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Calibration of a coupled canopy functioning and SVAT model in the ReSeDA experiment. Towards the assimilation of SPOT/HRV observations into the model

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Abstract – In the framework of the Alpilles-ReSeDA experiment [12], a coupled canopy functioning and SVAT model was used to simulate wheat crops. Each sub-model was first initialized and calibrated separately, using literature and ground measurements. The model was then run in coupled mode and gave reasonable results in terms of vegetation model outputs. The results were less satisfactory for the SVAT outputs. As a conclusion we pointed out that the SPOT/HRV measurements could be used through a calibration procedure to retrieve some of the growth model key parameters.

functioning model / SVAT model / remote sensing / assimilation / ReSeDA

Résumé – Calage d'un modèle couplé de fonctionnement du couvert et de SVAT dans l'expérience ReSeDA. Vers l'intégration des observations SPOT/HRV dans le modèle. Dans le cadre de l'expérimentation Alpilles-ReSeDA, un modèle couplé de fonctionnement du couvert et de SVAT a été utilisé pour simuler les cultures de blé. Chaque sous-modèle a été tout d'abord initialisé et calé séparément en utilisant les données de la littérature et les mesures au sol. Le modèle a ensuite été utilisé en mode couplé et a donné des résultats raisonnables en terme de sortie de modèle de végétation. Les résultats ont été moins satisfaisants pour les sorties du modèle SVAT. En conclusion, nous avons mis en évidence que les mesures SPOT/HRV peuvent être utilisées à travers une procédure de calage pour fournir un certain nombre de paramètres-clés des modèles de croissance.

modèle de fonctionnement / modèle SVAT / télédétection / assimilation / ReSeDA

1. INTRODUCTION

Crop growth models are commonly used to describe the crop seasonal dynamics. In water stress conditions, the simulation of the water available for the plant throughout the season is of great importance. Similarly, the seasonal development of plant canopies controls evapotranspiration rates. This makes the plant and soil a fully coupled system. In this study, our main objective was to simulate the seasonal course of soil moisture and plant biomass for crops. The methodology consists in coupling a SVAT model (hereafter

S) to a canopy functioning model (hereafter V). The resulting coupled canopy functioning and SVAT model (hereafter V-S) simulates the vegetation growth, as well as the surface energy and water fluxes, with an hourly time step over the whole growing season. An alternative to the use of ground based measurements for calibrating the coupled model was suggested. This alternative consists in constraining the model with satellite observations. The use of such vegetation/SVAT models over different crops and fields requires, for each field, the knowledge of a large set of model parameters. Remote sensing data are of great interest if they can be used to fit

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some of those field-specific parameters. Here we proposed to use satellite optical measurements in combination with the coupled model, through the assimilation technique, in order to simulate the seasonal dynamics of a wheat crop. The radiometric signal was computed by linking the coupled V-S model to a radiative transfer scheme. We investigated the feasibility of such techniques by retrieving two key parameters of the V-S model. The paper is organized as follows: the results section is structured in 3 parts. The first part describes the calibration of the S sub-model and evaluates the results against measurements of the water and energy budget components. The second part presents the calibration of the V sub-model and evaluates the simulation using biological measurements. The simulation in coupled mode (V-S) is then presented. Finally, a way to calibrate the V-S model using the assimilation of SPOT/HRV measurements was investigated.

2. MATERIALS AND METHODS

The Alpilles-ReSeDA (Remote Sensing Data Assimilation) project [12] aims at developing methods to improve the monitoring of soil and vegetation. The main technique consists of assimilating remotely sensed data into soil and crop functioning models, taking advantage of the multi-temporal, multi-spectral or multi-angular characteristics of the observations. The experiment consists in ground, airborne and satellite measurements collected over a whole crop growing season (1996/1997) on a site located in the South-East of France (N 43°47', E 4°45'), namely the Alpilles test site. Sixteen fields were concerned (wheat, sunflower and alfalfa) with 3 different levels of investigations ("calibration", "validation" and "remote sensing" fields). The work presented here focuses on a "calibration" wheat field of this experiment, referred to as field 101. This field was sown on 7 November 1996 (Day of Experiment (DoE) 312 (DoE 1 is 1st of January 1996)) with Armet cultivar. The ReSeDA project federated several European teams which worked on the determination of the appropriate SVAT model parameters (see [10]).

A detailed description of the vegetation/SVAT model is given in [3]. The V sub-model provides the leaf area index (LAI), which is used by the SVAT in the computation of the energy partitioning between soil and vegetation as well as in the parameterization of turbulent transport and evapotranspiration. The SVAT sub-model updates the soil water content in the root zone. In turn, the soil water content impacts plant physiology through the stomatal conductance. The stomatal conductance is shared by two sub-models, to compute transpiration and photosynthesis. The simulation of the satellite radiometric signal was obtained by coupling the V-S model with the SAIL [16] reflectance model.

The V-S model is controlled by the environment forces (air temperature, humidity, wind speed, rainfall, solar radiation), by soil parameters such as soil texture (% clay, % sand), soil thermal properties, root depth, and by vegetation parameters (Specific Leaf Area, maximum rate of photosynthesis, etc.). The soil and the vegetation are considered as

two different sources of latent and sensible heat fluxes [13]. The incoming energy is partitioned between bare soil and vegetation through a shielding factor [15]. The scheme uses the force-restore method for soil heat and water content [6], the coefficients being functions of soil texture [8].

The coupled model has been validated in different situations, mainly for grasslands [3, 4]. Since this model is not crop-specific, in this study, most of the growth model parameters were prescribed according to calibrated crop models, namely AFRCWHEAT [11] and SUCROS [14].

3. RESULTS

The S and V sub-models were first initialized and calibrated separately using literature and ground measurements. The SVAT sub-model predictions were compared to soil water content and energy flux measurements, while the canopy functioning sub-model simulations were compared to the LAI and biomass data. The model was also run in coupled mode and compared to the ground measurements. The calibration of the coupled model with SPOT/HRV data was investigated.

3.1. SVAT model calibration

The SVAT was calibrated with data from the wheat calibration field number 101. In order to test the S sub-model, the LAI used in the simulation came from the measurements. Due to the large variability in the LAI2000 dataset values, we used the LAI data obtained from the destructive measurements with a surface-meter, although there were only measurements available for the leaves and not for other green organs. Surface and root zone soil moisture were initialized using gravimetric measurements (for the surface) and neutron probe data (for the root zone). The soil surface resistance of the ground was parameterized as a function of the surface soil moisture, after Chanzy [5]. The soil characteristics such as field capacity, wilting point and humidity at saturation were prescribed according to values proposed by [1]. The soil moisture was measured from 0 to 140 cm (depth) for wheat. The maximum root depth was prescribed according to this value. Most of the input parameter values are reported in Table I and were prescribed by the SVAT group of the ReSeDA program [10].

Figure 1 shows the simulated bulk water content compared to the measurements performed with the neutron probe technique over 0–140 cm, for the wheat calibration field. The simulated energy fluxes were compared to the measurements for field 101, for the whole growing period. As an illustration, a comparison of measured and simulated fluxes is shown in Figure 2 for a 10-day period. Due to some failures in the instrumentation, latent heat flux and sensible heat flux were computed with the Bowen ratio method using 2 sets of temperature gradients from 2 different devices (see [9] for details).

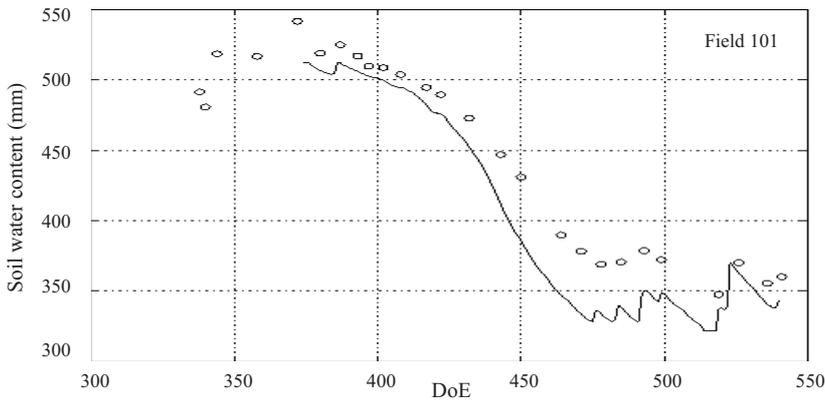


Figure 1. Measured (o) and S-model simulated (-) soil water content, wheat calibration field (101).

Table I. SVAT input parameters.

Field	101
Depth (cm)	140 or 200
% clay	41.8
% silt	53.9
% sand	4.3
Dry bulk density ($\text{g}\cdot\text{cm}^{-3}$)	1.6
Saturated water content ($\text{m}^3\cdot\text{m}^{-3}$)	0.39
Wilting point ($\text{m}^3\cdot\text{m}^{-3}$)	0.23
Field capacity ($\text{m}^3\cdot\text{m}^{-3}$)	0.366
Minimum stomatal resistance ($\text{s}\cdot\text{m}^{-1}$)	75
Vegetation albedo	0.22
Soil albedo	f(wg*)
Vegetation emissivity	0.98
Soil emissivity	0.96

* wg: surface soil moisture.

Table II. Canopy functioning model input parameters.

Green biomass initial value ($\text{kgC}\cdot\text{m}^{-2}$)	0.0039
Minimal stomatal resistance ($\text{s}\cdot\text{m}^{-1}$)	75
Growth respiration coefficient (unit less)	0.34
Maintenance respiration coefficient ($\text{kgC}\cdot\text{kgC}^{-1}\cdot\text{d}^{-1}$)	0.002
Quantum yield ($\mu\text{molCO}_2\cdot\mu\text{molPAR}^{-1}$)	0.044
Maximum rate of leaf photosynthesis ($\mu\text{molCO}_2\cdot\text{m}^{-2}\cdot\text{s}^{-1}$)	44
Initial Specific Leaf Area ($\text{m}^2\cdot\text{kgC}^{-1}$)	40

Considering that the maximum root depth proved to be approximately 2 meters for the wheat, and 6 m for alfalfa, these results are reasonably good in terms of soil moisture.

3.2. Canopy functioning model calibration

Because of the availability of eco-physiological parameters in the literature, we mainly focused on wheat for the V model calibration. In order to test the V sub-model, the root zone soil moisture was prescribed according to neutron probe measurements integrated over 0–140 cm.

On the first day of the simulation, the green biomass value was initialized with the first measured value of aboveground green biomass. The minimal stomatal resistance, growth and maintenance respiration coefficient, quantum yield and maximum rate of leaf photosynthesis were set as prescribed in the AFRCWHEAT model [11] or SUCROS model [14]. To preserve the simple structure of a generic vegetation growth model, we used a single green aboveground pool (no distinction was made between leaves, stems, tillers and collar). The main phenological stages were prescribed according to the observed distribution of the biomass in the different organs. Three periods were distinguished: (i) the initial period: from the beginning of the simulation to the day when the amount of biomass allocated to the green parts begins to decrease ($t_1=\text{DoE } 410$), (ii) from t_1 to the beginning of the grain filling ($t_2=\text{DoE } 460$), and (iii) from t_2 to the end of the simulation. For each phenological stage and each organ (aboveground green biomass, ear, root), dry matter allocation coefficients were prescribed according to SUCROS values. The relationship between the SLA and green biomass was derived from destructive LAI and green biomass measurements. The SLA value was found to be $40 \text{ m}^2/\text{kgC}$ at a low level of biomass. The main V model input parameters are reported in Table II.

Figure 3 shows the simulation of leaf area index and green biomass as compared with ground measurements (green leaves, stems, tiller and collar), and Figure 4 shows the temporal course of the total aboveground biomass (green biomass, phytomass and ears) and ear biomass. The model was found to be sensitive to several parameters like the SLA at a low biomass level (see [3]). When accurate values of these parameters are available, the agreement between the prediction and the data is good: root mean square errors are 0.19 for the LAI during the growing period, 0.021 for green biomass and 0.035 for aboveground biomass.

Finally, after calibrating the S and V models for field 101, the fully coupled V-S model was run. Despite the lack of soil moisture measurements in deep layers, the observed maximum rooting depth was used in this simulation (root depth of 200 cm), in accordance with real conditions. The simulation obtained with the coupled model for field 101 is in good agreement with measurements in terms of the LAI and

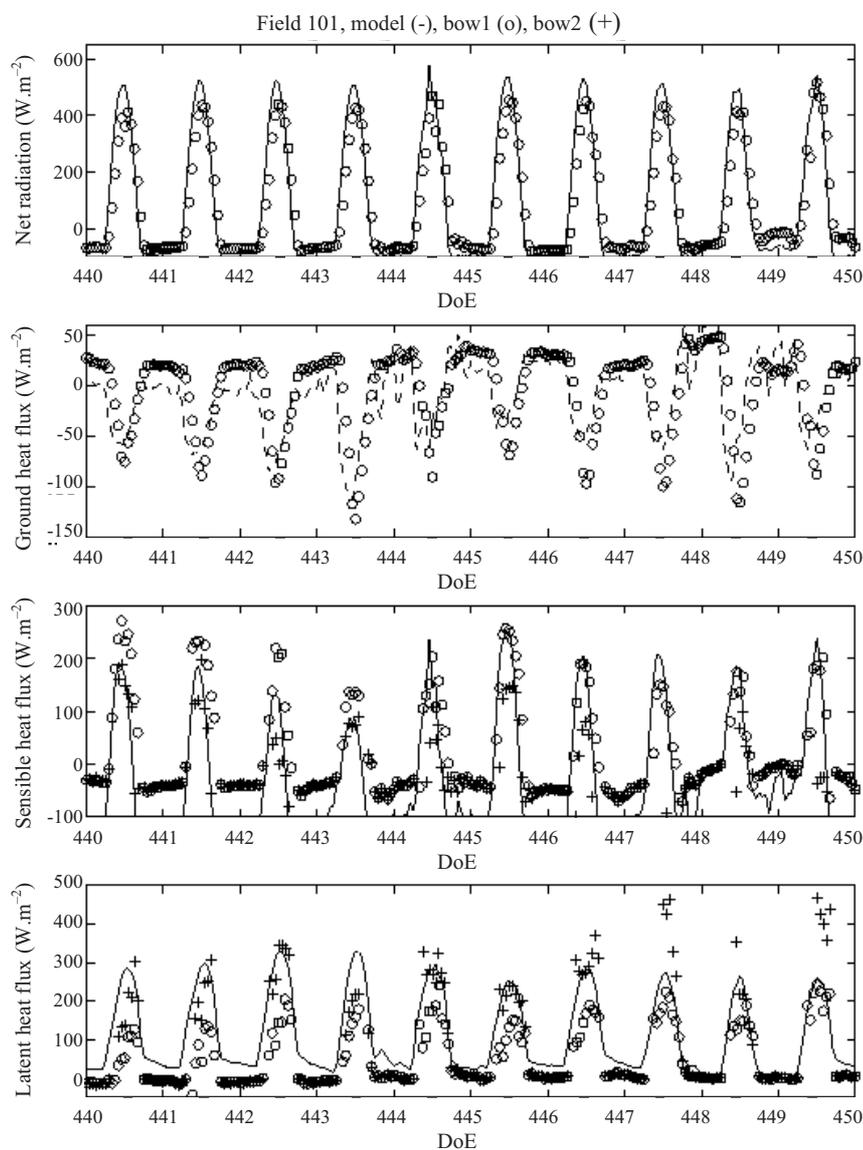


Figure 2. Measured (o, +) and S-model simulated (-) energy fluxes, wheat calibration field (101). The flux values (o, +) were computed with measured temperatures from 2 different devices.

biomass. Root mean square errors are 0.16 for the LAI during the growing period, 0.019 for green biomass and 0.050 for aboveground biomass. Concerning the energy fluxes, the results were not significantly different from those obtained with the uncoupled SVAT model. No drift was obtained in the simulation of V or S model variables.

3.3. Assimilation process

An alternative to the use of ground measurements for model calibration is the use of remote sensing data. Through a feasibility study, the question of model calibration with spatial observations was addressed. The SAIL scheme was coupled to the V model (through the LAI) to predict bi-directional reflectances observed by a SPOT/HRV sensor. The SPOT data were radiometrically, atmosphere

(MODTRAN) and geometrically corrected. The SAIL input parameters are presented in Table III.

The V-S-SAIL predicted reflectances and NDVI are directly comparable with the satellite measurements. The assimilation technique was tested using biased values of the initial aboveground biomass and SLA at a low biomass level (hereafter referred to as initial SLA). As a matter of fact, this model – not initially developed for crops – requires the knowledge of those variables at the beginning of the simulation which does not correspond to the sowing date. An iterative process was used to minimize the differences between simulated and observed NDVIs. The minimization was performed by tuning the 2 parameter values. The results presented in Table IV show that, on this wheat field, the assimilation of SPOT/HRV measurements led to the fit of unknown model initial conditions

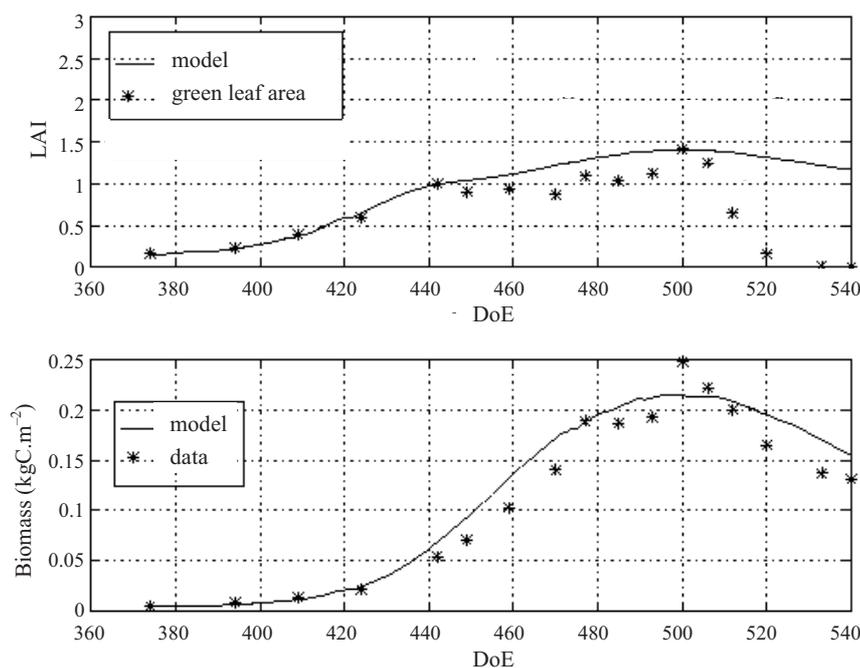


Figure 3. Measured (*) and V-model simulated (-). (a): LAI, (b): aboveground green biomass, wheat calibration field (101).

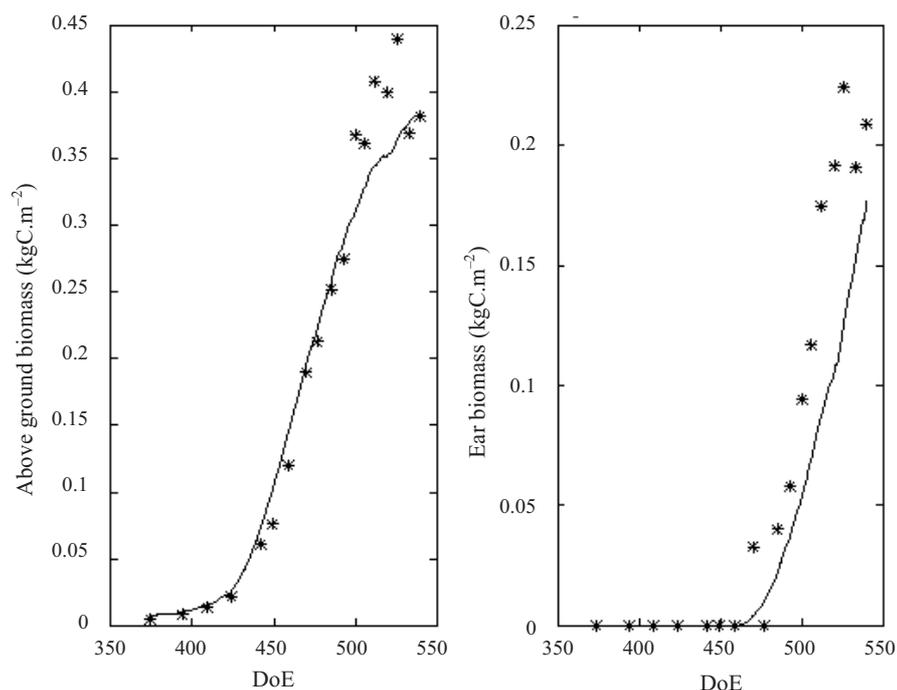


Figure 4. Measured (*) and V-model simulated (-). (a): total aboveground biomass, (b): ear biomass, wheat calibration field (101).

and improved the radiometric variable prediction (the residual relative error on NDVI is about 15% as compared with 50% before assimilation). Note that the retrieved values (biomass and SLA related parameters) are significantly different from the reference parameters, because they partly compensate each other: a larger initial biomass tends to enhance growth whereas a smaller SLA tends to decrease growth. This effect is related to the ‘equifinality’ problem, which is exten-

sively discussed by [7] and [2]. The overall simulation of LAI and biomass is nevertheless reasonable.

4. CONCLUSION

The calibration of the canopy functioning sub-model gave satisfactory results in terms of biomass and LAI prediction. In this study, the main phenological stages were prescribed

Table III. Specification of the SAIL model input parameters. Leaves and soil optical properties were prescribed according to spectral measurements on wheat leaves and soil. Mean leaf angle and hot spot parameter were prescribed by F. Baret (INRA, Avignon).

<i>Canopy structure parameters</i>		
LAI	as predicted by the V model	
Hot spot parameter	0.1	
Leaf angle distribution	mean leaf angle = 60°	
<i>Canopy and soil optical properties</i>		
	SPOT wavebands	
	λ_1	λ_2
Soil reflectance	0.20	0.23
Leaf reflectance	0.05	0.52
Leaf transmittance	0.01	0.43
<i>Illumination and view conditions</i>		
Diffuse fraction of solar radiation	20%	
View zenith angles	sensor configuration	
Solar zenith angles	Avignon configuration	
Relative azimuth	ϕ (sensor – Avignon)	

λ_1 and λ_2 are for visible and near infrared, respectively. ϕ is for azimuth.

Table IV. Results of the assimilation test. The RMSE was computed from predicted and measured NDVI values.

	Reference value	Retrieved value
Initial biomass ($\text{kgC}\cdot\text{m}^{-2}$)	0.039	0.0050
Initial SLA ($\text{m}^2\cdot\text{kg}^{-1}$)	40	25
RMSE	0.147	0.047

according to the observed distribution of the biomass in the different organs. However, in operational mode and when no ground measurements are available, those stages could be computed as a function of the thermal time after sowing or emergence, as it is the case in regular crop models. Concerning the SVAT model, we obtained consistent results for wheat field 101 as well as for alfalfa field 203 (not shown in this paper) in terms of energy fluxes and soil water content prediction. However, we encountered some difficulties in determining some parameters such as the root depth. In particular, due to unexpected very dry conditions, the rooting depth was larger than the maximum investigated depth (2 m for wheat and 6 m for alfalfa). We expect to improve those results by comparing and analyzing simulations obtained with different SVATs. The coupled V-S model, however, gave reasonable results in terms of vegetation model outputs, but it was more difficult to conclude concerning the simulation of the energy fluxes. This V-S model also gave good results in terms of inter-site and inter-annual variability for semi-arid grasslands [3, 4]. However, it was shown in each case that many ground measurements are required to obtain an accurate model calibration.

The example of assimilation presented here, as well as those published in [3] make us feel confident concerning the use of short wave satellite measurements to constrain the coupled V-S model. It was found that such a ‘remote’ calibration is possible, and might be used whenever intensive field mea-

surements are not available, for instance on a regional scale or on a field scale for precision farming purposes.

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