USING PILOTE MODEL TO DETERMINE WATER USE EFFICIENCY OF DIRECT SEEDING INTO MULCH COMPARED WITH CONVENTIONAL TILLAGE

UTILISATION DU MODELE PILOTE POUR DETERMINER L'EFFICACITE D'UTILISATION DE L'EAU DU SEMIS DIRECT SOUS COUVERTURE VEGETALE EN COMPARAISON PAR LABOUR CONVENTIONNEL

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ABSTRACT

Direct seeding into mulch (DSM) is planting a new crop with the residue of the previous crop as mulch. Mulch reduces evaporation. Therefore DSM can reduce water use and increase water use efficiency (WUE). In the Mediterranean countries, the 2003 and 2005 droughts, especially in Spain and France confirm the urgent need for the implementation of strategies to face the problem. The present study assessed the impact of DSM on WUE compared with conventional tillage (CT) for a target yield. As field experiments are expensive, time consuming and hard to handle, so an operational model, PILOTE (Mailhol et al. 1997) was employed to test the hypothesis that DSM is more efficient in water use than CT. PILOTE was adopted, calibrated and validated in the same experimental station (Khaledian et al. 2009). The model adapted to simulate the water consumption by the cover crop. The model simulated the irrigation amount and yield for DSM and CT for a long climate series (1991-2007). WUE was calculated according to model simulations. The model satisfactorily simulated the consumption of water by cover crop. The results showed an increase in WUE from 77/mm with CT to 102 kg/mm with DSM for a target yield of 14 t/ha for maize. DSM can significantly improve the WUE and save approximately one irrigation compared to CT system, which is important in the context of water scarcity.

Keywords: *PILOTE model, Water productivity, Direct seeding into mulch, Maize.*

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RESUME ET CONCLUSIONS

Le semis direct sous couverture végétale (SCV), un système de production des cultures sans travail du sol, est caractérisé par la création d'une culture de couverture pour produire du paillis. La présence de paillis sur la surface du sol réduit l'évaporation du sol. Par conséquent SCV peut diminuer la consommation d'eau. Aujourd'hui défi majeur en matière d'irrigation est d'augmenter l'efficience d'utilisation de l'eau (WUE) ou en d'autres termes: produire plus avec moins d'eau. En ce qui concerne les pays méditerranéens, les sécheresses de 2003 et 2005 en particulier en Espagne et en France définitivement confirmaient la nécessité urgente pour la mise en œuvre des stratégies communes pour faire face au problème. Dans le cadre d'un effort d'adaptation de SCV dans le SE de la France, la présente étude a évalué l'impact de SCV sur le WUE afin de déterminer si SCV améliorerait WUE par rapport a labour conventionnel (CT) pour un rendement cible. Comme les expériences sur le terrain sont coûteuses, longues et difficiles, donc un modèle opérationnel, PILOTE (Mailhol et al. 1997) a été utilisé pour tester l'hypothèse que le SCV peut être plus efficaces dans l'utilisation de l'eau que la CT. PILOTE a été adopté, puis calibré et validé dans la même station expérimentale (Khaledian et al. 2009). En plus, le modèle a été adapté pour simuler la consommation d'eau par la plante de couverture. Le modèle simule la quantité d'eau d'irrigation et la production des SCV et CT pour une série climatique longue (1991-2007). WUE a été calculé d'après les simulations du modèle. Le modèle simule de façon satisfaisante la consommation d'eau par la culture de couverture. Les résultats ont montré une augmentation de WUE de 77 avec CT à 102 kg / mm avec SCV pour un rendement ciblé de 14 t / ha pour le maïs. Le système SCV pouvait améliorer la WUE et d'économiser environ une irrigation par rapport au système de CT, ce qui est intéressant dans notre contexte caractérisé par la pénurie en eau. Utilisation du semis direct sous couverture végétale permet de réduire la consommation d'eau dans l'agriculture étant le plus gros consommateur d'eau. Cependant, il existe certains problèmes techniques par exemple, adéquates machine semis direct et le contrôle des mauvaises herbes, à résoudre pour adapter ce système en climat méditerranéen.

Mots clés: *Modèle PILOTE, productivité de l'eau, semis direct sous couverture végétale, maïs.*

(Traduction française telle que fournie par les auteurs)

1. INTRODUCTION

Irrigation has a dominant role in agricultural production, especially in the Mediterranean climate, because of varying distribution of the rainfall 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.

Water is the most limiting factor for crop production in the SE of France due to the erratic distribution of annual rainfall. Therefore, it is essential to reduce irrigation demand while maintaining crop production. It can be realized by improving water use efficiency (WUE), i.e., grain yield per unit of irrigation water use (Viets, 1962).

World food demand, and hence agricultural water consumption, will continue to increase during the coming years. With a growing population, rising income, and changes in diet; food demand may grow by 70%–90% by 2050. Without improvement in the efficiency of agricultural water use, crop water consumption would have to grow by the same order of magnitude (de Fraiture et al., 2007). Competition between water for food production and water for cities and the environment will intensify; in addition climate change will increase pressures on water resources. Irrigation development assistance from major international donors has been on the decline over the years as a result of high capital costs, water scarcities, limited benefits to the poor rural communities and negative environmental impacts (Postel, 1989). Thus more effort is needed to improve WUE so that farmers can continue to produce.

One possible solution can be direct seeding into mulch system (DSM) which is planting a new crop with high levels of previous crop residues. Mulch shields the soil from solar radiation thereby reducing evaporation from the soil (Holland, 2004). There is a major effect on the conservation of water by reducing runoff and evaporation losses in DSM. Therefore, more water is retained in the soil, where it remains available for crop growth consequently reducing irrigation demand (Kalra et al. 1984; Gonzalez-Sosa et al. 1999; Bussière and Cellier, 1994; Govaerts et al. 2007; Dahiya et al. 2007). Increasing the efficiency of water use in agriculture is a way to address water scarcity issue. DSM can increase the efficiency of water use. To test this hypothesis, there are scientific procedures, i.e. field experiments and crop models. Field experiments are time consuming, expensive, and limited to the prevailing soil, climate, and crop conditions. The experiments 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 response time is too long considering the rapid change of varieties and all the cropping system components used and modified by farmers. Model simulations under various climatic conditions can help the farmer to identify the best crop management towards different cropping system (Maraux et al. 2004). Jamieson et al. (1998) believe that developing empirical models provide a good basis for decision support at the farm level by providing 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 N is not limiting, water management is the main factor influencing yield. Mechanistic crop models are large 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).

The objectives of the present study were: 1) to evaluate the PILOTE model to simulate the water consumption of cover crop and 2) to assess the impact of DSM on WUE improvement compared with CT for a target yield.

2. MATERIALS AND METHODS

As part of an effort to adapt DSM in the SE of France, the present study assessed the impact of DSM on WUE to determine if DSM would improve WUE compared with conventional tillage (CT) for a target yield. The operational model, PILOTE (Mailhol et al. 1997) was employed to test the hypothesis that DSM can be more efficient in water use than CT. PILOTE was adopted and then calibrated and validated in the same experimental station (Khaledian et al. 2009). Furthermore, the model adapted to simulate the water consumption by the cover crop. The model simulated the irrigation amount and yield for DSM and CT for a long climate series (1991-2007). WUE was calculated according to model simulations.

• Water use efficiency

Generally, WUE is defined in agronomy (Viets, 1962) as:

$$WUE = \frac{yield}{water\ used\ by\ crop} \qquad (1)$$

According to Rodrigues and Pereira (2009) the concept of water use efficiency to more consistently discriminate the role of irrigation in crop production can be rewritten as:

$$IWUE = \frac{yield}{irrigation\ water} \qquad (2)$$

where yield is grain yield in kg/ha and irrigation is irrigation water depth in mm/ha; so IWUE will be in kg/mm.

• Model description

PILOTE is an operational model based on the leaf area index (LAI) simulation (Mailhol et al. 1997 and 2004) which simulates water balance and yield. It simulates the soil water reserve (SWR) evolution on a daily time step. SWR refers to three reservoirs. The first one has a 10 cm depth while the others vary with root development. In DSM, the mulch effect limits soil evaporation and creates a microclimate in the case of consecutive irrigations or rainfalls. In the modified version of PILOTE (Khaledian et al. 2009) these new conditions were taken into account by introducing a coefficient to reduce soil evaporation (X_{sr}) and by reducing K_{cmax} for corn from 1.2 to 1.1 to account for the modified microclimate conditions.

Our modeling approach consisted of a simple quantitative description of surface residue impact 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 impact on soil water content by solving the balance of energy and water at the soil surface (Ross et al. 1985; Bussiere and Cellier 1994; Findeling et al. 2003). Parameterization of such models to address practical problems are difficult due to non-availability of necessary measured data for a wide range of conditions. Moreover a large number of these parameters related to the physical properties of the mulch layer may change considerably over the season due to mulch decomposition. X_{sr}, our single parameter related to mulch quantity on the soil surface has a direct influence on the soil water balance. Other relationships describing mulch impacts were not incorporated in PILOTE model (Khaledian et al. 2009) to retain model simple and easy to calibrate in different environments. So, soil evaporation (E_s) assumed to only affect the shallow reservoir, is calculated according to:

$$E_s = \frac{ET_0 \exp(-\varepsilon LAI)}{1 + X_{sr}} \quad (3)$$

where ET_0 is the reference evapotranspiration, ε is the extinction coefficient for net radiation in the crop canopy layer (being 0.7), X_{sr} is an empirical parameter that could be linked to the quantity of mulch on the soil surface ($0 \le X_{sr} \le 1$; $X_{sr} = 0$ in CT system). Indeed, this modification was initiated by the approach experimentally deduced by Gusev (2002) where a hyperbolic decrease of Es vs. mulch accumulation (MA, Mg/ha) was found. Although Es estimation proposed by Eq. (5) is empirical, a physical meaning can be proposed to X_{sr} (see Khaledian et al. 2009) when comparing with the Scopel approach (Scopel et al. 2004). They used a mulch area index which varies over the crop season (variation not easily predictable), in contrast with PILOTE.

The previous developments attest that experiments could be used to establish a robust link between X_{sr} and the mulch quantity. In our modeling approach, X_{sr} is derived from model calibration by trial and error. The 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) when LAI is low and, consequently, soil evaporation is high, especially for summer crops e.g. corn crop.

The root mean squared error (RMSE) and the prediction efficiency of model (PE: Nash and Sutcliffe, 1970) were used to evaluate grain yield (GY) and SWR simulations.

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(M_i - S_i)^2}{n}} \quad (4)$$

$$PE = 1.0 - \frac{\sum_{i=1}^{n}(M_i - S_i)^2}{\sum_{i=1}^{n}(M_i - M_{avg})^2} \quad (5)$$

where M_i is the i^{th} measured value, S_i is the ith simulated value, M_{avg} is the average of measured values, and n is the number of data pairs. The same criteria were used to evaluate SWR simulations during the cover crop season.

The experimental limitations did not allow us to test different scenarios of water supply on both DSM and CT systems, to check the potential of DSM regarding IWUE compared with CT. Hence, we used the PILOTE model (Khaledian et al. 2009) for corn in both systems. As we need to initialize the SWR at sowing for simulating the irrigation demand and the yield of the main crop (corn) we must first ensure that the model satisfactorily simulates SWR during the cover crop season. After verification, we can apply this model on a climatic series to analyze the benefits of adopting DSM rather than CT regarding water saving.

According to the current DSM practice in the Southeastern of France, the cover crop is set up between the harvest and the sowing of the main crop. After the harvest of durum wheat under DSM in 2006, a mixture of vetch, oat and rape was sown in mid-October. This cover crop was destroyed before planting a corn crop in 2007 by glyphosate. During this period, SWR was monitored using Campbell® FDR CS615 sensor (for 0-30 cm) and neutron probe (for 0-120 cm). To simulate the LAI of the composite cover crop, we have assumed that it has an evolution comparable to that of wheat; this appears consistent with observations, oat being the crop which was by far the most developed in the mixture as a result of seeding conditions and climate.

We intended therefore, using the PILOTE model to compare the irrigation need and the yield of DSM compared with CT. We perform simulations on a climatic series, available at Lavalette from 1991 to 2007 for the case of corn (*Pioneer PR35Y65* variety). PILOTE model defines the timing and doses of irrigation. The irrigation strategy adopted aims to obtain an average yield of 14 Mg/ha, lower than the potential yield (18 Mg/ha) to be realistic. The X_{sr} coefficient of soil evaporation reduction, introduced for DSM case, is set at 0.5 according to the quantity of mulch on the soil surface (Khaledian et al. 2009). In DSM, the crop management consists of the sowing of a cover crop such as that adopted in 2006/07, which was destroyed, using an herbicide i.e. glyphosate, on March 15 or 20 days before planting the main crop.

3. RESULTS AND DISCUSSION

A better soil water storage in DSM led us to hypothesize that in the Mediterranean climate with water scarcity and erratic rainfall, DSM would have a better IWUE compared with CT. This hypothesis has been assessed in our study.

• Experimental irrigation water use efficiency

Table 1 summarizes the GY and WUE of corn, sorghum and durum wheat as well as irrigation and rainfall from 2001 to 2007.

Table 1. Grain yield (GY), irrigation, rainfall, and water use efficiency (WUE) from 2001 to 2007 seasons with conventional tillage (CT) and direct seeding into mulch (DSM) (le rendement en grains (GY), l'irrigation, les précipitations, et l'efficacité de l'utilisation de l'eau (WUE) de 2001 à 2007 avec labour conventionnel (CT) et le semis direct sous couverture végétale (SCV))

Season/ crop	treatment	GY (Mg/ha)	irrigation (mm)	rainfall (mm)	WUE (kg/mm)
2001/corn	CT	10.9 a	206	141	53 a
	DSM	7.95 b	216	141	37 b
2002/corn	CT	11.9 a	346	311	34 a
	DSM	10.68 a	292	311	37 a
2003/ sorghum	CT	7.12 a	123	99	58 a
	DSM	6.71 a	68	109	99 b
2004/ sorghum	CT	8.12 a	289	133	28 a
	DSM	8.52 a	276	133	31 a
2004-05/ durum wheat	CT	6.3 a	50	229	126 a
	DSM	3.1 b	36	224	86 b
2005-06/ durum wheat	CT	5.98 a	93	71	64 a
	DSM	2.95 b	90	71	33 b
2007/corn	CT	13.8 a	218	203	63 a
	DSM	12.85 a	182	203	71 a

Different letters represent significant differences between means ($P < 0.05$).

During the whole trial period the DSM GY were lower than CT GY. Statistically, except of the first season which was the season of DSM installation, the GY of corn and sorghum were not significantly different from those of CT. For durum wheat the grain yield was significantly lower with DSM, because of a lower plant population (84 in DSM vs. 264 plants/m^2 in CT) and cereal leaf beetle attack.

Except of the first season and the two seasons of durum wheat, IWUE was higher with DSM; however except of 2003 the differences were not significant. Lower IWUE of durum wheat with DSM was related to a lower grain yield as explained above. For 2003 season with a lower irrigation amount (68 in DSM vs. 123 mm in CT) DSM had a significantly higher IWUE which demonstrates its potential to improve IWUE.

In DSM not only there is a thick layer of mulch on the soil surface but also there is a more humid micro climate DSM than in CT. These two factors result in decreasing soil evaporation or in other words actual evapotranspiration. But it is not evident that all of this saved water being beneficial to produce more total dry matter and GY due to crop production limitations i.e. lower plant population, plant N uptake, the presence of pests, irrigation timing, etc.

- Simulated irrigation water use efficiency (Model verification for cover crop

Water uptake of cover crop is important during the beginning period of winter. The comparison was made between the measured (with FDR CS615 sensor) and the simulated values of SWR for the layer of 0-30 cm.

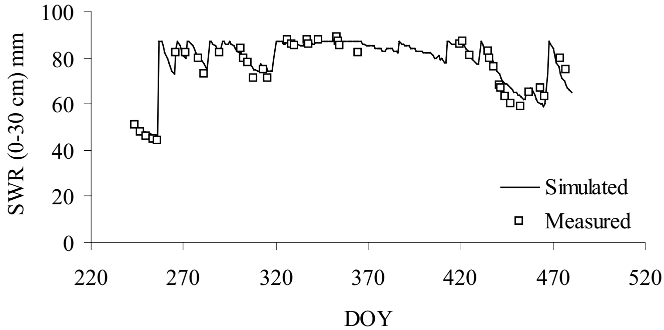

Figure 1. Simulated and measured soil water reserve (SWR; measured with FDR S615 sensor) in DSM for the first soil layer (0-30 cm) with a mixed oat, vetch and rape cover crop (RMSE=3 mm and PE=0.946; DOY: day of year) (Les valeurs simulées et mesurées de réserve en eau du sol (SWR, mesurée par le capteur CS615 FDR) dans le SCV pour la première couche de sol (0-30 cm) avec une couverture mélange d'avoine, vesce et colza (RMSE = 3 mm et PE = 0,946; DOY: jour de l'année)).

As can be seen in Figure 1, the PILOTE model simulates satisfactorily the SWR of this layer (RMSE=3 mm and PE=0.946). Furthermore the model satisfactorily simulates the SWR during the cover crop season in 0-120 cm compared with neutron probe measurements (Fig. 2, RMSE=15 mm and PE=0.998). The model can take into account the effects of mulch on the evapotranspiration and provides an accurate SWR at sowing date of the main crop. Therefore we can use it to simulate the practice of DSM over the climatic series of 1991-2007.

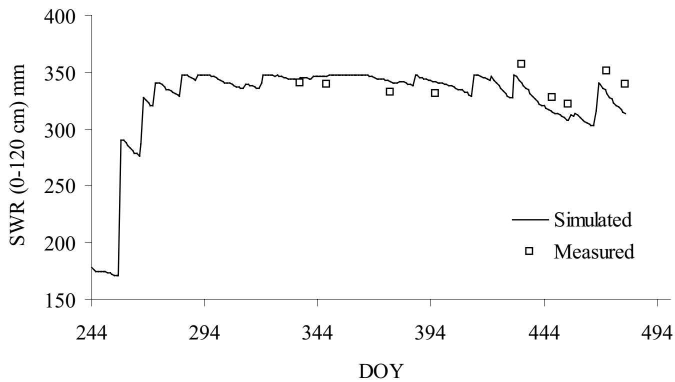

Fig. 2. Simulated and measured soil water reserve (SWR; measured with neutron probe in 0-120 cm) in DSM with a mixed oat, vetch and rape cover crop (RMSE=15 mm and PE=0.998; DOY: day of year) (les valeurs simulées et mesurées de réserve en eau du sol (SWR, mesurée avec une sonde à neutrons dans 0-120 cm) dans le SCV avec une couverture mélange d'avoine, vesce et colza (RMSE = 15 mm et PE = 0,998; DOY: jour de l'année))

• Model application on the climatic series

PILOTE simulates satisfactorily the yield and the SWR during the growth season of main crop with RMSEs of 0.87 Mg/ha and 13 mm for yield and SWR, respectively and the minimum PE of 0.9 for SWR (see Khaledian et al. (2009) for more details).

Table 2 presents the results of PILOTE simulations on the climatic series of 1991-2007. IWUE was found to increase from 77 with CT to 102 kg/mm with DSM in the climate of Lavalette. Furthermore we can say that in average a water application depth of 40 mm was saved with DSM compared with CT.

There were some years where the gain in terms of water saving was insignificant because of low rainfall after destruction of the cover crop. It is clear that by the spring rainfall, the soil water reserve will be more or less restored at sowing of the main crop. One example for the 2006/07 season is presented in Figure 3. But water savings expected in DSM compared to CT may be lacking in some years with a dry spring.

Table 2. Simulation results on the climatic series of 1991-2007 at Lavalette to calculate irrigation water use efficiency (IWUE) with conventional tillage (CT) and direct seeding into mulch (DSM) (les résultats de simulation sur la série climatiques de 1991-2007 à Lavalette pour calculer l'efficacité d'utilisation de l'eau d'irrigation (IWUE) avec travail du sol (CT) et le semis direct sous couverture végétale (SCV)).

Year	CT			DSM		
	applied water (mm)	yield (Mg/ha)*	IWUE (kg/mm)	applied water (mm)	yield (Mg/ha)*	IWUE (kg/mm)
1991	210	14.3	68	175	13.6	78
1992	85	15	176	50	15.3	306
1993	175	14	80	140	13.8	99
1994	225	13.8	61	190	13.8	73
1995	225	13.5	60	190	12.8	67
1996	140	14.3	102	105	13.8	131
1997	120	13.1	109	85	13.2	155
1998	210	13.9	66	155	13.6	88
1999	190	15.5	82	140	15.6	111
2000	190	15.7	83	190	15.7	83
2001	225	15.5	69	155	16	103
2002	225	16.1	72	190	15.8	83
2003	330	13.9	42	260	13.8	53
2004	225	14.8	66	175	14.4	82
2005	225	15	67	225	15.1	67
2006	295	14.9	51	260	14.5	56
2007	225	15.4	68	155	15.4	99
Mean	207	14.6	77	167	14.5	102
SD**	58	0.9	30	55	1	59
CV (%)***	28	5.9	39	33	7	58

*with 15% of humidity, **standard deviation, ***coefficient of variation

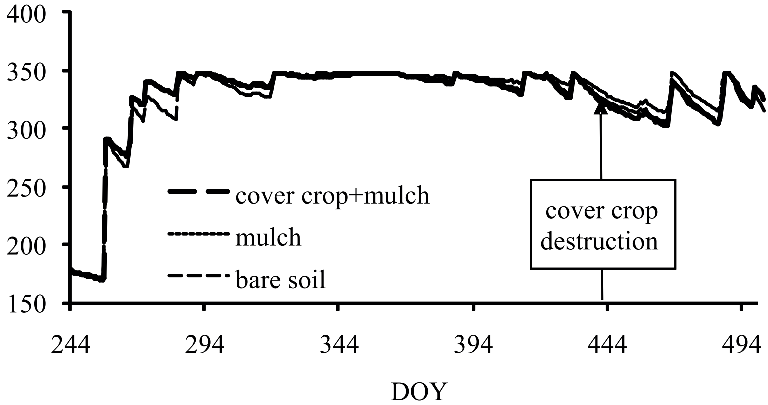

Fig. 3. Simulated soil water reserve (SWR) in DSM in 0-120 cm with bare soil, soil covered by mulch and soil covered by mulch and with a mixed oat, vetch and rape cover crop in 2006/07 (DOY: day of year) (la réserve en eau du sol simulée (SWR) dans le SCV au 0-120 cm avec le sol nu, sol recouvert de résidu et le sol recouvert de résidu et aussi avec une mélange d'avoine, vesce et colza en 2006/07 (DOY: jour de l'année)).

4. CONCLUSIONS

The present study compared the N balance and IWUE for corn, sorghum and durum wheat under DSM and CT systems. A better soil water and nutrient storage in DSM led us to hypothesis that in the Mediterranean climate with water scarcity and erratic rainfall, DSM would have a better N balance and IWUE compared with CT.

The experimental results showed that DSM is able to increase IWUE in the Mediterranean climate and accordingly makes a contribution to address water scarcity. With the exception of the first season, when DSM was not yet installed, IWUE for corn and sorghum had tended to be higher; however the differences were not significant. Because of experimental limitations to check the potential of DSM to improve IWUE, PILOTE model was used to verify IWUE in DSM compared with CT. Average IWUE values are 77 and 102 Kg/mm for CT and DSM, respectively. The standard variation of IWUE is higher with DSM. Indeed, some years DSM was not advantageous compared with CT in terms of water saving, because of lower spring rainfall which cannot refill the soil water reserve depleted by the cover crop. It should be noted that such so high IWUE values were obtained assuming that all of production factors, except of water, are under optimal conditions e.g. nutrients. The results of the model during the long climatic series of 1991-2007 confirm that DSM can be more efficient in water use than CT. DSM saved in average a water application depth of 40 mm compared to CT system, which is interesting in a context characterized by water scarcity.

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