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Adapting PILOTE model for water and yield management under direct seeding system: the case of corn and durum wheat in a Mediterranean context

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Abstract

Crop models are useful tools for integrating knowledge of biophysical processes governing the plant-soil-atmosphere system. But few of them are easily usable for water and yield management especially under specific cropping systems such as direct seeding. Direct seeding into mulch (DSM) is an alternative for conventional tillage (CT). DSM modifies soil properties and creates a different microclimate from CT. So that, we should consequently consider these new conditions to develop or to adapt models. The aim of this study was to calibrate and validate the PILOTE (Mailhol et al. 1997; Mailhol et al. 2004), an operative crop model based on the leaf area index (*LAI*) simulation, for corn and durum wheat in both DSM and CT systems in Mediterranean climate. In DSM case, simple model modifications were proposed. This modified PILOTE version accounts for mulch and its impact on soil evaporation. In addition root progression was modified to account for lower soil temperatures in DSM for winter crops. PILOTE was calibrated and validated against field data collected from a 7-year trial at the experimental station of Lavalette (SE of France). Results indicated that PILOTE satisfactorily simulates *LAI*, soil water reserve (*SWR*), grain yield, and dry matter yield in both systems. The minimum coefficient of efficiency for *SWR* was 0.90. This new version of PILOTE can thus be used to manage water and yield under CT and DSM systems in Mediterranean climate.

Key words: crop model, soil water balance, direct seeding, conventional tillage

Nomenclature

The following symbols are used in the paper:

FC	field capacity (cm^3/cm^3)
PWP	permanent wilting point (cm^3/cm^3)
TAW	total available water in soil (-)
Kr	ratio between easily usable soil water reserve and *TAW* (-)
Xsr	Parameter governing the soil water evaporation reduction by mulch (-)
Rmax	maximum root depth (m)
Pr	root depth (m)
Ps	the depth of first reservoir in the model (m)
Vr	Root growth rate (m/day)
Vrs	imposed root growth rate (m/day)
Vrt	Thermal root growth rate (m/degree.day)
Kc	crop coefficient (-)
Ksoil	resistance of soil to evaporation (-)
RUE	Radiation use efficiency
Cp	partitioning coefficient (-)
ε	extinction coefficient (-)
Tp	transpiration (mm)

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Tpm	maximum of transpiration (mm)
ET_o	reference evapotranspiration (mm)
Es	soil evaporation (mm)
Emo	evaporation from a soil without mulch (a bare soil) (mm)
Tav	average daily temperature (°C)
Ts_1	the beginning of critic phase (°C-day)
Ts_2	the end of critic phase (°C-day)
Tf	cumulative temperature to reach *LAImax* (°C-day)
Ts	temperature sum for emergence (°C-day)
Tb	base temperature for a specific crop (°C)
Tinst	temperature sum of root installation (°C)
Tm	temperature sum of maturity (°C)
α, β, γ	the shape parameter of *LAI* curve (-)
λ	parameter governing the plant sensitivity to water stress (-)
HI	harvest index (-)
HIpot	Potential harvest index (-)
a_r	a calibration parameter for simulating water stress impact on *HI* (-)
Ya	actual dry matter yield (Mg/ha)
Ym	potential dry matter yield (Mg/ha)
LAI	leaf area index (m²/m²)
LAIav	averaged *LAI* values calculated between Ts_1 and Ts_2 (m²/m²)
LAIopt	required averaged *LAI* value for obtaining the potential yield (m²/m²)
LAIst	*LAI* threshold value under which *HIpot* is affected by water stress (m²/m²)

1. Introduction

Irrigation has a dominant role in agricultural production especially in Mediterranean climate, because of variant distribution of the rainfalls over the year. Improving irrigation management is important not only for saving water, but also for improving crop profitability. In addition, there is a growing competition for water by agricultural, domestic and industrial uses, hence there is a need for farmers to save water and make judicious use of it, especially during the dry season. Efficient use of water in agriculture requires proper irrigation scheduling and sowing date to obtain optimum water use and yield (Adekalu and Fapohunda, 2006). Field experiments are time consuming, expensive, and limited to the prevailing soil, climate, and crop … conditions. The experiments generally conducted in this aim, often give a partial response because the range covered (of soils types, climates, crop managements) are limited compared with agricultural conditions in which these systems can be used. Furthermore, the required time to get a response is too long considering the rapid change of varieties and all the cropping system components used and modified by farmers. Model simulations in different climates can help the farmer to better identify the best crop management towards different cropping system. Jamieson et al. (1998) believe that developing empirical models provides a good basis for decision support at the farm level by giving quick estimations of the likely costs and benefits of farm management decisions. Models that satisfactorily simulate the impacts of water stress on yield can be reliable tools in irrigation management (Cavero et al. 2000). In addition, crop models are useful tools for considering the complex interactions between a range of factors that affect crop performance, including weather, soil properties and management (Timsina and Humphreys, 2003). Where pests and diseases are controlled, and nitrogen is not a limiting factor, water management is the main factor influencing yield for a given environment. Mechanistic crop models typically require a large number of parameters and are therefore highly data-demanding to give accurate and reliable simulation results. Even if these requirements are met, simulation results may deviate from actual field observations for a variety of reasons (Jongschaap, 2007). Crop models are formalized collections of testable hypotheses about how environmental variations affect plant processes (Jamieson et al. 1998). Before models can be applied with confidence, they need to be calibrated and validated for the varieties and environment of interest (Timsina and Humphreys, 2003).

Direct seeding into mulch (DSM) is a cropping system which is more and more used in the world. The absence of tillage reduces significantly production costs. Biological activities develop in the first soil layer (0-10 cm) due to a crop residue accumulation. Organic matter provided by those biological activities contributes in soil fertility increment (Lamarca, 1996; Rhoton, 2000). In addition, improving the liberation of mineral nitrogen (N) and infiltration rate due to macro-fauna, facilitate N absorption by plants. All these conditions should increase farmers' income which is their goal on their degraded soil by conventional tillage system, CT (Findeling, 2001). But a possible positive impact on yield due to DSM needs some years, at least 3 years according to Scopel (1994). However a major concern among producers is the possible yield penalties associated with DSM compared to CT. There are some negative impacts induced by DSM such as lower soil temperature over winter, temporary N lockup and frequently lower yield for winter crop, greater risk of diseases (Fischer et al. 2002), difficulties with weed control, poor seed emergence and a greater risk of frost damage in the spring (Weill et al. 1989). Khaledian et al. (2006a) found that lower soil temperature in DSM can decrease or retard root development of winter crops such as durum wheat. Lower soil temperature due to mulch induces lower root depth in DSM than in CT at the beginning of grain filling when all assimilation remobilizes during kernel growth. Generally, this period corresponds to *LAImax* (maximum leaf area index) reaching and it is the most sensitive growth period to water stress due to its negative impacts on spikelet number and kernel per spike (Shpiler and Blum, 1991). In this regard, crop growth models considering this problem can be useful tools in assessing different impacts of tillage systems on growth and final crop yield. Compared to field experimentation, using crop model to evaluate crop responses to a wide range of management and environmental scenarios can give more timely answers to many management questions at a fraction of field trial cost (Andalesa et al. 2000).

The complexity of biological and biophysical process existing within the first soil layer makes it difficult to develop operative concepts for modeling. That affects significantly the reliability of existing crop models in spite of their sophistication level; hence further researches on this topic are needed. Thus, in this study, we only focus on the role played by water in DSM system. The mulch emanated from crop residue, reduces soil evaporation (Unger and Parcker, 1976; Gusev et al. 1993; Gusev, 2002). This reduction, varies from 5 to 10% (Braud, 1998), has favorable impacts on plant development (Enrique et al. 1999). In addition, we observed during our field experiments that the humidity level of the first soil layer allows a crop emergence without a sowing irrigation which is often necessary in CT system. When irrigation or rainfall is frequent, water initially stored into mulch evaporates (Findeling, 2001). This evaporation leads to a temperature decrease in mulch inducing in its vicinity, a reduction of the global climate demand and as a consequence, a reduction of the potential evapotranspiration.

The purpose of this study was to ascertain that PILOTE, an operative crop model for soil water balance and yield estimations under CT, can still remain an efficient tool once adapted to DSM for corn and durum wheat. This topic was identified as being of importance to agricultural advisors in providing them the necessary tool to manage water and crop system on the basis of a climatic scenario.

2. Material and methods

2.1 Field experiments

Field experiments with corn (*Samsara* and *Pioneer* varieties) and durum wheat (*Artimond* variety) were carried out at the Cemagref institute of Montpellier, France (43° 40' N, 3° 50' E and altitude 30 m) in the Mediterranean climate with 750 mm of average annual rainfall on a loamy soil (18% clay, 47% silt, 35% sand). Two main plots are considered in this study: a DSM plot of about 1 ha and a CT plot of 1.7 ha. Field experiments have been conducted over 7 years (1997, 1998, 1999, 2001, 2002, 2005 and 2007). For a given year, the crop is generally subject to different irrigation treatments (T1-T5), with always at least a full irrigated (T1) and a rainfed treatment (T5), (Table 1). From 1997 to 1999, corn was cultivated in CT only, while in 2001, 2002 and 2007 corn was cultivated in DSM too. The date of tillage, sowing, harvest and total N application are summarized in Table 2.

Table 1. Total water application (mm) in different irrigation treatments (Ti) and rainfall (mm) during the cropping cycle of corn (*Samsara* variety in 1997-2002 except of 2000 and *Pioneer* variety in 2007) and durum wheat (*Artimond* variety in 2005) under conventional tillage and direct seeding into mulch which is underlined (rainfed treatment T5 was irrigated after sowing when necessary)

Year	T1	T2	T3	T4	T5 (rainfed)	Rainfall
1997	222	111	86	89	0	271
1998	323	506	130	358	36***	146
1999	236*	-	-	-	29**	392
2001	232	<u>216</u>	<u>184</u>	206	16	148
2002	344	<u>250</u>	<u>298</u>	279	24	312
2005	88*	71	49**	<u>36</u>	0***	223
2007	430	218	<u>182</u>	<u>0</u>	0	171

* *LAI* shape parameters, ** *LAIst* parameter, *** a_r parameter calibration

DSM was initiated (for the 2001 season) by sowing oat (October 15th in 2000) which was then destroyed by glyphosat (Rounup®) two weeks prior to corn sowing. The same operation was repeated over the following years except of 2005 where no cover crop was sown before durum wheat cultivation. However there was enough mulch on the soil surface from the precedent crop. The experiments relative to 2003, 2004 and 2006 are out of the scope of this paper because sorghum was sown. For the preparation of the 2007 cropping season, a mixed of oat, vetch and rape was sown in October 2006 in the DSM treatments as cover crop and was destroyed by glyphosat (Rounup®) in April 2007 before corn sowing. In CT plots, at the end of July disc harrow was used to chop and bury the residues of the precedent crop. At the middle of November, tillage with plough was performed. In DSM plots, the cover crop was sown by a specific seeder namely Semeato®. After destroying the cover crop the same seeder was used to sow the main crop. At the end of November 2004, after two years of a sorghum crop, durum wheat was sown in CT and DSM.
For calibration and validation of the model a database was obtained from experiments on corn in 1997, 1998, 1999, 2001, 2001 and 2007, and on durum wheat in 2005. Fertilizers (N, P, and K) were applied prior to planting and during the season on the basis of soil analysis in such a way that fertilization to be not a limiting factor. To determine the grain yield (*GY*) and dry matter yield (*DM*) ten 3 m^2 sub-plots were hand harvested. The measured *GY* and *DM* variation coefficient (*Cv*) varies from 6 to 12%.

Table 2. Tillage, sowing and harvest date and N ($Kg.ha^{-1}$) application for corn (*Samsara* variety) in 1997, 1998, 1999, 2001, 2002; for durum wheat (*Artimond* variety) in 2005 and for corn (*Pioneer* variety) in 2007 with conventional tillage (CT) and direct seeding into mulch (DSM)

Year	treatment	Tillage date	Sowing date	Harvest date	N
1997	CT	1/15/1997	5/2/1997	9/15/1997	200
1998	CT	1/10/1998	5/6/1998	9/20/1998	200
1999	CT	1/20/1999	5/26/1999	10/10/1999	150
2001	CT	12/10/2000	5/2/2001	9/10/2001	120
	DSM	-	5/4/2001	9/10/2001	120
2002	CT	1/6/2002	5/17/2002	9/18/2002	140
	DSM	-	5/17/2002	9/24/2002	140
2005	CT	9/30/2004	11/17/2004	6/28/2005	149
	DSM	-	11/30/2004	7/5/2005	149
2007	CT	11/15/2006	4/24/2007	9/28/2007	179
	DSM	-	4/24/2007	9/28/2007	181

An access tube was installed in each experimental treatment. Soil water reserve (*SWR*) was monitored once a week using a neutron probe from 0 to 2 m and at 0.1 m depth interval. According to Haverkamp et al. (1984) the accuracy of the measurements ranges from 8 to 10%. A series of mercury tensiometers at 0.1, 0.2, 0.3, 0.4, 0.6, 0.9, 1.0, 1.2, 1.4, 1.6 and 1.8 m depth were located at a distance of 0.4 m from the access tube. They were monitored every morning.

The experimental plan as well as details of the experimental procedure (physiological and meteorological measurements are the same in both field experiments) were similar to that of Olufayo et al. (1996). The *LAI* measurements were obtained using a Picqhelios apparatus from 1997 to 1999 and using a LI-COR LA1 2000 apparatus for 2001, 2002, 2005 and 2007. According to Mailhol et al. (1997) these two devices give approximately the same *LAI* values. The *Cv* of the measured *LAI* depends on the plant water status and on the phenological stage. It was lower than 15% for corn and durum wheat.

The frequency of irrigation for the full irrigated treatment (without water stress) was derived from Eq.(1):

$$ETc=R+I-\Delta S \quad (1)$$

, where ETc = crop evapotranspiration, R = rainfall, I =irrigation and ΔS = the change in soil moisture between soil surface and the depth of zero flux plan determined using tensiometers (Vachaud et al. 1978). The soil moisture was measured using a neutron probe. Using *Kc* from Doorenbos and Kassam (1979) and *ETo* (reference evapotranspiration) from climatic data, we can calculate *ETc*. Combining this calculated *ETc* and *ETc* from Eq.(1) we program the irrigation as there is not any water stress. According to tensiometers monitoring, there were not any water stress, drainage or capillary rise over the crop season. There was not any runoff too.

Although this article does not focus on the N problem, N amounts are applied in order to fully satisfy plant requirement as soon as a N soil profile was established just before sowing. Two N applications are generally performed, the first one at sowing and the second one 30 to 40 days after sowing (DAS) in the case of corn. For durum wheat, three applications have been done: the first one of 54 Kg/ha on 15 DAS, the second one of 65 Kg/ha on 43 DAS and the third one of 30 Kg/ha on 100 DAS. Due to a problem of equipment availability the usual setup for corn was not respected in 2007. Indeed, the first application of 93 Kg/ha was done in CT but only of 27 Kg/ha in DSM, while the second application was much later than normally (it was plan to apply one month after sowing) indeed on 70 DAS with 86 Kg/ha for CT and 154 Kg/ha for DSM. With initial N content of 140 Kg/ha in 1.2 m depth for CT vs. 79 Kg/ha for DSM, a lower crop growth potential under DSM than that of CT is predictable despite of a higher second application in DSM. The total N applications are summarized in Table 2.

2.2 Model description

2.2.1 Soil module

The soil module calculates the water balance on a daily (j) time step by means of 3 reservoirs. The basic parameter of this model is the total available water (*TAW*) expressed in mm/m. It defines as the difference between field capacity (*FC*) and permanent wilting point (*PWP*).

A shallow reservoir (R1) with a fixed depth, *Ps* (*Ps* = 0.1 m) manages evapotranspiration after a supply of water i.e. irrigation or rainfall. The maximum capacity of R1 is:

$$R_1max=TAW\ Ps \quad (2)$$

R1 supplies the second reservoir R2 with drainage (d_1):

$$d_1(j) = Max\{0; R_1(j) - R_1max\} \quad (3)$$

R2 varies with root growth. The root depth (*Pr*) can be simulated by:

$$Pr(j) = Pr(j-1) + Vr \quad (4)$$

, where *Vr* is the root growth rate (m/day). From sowing, the root system is assumed to be confined to a soil depth of 0.3 m. The duration of this installation is governed by a sum of temperature, *Tinst*. The value of *Tinst* can be derived from a zero flux plan monitoring. In some models *Vr* is linked to the temperature sum. In PILOTE, *Vr* of the considered day (j) is based on the minimum between a *Vr* according to thermal conditions (*Vrt* m/degree.day) and a *Vr* imposed (*Vrs* in m/day). The model makes root system to reach the maximum root depth (*Rmax*) coincide with the *LAImax*, at this stage the plant mobilizes the available energy to develop the aerial part. However, related to the soil conditions e.g. compaction which affects *Vr*, it is relevant in some cases to make the model uses *Vrs* (case of very compacted soil).

The roots can reach the *Rmax* which is a plant characteristic where the soil does not physically limit root growth e.g. rock. Initial root depth is set at 0.3 m. After a duration governed by a cumulative temperature threshold (*Tinst)*, rooting evolves from 0.3 m to *Rmax* (or <*Rmax* according to thermal conditions).

In the model, first the plant transpiration, *Tp* and soil evaporation, *Es* feed from R1 that evolves according to:

$$R_1(j) = R_1(j-1) + R(j) + I(j) - Tp_1(j) - Es(j) - d_1(j) \quad (5)$$

, where Tp_1 is transpiration which can be calculated as:

$$Tp_1 = Cp\ ETmax \quad (6)$$

, where *Cp* is the partitioning coefficient between transpiration and soil evaporation. *ETmax* can be calculated as:

$$ETmax = Kc\ ETo \quad (7)$$

It is considered that in R1, the plant in competition with soil evaporation can take water without restriction until the R1 becomes empty. *Cp* is a function of *LAI* as in Varlet-Grancher et al. (1982):

$$Cp = 1 - \exp(-0.7LAI) \quad (8)$$

, so *Es* becomes:

$$Es = (1 - Cp)\ ETo \quad (9)$$

, *Kc* is calculated from *LAI* according to Allison et al. (1993):

$$Kc = Kcmax\ [1-\exp(-LAI)] \quad (10)$$

, where *Kcmax* is the maximum value of the crop coefficient. At each time step, R2 is supplied by drainage, d_1 from R1 as:

$$d_1 = \max(0, R_1max - R_1) \quad (11)$$

R2 is growing with $\theta.Vr$, θ (mm/m) being the soil water content of the layer under the root front or the soil humidity of third reservoir, R3. The water balance in R2 can be expressed by:

$R_2(j) = R_2(j-1) + \theta\ V_r - Reste(j) + d_1(j) - d_2(j)$ (12)

Reste is the complementary water that must be taken by plant from R2 to meet *ETmax*. When R1 is empty ($\theta = PWP$) plant takes water only from R2 according to:

$Tp_2 = Kc\ ETo$ (13)

The water balance in R3 can be expressed as:

$R_3(j) = R_3(j-1) - \theta\ V_r + d_2(j) - D(j)$ (14)

, where *D* is drainage from R3 which will be lost completely and it can be calculated according to:

$D = Max\{0\ ;\ R_3max - R_3\}$ (15)

, where R_3max is:

$R_3max = TAW[Rmax - Pr(j)]$ (16)

It is assumed that *ET* is equal to *ETmax* as long as R1 contains water and / or the easily usable soil water in R2 is not exhausted. *ET* calculation in R2 is based on the linear reduction of the *ETmax*. The reduction takes effect when the water content of R2 drops below the threshold value *Rs(j)* defined by:

$Rs(j) = (1 - Kr).Pr(j).TAW$ (17)

, where *Kr*, as proposed by Doorenbos and Kassam (1979), is the ratio between *TAW* and easily usable soil water. So, transpiration, Tp_2 in R2 is calculated by:

$Tp_2 = Tp\ Kc\ ET_0 \min\{1.0, R_2(j)/Rs(j)\}$ (18)

As explained in Mailhol et al. (1997), *Ps* can be set to 10 cm. Soil evaporation is modeled in a very simplified way. But it is not less robust and furthermore it is consistent with more elaborate theories (Hillel, 1980; Campbell, 1985). As long as R1 is not exhausted, evaporation is equal to that imposed by the climate conditions (*ETo*). In the absence of a crop the R1 is therefore subject to depletion to feed *ETo.* The R1 protects somewhat the moisture of deeper layers from evaporation producing a mulch effect. Outside the crop season and until a decade after sowing, we consider that evaporation can affect lower layers (below 10 cm) when R1 is exhausted. The R2 contributes in soil evaporation (Es_2) according to:

$Es_2 = Ksoil \exp[-(1 - \theta_{R2})]\ ETo$ (19)

, in this empirical formula *Ksoil* is similar to a resistance of soil to evaporation, being a calibration parameter (close to 0.3 for almost all soils). θ_{R2} is a function equivalent to the full up level of second reservoir:

$\theta_{R2} = Min[1, R_2/TAW_{R2}]$ (20)

Es_2 can be stopped when the humidity in the second reservoir reaches to *PWP*.

2.2.2 The plant module

LAI is a visible indicator of potential production (quantity of dry matter) of the plant over its growth. PILOTE simulates the effects of water stress on *LAI*. We suppose that all factors of production other than water are at their optimum. The formula adopted for the *LAI* includes the availability of water for the plant through a stress index based on the evapotranspiration calculation provided by the soil module. The *LAI* increases when the temperature sum (*TT(j)*) exceeds the temperature sum for emergence *Ts*. The temperature index is calculated using this expression:

$$TT_{(j)} = \sum_{k=1}^{k=j} (Tav - Tb) \quad (21)$$

, where *Tav* is the average daily temperature and *Tb* is the base temperature. The expression of *LAI* as in Mailhol et al. (1997) is given by:

$$LAI_{(j)} = LA\operatorname{Im}ax\left[\left(\frac{\sum_{k=1}^{j} TT - Ts}{T_f}\right)^{\beta} \exp\left\{\frac{\beta}{\alpha}\left(1-\left(\frac{\sum_{k=1}^{j} TT - Ts}{T_f}\right)^{\alpha}\right)\right\} - \left(1 - stress^{\lambda}\right)\right] \quad (22)$$

, where *LAImax* is the maximum *LAI* value for a crop growing under no limiting conditions (deductible from literature or by measurement), *Tf* is the temperature sum required to reach *LAImax*. This value for most crops, particularly corn, corresponds to flowering. α and β are calibration parameters. α allows model to simulate both growth and senescence. The model provides transition from $\alpha=\alpha_1$ to $\alpha=\alpha_2=\gamma$ when *TT* exceeds *Tf*, so that three parameters have to be calibrated. An automatic calibration procedure exists for this purpose. λ is an empirical parameter reflecting the aversion of the plant to water stress. The practice with the model suggests that a constant value of 1.25 for λ can be adopted for crops such as wheat, corn, soybean, sunflower, and sorghum. The stress index is:

$$stress = \frac{\sum_{j-10}^{j} Tp}{\sum_{j-10}^{j} Tpm} \quad (23)$$

, where Tp ($=Tp_1+Tp_2$) is the actual transpiration and *Tpm* is the maximum transpiration. The model calculates the actual dry matter yield (*Ya*) as:

Ya = Ym min (1.0, LAIav/LAIopt) (24)

, where *Ym* is potential dry matter obtained without water stress. *LAIav* is the average *LAI* calculated during a critical period (which is linked to the effect of water stress on yield), and *LAIopt* is the averaged *LAI* value that should have a non-stressed treatment during the same period in order to obtain the potential yield. It can be derived using the model with *stress* = 1 in Eq.(22). The critical period can be defined by two temperature threshold corresponding to phonological stages (Ts_1, Ts_2). *LAIav* can be calculated according to:

$$\text{LAIav} = 1/\text{Nj} \sum_{Ts_1}^{Ts_2} \text{LAI(j)} \quad (25)$$

, where *N* is the number of days between Ts_1 and Ts_2. *LAIopt* can be calculated with Eq.(25) by *LAI* in the treatment without stress. *Ym* can be obtained by:

$$\text{Ym} = \text{RUE} \sum_{sowing}^{maturity} S_{(j)}\, I(j) \quad (26)$$

, where *S(j)* is the solar radiation (J/m^2) from sowing to maturity where the maturity will be driven from maturity temperature sum (*Tm*, available in the literature or can be measured). *I(j)* is the fraction of intercepted solar radiation (Moussi and Sacki, 1953):

$I_{(j)} = 1- e^{-k\,LAI(j)}$ (27)

with:

$k = \min(1.0, 1.43\ LAI^{-0.5})$ (28)

, where *k* is the extinction coefficient (Zaffaroni and Schneider, 1989). *RUE* (g/MJ) is the efficiency of solar radiation interception. It represents the efficiency with which the intercepted radiation is used to produce biomass. The evolution of this parameter over the season is difficult to model because of its dependence (little known) to many factors (Villalobos et al. 1996). Therefore it is better to propose a fixed value for this parameter similar to that at maturity. The approach used here for computing *Ym* is comparable to that proposed by Villalobos et al. (1996) and Chapman et al. (1993). The *RUE* value can be calibrated on a full irrigated treatment or derived from literature. In this case, the latter has to be multiplied by the part of active radiation vs. global radiation (Varlet-Grancher et al. 1982), the value of which is close to 0.5.

2.2.3 Modeling the harvest index (*HI*) for the grain yield calculation

Grain yield is obtained by multiplying dry matter production by harvest index. *HI* prediction is not always accurate when modeling the evolution of this factor on the basis of a degree day accumulation. This difficulty is often circumvented by assigning a value often close to the average *HIpot*, potential harvest index, close to 0.5 for many crops. However this proves satisfactory for the crop whose *HI* is not sensitive to water stress such as sorghum and sunflower (Mailhol et al. 1997; Cox and Joliffe, 1986) but for other crops such as corn or wheat especially when severe water stress occurs in the process of grain filling it will be different. In the continuity with the approach based on *LAI*, it is proposed to model *HI* by:

HI =Min [HIpot; (HIpot - a_r (LAIst - LAIav)] (29)

, where *LAIst* being the *LAI* threshold below which the *HI* decreases (parameter a_r, a calibration parameter) from its potential value. Note that Eq.(29) offers some flexibility e.g. some crops can have a better *HI* under a moderate water stress. Such conditions can be simulated when adopting a negative value for a_r and an appropriate *LAIst*. Note that *HI* is limited to 0.17 in the model. Indeed, the lowest *HI* value measured at Lavalette what ever the crop type is about 0.2.

2.3 Modifications to account for mulch impacts

Our modelling approach consists of a simple quantitative description of surface residue effects on the water balance, requiring limited data inputs. That is in contrast with other published more detailed, physically-based mulch models that quantify surface residue impacts on soil water content by solving the balance of energy and water at the soil surface (Bussiere and Cellier (1994); Findeling et al. (2003); Ross et al. (1985)). Parameterization of such models for application to practical problems remains difficult due to the measurement of necessary parameters which are not available for a wide range of conditions. Moreover a large number of these parameters that are related to the physical properties of the mulch layer may change considerably over the season due to decomposition. *Xsr*, our sole surface residue parameter related to mulch quantity on the soil surface has a direct influence on soil water balance processes. In the present model we did not incorporate other relationships describing mulch impacts to retain model simple and easy to calibrate in different environments.
As previously evoked and shown in Khaledian et al. (2006a) for the Lavalette context, the presence of mulch reduces soil evaporation. A first modification of PILOTE to account for soil evaporation reduction due to mulching is proposed. As the shallow reservoir is mainly concerned by this reduction, soil evaporation is calculated according to:

$$Es = \frac{ET_0 \exp(-\varepsilon LAI)}{1 + Xsr} \qquad (30)$$

In Eq.(28), ε is the extinction coefficient for net radiation in the crop canopy layer ($\varepsilon \approx 0.7$ in Eq.(28)), *Xsr* is an empirical parameter that could be linked to the quantity of mulch on the soil surface ($|Xsr|<1$; $Xsr=0$ in CT system). Indeed, this modification is initiated by the approach experimentally deduced by Gusev (2002) where a hyperbolic decrease of *Es* versus mulch accumulation (*MA*, Mg/ha) was shown. *Es* estimation proposed by Eq.(30) is empirical in contrast to that of Perrier and Tuzet (1991) which is physically based but involving parameters which are not easily accessible such as soil resistance or semi empirical approach (Brisson and Perrier, 1991). In the case of existing contrasted mulch treatments, an empirical relationship between *Xsr* and *MA*, such as which proposed by Gusev (2002), could be established. That proposed by Gusev (2002) represents *Es*/*Emo* vs. mulch quantity (kg/ha), where *Emo* is evaporation from a soil without mulch. A comparison with the Scopel approach (Scopel et al. 2004) allows us to give a physical meaning to *Xsr*. Scopel et al. (2004) used a mulch area index which varies over the crop season (variation not easily predictable), in contrast with PILOTE. Relating to the modifications proposed by Scopel et al. (2004), *Es* can be calculated as:

$$Es = ETo \exp(-\varepsilon\, LAI) \exp(-\chi\, \eta\, SR) \qquad (31)$$

, where χ= the extinction coefficient for net radiation in the surface residue layer, η = the area covered per unit of residue dry weight (ha/kg *DM*), *SR*: the mass of surface residue (expressed as dry matter, *DM*, per unit area, kg *DM*/ha). If we compare Eq.(30) and Eq.(31) we find that:

$$\frac{1}{1+Xsr} = \exp(-\chi\, \eta\, SR) \qquad (32)$$

, developing the left hand part of Eq.(32):

$$\frac{1}{1+Xsr} = 1 - Xsr + Xsr^2 + \ldots + (-1)^n Xsr^n + \ldots \qquad (|Xsr|<1) \qquad (33)$$

, and its right hand part:

$$\exp(-\chi\, \eta\, SR) = 1 - \chi\, \eta\, SR + \frac{(\chi \eta SR)^2}{2!} + \frac{(\chi \eta SR)^n}{n!} + \ldots \qquad (|\chi\, \eta\, SR|<1) \qquad (34)$$

, yields: $Xsr \approx \chi\, \eta\, SR$. For example, if the mulch quantity is 2000 kg/ha, *Es/Emo*=0.45 (according to Gusev, 2002) or *Xsr* =0.55 so, the left hand part of Eq.(32) gives $\frac{1}{1+Xsr} \approx 0.6$.

In Scopel et al. (2004) with the same quantity of mulch we have *SR*=2000 kg/ha, (χ= 0.8 and η= 0.00037; $\exp(-\chi\, \eta\, SR) \approx 0.6$). The previous developments attest that an experimental approach could be used to establish a robust link between *Xsr* and the mulch quantity. For that, the lysimeter method or the zero flux plan method, requiring a TDR probe or a neutron probe and tensiometer monitoring, can be used for soil evaporation assessment. In our study, *Xsr* is derived from model calibration by a classical trial and errors approach. The effort of calibration focuses on a period where its sensitivity on the water balance estimation is the highest. This period is the beginning of the cropping season (from sowing to *LAI*<3) where *LAI* is low and, consequently, soil evaporation is presumed to be high especially for summer crops (for corn: T3 in 2002).

The second modification concerns root growth rate, *Vr*, of winter crops which is lower under DSM than under CT. As shown in Fig.1, soil temperature is lower with DSM than CT. This phenomenon is due to soil surface isolation from solar radiation by mulch which retards and limits root development. The impact of this factor on root progression is especially perceptible for crops sown in autumn (or in winter) and for which an adequate and simple *Vr* has to be proposed. Generally under CT, *LAImax* and *Rmax*, are reached at the same time, when all the nutriments allocate to aerial production (grain production mainly). In the case of a winter crop a significant root depth difference can exist between CT and DSM at *LAImax* for both systems. Consequently, *Rmax* under DSM is lower than that of CT (Khaledian et al. 2006b). To account for the impact of lower soil temperatures on root progression this second modification was proposed which consisted in the *Vr* calculation according to:

$$Vr(j) = \min(Vrs, Vrt(j)) \qquad (35)$$

In Eq.(35), which is applied for both systems, *Vrs* is derived from CT system (under no limited water conditions), while *Vrt(j)* which is related to daily air temperature (m/degree.day) in the case of CT, was calibrated as *Rmax* and *LAImax* are reached at the same time. The calibration of empirical relationships between soil temperature under CT (T_{CT}) and DSM (T_{DSM}) allows an adaptation of Eq.(35) to DSM by correcting *Vrt(j)* of CT with the T_{DSM}/T_{CT} ratio.

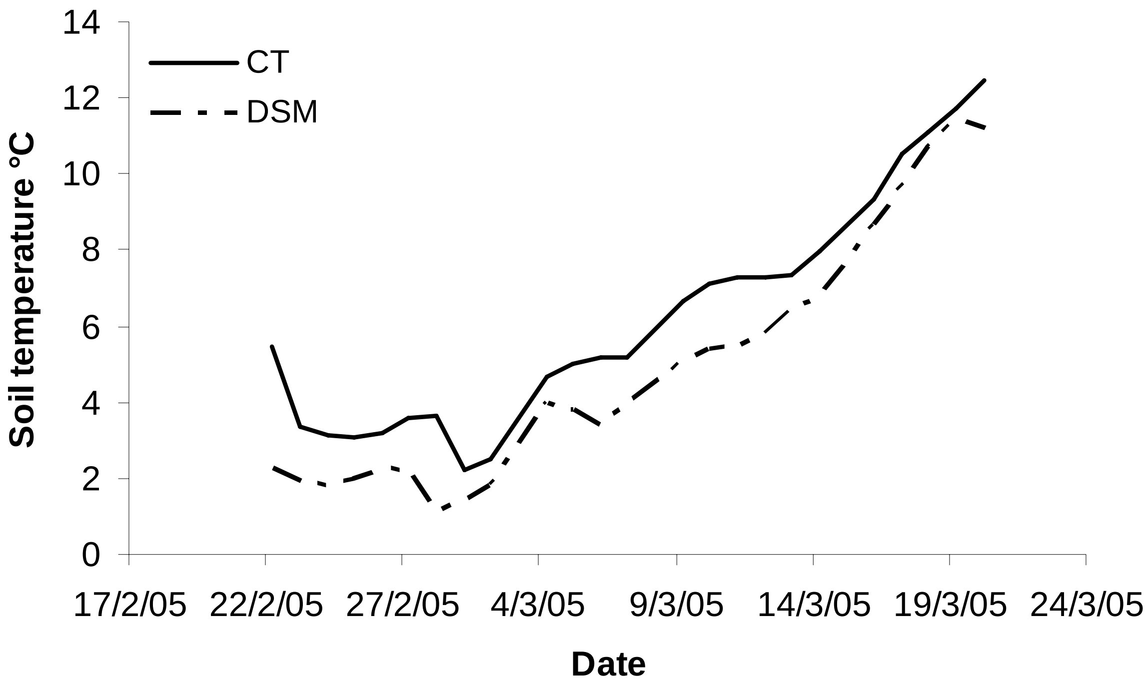

Fig. 1: Soil temperature at 6 cm in both direct seeding into mulch (DSM) and conventional tillage (CT) systems in 2005 with durum wheat (*Artimond* variety).

2.4 Input parameter sensitivity

A sensitivity analysis is useful to indicate which input parameters have the most significant effect on the model output. Particular focus must be set on the measurement or calibration of those parameters. Sensitivity of a certain model output to a given parameter can be defined as the rate of change in the output value resulting from a change of this input parameter while keeping all other parameters constant (Wöhling, 2005). The sensitivity index, *SI*, proposed by Ng and loomis (1984) was selected for this purpose in the present study. The *SI* is calculated in (%) by:

$$SI=\frac{\frac{100}{N}\times\sum_{i=1}^{N}\frac{(Xni-Xci)}{Xci}}{\Delta} \quad (36)$$

, where:

Xni: the new value of the ith data point with a changed value of the input parameter
Xci: the value of output for the ith point in the control simulation run
N: the number of point
Δ: the absolute change in the input parameter

SI in the given form is a measure of the percentage change in the output from that in the control simulation resulting from a one percent change in the value of the input parameter. All input parameters were changed by ±25% and ±10% in accordance with the amount of these parameters that we can find for target varieties in our environment.

3. Results and discussions

Calibration and validation are the two necessary steps before model application with confidence, for the varieties and target environment. Results from other environments across the world can be used, reemphasizing the importance of model validation before an application to the definite environment. There are many reports of different crops in different environments around the world. But most of reports provide very little detail on determination of genetic coefficient, and the values which are used. Therefore genetic coefficients for commonly grown varieties of corn and durum wheat are not readily available. Where this information is available, genetic coefficient have generally been determined from only one study. Thus, results of validation may be impaired by poorly derived genetic coefficients, or the conditions between calibration and validation period being different. While the ability of models to simulate the performance of individual crops is very important, it is also desirable to evaluate the performance of cropping systems over a long period.

3.1. Calibration and model validation

The model results were evaluated using two performance criteria: the root mean square error (*RMSE*) and the coefficient of efficiency (*CE*) of Nash-Sutcliffe (ASCE, 1993; ASCE: American Society of Civil Engineers). These criteria are used to quantify and to better understand the degree with which the model under/over-estimates.

As explained in Mailhol et al. (1997) the first calibration step consists of determining the shape parameters for the *LAI* simulation once *LAImax* is set. The calibration of these shape parameters is done on a full irrigated (non water stressed) treatment by means of the Rosenbrock optimization technique (Rosenbrock, 1960). *LAImax* values proposed for corn by literature vary from 4 to 5 m²/m², according to plant density and variety. For *Samsara*, a semi-precocious variety, a *LAImax* value of 4.5 m²/m² was measured in 1999 on T1 (a non stressed treatment) for a density of 10 plants/m^2 with a *Tf* of 1005 °C (6 °C as *Tb*) and 1850 °C as *Tm*. These values were derived from AGPM info (1996; AGPM: l'Association Générale des Producteurs de Maïs) and were verified at Lavalette (Nemeth, 2001). The *RUE* for corn is set at 1.35 g/MJ, as proposed by literature (Kinitry et al. 1989; Muchow, 1990), after multiplication by 0.5. The *Kr* parameter was set to 0.6 as the average value for corn (Doorenbos and Kassam, 1979) which is adapted to the potential ET_0 rates of the country. *Kcmax* was set to 1.2 in CT case as suggested by Doorenbos and Kassam (1979) for corn. *Rmax*, measured at the end of cropping season (1999 T1) in soil profile was 1.2 m, while the *Vrs*, obtained by using the zero flux plan monitoring, was *Vrs* =0.015 m/day and *Vrt* = 0.001m/degree.day. These values allows the root system to reach at 1.2 m when *LAI*=*LAImax*. The maximum yield values (23.1 and 14.2 Mg/ha for *DM* and *GY* at 15% of humidity, respectively) were obtained in the full irrigated treatment of 1999 (T1). The two cumulative temperature thresholds Ts_1 and Ts_2 within which *LAI* is averaged to correct the potential dry matter value are 900 and 1600 °C for *Samsara*, respectively. As proposed in Mailhol et al. (1997; 2004) Ts_1 is set at *Tf*-100 °C while Ts_2 corresponds to the vegetative stage measured at Lavalette: the end of grain filling (pasty grain). As the *LAIav* value calculated by the model for the rainfed treatment of 1999 is equal to 2.6 m²/m², we suggest to set *LAIst* at 2.5 m²/m², since *HI* = *HIpot* for the rainfed treatment of 1999. As the latter treatment was not subject to a high water stress, the a_r parameter of Eq.(29) was calibrated on the rainfed treatment of 1998 where *GY* was 4.6 Mg/ha (at 15% of humidity) i.e. twice lower than that of 1999. The obtained value is a_r =0.12. Previously, it was checked that λ, used in the *LAI* formulation to account for water stress condition on *LAI*, allows a correct simulation of *DM* for the rainfed treatment in 1998 (9.6 Mg/ha) when setting it to the value obtained in Mailhol et al. (1997; 2004): λ =1.25.

For *Pioneer*, a late variety, *LAImax* = 5 m²/m² for a density of 10 plants/m^2 is often proposed in literature (Howell et al. 1996). This value was measured on T1 at Lavalette in 2007 with CT. Compared with *Samsara*, only the temperature thresholds were modified according to variety characteristics. *Tm* is set at 2000 °C according to that variety (AGPM, 1996) while the measured *Tf* (cumulative temperature to reach *LAImax*) was 1050 °C. The temperature threshold Ts_2 for *Pioneer* is set to that of *Samsara* increased by the difference between *Tf* values of these two varieties i.e. Ts_2=1650 °C (these values were verified at Lavalette). On CT, from the yield of sub-plots (*Cv*= 5%) an average value of 29.4 and 17.4 Mg/ha were obtained for *DM* and *GY*, respectively on T1 in 2007, the full irrigated treatment. PILOTE for this treatment simulates 29.2 and 17.2 Mg/ha, respectively. *DM* and *GY* were satisfactorily simulated by PILOTE: 24.3 vs. 25.2 Mg/ha and 14.3 vs. 14.8 Mg/ha, while the yield on the rainfed treatment is a little under estimated: 11 vs. 12.7 Mg/ha and 4.6 vs. 4.9 Mg/ha.
LAI and *SWR* are satisfactorily simulated for corn and durum wheat in CT. Two examples of *LAI* and *SWR* simulations are presented in Fig. 2 and Fig. 3, respectively.
For durum wheat (*Artimond* variety) the same calibration procedure was used (T1 for the shape parameters). A value of 5 m²/m² is adopted for *LAImax* value with a plant density of 300 plants/m² (Casals, 1996; Laguette, 1997) with a *Tf* value of 1200 °C (0 °C as *Tb*) and 2100 °C as *Tm*. According to Morgan (1971), the vegetative stage Ts_1= *Tf*-100 (the beginning of kernel growth stage) and Ts_2 = 2000 °C (pasty grain stage). These values were verified at Lavalette. A *RUE* value of 1 g/MJ (Casals, 1996, Mailhol et al., 2004) was adopted, *Kr* = 0.6 and *Kcmax* = 1.2 were used as suggested by Doorenbos and Kassam (1979) for durum wheat. *Rmax* measured at the end of the cropping cycle in a soil profile was 1.5 and 1 m for CT and DSM, respectively. The stressed treatments T3 and T5 were used for the calibration of *LAIst* and a_r respectively, the *HI* value for the rainfed treatment was 0.36, being lower than *HIpot* = 0.5. *Rmax* decrease in DSM can be explained by DSM impact on root development related to soil temperature. The *Vrs*, obtained by the zero flux plan monitoring on CT was *Vrs* = 0.01 m/day, while *Vrt* is set at 0.0015 m/degree.day in the model. These combined values used in Eq.(35) corrected by the T_{DSM}/T_{CT} ratio, allows *Rmax* of DSM to be satisfactorily simulated (*Rmax* = 1.05 m when *LAI* ≈ *LAImax*). Table 1 indicates the treatments involved in model calibration for corn and durum wheat.

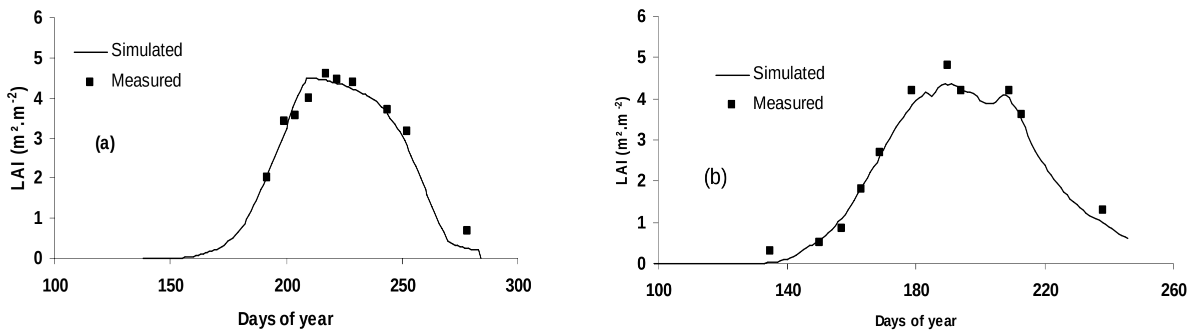

Fig. 2: Leaf area index (*LAI*) in conventional tillage for corn: (a) *Samsara* variety in 2002 (T1) and (b) *Pioneer* variety in 2007 (T2)

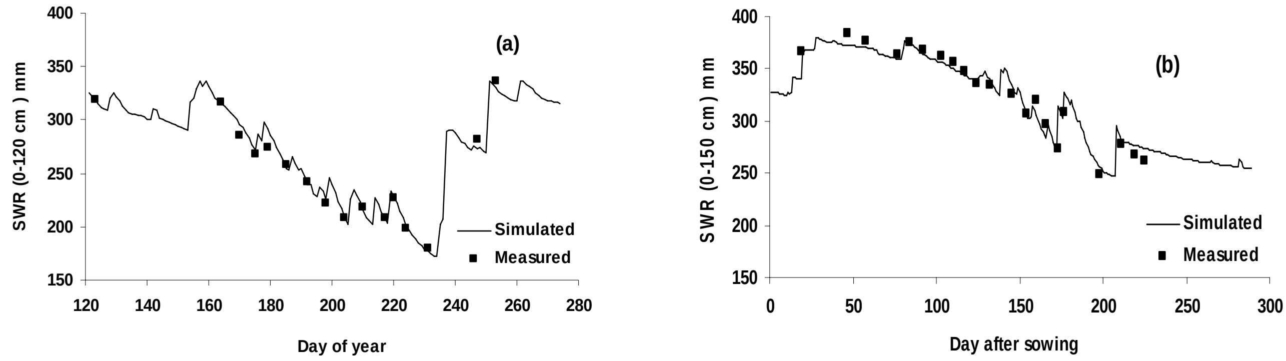

Fig. 3: Soil water reserve (*SWR*): (a) in 2002 (T1) for corn (*Samsara* variety; *CE*=0.98 and *RMSE*=6 mm) and (b) in 2005 (T1) for durum wheat (*Artimond* variety; *CE* = 0.90 and *RMSE* = 13 mm) with conventional tillage system

3.2 The mulch parameter Xsr

In DSM, both soil evaporation and transpiration are reduced. Transpiration diminution results from the presence of a local micro climate emanated by mulch impacts that retains a steady humidity level at the soil surface. This micro climate can limit the convective transfer while reducing the evaporative power of atmosphere. Irrigation rates contribute to this micro climate maintaining more especially for summer crops. It is in agreement with Gusev (2002) who suggested in addition that the mulch thickness must be sufficiently high (5 cm at least) to perceive significant impact on evapotranspiration process. We will see later how to take into account this phenomenon for the soil water balance simulation.

We calibrated PILOTE model with a simple surface residue module in which major mulch effects modify the dynamic of soil evaporation. As previously evoked, our objective is to evaluate the impact of the surface crop residue using a simple modeling approach. Surface residue limits the energy reaching at soil surface, decreasing the first stage of soil evaporation. On the other hand, a layer of surface residue can store an amount of water that evaporates at the first stage. The simulated reduction of soil evaporation by a mulch residue of 1 Mg/ha is about three times larger than the amount of water intercepted and subsequently evaporated from the mulch (Scopel et al. 2004). More especially, under the Mediterranean climate where rainfalls are often high, the ratio between mulch interception and rainfall will be assumed to be negligible, so that we did not take into account mulch interception.

The calibration method used for *Xsr* in T3 in 2002 yields *Xsr* =0.5. This value gives correct results for durum wheat too, as further shown.

The example proposed in Fig. 4 shows that mulching, imputable to *Xsr* only (*Kcmax* being set to 1.2), has a significant impact on the *SWR* evolution according to PILOTE. That lets us to presume that the potential *GY* value for corn (*Samsara* variety, 14.5 Mg/ha) could have been probably reached with a lower water amount than 236 mm (T1) if DSM had been practiced in 1999 where rainfall was particularly high.

Using *Xsr* = 0.5 and decreasing *Kcmax* for corn (from 1.2 to 1.1) as previously justified, could improve *SWR* simulations in the active root zone in DSM. As shown in Fig. 5 for irrigated corn (*Samsara* variety) and for irrigated durum wheat (*Artimond* variety), *LAI* is correctly simulated.

The course of *SWR* is simulated reasonably well for the DSM treatments (Fig. 6b: *CE*=0.91, *RMSE*=13 mm; Fig. 7b: *CE*=0.93, *RMSE*=12 mm; Fig. 8b: *CE*=0.95, *RMSE*=11.9 mm) for corn and durum wheat, while before calibration, some strong discrepancies can be observed for corn (Fig. 6a: *CE*=0.69, *RMSE*=25 mm) and for durum wheat (Fig. 7a: *CE*=0.64, *RMSE*=29 mm). For the latter, the modifications in *Rmax* and *Vr* considerably improve the *SWR* simulation. Note that a *SWR* simulation on 1 m depth (in the active root zone) would give better results for DSM (*CE* = 0.96, *RMSE* = 8 mm). For corn, *SWR* is correctly simulated in both cropping system after PILOTE adaptation (Fig. 8a with CT: *CE*=0.98, *RMSE*=7.3 mm and Fig. 8b with DSM: *CE*=0.95, *RMSE*=11.9 mm). Generally, one can say that *SWR* is satisfactorily simulated by PILOTE for the two corn varieties and durum wheat in CT and in DSM after PILOTE adaptation.

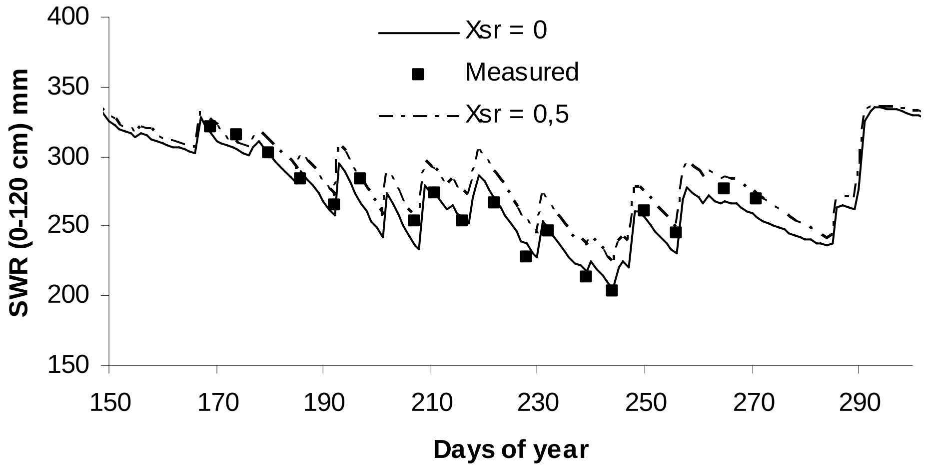

Fig. 4 Mulching impact on the soil water reserve (*SWR*) evolution according to PILOTE on the climatic scenario of 1999 for corn (*Samsara* variety; T1 in conventional tillage: X*sr* = 0; *CE* = 0.92, *RMSE* = 9.0 mm))

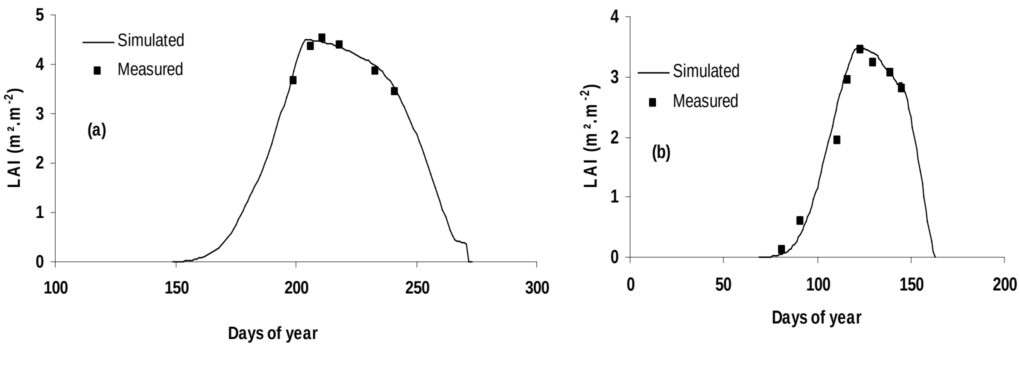

Fig. 5: Leaf area index (*LAI*) in direct seeding into mulch with (a): corn (*Samsara* variety) in 2002 (T2) and (b): durum wheat (*Artimond* variety) in 2005 (T4)

3.3 Dry matter yield (*DM*) and grain yield (*GY*)

Before model adaptation, a disagreement between simulated and observed *DM* was seen and the simulated results of *GY* were similar too. This can be related to the over/under-estimation of *SWR* for treatments where water can be a limiting factor. Indeed, after model adaptation to DSM, improving *SWR* estimation resulted in better crop yield simulations.

A significant discrepancy is nevertheless noticeable for treatment T3 on DSM in 2007 where the model over estimates the yield (*DM*: 27.8 vs. 26 Mg/ha, *GY*: 15.9 vs. 14.1 Mg/ha). The delay of the second N application (70 days after sowing) can be a reasonable explanation of this state of fact, *LAI* being close to its maximal value at this N application date. Moreover, the low initial N content: 79 vs. 140 kg/ha on CT, (due to N amount initially consumed by cover crop) is another reason of this over estimation by a model that does not consider N as a limiting factor.

Although *LAI* of the rainfed treatments in CT and DSM for corn in 2007 were not very well simulated (Fig. 9), PILOTE follows the observed tendency regarding the yields. Indeed, in DSM (T4), measured *DM* and *GY* are 13 and 6.1 Mg/ha, respectively; while the simulated values are 12.9 and 5.8 Mg/ha i.e. higher than that of simulated in CT (11 and 4.6 Mg/ha). Thanks to soil evaporation reduction under DSM, the soil maintains a humidity level which can delay the water stress occurrence. That is an interesting statement for the regions where sowing irrigation is not usually applied such as in Charente (Ruelle et al. 2003). Indeed, in the perspective of the climatic change (with a spring rainfall decrease), a cropping system avoiding a significant modification of the irrigation scheduling would be probably appreciated by the farmers.

Over the contrasted climatic series for 1997, 1998, 1999, 2001, 2002, 2005, and 2007 the model satisfactorily simulates *GY* and *DM* for irrigated and rainfed corn and durum wheat in both DSM and CT systems (Fig. 10). Thus PILOTE, an operative crop model, can be used for water and yield management in CT and DSM systems under Mediterranean climate.

Since it was not the objective of this paper, we did not discuss about the yield difference between CT and DSM systems. One can only refer to published works e.g. Khaledian et al. (2006a; 2006b) showing that for winter crops such as durum wheat, the yields are lower in DSM than in CT, while they are not significantly different for summer crops such as corn.

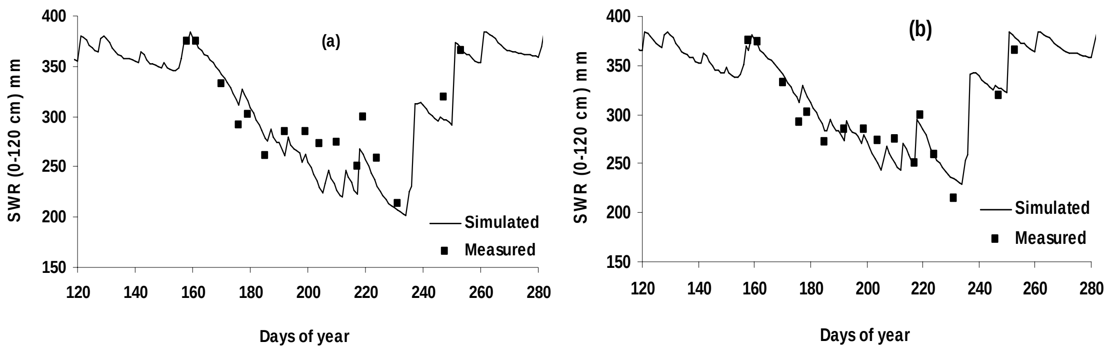

Fig. 6: Soil water reserve (*SWR*) simulation before (a): (*CE*=0.69 and *RMSE*=25 mm) and after (b): model adaptation (*CE*=0.91 and *RMSE*=13 mm) to direct seeding into mulch for corn (*Samsara* variety) in 2002 (T2)

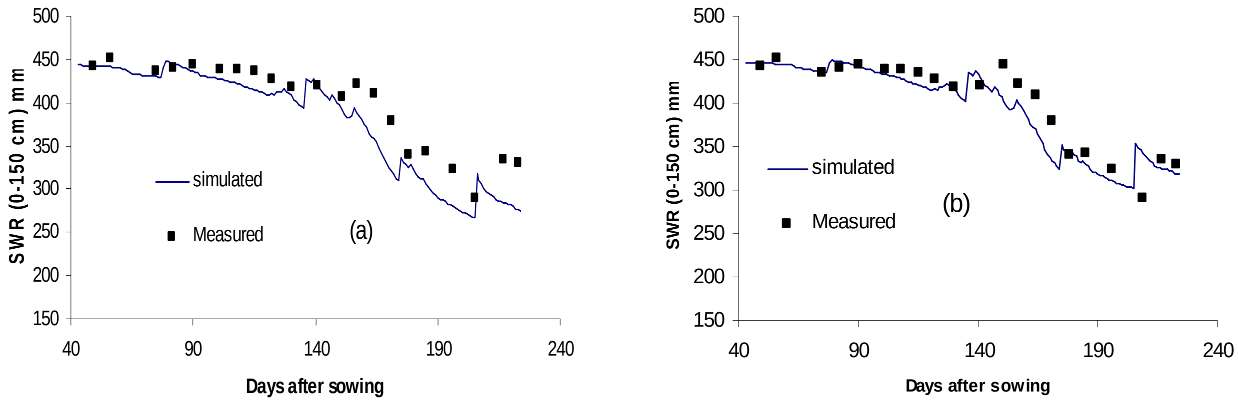

Fig.7: Soil water reserve (*SWR*) simulation before (a): (*CE*=0.64, *RMSE*=29 mm) and after (b): model adaptation (*CE*=0.93, *RMSE*=12 mm) to direct seeding into mulch for durum wheat (*Artimond* variety in 2005, T4)

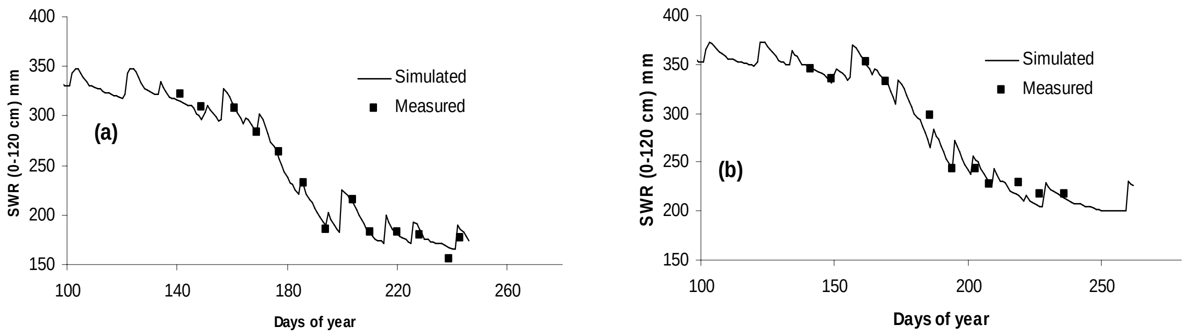

Fig. 8. Soil water reserve (*SWR*) simulation (a): under conventional tillage (T2; *CE* = 0.98 and *RMSE* = 7.3 mm) and (b): under direct seeding into mulch (T3; *CE*=0.95 and *RMSE*=11.9 mm) for corn (*Pioneer* variety) in 2007

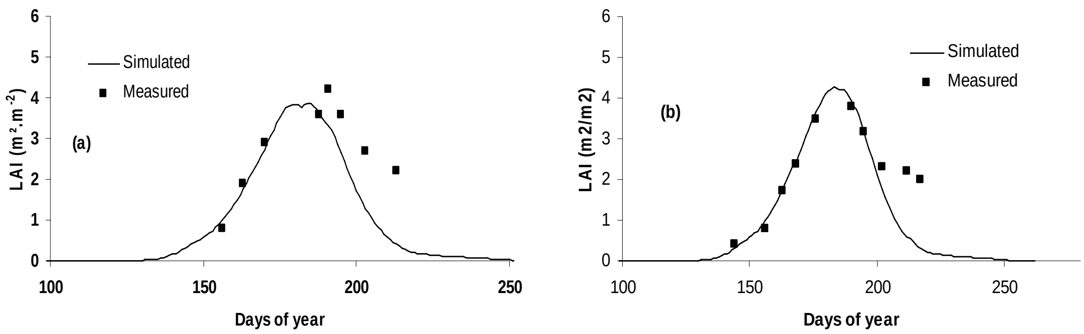

Fig. 9. Leaf area index (LAI) (a): under rainfed conventional tillage (T5) and (b): under rainfed direct seeding into mulch (T4) in 2007 for corn (*Pioneer* variety)

3.4. Sensitivity analysis

A variation of ±25% was adopted for parameters proper to the model while a variation of ±10% for those measured or derived from literature. For instance, it would not be relevant to make vary a lot a temperature sum characterizing a phonological stage. Indeed, that could either result in a vegetative stage interaction or in a variety change. Table 3 and 4 show variations in *GY* and *SWR* vs. variations in input variables using 2007 weather and experiment conditions for corn (*Pioneer* variety). Simulated *GY* was most sensitive to *FC*, high *Kcmax*, *Tm*, *HI* and *RUE*. Predicted corn *GY* is relatively insensitive to the shape parameters of *LAI* curve (α, β, γ) and a_r. Predicted *SWR* for corn is most sensitive to *Rmax*. *SWR* is low sensitive to *Xsr*. It is relatively insensitive to *LAImax* and the shape parameters of *LAI* curve (α, β, γ).
Table 5 and 6 show the variations in *GY* and *SWR* vs. variations in input variables using 2005 weather and experiment conditions for durum wheat (*Artimond* variety). Simulated *GY* is most sensitive to *Tb*, initial *SWR*, high *FC*, high *LAImax*, high Ts_1, low *Kcmax*, *Tf*, *PWP*, *RUE*, *HI*, *LAIst*, and Ts_2. Predicted durum wheat *GY* is relatively low sensitive to *Vr, Ksoil*, *LAIst* and a_r. Predicted *SWR* for durum wheat is most sensitive to initial *SWR* and *PWP. SWR* is low sensitive to *Xsr.*
As evoked in Mailhol et al. (1997), initial *SWR* is a sensitive factor of the model and should be measured as close as possible to the sowing date. From a practical point of view if the initial *SWR* cannot be measured, it is suitable to start model simulation early in the season i.e. at least one month before sowing date e.g. winter precipitation can fill the *SWR* in durum wheat case.

Table 3. Input parameter sensitivity for corn (*Pioneer* variety in 2007) with ±25% changes in input parameters

Input parameter	Sensitivity index of grain yield (%)		Sensitivity index of soil water reserve (%)	
	-25%	+25%	-25%	+25%
Rmax	-0.9	-0.3	-1.1	0.9
Kr	-0.22	0.4	0.12	-0.11
Kcmax	0.86	-1.3	-0.34	-0.15
λ	0.30	-0.22	-0.01	0.01
LAImax	0.07	-0.35	0.05	-0.04
α	0	0.06	-0.02	0.01
β	0.11	0	-0.01	0.01
Γ	0.06	0	-0.06	0.03
Vr	-0.15	0.15	0.07	-0.06
Tinst	0.07	0.14	-0.02	0.00
Ksoil	0.2	-0.2	0.01	-0.02
LAIst	0	-0.55	-*	-*
a_r	0	-0.1	-*	-*
Xsr	-0.10	0.03	-0.03	0.01
Initial *SWR*	-0.74	0	-0.46	0.06

*not involved in *SWR* simulation or *SI*=0

Table 4. Input parameter sensitivity for corn (*Pioneer* variety in 2007) with ±10% changes in input parameters

Input parameter	Sensitivity index of grain yield (%)		Sensitivity index of soil water reserve (%)	
	-10%	10%	-10%	10%
FC	-1.2	1.1	-0.8	0.6
PWP	-0.3	0.8	0.2	-0.2
RUE	-0.97	1.03	-*	-*
HI	-0.97	1.03	-*	-*
Ts_1	0.35	-0.35	-*	-*
Ts_2	0.9	-0.55	-*	-*
Tf	-0.48	0.21	0.07	0.02
*Tm***	-1.17	1	-0.02	0.02
Ts	0.07	0.14	-0.01	0.00
Tb	0	0.28	-0.03	0.03

*not involved in *SWR* simulation or *SI*=0
** depending on the importance of water stress during senescence

Table 5. Input parameter sensitivity for durum wheat (*Artimond* variety in 2005) with ±25% changes in input parameters

Input parameter	Sensitivity index of grain yield (%)		Sensitivity index of soil water reserve (%)	
	-25%	+25%	-25%	+25%
Rmax	0.11	-0.37	-0.00	1.05
Kr	0.47	-0.74	0.09	-0.08
Kcmax	-1.26	0.68	0.16	-0.08
λ	-0.16	0.11	0	0
LAImax	0.05	-1.21	0.03	-0.01
α	-0.05	0.11	-0.00	0.00
β	-0.37	0.37	-0.01	0.00
Γ	-0.42	0.47	-0.02	0.01
Vr	0	0	0	0
Tinst	0	-0.13	-0.00	0.01
Ksoil	0	0	-0.02	0.02
LAIst	1.18	-1.32	-*	-*
a_r	0.13	-0.13	-*	-*
Xsr	0.13	-0.13	-0.01	0.01
Initial *SWR*	-1.85	1.9	-0.4	0.66

*not involved in *SWR* simulation or *SI*=0

Table 6. Input parameter sensitivity for durum wheat (*Artimond* variety in 2005) with ±10% changes in input parameters

Input parameter	Sensitivity index of grain yield (%)		Sensitivity index of soil water reserve (%)	
	-10%	10%	-10%	10%
FC	0.53	-1.18	-0.14	0.07
PWP	1.05	-1.45	-0.27	0.29
RUE	-1.05	1.05	-*	-*
HI	-1.18	1.05	-*	-*
Ts_1	0.39	-1.32	-*	-*
Ts_2	1.84	-1.32	-*	-*
Tf	-2.5	1.05	0.02	0.01
*Tm***	0.53	0	-0.02	-0.06
Ts	0.13	-0.13	-0.00	0.00
Tb	2.5	1.5	-0.08	-0.08

*not involved in *SWR* simulation or *SI*=0

** depending on the importance of water stress during senescence

4. Conclusion

This study attempted to present a simple model, namely PILOTE, for both direct seeding into mulch (DSM) and conventional tillage (CT) systems. The model was calibrated and validated using a 7-year field trial for corn (*Samsara* and *Pioneer* varieties) and durum wheat (*Artimond* variety). The results showed that the model satisfactorily simulates leaf area index, soil water reserve, grain yield and dry matter yield with a minimum coefficient of efficiency of 0.90. This model requires a low number of parameters which most of them can be derived from literatures. Its adaptation to DSM was based on the soil evaporation reduction involving one parameter only in good agreement with the model structure and on the root growth rate for winter crops. PILOTE can be easily calibrated in new environments and for other crops. On the example of corn, the simplicity to adapt the model parameters to a new variety was demonstrated. PILOTE can be used as a reliable tool to provide irrigation programs for a given yield target. We readily acknowledge that PILOTE can be used where water is the only limiting factor which is often the case in Mediterranean countries. A model application on a climatic series would show if yes or not water savings can be obtained under DSM compared with CT for a given yield target. For the evaluation of the environmental benefit that could result from the DSM practice, more complex models than PILOTE have to be used.

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