θ_{wilt} is the wilting point and γ is a parameter of the water stress function. Note that whereas the second term of the *Max* function in Eq. (9) is always less than one, the first one can be greater than one. If it was not the case, the compensation mechanisms would necessary lead to a transpiration lower than the case without compensation where $\alpha_1^{LK}(\theta,z) = 1$.

The LI01 module is derived from the initial model of Feddes et al. (1978). To account for a compensation mechanism, an $\alpha_1(\theta z)$ function can be defined as:

$$\alpha_1^{LI}(\theta,z) = \frac{\alpha_2^{LI}(\theta,z)G(z)^{\lambda-1}}{\sum_{z=0}^{z_R} \alpha_2^{LI}(\theta,z)G(z)^{\lambda}} \tag{11}$$

where λ is a parameter of the module. $G(z)$ is the fraction of the total root length in a layer of thickness Δz at depth z. The water stress function $\alpha_2(\theta,z)$ is written as a function of the soil matric potential $\psi(z,t)$ (m), which can be expressed as a function of the soil moisture content through the retention curve $\psi(\theta)$.

$$\begin{cases} \alpha_2^{LI}(\theta,z) = 0 & \text{if } \psi \geq \psi_1 \text{ or } \psi \leq \psi_4 \\ \alpha_2^{LI}(\theta,z) = 1 & \text{if } \psi \leq \psi_2 \text{ and } \psi \geq \psi_3 \end{cases} \tag{12}$$

and decreases (respectively increases) linearly between ψ_2 and ψ_1(respectively ψ_4 and ψ_3), leading to a trapezoidal curve. Note that in Eq. (12) $\psi \leq 0$ and that $\psi_4 \leq \psi_3 \leq \psi_2 \leq \psi_1$.

Note that the suppression of the compensation mechanism can be easily achieved for both models by setting $\alpha_1^{LK}(\theta,z) = \alpha_1^{LI}(\theta,z) = 1$.

2.3. *Inclusion of Lai and Katul (2000) and Li et al. (2001) models within the SiSPAT model*

We conducted two sets of numerical experiments aiming (i) at assessing the accuracy of the root uptake modules and compensation mechanisms proposed by LK00 and LI01 and (ii) at estimating the loss of accuracy when potential transpiration is used instead of actual transpiration as calculated with SiSPAT's surface energy balance.

To reach the first goal, we used the surface energy balance calculations of the original SiSPAT model in order to derive actual transpiration, but replaced the original root uptake module by either the LK00 or LI01 modules. Contrary to the SiSPAT root extraction module, the LK00 and LI01 modules require a 'potential' transpiration rate. The latter was calculated at each time step within the runs, after solving of the surface energy balance equation, using the aerodynamic resistance, the net radiation calculated by SiSPAT, and by setting the stomatal resistance to its minimum value (50 s m^{-1} for wheat and 70 s m^{-1} for soybean). This potential transpiration was provided as input for the LK00 and LI01 root extraction modules. We forced the total root uptake calculated by either the LK00 and LI01 models not to exceed the actual transpiration calculated from the energy and mass balance at the surface by SiSPAT. If the LK00 and LI01 modules were not able to fulfil the SiSPAT transpiration rate, the stomatal resistance corresponding to the possible root extraction was recalculated and the surface energy and mass balance equations re-evaluated, providing another actual transpiration rate. The procedure was iterated until convergence was reached, i.e. there was no longer an imbalance in the surface energy budget.

To reach the second goal we used a modified version of the SiSPAT model, where the surface energy balance was not solved and actual transpiration was calculated using the procedure described in Section 2.2 (in other words we only activated the soil water transfer module of the SiSPAT model). This second set of simulations required a potential transpiration as a forcing variable. We used two calculations for this purpose. The first one was based on a reference hourly evapotranspiration E_p derived from the weather data available according to the method proposed by FAO (1998), assuming a constant surface resistance of 70 s m^{-1}. The second potential evapotranspiration we used was that derived a posteriori from the detailed SiSPAT model calculations in the first set of simulations. These evapotranspirations are referred to as FAO E_p and SiSPAT E_p, respectively. Note that the FAO method is giving values valid for well-watered grass and the use of crop coefficient is advised by FAO (1998) for other crops. We did not used crop coefficients in this paper, except when specified. Potential soil evaporation E_{sp} and potential transpiration T_p were then evaluated as (e.g. Huygen et al., 1997):

$$E_{sp} = E_p \exp(-a\,\mathrm{LAI}) \quad (13)$$

$$T_p = E_p - E_{sp} \quad (14)$$

where a, assumed to be 0.5, is a parameter accounting for the interception of incoming solar radiation by the vegetation. The model was then run using only the soil module, without solving the energy budgets (no interface). We estimated actual soil evaporation according to Mathieu and Bariac (1996) (Eq. (15)) and actual transpiration using the LK00 or LI01 root extraction module.

$$E_s = E_{sp} \frac{h_s - h'_a}{1 - h_a} \quad (15)$$

where h_a and h_s are the air and soil surface relative humidity respectively and h'_a is the air relative humidity normalised at the soil surface temperature T_s:

$$h'_a = h_a \frac{\rho_{sat}(T_a)}{\rho_{sat}(T_s)} \quad (16)$$

where $\rho_{sat}(T)$ is the saturated air volumetric mass as a function of temperature.

The SiSPAT model (coupled with the various root extraction modules) was run using an half or hourly forcing in order to correctly describe the surface energy balance and the diurnal cycle of surface fluxes. The root extraction modules of LK00 and LI01 were designed to be used at a daily time step. They were consequently tested in 'adverse' conditions as we discuss the performance of the modules on the simulated hourly surface fluxes (see Tables 4 and 5). The analysis is however complemented by a discussion of the results at the daily time step for evapotranspiration for the soybean crop.

2.4. The winter wheat data set

The data set is fully described in Olioso et al. (2002a) and the data base accessible at http://www.avignon.inra.fr/reseda. The experiment was designed to study assimilation techniques of various remote sensing data sets within crop simulation and SVAT models. Several fields were instrumented within a 5×5 km^2 region in the South-East of France near Avignon, (43°47′N, 4°45′E). Measurements of the soil moisture water balance, surface energy budget, plant physiology were acquired during the whole cycle of the crop (from December 1996 to September 1997). The data set used in this paper was collected in a winter wheat field with the simulation period from January 21 to June 25, 1997. Exceptional dry winter and spring (no rainfall between January and April 1997—see Fig. 1, top panel) generated severe water stress for the wheat and the maximum Leaf Area Index (LAI) only reached about 1.5. Hourly data of the surface energy budget components measured using the Bowen ratio and eddy covariance method (sensible and latent

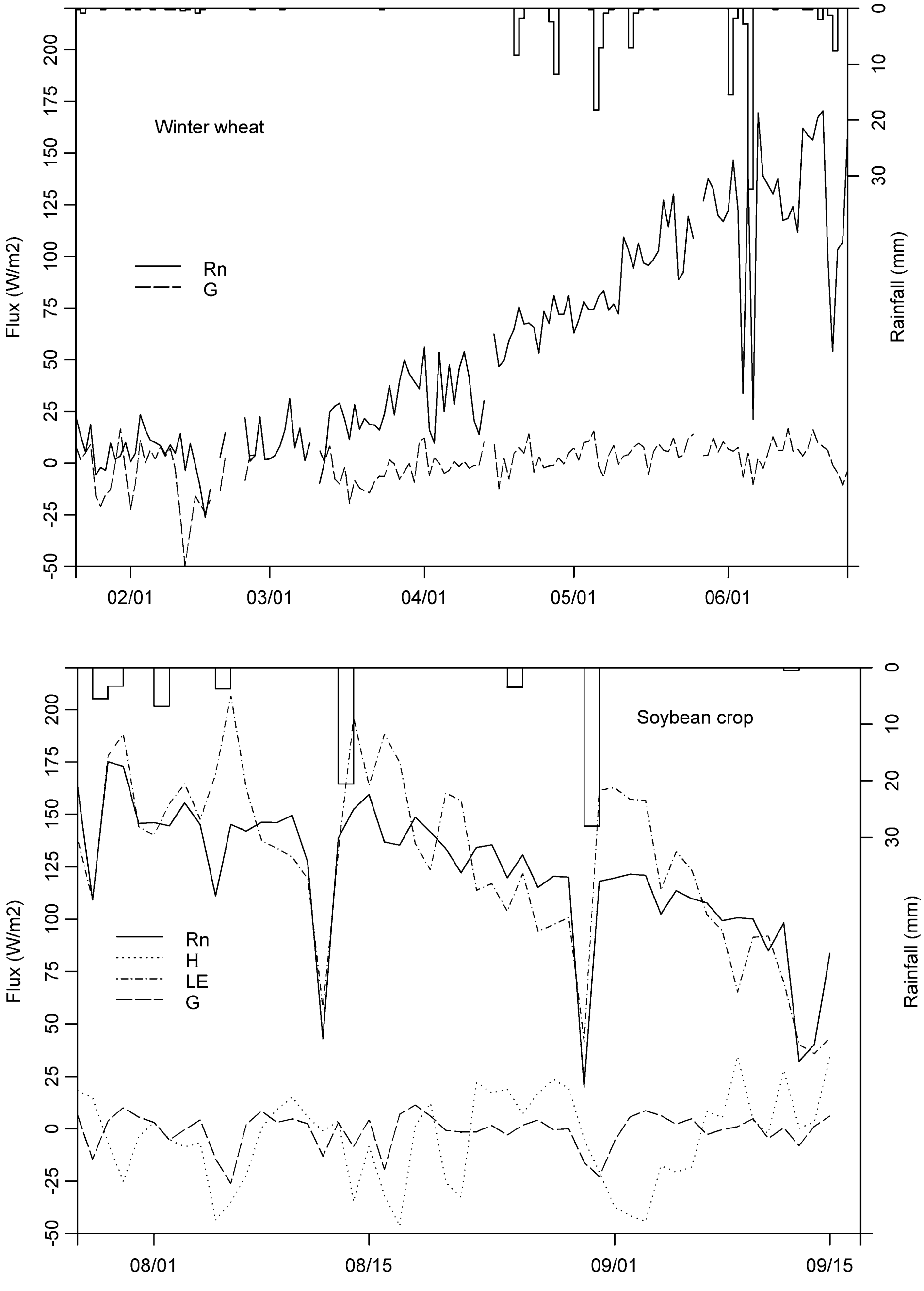

Fig. 1. Daily values of rainfall (+irrigation for soybean crop), net radiation (*Rn*), sensible (*H*), latent (*LE*) and soil heat flux (*G*). Top panel: winter wheat data set (1997). Daily sensible and latent heat flux are not shown due to a large amount of missing data. Bottom panel: soybean data set (1990).

heat fluxes, soil heat flux, net radiation) were available. The Root Mean Square Error (RMSE) between Bowen ratio and eddy covariance method was 36 W m^{-2} for day+night values and 50 W m^{-2} for daylight values (Olioso et al., 2002a). The RMSE was twice that for the soybean data set (see below) due to problems with the home-made Bowen ration system (Olioso et al., 2002a). In this study we used the sensible heat flux measured using the eddy correlation technique and the latent heat flux calculated from the surface energy balance as in Olioso et al. (2002b). Fig. 1 (top panel) gives the daily net radiation and soil heat flux and shows a regular increase of net radiation during the growing season. The soil water balance was monitored weekly using tensiometers and field volumetric water content derived from neutron probe soundings. Measurements were performed every 10 cm from 5 to 135 cm every 4 to 15 days. A field average was derived as the mean of the measurements performed at three sites. The standard deviation of these values was about 0.02 $m^3\,m^{-3}$. Field and laboratory measurements were carried out in order to derive the hydraulic and thermal properties of the soil (Braud and Chanzy, 2001). Time evolution of plant physiology was followed regularly and included amongst others LAI and crop height. Three root density profiles were measured using washed samples, within the growing cycle of the wheat (February 5, May 13 and June 10 1997). Due to water stress, roots were found below 1.4 m depth which was the depth of the deepest tensiometer and moisture measurement. A 2.0 m soil column, with zero flux at the bottom, had to be considered to consistently model the data set, with the drawback that the lower boundary condition at the bottom of the column was not known, introducing uncertainties in model results (Olioso et al., 2002b).

2.5. The soybean data set

The data set was collected from a soybean crop in Avignon, France (43°54′N, 4°48′E) from July 28 to September 15 1990. The objective of the experiment was the characterization of vegetation fluxes, leaf water potential, stomatal conductance and leaf photosynthesis under stressed conditions (Olioso et al., 1996). The crop was irrigated during the first month, until the LAI reached a value of 2.0. Two rainfall events occurred on August 14 (19 mm); and August 30 (30 mm) after the irrigation was stopped (see Fig. 1 bottom panel). The maximum value reached by the LAI was 3.8 on August 22. The data set included continuous measurements of soil and vegetation characteristics, and energy and mass transfer, obtained from classical meteorological observations combined with surface and water budget measurements. Incoming radiation, air temperature, wind speed and vapour pressure were recorded above the canopy. The energy balance was monitored using various sets of instruments (aerodynamic, Bowen ratio and eddy covariance methods). Comparison between Bowen ratio and eddy covariance led to a RMSE of about 20 $W\,m^{-2}$ for latent heat flux (day + night values).We use the measured net radiation and ground heat flux, the sensible heat flux derived using the aerodynamic method and the latent flux derived from the surface energy balance. Fig. 1 gives the components of the daily surface energy balance. It shows a decrease of the latent heat flux during the growing season, associated with increased water stress. Latent heat flux is sometimes higher than net radiation due to a negative sensible heat flux. Surface soil moisture (0–0.05 m, 0.05–0.1 m, 0.1–0.2 m) was monitored daily or every two days using a gravimetric method. Soil moisture in deeper layers was recorded every two or three days with three replicates using a neutron probe from 0.2 to 1.8 m, every 10 cm. The standard deviation of the values was about 0.02 $m^3\,m^{-3}$ for water content between 005 and 0.15 $m^3\,m^{-3}$ and about 0.005 $m^3\,m^{-3}$ for higher water contents. More details on errors linked to the sampling strategy can be found in Bertuzzi et al. (1994). Soil matric potential was recorded every 2–3 days from 0.1 to 1.8 m, every 10 cm. We used a 1.8 m depth soil column for the simulation, with a bottom boundary condition provided by the measured soil matric potential at 1.8 m, interpolated daily. Comparison of cumulative evapotranspiration derived from the water balance and surface energy budget led to an error of less than 6%, showing the consistency of the whole data set (Brisson et al., 1993). The LAI and vegetation height were measured every two or three days. Root density profiles were observed weekly using a grid method with three replicates (Brisson et al., 1993). More details on the data set can be found in studies published by Brisson et al. (1993), Taconet et al. (1995), Olioso et al. (1996), Wigneron et al. (1999) and Ortega-Farias et al. (2004).

2.6. Criteria to assess model performance

In order to assess model performance as compared to observations, we used the following criteria:

(i) the bias B, measuring the average difference between measurements and model

$$B = \frac{1}{n}\sum_{i=1}^{n}(Y_{i\,\mathrm{mod}} - Y_{i\,\mathrm{obs}}) \tag{17}$$

(ii) the root mean square error RMSE,measuring the scatter between measurements and model.

$$\mathrm{RMSE} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(Y_{i\,\mathrm{mod}} - Y_{i\,\mathrm{obs}})^2} \tag{18}$$

(iii) the efficiency or Nash-Stucliffe coefficient E (Nash and Sutcliffe, 1970) which must be as close as possible to one in order to achieve a good agreement between model and observations. If the efficiency becomes negative, model predictions are worse than a prediction performed using the average of all observations.

$$E = 1 - \frac{\sum_{i=1}^{n}(Y_{i\,\mathrm{mod}} - Y_{i\,\mathrm{obs}})^2}{\sum_{i=1}^{n}(Y_{i\,\mathrm{mod}} - \bar{Y}_{\mathrm{obs}})^2} \tag{19}$$

In the above formula Y_{mod} is the modelled variable, Y_{obs} is the observed one, $\bar{Y}_{\mathrm{obs}}$ its average and n is the number of available measurements.

3. Results

3.1. Comparison of the analytical formulations of the two root extraction modules

The presentation of the modules given in Section 2.2 shows that although the initial formulation given by their authors might appear different, both modules could be written in similar ways, with terms related to the root distribution with depth, to the water stress function and to the compensation mechanism. Fig. 2b gives the comparison of the water stress functions, corresponding to the surface soil water retention curve of the winter wheat data set (Fig. 2a). It shows that for small values of the γ parameter the LK00 model function is comparable to the LI01 function. However, for higher values of the γ parameter (the chosen range for γ spans the range explored by LK00), the LK00 function becomes much less sharp than the LI01 one. The LI01 function depends on

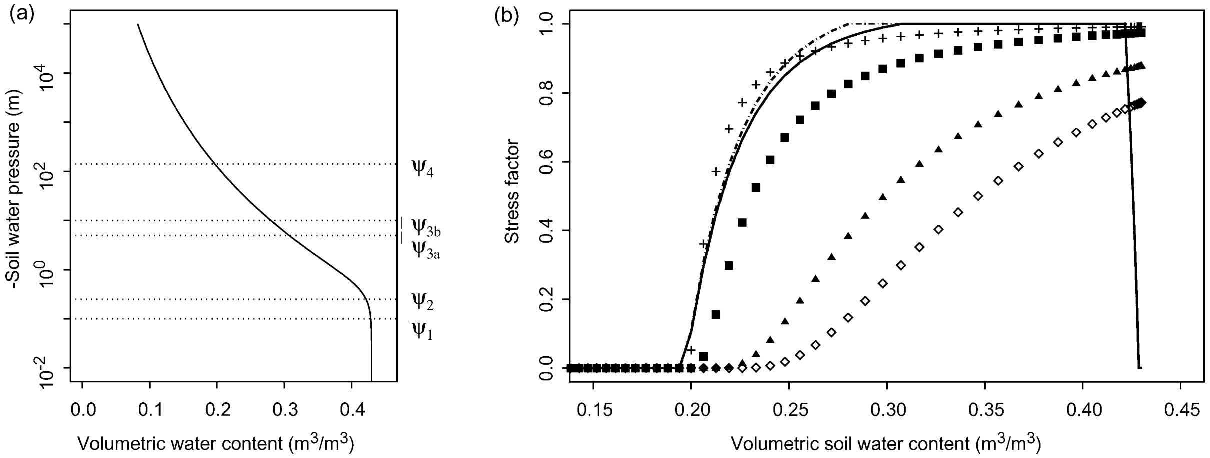

Fig. 2. (a) Soil water retention curve used in the calculation of Figs. 2b and 3. The values of $\psi_1 = -0.1$ m, $\psi_2 = -0.25$ m, $\psi_{3a} = -5$ m for $Tp = 5$ mm day^{-1}, ψ_{3b}=-10 m for $Tp = 1$ mm day^{-1}, $\psi_4 = -140$ m used in the LI01 module are also shown. (b) Comparison of the water stress functions $\alpha_2(\theta,z)$ for the LK00 and LI01 modules. The function is plotted for various values of the γ parameter (crosses: $\gamma = 0.003$; black squares: $\gamma = 0.01$; black triangles: $\gamma = 0.05$; open diamonds: $\gamma = 0.1$) for the LK00 model and for a potential transpiration of 1 (full line) and 5 (dotted line) mm day^{-1} for the LI01 model.

the potential transpiration, but the influence on the water stress function is much less than the influence of the γ parameter in the LK00 module. Note also that the LI01 module accounts for a sharp decrease of transpiration when the water content approaches the saturated value, whereas the LK00 does not.

Fig. 3 shows the comparison of the water stress function $\alpha_2(\theta,z)$, the compensation function $\alpha_1(\theta,z)$, and the total function $\alpha(\theta,z)=\alpha_1(\theta,z)\alpha_2(\theta,z)g(z)$ for a typical soil water content profile and various values of the λ and γ parameters. Remember that λ influences the compensation function, $\alpha_1^{\mathrm{LI}}(\theta,z)$ of the LI01 module and γ the stress function, $\alpha_2^{\mathrm{LK}}(\theta,z)$ of the LK00 module. Fig. 3 shows that, provided the γ value is high (e.g. 0.1), the LK00 water stress function is much more sensitive to change in the soil moisture content than the LI01 module. Changes in the compensation function are also much sharper for the LK00 module than the LI01 one. Consequently, changes in root water uptake will be much sharper for the LK00 module than for the LI01 module, when changes in soil moisture content occur.

LK00 stated that the following constraints had to be fulfilled:

$$\int_0^{z_R} \alpha_1(\theta,z)\alpha_2(\theta,z)g(z)\mathrm{d}z \le 1 \tag{20}$$

$$\frac{1}{z_R}\int_0^{z_R} \alpha_1(\theta,z)\alpha_2(\theta,z)\mathrm{d}z \le 1 \tag{21}$$

On the example presented in Fig. 3, both constrains are fulfilled for the LI01 module with $\lambda=0.5$ or 1, where the integrals values lie between 0.95 and 1, and the LK00 module with $\gamma=0.1$ where the first and second integrals are 0.65 and 0.81, respectively. Such low value of the first integral is mainly associated with low values of the stress function

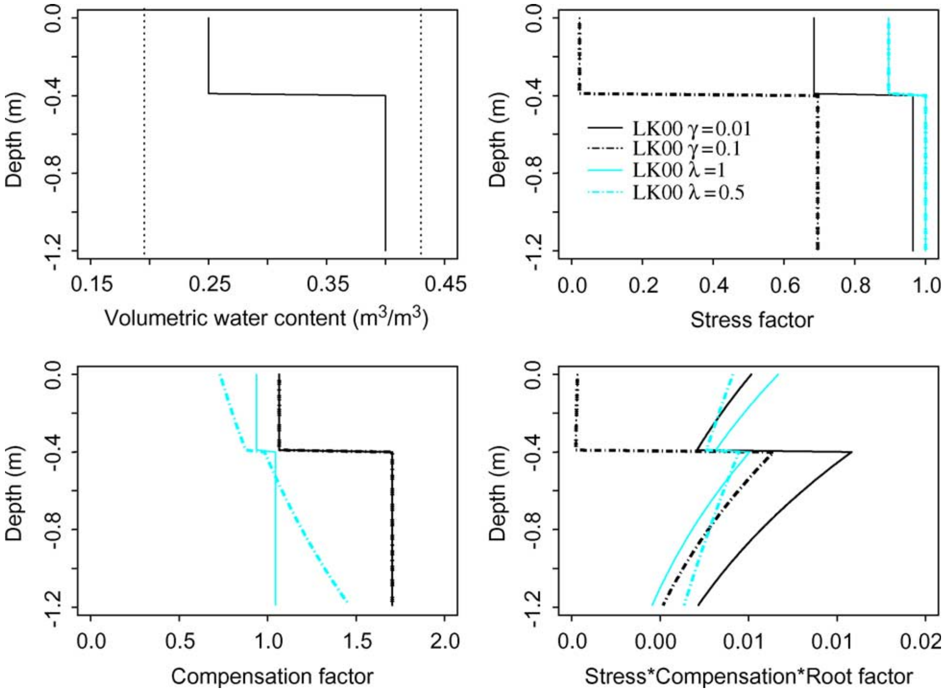

Fig. 3. Comparison of the water stress and compensation functions for the LK00 and LI01 modules. Top left panel: a typical soil moisture profile (full line) was considered. The retention curve is that of Fig. 2a. The vertical bars represent the wilting and saturated water contents. For the LK00 module with $\gamma=0.01$ (full black line), $\gamma=0.1$ (dotted black line) and the LI01 model for $\lambda=1$ (full grey line), $\lambda=0.5$ (dotted grey line), we show: Top right panel: stress function $\alpha_2(\theta,z)$. Note that the LI01 stress function does not depend on λ. Both curves are therefore confounded. Bottom left panel: compensation function $\alpha_1(\theta,z)$. Note that the LK00 compensation function does not depend on γ. Both curves are therefore confounded. Bottom right panel: Stress*compensation*Root density function.

(see Fig. 2). On the other hand, for the LK00 module with $\gamma = 0.01$, the first integral is equal to 1.22, i.e. total transpiration can be higher than the potential value, whereas the second one is equal to 1.35. Note that in the chosen example, only the first term in the *Max* function in Eq. (9) is activated, leading to $\alpha_1^{\mathrm{LK}}(\theta, z) \geq 1$ at all depths. It seems therefore that there is a problem in the formulation of the compensation function. We considered the replacement of the first term

$$\frac{\theta}{\theta_s - \theta_{\mathrm{wilt}}}$$

by

$$\frac{\theta - \theta_{\mathrm{wilt}}}{\theta_s - \theta_{\mathrm{wilt}}}$$

within Eq. (9). However, such a modification led to $\alpha_1^{\mathrm{LK}}(\theta, z) \leq 1$ at all depths and consequently the compensated actual transpiration was necessarily lower than without compensation. We therefore decided to use the LK00 module as presented by their authors for the data sets considered in the remaining of the paper. We must also underline that the stress and compensation function of the LK00 module are much more dependent on the actual values of the soil characteristics than the LI01 module because they use the saturated and wilting water content. The range of these values is much more soil dependent than the matric potential formulation of the LI01 module. Extensive simulation tests using a large range of soil types were performed (Varado et al., 2004) showing problems for the LK00 module on sandy soils. Unfortunately the two data sets used in this study were mainly clayey soils and we were not able to test the models performance under field conditions for more coarser soils.

This formal comparison of the root extraction modules shows that the LK00 module is more sensitive to soil hydraulic properties than the LI00 module, due to stress and compensation factors formulations based on the volumetric water content rather than on the soil matric potential. The consequence is, for the LK00 module, a much sharper decrease of root extraction when soil water content decreases than with the LI01 module. For some soils, the compensation function of the LK00 also fails to fulfill physical constraints on root extraction.

3.2. Reference simulations for the winter wheat and soybean data sets

In order to compare the root extraction modules in optimal conditions, we determined reference parameter sets, leading to the 'best' agreement (in the sense of the statistical criteria listed in Section 2.6) between the model simulation and the observations of the various output variables. These reference simulations are briefly described below.

Estimation of parameters required by the SiSPAT model on the winter wheat data set is reported in Olioso et al. (2002b) and Braud and Chanzy (2001). In the present study however, we replaced the original trapezoidal root density function of the SiSPAT model by the exponential distribution of Eqs. (5) and (6). The time evolution of its parameters, namely the maximum rooting z_R depth, the fraction of roots within the 10 first % of the total rooting depth F_{10} and the surface root density g_o were determined as follows. The rooting depth was assessed from tensiometric and soil moisture measurements (Olioso et al., 2002a and b) and the F_{10} and g_o parameters were calculated so that the exponential root distribution led to the same averaged root density as the one obtained using the trapezoidal shape. We had to perform slight adjustments to some plant parameters (maximum root density and total plant resistance) in order to obtain similar performance of the model, but their discussion is not given here, as the objective is not to discuss the relevance of the SiSPAT model.

Prior to this study, the SiSPAT model had not been applied to the soybean data set. A synthesis of the parameters used in the reference simulation is given in Table 1. We used the same atmospheric forcing and time evolution of the LAI and vegetation height as in previous studies (Olioso, 1992; Calvet et al., 1998; Olioso et al., 1999; Wigneron et al., 1999). Table 1 also gives some statistics comparing model simulation of surface fluxes and observations as well as results obtained in the previous studies. The performance of the SiSPAT model is comparable to the other models and to those obtained for the winter wheat data set.

A restriction to the use of reference simulations is that the 'optimal' parameter set is derived using the structure of the original SiSPAT model, especially its root extraction module. An 'optimal' set of parameters could also have been derived for

Table 1
Parameters used in the SiSPAT reference simulation for the soybean data set

Soil depth	1.8 m			
Bottom boundary condition	Measured time evolution of the soil matric potential and constant soil temperature			
Depths of horizons	0–10 cm	10–25 cm	25–120 cm	120–200 cm
Retention curves	Chanzy (1991) data fitted to the extended Van Genuchten (1980) model (Braud and Chanzy, 2001)		Brisson et al., 1993	
Hydraulic conductivity curves	Chanzy and Bruckler (1993)			
Root density	Derived from rooting depth and hydraulic conductance of Olioso (1992)			
Critical leaf water potential	−165 m Olioso (1992)			
Results	RMSE (W m^{-2}) between model and observation			
Model	*LE*	*H*	R_n	Reference
SiSPAT	47	38	21	Present study
AliBi	43	38	17	Olioso (1992)
AliBi	32	34	–	Olioso et al. (1999) using remote sensing data to optimise the parameters
ISBA	53	–	–	Calvet et al. (1998)
ISBA	40	30	41	Wigneron et al. (1999)

Performance of the model and comparison with other models are also shown.

each of the root extraction module. We chose not to perform the study in this way because our objective was not the evaluation of the whole SiSPAT model but the assessment of each root extraction module individually, everything being equal otherwise, especially soil hydraulic properties. However, we see here the limits of such an exercise. The root extraction modules are not 'self-sufficient' and must be embedded into another more complete model in order to be compared. The drawback is that the assessment of each sub-model performance depends partly on the structure of the complete model. This fact was recognised by Xu and Guo (2003) who showed that the sensitivity of several land surface schemes to one parameter or sub-model was strongly related to the whole model structure. We think that, although dependent on the choice of the SiSPAT model, the results of our study are of broader interest to the hydrology community.

3.3. Results of the root extraction modules on the volumetric soil moisture content, water storage and surface fluxes

Tables 2 and 3 show the statistics calculated between model and observations for the soil moisture content at various depths for the winter wheat and soybean data sets, respectively. Tables 4 and 5 show the statistics calculated on hourly values of net radiation (*Rn*), sensible (*H*), latent (*LE*) and soil (*G*) heat flux. Results are also provided for the soil water storage (*S*) and daily total evaporation (for soybean only). They are presented for the reference simulation using SiSPAT, the LK00 and LI01 with and without (i.e. $\alpha_1^{\mathrm{LK}}(\theta,z)=\alpha_1^{\mathrm{LI}}(\theta,z)=1$) compensation mechanism.

On the winter wheat data set, statistics in Tables 2 and 4 are very close for all the simulations. RMSE for all models are close to the field standard deviation, except near the soil surface where they are slightly larger. As compared to the original SiSPAT model, we can see that the efficiency calculated on soil water content between 45 and 65 cm depth are smaller, whereas they are larger between 75 and 95 cm depth when using the LK00 or LI01 modules. The bias in soil water storage is larger than the original SiSPAT model for all simulations performed using either the LK00 or the LI01 module. For all models RMSE on sensible heat flux is larger than the day + night experimental error but of the same order of magnitude as the daylight error value. The LK00 module without

Table 2
Bias B ($\mathrm{m}^3\ \mathrm{m}^{-3}$), efficiency, *E* and Root Mean Square Error, *RMSE* ($\mathrm{m}^3\ \mathrm{m}^{-3}$) calculated between modelled and observed soil volumetric water content for the winter wheat data set

Depth (cm)	0–15 (20)	25–35 (21)	45–55 (21)	75–85 (21)	95–105 (21)
	Bias B ($\mathrm{m}^3\ \mathrm{m}^{-3}$)				
SiSPAT	0.014	0.010	0.029	−0.007	−0.045
LK00, NC, $\gamma=0.01$	0.016	0.014	0.034	−0.001	−0.039
LI01, NC	0.013	0.012	0.032	−0.004	−0.041
LK00, C, $\gamma=0.01$	0.015	0.013	0.031	−0.004	−0.047
LI01, C	0.012	0.010	0.030	−0.005	−0.042
	Efficiency E				
SiSPAT	0.87	0.94	0.64	0.86	−0.31
LK00, NC, $\gamma=0.01$	0.86	0.90	0.48	0.96	0.03
LI01, NC	0.88	0.94	0.58	0.91	−0.11
LK00, C, $\gamma=0.01$	0.86	0.92	0.59	0.92	−0.11
LI01, C	0.89	0.95	0.61	0.91	−0.13
	Root Mean Square Error, RMSE ($\mathrm{m}^3\ \mathrm{m}^{-3}$)				
SiSPAT	0.027	0.017	0.030	0.015	0.048
LK00, NC, $\gamma=0.01$	0.028	0.022	0.037	0.008	0.041
LI01, NC	0.026	0.017	0.033	0.013	0.045
LK00, C, $\gamma=0.01$	0.028	0.019	0.033	0.012	0.044
LI01, C	0.024	0.016	0.032	0.012	0.045

NC, no compensation; C, compensation. Results are given for the original SiSPAT model (reference) and the LK00 and LI01 root extraction module with and without compensation mechanisms. Figures in brackets are the number of observations used in the calculation of the statistical criteria.

Table 3
Bias *B*, efficiency, *E* and Root Mean Square Error, RMSE calculated between modelled and observed (winter wheat data set) hourly values of net radiation R_n, sensible heat flux *H*, latent heat flux *LE*, soil heat flux *G* and soil water storage over the 0–140 cm layer, *S,* for the original SiSPAT model (reference) and the LK00 and LI01 root extraction module with and without compensation mechanisms

	R_n (3714)	*H* (1112)	*LE* (1112)	*G* (3689)	*S* (20)
	Bias *B* ($\mathrm{W\ m}^{-2}$)			Bias *B* (mm)	
SiSPAT	−7.8	1.4	−1.9	0.1	2.3
LK00, NC, $\gamma=0.01$	−8.2	5.3	−7.1	0.2	8.9
LI01, NC	−8.1	3.8	−5.0	0.2	6.6
LK00, C, $\gamma=0.01$	−8.0	2.2	−4.0	0.2	5.6
LI01, C	−8.2	2.7	−4.4	0.2	−5.5
	Efficiency E				
SiSPAT	0.96	0.49	0.88	0.61	0.97
LK00, NC, $\gamma=0.01$	0.96	0.46	0.86	0.60	0.94
LI01, NC	0.96	0.48	0.87	0.61	0.96
LK00, C, $\gamma=0.01$	0.96	0.49	0.88	0.60	0.96
LI01, C	0.96	0.47	0.87	0.61	0.96
	RMSE ($\mathrm{W\ m}^{-2}$)			*RMS*E (mm)	
SiSPAT	39.5	47.2	36.0	28.0	11.0
LK00, NC, $\gamma=0.01$	39.3	48.8	37.9	28.3	16.4
LI01, NC	39.4	47.8	36.5	28.0	13.9
LK00, C, $\gamma=0.01$	39.5	47.1	39.1	27.1	12.8
LI01, C	39.7	48.8	36.7	27.8	12.9

NC, no compensation; C, compensation. *B* and *RMSE* are given in $\mathrm{W\ m}^{-2}$ for fluxes and mm for soil water storage. Figures in brackets are the number of observations used in the calculation of the statistical criteria.

Table 4
Bias B ($m^3\ m^{-3}$), efficiency, *E* and Root Mean Square Error, *RMSE* ($m^3\ m^{-3}$) calculated between modelled and observed (neutron probe soundings) soil volumetric water content for the soybean data set

Depth (cm)	0–5 (16)	10–20 (16)	30–40 (16)	50–60 (16)	70–80 (16)	80–90 (16)
	Bias B ($m^3\ m^{-3}$)					
SiSPAT	−0.017	0.004	−0.007	−0.004	−0.021	−0.031
LK00, NC, $\gamma=0.01$	−0.026	−0.036	0.001	0.021	0.009	−0.005
LI01, NC	−0.018	0.010	0.001	0.014	0.004	−0.008
LK00, C, $\gamma=0.01$	−0.012	−0.003	−0.006	0.006	−0.006	−0.018
LI01, C	−0.018	0.008	−0.000	0.009	−0.013	−0.028
	Efficiency E					
SiSPAT	0.84	0.76	0.89	0.98	0.47	−1.17
LK00, NC, $\gamma=0.01$	0.67	−0.66	0.96	0.73	0.91	0.95
LI01, NC	0.79	0.51	0.94	0.87	0.97	0.87
LK00, C, $\gamma=0.01$	0.78	0.74	0.89	0.98	0.93	0.31
LI01, C	0.82	0.63	0.90	0.96	0.75	−0.80
	Root Mean Square Error, RMSE ($m^3\ m^{-3}$)					
SiSPAT	0.024	0.016	0.014	0.006	0.024	0.036
LK00, NC, $\gamma=0.01$	0.034	0.043	0.038	0.023	0.010	0.005
LI01, NC	0.027	0.033	0.010	0.016	0.005	0.009
LK00, C, $\gamma=0.01$	0.029	0.017	0.013	0.007	0.009	0.020
LI01, C	0.025	0.020	0.013	0.009	0.017	0.033

NC, no compensation; C, compensation. Results are given for the original SiSPAT model (reference) and the LK00 and LI01 root extraction module with and without compensation mechanisms. Figures in brackets are the number of observations used in the calculation of the statistical criteria.

Table 5
Bias *B*, efficiency, *E* and Root Mean Square Error, RMSE calculated between modelled and observed (soybean data set) hourly values of net radiation R_n, sensible heat flux *H*, latent heat flux *LE*, soil heat flux *G* and daily evapotranspiration and soil water storage over the 0–140 cm layer, *S,* for the original SiSPAT model (reference) and the LK00 and LI01 root extraction module with and without compensation mechanisms

	R_n (1176)	*H* (1176)	*LE* (1176)	*G* (1176)	Daily evapotranspiration (49)	*S* (16)
	Bias B ($W\ m^{-2}$)				*Bias B* (mm)	
SiSPAT	6.3	1.9	−0.9	5.6	−0.03	−13.0
LK00, NC, $\gamma=0.01$	4.7	10.9	−12.6	5.9	−0.44	−1.7
LI01, NC	4.2	11.1	−12.8	5.9	−0.63	−3.4
LK00, C, $\gamma=0.01$	4.8	8.4	−9.3	5.7	−0.33	−5.7
LI01, C	5.7	2.5	−2.4	5.6	−0.08	−7.5
	Efficiency E					
SiSPAT	0.99	0.57	0.87	0.85	0.64	0.86
LK00, NC, $\gamma=0.01$	0.99	0.40	0.85	0.84	0.59	0.99
LI01, NC	0.99	0.33	0.83	0.84	0.54	0.96
LK00, C, $\gamma=0.01$	0.99	0.47	0.86	0.84	0.64	0.96
LI01, C	0.99	0.54	0.87	0.85	0.65	0.95
	Root Mean Square Error, RMSE ($W\ m^{-2}$)				*RMSE* (mm)	
SiSPAT	21.2	38.0	47.3	21.9	0.85	14.2
LK00, NC, $\gamma=0.01$	20.1	44.9	51.1	22.2	0.92	4.3
LI01, NC	19.9	47.4	52.9	22.0	0.97	7.3
LK00, C, $\gamma=0.01$	20.4	42.2	49.1	22.0	0.85	7.0
LI01, C	20.9	39.3	47.2	21.8	0.84	8.6

NC, no compensation; C, compensation. *B* and RMSE are given in $W\ m^{-2}$ for fluxes and mm for soil water storage. Figures in brackets are the number of observations used in the calculation of the statistical criteria.

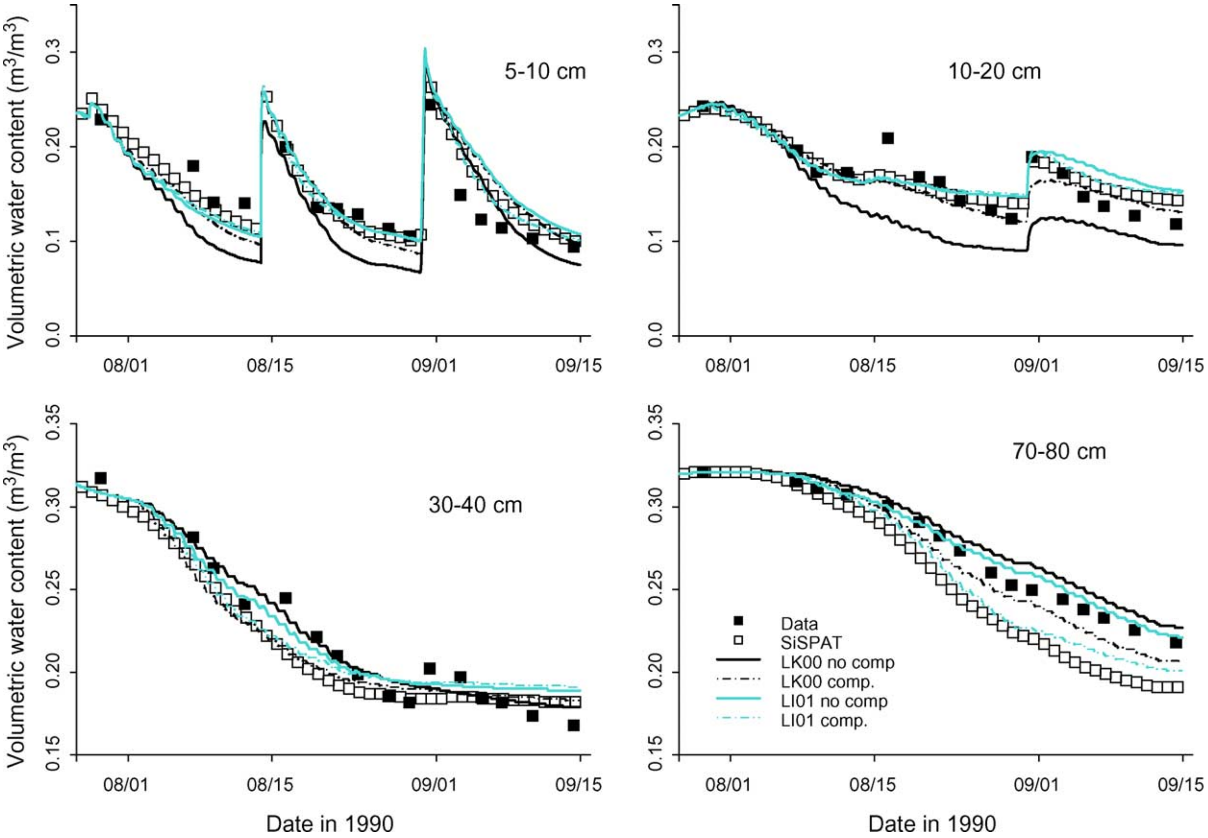

Fig. 4. Time evolution of the observed (squares) and simulated soil water content at various depths for the soybean data set. The open squares show the SiSPAT reference simulation. The full and dashed black curves correspond to the LK00 ($\gamma=0.01$) simulation without and with compensation, respectively. The full and dashed grey curves correspond to the LI01 simulation without and with ($\lambda=0.5$) compensation, respectively.

compensation leads to slightly poorer statistics, but all models perform well.

On the soybean data set, differences between the simulations are more noticeable (see Fig. 4). When no compensation is considered, efficiency on soil water content is generally smaller and RMSE generally higher, except below 70 cm depth, especially for the LK00 module. RMSE on soil moisture is larger than the field standard deviation down to 30 cm and lower for deeper depths, showing that model errors are not significant for deeper layers. Statistics on soil moisture obtained using the LI01 module with compensation are very close to that of the original SiSPAT model and are very good, except below 70 cm depth where they are better than SiSPAT (Fig. 4). On the sensible and latent heat flux and especially daily evapotranspiration, the LK00 and LI01 modules without compensation show poorer statistics, whereas the original SiSPAT model and the LK00 and LI01 modules with compensation lead to similar results. The RMSE on latent heat flux is about twice that of the measurement error for all models. On the other hand, the bias on soil water storage is the highest, and efficiency the poorest, using the original SiSPAT model, whereas the use of the LK00 and LI01 modules with or without compensation leads to better statistics on this quantity. These results can be associated with the underestimation of soil moisture in deeper layers by the original SiSPAT model. This result shows that evaluation of model performance using several criteria is necessary to better analyse the strengths and weaknesses of the various models.

Differences between both data sets can be related to differences in the water stress. Indeed, when water is not a limiting factor or stress is moderate, both modules are constrained by the transpiration derived from the SiSPAT energy balance and performance is expected to be similar (as for the winter wheat data set). On the other hand, when additional water stress occurs and transpiration cannot be fulfilled by root extraction, the modules behave differently with respect to decreasing plant transpiration. This is certainly the case for the soybean crop.

The discussed statistics only provide an average view of the model behaviour. In order to better analyse the compensation mechanism, Fig. 5 shows the comparison of simulated and observed soil water content profiles at 4 dates for the soybean data set. For the winter wheat data set, differences between the profiles simulated with or without compensation are small and are not shown here. For both the LK00 and LI01 modules, differences between simulated profiles with or without compensation are larger as the soil dries out, especially for the LI01 module. For all profiles, the compensation mechanism of the LK00 module leads to higher soil moisture close to the surface and lower values in deeper layers. The drying front is deeper with compensation, showing, as expected, that root extraction is favoured in deeper layers when compensation is taken into account. For the LI01 module, the compensation mechanism is not very active on August 7 because the profiles with or without compensation are very similar. The compensation mechanism of the LI01 module tends to deplete soil moisture in deeper layers more rapidly than the LK00 module and more rapidly than without compensation. Similar results were presented by Li et al. (2001) on a 27-year long-term data set.

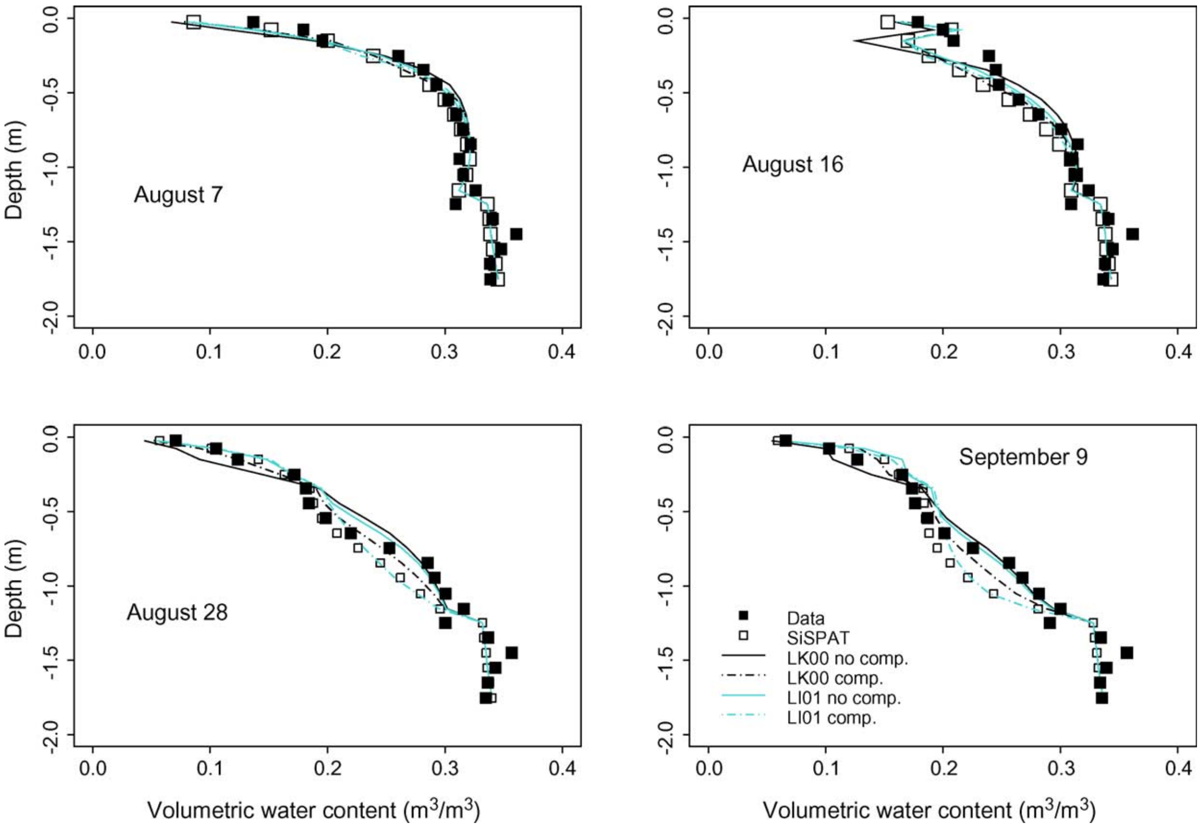

Fig. 5. Soil volumetric water content ($m^3\ m^{-3}$) profiles for various dates during the soybean experiment. Black squares are observations. Open squares show the SiSPAT reference simulation. The full and dashed black curves correspond to the LK00 ($\gamma=0.01$) simulation without and with compensation, respectively. The full and dashed grey curves correspond to the LI01 simulation without and with ($\lambda=0.5$) compensation, respectively.

However, conversely to the LK00 module, soil moisture content of surface layers with or without compensation is very close. Profiles simulated using the LI01 module with compensation are very close to those of the SiSPAT reference simulation and depletion of deeper layers seems to be too active on September 9. Note however that on August 28 and September 9 the LI01 without compensation leads to a better agreement with observations than when compensation is taken into account. Such feature is also noticeable on Fig. 4 (bottom right panel). Li et al. (2001) showed that deep soil moisture was overestimated when no compensation mechanism was considered in their case study. In our case, the LI01 module with compensation leads to an underestimation of deeper layers soil moisture, whereas it is better simulated without compensation.

The evaluation of the compensation mechanisms proposed by LK00 and LI01 shows that they are generally efficient in improving simulated soil moisture content profile and total evaporation flux, although simulations without compensation also lead to satisfactory results. Compensation is even too high, depleting deeper layers too much with the LI01 model. The mathematical problem identified in Section 3.1 for the LK00 module does not lead to overestimation of transpiration as might have been feared. On the contrary, the LK00 module leads to lower transpiration rates than the LI01 and SiSPAT models (see also Section 3.4). The present evaluation of the compensation mechanisms confirms previous results of their authors on independent data sets. Furthermore, the stress conditions encountered in both experiments allowed a comprehensive testing of the root extraction modules.

3.4. Sensitivity of the results to the γ and λ parameters

Table 6 shows, for the soybean data set, the values of the efficiency between modelled and observed soil moisture content at representative depths and soil water storage for different values of the γ and λ parameters, chosen in the range proposed by LK00 and LI01 respectively. Cumulative values of transpiration, evaporation and total evapotranspiration are also provided. Results on the winter wheat data set were very similar and are not shown here. Remember that the γ parameter of the LK00 module influences the water stress function (Eq. (10)) whereas the λ parameter of the LI01 module influences the compensation function (Eq. (11)). Results without compensation mechanisms are also given for comparison (note that for the LK00 module a value of γ must be specified even without compensation

Table 6
Sensitivity of calculated efficiency of soil moisture content at representative depth, daily evapotranspiration and soil water storage to the γ and λ parameters of the LK00 and LI01 modules (left)

	Efficiency E					Cumulative values (mm)				
	0–5	5–10	10–20	30–40	70–80	Storage	Daily E_{tot}	Transpiration	Evaporation	Total evaporation
SiSPAT	0.84	0.73	0.76	0.89	0.47	0.86	0.64	163	51	221
	Sensitivity to γ for the LK00 module									
NC, $\gamma=0.01$	0.67	0.24	−0.66	0.96	0.91	0.99	0.59	145	49	201
C, $\gamma=0.003$	0.74	0.45	0.57	0.82	0.93	0.95	0.64	152	50	210
C, $\gamma=0.01$	0.78	0.46	0.74	0.89	0.93	0.96	0.64	149	51	207
C, $\gamma=0.05$	0.83	0.27	0.02	0.60	0.91	0.82	0.29	114	54	175
C, $\gamma=0.1$	0.85	0.06	−1.61	−0.09	0.54	0.31	−0.37	87	56	151
	Sensitivity to λ for the LI01 module									
LI01, NC	0.79	0.44	0.51	0.94	0.97	0.96	0.54	133	52	192
C, $\lambda=0.1$	0.82	0.73	0.64	0.91	0.80	0.95	0.65	161	51	220
C, $\lambda=0.5$	0.82	0.71	0.63	0.90	0.75	0.95	0.63	161	51	219
C, $\lambda=0.75$	0.81	0.67	0.60	0.89	0.68	0.94	0.66	159	51	217
C, $\lambda=2.0$	0.80	0.54	0.41	0.86	0.58	0.96	0.66	154	51	212

NC, no compensation; C, compensation. Cumulative values of transpiration, evaporation and total evapotranspiration are also provided (right). Interception was about 5 mm and is not shown. Soybean data set.

whereas the simulation without compensation is independent of λ for the LI01 module).

Table 5 shows that the γ parameter of LK00 module is influential on the calculated partition between transpiration and evaporation. We obtain a decrease of 65 mm for transpiration and an increase of 6 mm for evaporation when γ is decreased from 0.003 to 0.1. Changes in the λ parameter of the LI01 module induce a change of less than 10 mm for both quantities. The partition between transpiration and evaporation calculated using the LI01 module is very close to the one calculated using the SiSPAT reference model. The LK00 module leads to lower transpiration and total evaporation amounts. For the LK00 and LI01 modules transpiration (and total evaporation) is increased when compensation is taken into account. For the LK00 module, the parameterisation of the water stress function through the γ parameter choice seems however to be much more influential than taking into account a compensation mechanism. On the other hand, the LI01 module compensation mechanism is efficient in increasing transpiration.

An increase of γ leads to better efficiencies for surface layers soil moisture, at the expense of a lower efficiency for deeper layers. An optimum value of γ can be found for soil moisture storage and evapotranspiration prediction using a value of $\gamma=0.01$.For the LI01 module, the lowest value of λ led to the best agreement with measured soil moisture at all depths. However soil water storage and daily evapotranspiration were equally well predicted for all values of λ.

The value of $\lambda=0.5$ proposed as a standard by LI01 leads to satisfactory results both on soil moisture and daily evaporation, with a relatively low sensitivity of model results on this parameter. On the other hand the γ parameter is much more influential and the parameterisation of the water stress function has a larger impact on model results. A value of $\gamma=0.01$ provides the best agreement between measured and modelled values. This value was also obtained by LK00 on their data set.

3.5. What is lost when ‘potential transpiration’ is used instead of the surface energy balance?

The previous results were obtained while the actual transpiration was determined from the solution of the surface energy balance. The second step in our study was to estimate the loss of accuracy on calculated transpiration and soil moisture when potential evapotranspiration is used as input instead of solving the surface energy balance. The results for the winter wheat and soybean data appear in Tables 7 and 8, respectively, where we show results using both the FAO and SiSPAT E_p as direct input or when the energy budget is solved (simulations discussed in Section 3.4). When FAO (1998) formula (without accounting for crop coefficients) is used for evaluating

Table 7

Comparison, for the LK00 and LI01 modules, of simulations with the solution of the surface energy balance (Energy balance) and the use of two potential evapotranspiration estimates (FAO E_p and SiSPAT E_p) on efficiency of soil moisture content at representative depth and soil water storage (left)

	Efficiency *E*				Cumulative values (mm)			
	0–15	15–25	45–55	75–85	Storage	Transpiration	Evaporation	Total evapotranspiration
LK00 $\gamma=0.01$								
Energy balance	0.86	0.86	0.59	0.92	0.97	231	119	355
SiSPAT E_p	0.67	0.62	0.31	0.95	0.89	210	109	323
FAO E_p	0.64	0.60	0.24	0.95	0.84	193	114	310
LI01 $\lambda=0.5$								
Energy balance	0.89	0.90	0.61	0.91	0.96	237	112	355
SiSPAT E_p	0.68	0.64	0.91	0.94	0.84	201	106	311
FAO E_p	0.66	0.61	0.88	0.90	0.78	180	112	295

Cumulative values of transpiration, evaporation and total evapotranspiration are also provided (right). Interception was about 7 mm and is not shown. Winter wheat data set.

Table 8
Comparison, for the LK00 and LI01 modules, of simulations with the solution of the surface energy balance (Energy balance) and the use of two potential evapotranspiration estimates (FAO E_p and SiSPAT E_p) on efficiency of soil moisture content at representative depth, soil water storage and daily evapotranpiration (Daily E_tot) (left)

	Efficiency E					Cumulative values (mm)				
	0–5	5–10	10–20	30–40	70–80	Storage	Daily E_tot	Transpiration	Evaporation	Total evaporation
	LK00 γ = 0.01									
Energy balance	0.78	0.46	0.74	0.89	0.93	0.96	0.64	149	51	207
SiSPAT E_p	0.78	0.17	0.52	0.90	0.73	0.96	0.53	158	48	211
FAO E_p	0.42	−0.70	−1.72	0.92	0.98	0.88	0.45	132	46	182
FAO E_p*1.15	0.58	−0.31	−0.37	0.91	0.96	0.96	0.60	140	47	192
FAO E_p*1.4	0.70	0.11	0.59	0.86	0.79	0.95	0.70	151	48	205
	LI01 λ = 0.5									
Energy balance	0.82	0.71	0.65	0.90	0.75	0.95	0.65	161	51	219
SiSPAT E_p	0.89	0.74	0.60	0.91	0.44	0.89	0.23	186	47	237
FAO E_p	0.60	0.07	−0.35	0.87	0.98	0.89	0.50	139	45	189
FAO E_p*1.15	0.74	0.38	0.20	0.90	0.93	0.98	0.67	154	46	205
FAO E_p*1.4	0.84	0.67	0.56	0.85	0.39	0.87	0.69	176	43	229

potential transpiration, the decrease in simulated transpiration (and evapotranspiration) is large, especially for the winter wheat data set. Calculated efficiencies are smaller than when the surface energy balance is solved, except for the deeper layers soil moisture.

When the SiSPAT E_p is used, the same tendency is obtained for the winter wheat data set, except that the decrease in transpiration is smaller than with the FAO E_p. On the other hand, transpiration is increased for the soybean data set but efficiencies on soil moisture (except the 30–40 cm depth layer) and daily evaporation are poorer than when the surface energy balance is solved. This result is explained by the night SiSPAT E_p being positive (it was zero with the FAO E_p) and implying a non zero transpiration at night. When the surface energy balance is solved, actual transpiration at night is closed to zero.

Jamieson and Ewert (1999) pointed out an underestimation of the 'potential transpiration' by the Penman equation and recommended the use of the Penman–Monteith equation. Allen et al. (1994) refer to various studies showing overestimation of the 'potential' value by the Penman equation and better performance using the Penman–Monteith equation. Their recommendations were followed when defining FAO (1998) reference evapotranspiration, based on the Penman–Monteith equation. The FAO formula is valid for a reference crop (hypothetical well watered grass) and its use for any crop must take into account crop coefficient factors. For the soybean data set, field estimates gave a value of 1.4 for the crop coefficient. Its use in the simulation of the soybean data set improves the results as compared to the FAO E_p only (see Table 8). However, the use of standard values provided by FAO (1998) tables gives a maximum value of 1.15 for this coefficient. Such a value would still lead to underestimation of actual transpiration as compared to the solution of the surface energy balance (Table 8). A value of the crop coefficient close to 1.4 for the LK00 and LI01 modules respectively leads to results similar to those obtained by solving the energy budget. It shows that the determination of such coefficients without information on soil moisture evolution is difficult.

4. Conclusions

In this paper two root water uptake modules with compensation mechanisms were assessed against two data sets collected on water stressed crops. These two modules were included within the SiSPAT model. When the surface energy balance was solved, both modules were quite successful in reproducing the time evolution of soil water storage, daily evaporation and soil moisture at various depths. When a compensation mechanism was included, performance was generally improved as compared to simulations without compensation. The LK00 module was sensitive to the specification of its water stress function parameter, a value $\gamma = 0.01$ leading to the best performance. The smaller sensitivity of the LI01 module to its compensation parameter λ lead to the recommendation of its use in areas with little information on plant cover and physiology and for its inclusion into larger scale water balance models.

Our study showed however that, when the root extraction modules were used in the way they were conceived, i.e. with a potential evapotranspiration instead of the surface energy balance, the efficiency on soil water content, soil water storage and daily evapotranspiration was significantly lower. Transpiration was underestimated using the FAO potential evapotranspiration and even the use of standard crop coefficient did not solve the problem completely. The uncertainty induced by the choice of the 'correct' potential evapotranspiration appears much larger than the differences between root extraction modules. This raises the question of the generalisation of such E_p models to large-scale area water balance models. The uncertainty of potential evapotranspiration and crop coefficients should be assessed in order to obtain correct water balance results. There is clearly a difficulty in deriving a relevant potential evapotranspiration for any crop, from the value calculated for well-watered grass. More attention should be devoted to this problem, given the evolution of its use in hydrological models, more and more used in a continuous way, rather than on an event-based mode, requiring a better handle of the evapotranspiration component. A way to overcome this difficulty, although it is much more data demanding, could be to generalise the solution of the surface energy balance in hydrology and water balance modelling framework.

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