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Four Decades of Progress in Monitoring and Modeling of Processes in the Soil-Plant-Atmosphere System: Applications and Challenges

Assessment of the SiSPAT SVAT model for irrigation estimation in south-east France

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Abstract

In this study, we assess the interest of using a Soil – Vegetation – Atmosphere – Transfer model, the SiSPAT (Simple Soil Vegetation Atmosphere Transfer) model, which solves the surface energy balance, for the evaluation of theoretical crop water requirements in south-east France. First the relevance of the model results, when parameterized using information extracted from a soil data base and pedotransfer functions for the estimation of soil hydraulic properties, and when vegetation characteristics are prescribed using available data bases is assessed. We use long term time series of soil water content profiles for this purpose. The results show that evapotranspiration, as simulated by SiSPAT is sensitive to the soil parameter specification leading to large uncertainties in the model results.
Then, we present two methods implemented in SiSPAT to compute irrigation requirements. The first option mimics the soil water balance model principles by estimating the irrigation from the available soil water capacity filling. The second option relies on the model physics and estimates the difference between actual transpiration and the value corresponding to a minimal stomatal resistance, i.e. without water stress. Aspersion and drip irrigation can be simulated. Nine crop are chosen for the model evaluation. A comparison with two other water balance models is performed. The three models are consistent with determination coefficient between the simulated annual irrigation generally larger than 0.4. However, differences of the interannual irrigation needs, larger than several 100 mm, are sometimes found, especially for drip irrigation. This work provides a quantification of expected uncertainties when using water balance models or physically-based models for irrigation needs estimation.

Keywords: Irrigation; SVAT model; soil properties;

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1. Introduction

Crop irrigation represents the major fresh water use in the world. In the context of global change, models able to simulate the water demand evolution are valuable. Plant water requirements are generally estimated using water balance models or crop growth models. Those models use daily rainfall, temperature, reference evapotranspiration ET0. Water balance models require the specification of crop coefficients whereas crop growth models have the advantage of simulating directly the crop development and yield. They are therefore able to take into account the impact of temperature and/or rainfall restrictions on the crop development. However, some studies are also conducted using only water balance models (e.g Nkomozepi and Chung [1]; Savé et al. [2]) and our focus will be restricted to this type of models in the following.

Many uncertainties exist in terms of ET0 projection under climate change, depending on the climatic variables considered in its evaluation (temperature, radiation, humidity and/or wind speed) (e.g. Haddeland et al. [3]; Irmak et al., [4]). Soil- Plant- Atmosphere- Transfer models do not rely on the use of ET0 but solve the surface energy balance. They can be an alternative to simple water balance models for plant water requirements estimation in a climate change context. However, they require much more parameters than water balance models, especially in terms of soil and vegetation description.

In this study, we assess the value of using the SiSPAT (Simple Soil Vegetation Atmosphere Transfer) model (Braud et al. [5]) for the evaluation of theoretical crop water requirements in south-east France. First we assess the relevance of the model results, when parameterized using information extracted from a soil data base and pedotransfer functions for the estimation of soil hydraulic properties, and when vegetation characteristics are prescribed using available data bases. Then, we present the adaptation of the model to compute irrigation needs, its set up and the results for nine crops typical of south-east France in terms of theoretical irrigation and drainage below the root zone. The SiSPAT results are also compared with two other water balance models.

2. Methods

2.1. Presentation of the SiSPAT SVAT model and its adaptation for computing theoretical irrigation requirements

The SiSPAT model is a soil – vegetation – atmosphere transfer model which solves the coupled heat and water transfer equations in the soil. Water vapour transfer and the vertical soil heterogeneity are taken into account. A root extraction sink term is also included, where root extraction depends on the difference between the soil and the leaf water potential. Two distinct energy budgets for the bare soil and the vegetation (big leaf hypothesis) are solved to compute the components of the surface fluxes, and in particular soil evaporation and plant transpiration. Interception of rainfall by the vegetation is also taken into account. The model is forced by climatic variables: incoming solar and long wave radiation, air temperature and humidity, wind speed and rainfall at a time step of at least one hour and interpolated at the model variable time step. The vegetation growth (leaf area index – LAI-, root density profile and vegetation height) are prescribed and interpolated at a daily time step. In the Mediterranean area, a high fraction of coarse fragments is very common. The model has been improved to take into account its impact of soil retention curves (see Fies et al.[6]) and soil thermal conductivity (Verhoef [7]).

Two options for irrigation estimation are implemented in the model. In both cases, soil evaporation, E_s (mm) is added to the irrigation estimation. Aspersion and drip irrigation can be simulated. The first option mimics the soil water balance model principles by estimating the irrigation as the difference between a fraction of the available soil water capacity (*ASWC*, mm) - defined as the available soil water storage between field capacity and wilting point- and the actual soil water storage, S (mm), which can be summarized as follows:

$$If \quad S \leq \alpha ASWC \quad Irr = \left(\beta ASWC - S\right) + E_s \qquad (1)$$

For aspersion, we used α=0.2 and β=0.8 and for drip irrigation α=β=0.8.

The second options relies on the model physics and estimates the difference between actual transpiration, T_r, and a crop with a value of the stomatal resistance set to its minimum, $T_{r\_MinStomatal}$. In this case, irrigation requirements are summed up, until a value of a prescribed threshold (corresponding to the irrigation dosis) is reached. When this is the case, irrigation starts.

$$Irr = \left(T_{r\_MinStomatal} - T_r\right) + E_s \qquad (2)$$

In the case of aspersion, irrigation is added to the rainfall and can be partly intercepted. In the case of drip irrigation, irrigation is added to the throughfall and cannot be intercepted. For aspersion, the dosis is applied during a duration, *d*, chosen by the user. We used 6h in the following. In case of drip irrigation, irrigation is directly applied at the next time step.

2.2. Model set up

The hourly climate forcing is derived from the SAFRAN reanalysis (Vidal et al. [8]) which provides the climatic forcing on 8x8 km^2 grid. One full year is used as a warming up period. The model lower boundary condition is set to gravitational drainage and constant soil temperature. Soil parameters are derived from the IGCS/PACA soil data base where information about the soil vertical structure (soil horizons) and soil texture are available. We use the Rawls and Brakensieck [9] pefotransfer functions for computing the parameters of the Van Genuchten [10] retention curves and Brooks and Corey [11] hydraulic conductivity curves (see Manus et al. [12] for details). For plant development (vegetation height, leaf area index, root profile) description, we use an interannual cycle derived from existing data bases (ECOCLIMAP, Masson et al.[13]; FAO[14]). For annual crops, bare soil is assumed in the inter-crop period. The major uncertainty when using the IGCS/PACA soil data base is that each soil cartographic unit (SCU) is composed of several soil typological units (STU). Information on soil texture and soil horizons is only available for STU but their precise location within a SCU is not known. Several STU can therefore be assigned to a given location, leading to uncertainty in the soil hydraulic properties knowledge.

2.3. Model assessment using in situ soil moisture time series

In order to assess the relevance of the model set up based on pedotransfer functions and average vegetation characteristics, the model results are compared with soil water content time series. The data are acquired in non-irrigated fields, which are used to provide advices in terms of irrigation for the farmers. The data are acquired by CIRAME and SCP, monthly or bi-monthly. A neutron probe was used until the 20th and a Diviner 2000 sensor since then. The sensors are not calibrated using in situ soil samples; so the data can only be used based on relative values. We define *%ASWC* as the filling rate of the available soil water capacity and we compute it from the observations and model respectively.

$$\%ASWC = \frac{\left(S - S_{min}\right)}{\left(S_{max} - S_{min}\right)} \qquad (3)$$

where S_{min} (resp. S_{max}) are the minimum (resp. maximum) value of the soil water storage S (mm).

Monthly anomalies, calculated as defined below, are also computed for both the observations and model results, to assess the ability of the model to reproduce the interannual monthly variability.

$$Anom(m, year) = \frac{S(m, year) - Ave(S(m:))}{std(S(m:))} \quad (4)$$

where *Anom(m,year)* is the anomaly of month *m* in year *year*, *S(m,year),* is the soil water storage of month *m* in year *year*. *Ave(S(m :))* and *std(S(m :))* are respectively the mean and standard deviation of the storage *S* for month *m*.

For this intercomparison the STU soil units are chosen consistent with the observed soil depths and particle size data when available. For some locations, several STU are used in order to assess the model sensitivity to the soil characteristics specification. The model is run for the number of years corresponding to the observation period, with one year as warming up period.

Table 1: Summary of the performed simulations. For the Aubignan, Bollène, Piolenc and Vaison sites, two STU are compared. For the Visan site, two root depths *zrt* are compared.

Location	Aubignan	Bollene	Piolenc	Visan	Vaison	CabrièresA	CabrièresG	Lourmarin
Vegetation	Vineyard	Vineyard	Vineyard	Vineyard	Vineyard	Cherry tree	Vineyard	Cherry tree
Simulation duration (years)	30	24	8	24	24	13	18	19
Soil depth (m)	1.6	1.5	1.3	1.2	1.5	1.2	1.2	1.2
STU number and **simulation name**	STU 23 **Aub-a**	STU 67 **Bol-a**	STU 67 **Pio-a**	STU 114 *zrt*=0.7m **Vis-a**	STU 181 **Vais-a**	STU 123 **CabA**	STU 123 **CabG**	STU 1T3 **Lour**
	STU 25 **Aub-b**	STU 68 **Bol-b**	STU 68 **Pio-b**	STU 114 *zrt*=1.2m **Vis-b**	STU 185 **Vais-b**			

2.4. Intercomparison of three models for the assessment of theoretical crop water requirements

Nine crops, representative of the PACA (Provence Alpes Côte d'Azur) region in south-east France, are chosen for the model evaluation: hard wheat, corn, sunflower, grassland, vegetables, potatoes, vineyard, cherry tree and apple tree. Based on the agricultural sensing (RGA, 2000) at the "canton" level, we choose the location where each crop is the most cultivated and assign the climate forcing and soil characteristics, according to this location. For soil properties, STU leading to inconsistent results such as quasi-permanent soil saturation or unrealistic high drainage values are discarded. The simulations are performed for the 1979-2009 period, 1979 being used as a warming up period.

A comparison with two water balance models: Five-Core (Chopart et al. [15]) and MODIC (Sauquet et al. [16]) is also performed. Both models compute the soil water balance at the daily time step using as input: rainfall, temperature, ET0 and crop coefficients. They can also take into account farmers practices, but this possibility is not used in the present study where only theoretical water requirements are computed. Five-Core is used with a *ASWC* constant in time, whereas MODIC takes into account root growth in the definition of this variable. MODIC also takes into account the bare soil fraction in the computation of the crop coefficient.

3. Results

3.1. Simulation of observed soil water storage

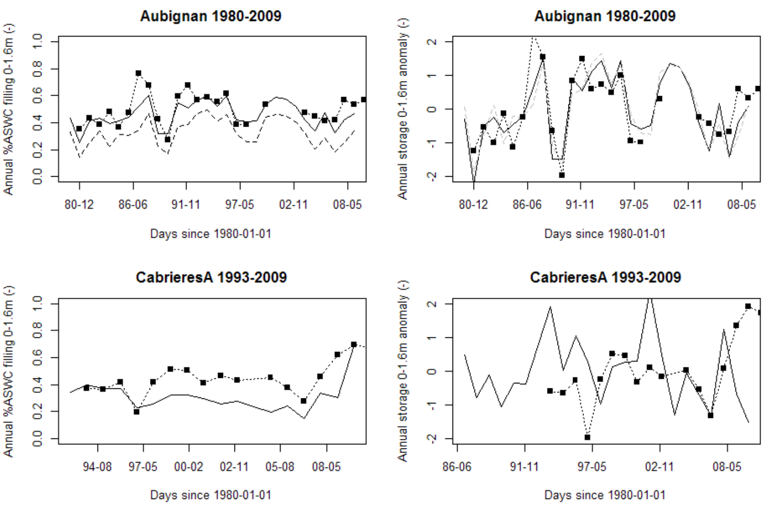

Figure 1: Left: *%ASWC* filling and, right *Anom* for the Aubignan (vineyard) and Cabrières-A (cherry tree) sites. Points are the observations and lines the modelled results. For Aubignan, the black and dashed lines correspond to simulation –a and –b respectively.

Table 2: Slope and determination coefficients R^2 of the regression between observed and modelled annual average *%ASWC* (left) and *Anom* (right) for the various simulations. NS= not significant

	%ASWC		*Anom*	
	Slope	R^2	Slope	R^2
Aub-a	0.63	0.57	0.77	0.57
Aub-b	0.58	0.45	0.68	0.45
Bol-a	0.74	0.34	0.47	0.22
Bol-b	0.51	0.37	0.46	0.22
Pio-a	0.92	0.54	1.00	0.90
Pio-b	0.69	0.59	0.97	0.83
Vis-a	0.30	0.35	0.60	0.35
Vis-b	0.23	0.41	0.64	0.41
Vais-a	1.21	0.44	0.70	0.44
Vais-b	0.51	0.70	0.87	0.70
CabA	0.65	0.36	0.72	0.36
CabG	0.4	0.49	0.85	0.49
Lour	NS	NS	NS	NS

Table 1 provides a summary of the performed simulations (without any irrigation). Fig. 1 illustrates the model results in terms of *%ASWC* and *Anom* for two sites: one vineyard and one cherry tree orchard. Table 2 provides the slope and determination coefficients of the regression between observed and simulated values. The agreement is reasonable, except for the Lourmarin site. However, for some sites, the agreement is sensitive to the choice of the STU describing the soil profile (Vaison, Aubignan) and to the root depth (Visan). The impact in terms of components of the soil water balance is also sensitive. For these long term simulations, soil water storage variation is close to zero. Actual evapotranspiration, *AET*, represents between 64 and 90% of the rainfall; runoff is most of the time null, except for some STU where it can reach 12%. Drainage below the root zone represents 3 to 34% of the rainfall. According to the STU choice, variations of up to 10% in terms of *AET* can be obtained. Note also that interception represents generally 5% of the total *AET*; bare soil evaporation between 25 and 46% of *AET*; and transpiration 48 to 65% of *AET*.

3.2. Simulations of irrigation water requirements

Table 3 summarizes the characteristics of the performed simulations. The same root depth were chosen for the three models. However, according to the model configuration, this leads sometimes to differences in terms of max *ASWC* value (Table 3). For SiSPAT, this is related to the STU chosen as representative of the location. The period of irrigation is the period over which irrigation requirements are computed. For SiSPAT, the simulations are performed with the two options presented in section 2.1.

Table 3: Summary of the performed simulations

Vegetation	Apple	Vineyard	Cherry	Sunflower	Wheat	Vegetable	Potatoes	Corn	Grassland
Period of irrigation	18/03-30/09	01/04-30/09	01/04-30/09	10/04-20/08	01/04-30/06	01/01-31/12	20/01-31/07	20/04-20/09	01/04-30/09
Irrigation type	Aspersion	Drip	Drip	Aspersion	Aspersion	Drip	Aspersion	Aspersion	Aspersion
Root depth (cm)	82	59	90	87	60	97	70	70	46
Max ASWC SiSPAT (mm)	141	89	82	116	76	93	140	100	56
Max ASWC Five-Core (mm)	90	59	90	104	72	97	77	100	46
Max ASWC MODIC(mm)	74	48	61	88	56	44	64	62	43

Table 4 provides the values of the interannual average and standard deviation calculated for the 9 crops and the four model configurations. Fig. 2 shows a comparison on the average values as barplots. Option %ASWC in SiSPAT leads to higher values than option Trmax for all the crops with drip irrigation. The contrary is observed for grassland and to a lesser extend corn and potatoes (Fig. 2). SiSPAT values are particularly high for row crops and/or trees, where the “big-leaf” model hypothesis may not be well suited for those crops where the bare soil fraction is large. Five-Core leads to the smaller irrigation except for vineyard and wheat. Brisson and Levrault [17] reports, for a climate forcing typical of south-east France, and the 1970-2000 period, average irrigation estimations of about 300 mm for corn; 80-250 mm for wheat according to the soil type; 140 mm for vineyard and 400 mm for grassland. Our results are consistent with those results for corn and wheat. For vineyard, our estimate is much larger, but the β factor (see section 2.1) is different as Brisson and Levrault [17] used only 0.3 for vineyard and grassland. The results, show, that, even at the interannuel time scale, there is a large uncertainty on the irrigation estimations amongst the models.

Table 4: Annual average and standard deviation (in parenthesis) values of irrigation for the three models and the two options in SiSPAT. All the quantities are in mm and are provided for the irrigation period defined in Table 3.

Vegetation	Apple	Vineyard	Cherry	Sunflower	Wheat	Vegetable	Potatoes	Corn	Grassland
Rainfall	314 (81)	252 (87)	307 (91)	156 (53)	187 (64)	704 (169)	267 (78)	293 (77)	497 (126)
Irrigation SiSPAT %ASWC	606 (91)	1004 (91)	673 (79)	147 (53)	147 (53)	781 (85)	379 (69)	293 (78)	245 (67)
Irrigation SiSPAT Trmax	521 (88)	747 (79)	508 (72)	358 (57)	161 (38)	673 (65)	443 (41)	398 (41)	495 (65)
Irrigation Five-Core	303 (78)	311 (50)	198 (48)	260 (74)	113 (63)	158 (44)	136 (55)	224 (62)	182 (70)
Irrigation MODIC	398 (75)	129 (23)	213 (63)	359 (70)	78 (35)	278 (55)	262 (39)	401 (85)	204 (66)
Drainage SiSPAT %ASWC	36 (25)	243 (43)	148 (53)	29 (19)	29 (19)	574 (126)	67 (49)	43 (25)	175 (88)
Drainage SiSPAT Tramax	19 (18)	28 (28)	37 (39)	63 (40)	70 (46)	480 (162)	139 (71)	105 (58)	393 (112)
Drainage Five-Core	73 (60)	105 (61)	149 (77)	26 (30)	26 (30)	501 (128)	84 (62)	78 (50)	203 (105)
Drainage MODIC	29 (43)	49 (51)	52 (59)	36 (35)	59 (45)	332 (151)	101 (59)	73 (47)	183 (90)

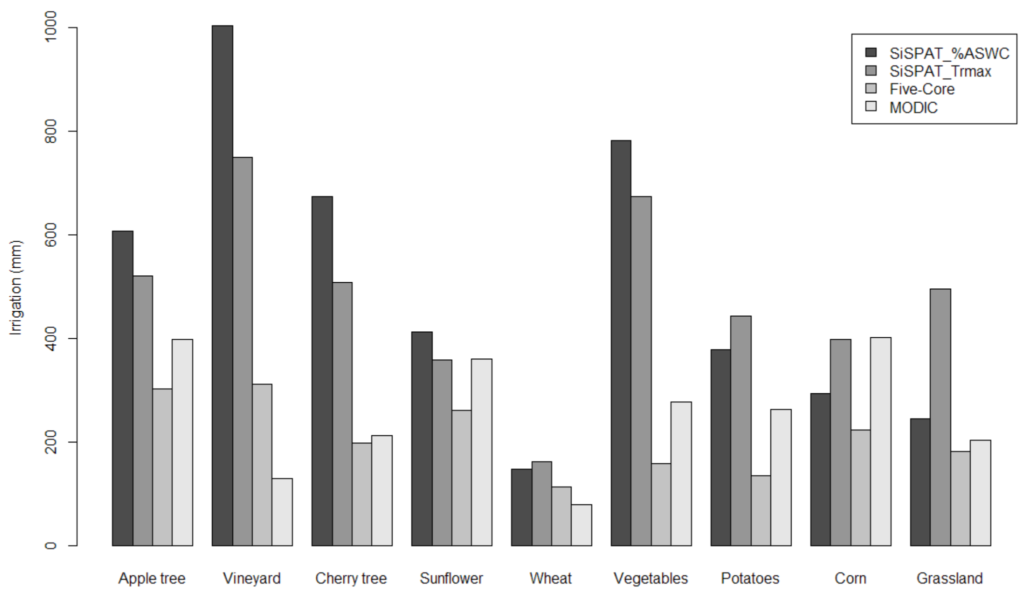

Figure 2: Barplot of the internnual average irrigation estimations for the four model configurations and the nine crops.

Table 5 provides the slope, intercept and determination coefficients of the regressions between the various models. Fig. 3 illustrates the results for sunflower. Table 5 shows that the results obtained with the various models are consistent in terms of interannual variability: all the models simulates lower (resp. larger) irrigation values at the same time (R^2 generally larger than 0.4). However, the slope are seldom close to 1 showing systematic under or over-estimation. The values of the intercept are also often very large, showing systematic bias between the models. The SiSPAT values provided by the two options are also generally consistent, although there is sometimes a large value of the intercept, leading to large differences in absolute values. The correlation is lower for corn and potatoes where the Trmax option leads to a much narrower range of irrigation estimates (not shown).

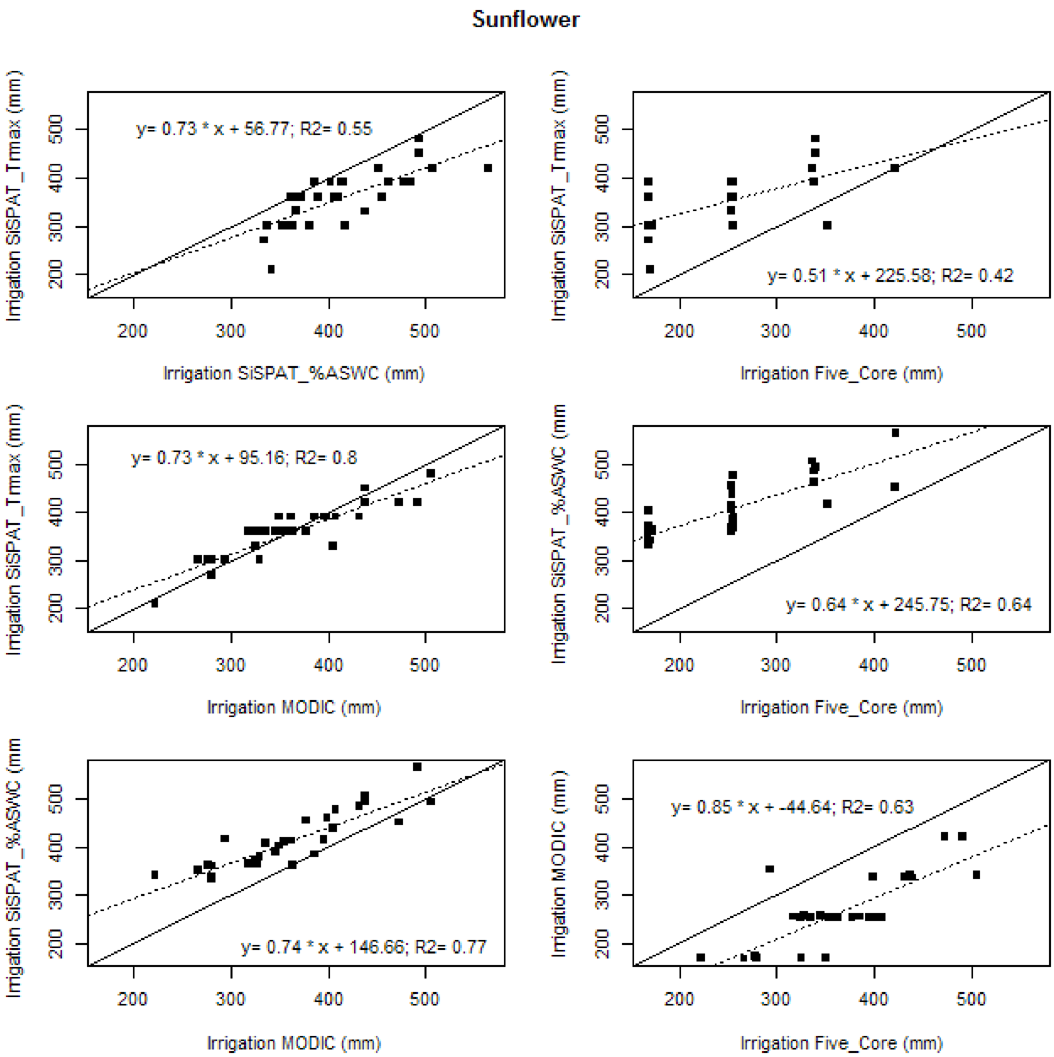

Figure 3: Correlations between the annual irrigation estimations of the various models for sunflower.

Table 5: Slope, intercept and regression coefficient of the annual irrigation estimation for combinations of the three models and the two SiSPAT options.

		Apple	Vineyard	Cherry	Sunflower	Wheat	Vegetable	Potatoes	Corn	Grassland
MODIC = f(Five-Core)	Slope	0.93	1.77	0.63	0.85	1.36	0.71	1.00	0.61	0.95
	Intercep	-65	83	64	-45	6	-41	-126	-21	-12
	R^2	0.79	0.66	0.69	0.63	0.57	0.79	0.48	0.70	0.77
SiSPAT_%ASWC = f(Five_Core)	Slope	0.79	1.17	1.41	0.64	0.6	1.6	0.8	1.13	0.83
	Intercept	365	639	-395	245	79	528	270	40	95
	R^2	0.45	0.4	0.71	0.64	0.49	0.68	0.38	0.78	0.75
SiSPAT_%ASWC = f(MODIC)	Slope	1.01	2.16	0.95	0.74	1.02	1.38	1.26	0.82	0.99
	Intercept	205	724	472	147	67	397	49	-35	44
	R^2	0.69	0.28	0.56	0.77	0.45	0.8	0.48	0.78	0.93
SiSPAT_Trmax = f(SiSPAT_%RU)	Slope	0.72	0.83	0.87	0.73	0.49	0.64	0.26	0.23	0.68
	Intercept	83	-82	-75	57	89	172	345	329	328
	R^2	0.54	0.91	0.89	0.55	0.44	0.68	0.15	0.17	0.48
SiSPAT_Trmax= f(Five-Core)	Slope	0.76	1.19	1.36	0.51	0.31	1.23	0.3	0.23	0.54
	Intercept	290	378	238	226	126	479	402	347	397
	R^2	0.44	0.57	0.8	0.42	0.23	0.68	0.13	0.09	0.32
SiSPAT_Trmax= f(MODIC)	Slope	0.97	2.13	1.00	0.73	06	0.95	0.54	0.32	0.7
	Intercept	136	474	296	95	114	409	301	268	352
	R^2	0.68	0.38	075	0.80	0.29	0.63	0.23	0.43	0.49

4. Conclusions and perspectives

In this study, we assess the interest of using a soil – vegetation – atmosphere transfer model for irrigation estimation. First, we show that, when used in a regional context where only soil data bases and pedotransfer functions are available for specifying the soil hydraulic properties, the result of such a model is very sensitive to the choice of the soil type chosen as representative. A sensitivity to this choice is therefore highly recommended. For long term simulations, a coupling with a crop growth model, able to simulate the LAI evolution, would also be very valuable.

In terms of theoretical irrigation requirements computation, the results of the various tested models are consistent in terms of simulation of low/high irrigation. However, the differences in absolute values may be very large (more than several hundreds of mm). This irrigation estimation is therefore prone to large uncertainty, leading to large uncertainties in water balance/water management planning.

We plan to test the results of the SiSPAT Trmax option by introducing a “stress” factor corresponding to the farmer practices (they do not systematically irrigate) in Eq. (2). Such an approach was performed in the study by Brisson et al. [17] where stress factors of 0.8, 0.7 and 0.3 were considered for corn, wheat and vineyard respectively. This is likely to provide more consistent results, especially in a context of climate change. We also plan to compare the results of the three models in a climate change context to see if they provide consistent increase/decrease of irrigation estimation, especially with the SiSPAT model, which do not rely on ET0 estimation.

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