RESTRICTIVE IRRIGATION UNDER SUBSURFACE DRIP IRRIGATION IN A MEDITERRANEAN CLIMATE: MODELLING APPLICATIONS TO A LOAMY SOIL WITH CORN

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ABSTRACT

This work deals with the analysis of conditions under which subsurface drip irrigation (SDI) can play a major role in water savings while insuring an acceptable crop yield level. Technical solutions for water savings have been implemented during 2 irrigation seasons (2008-2009 at Cemagref institute (Montpellier, SE, France) for a corn crop. They refer to buried drip irrigation. The later, even under the severe 2009 drought appears as very promising in terms of water productivity. This work focuses on the soil water and transfer under drip irrigation in relation with crop production. At this end, PILOTE, a crop model have been adapted to the specificity of the irrigation system and associated with the 2D numerical code Hydrus-2D. For the latter a special attention was paid to the root system behaviour under restrictive water conditions in view of proposing an adapted modelling approach for these conditions. Indeed, the presence of heterogeneous soil water content zones, exacerbated by the restrictive water application conditions, forces the plant adopting compensating processes to match the climatic demand. In other words, plant removes its water uptake capabilities to soil zones where water is more available. In the last Hydrus-2d version the compensated root water uptake process has not been implemented yet. Such a model version is not able to mimic this physiological behaviour, and consequently underestimate actual evapotranspiration, an essential condition for a correct yield prediction. When pedo-climatic conditions contribute to a good installation of the root system, PILOTE, an adapted lumped crop model regarding the root water uptake process, allows a satisfactory prediction of AET and corn yields. Considering the narrow relationship existing between Yield and actual evapotranpiration, such a relationship established by PILOTE in the application context, associated with the generic numerical code Hydrus-2D could be used to expand the domain of validation of PILOTE.

key words: Subsurface Drip Irrigation, crop model, Hydrus-2D, water productivity, actual evapotranspiration.

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RESUME

L'irrigation goutte à goutte enterrée (SDI) présente des potentialités certaines pour économiser l'eau tout en garantissant un bon niveau de production. Cette technique est relativement peu étudiée en conditions d'irrigation restrictive et plus particulièrement en grandes cultures. L'objet de ce travail et d'analyser la possibilité d'irriguer une culture comme le maïs selon ce système en contexte méditerranéen et sous irrigation restrictive. En effet des efforts supplémentaires seront demandés aux agriculteurs en termes d'économies d'eau dans une perspective de changement climatique. Il faudra alors être à même non seulement de proposer un écartement des gaines adapté au contexte d'une part et, d'autre part, une stratégie d'irrigation visant à maximiser le rendement sous contrainte hydrique. Un tel objectif peut être atteint grâce à la modélisation. Celle-ci doit résulter du couplage un modèle de transfert de l'eau dans le sol de type 2D à un modèle de culture pour prédire les rendements. A notre connaissance ce type de modèle n'existe pas encore. Cependant, on montre ici, à la faveur de deux années d'essais climatiquement contrastées, que le modèle de culture PILOTE, adapté à l'irrigation enterrée, permet de simuler de façon satisfaisante l'évapotranspiration réelle et les rendements du maïs en sol limoneux et ce, pour deux écartement de gaines : 120 et 160 cm. Dans ce type de sol généralement bien alimenté par les pluies de printemps favorisant la mise en place du système racinaire, PILOTE, un modèle opérationnel, peut être utilisé en vue d'améliorer la productivité de l'eau sous SDI. Cependant pour des objectifs plus ambitieux comme le choix d'écartements de gaine dans d'autre contexte et l'identification de stratégies associées à de nouveaux contextes de sol tels que des sol plus grossiers par exemple PILOTE affiche ses limites. Afin d'étendre ces limites on a étudié dans le cadre de ce travail, la possibilité d'associer PILOTE au code numérique Hydrus-2D, un modèle à bases physiques pour simuler les transferts 2D eau-solutés dans le sol. Cette association est conçue sur la base d'une relation liant le rendement à l'évapotranspiration réelle (ETR). Il est alors possible de simuler le transfert d'eau selon un processus 2D quel que soit le type de sol ainsi que ETR sur l'ensemble du cycle pour en déduire le rendement. Cependant en raison d'une distribution hétérogène de l'humidité du sol inhérente au système d'irrigation d'une part et, d'autre part en raison d'une pratique d'irrigation restrictive générant du stress hydrique, la plante met œuvre un processus de compensation du prélèvement de l'eau. Cela signifie qu'elle reporte ses potentialités d'extraction vers les zones où l'eau est plus disponible. Ce phénomène n'est pas encore intégré dans les dernières versions d'Hydrus. Cela met en lumière les avantages d'un modèle d'extraction de type global comme PILOTE sur un modèle où le processus d'extraction de l'eau est distribué comme dans Hydrus qui en conditions de stress trop prononcé sous estime ETR

MOTS CLES: goutte à goutte enterré, modèle de culture, Hydrus-2D, productivité de l'eau, évapotranspiration réelle.

INTRODUCTION

Mediterranean countries face more and more drastic water scarcity. Consequently, farmers are encouraged to adopt efficient irrigation systems. Sub-surface drip irrigation (SDI), considered as an innovative irrigation system, has capabilities to improve the irrigation water productivity. That is due to a reduction of evaporation losses and to its good efficiency compared with sprinkler irrigation affected in

Maghreb countries by maintenance problems. But, as the water resource is more and more subject to conflicts between different users, supplementary efforts from farmers are required to save water by optimizing their irrigation strategies. This can promote the application of restrictive irrigation strategies (RIS) which can be very far from the classical drip irrigation consisting to apply little doses at high frequency. The latter being generally touted as a major advantage of micro irrigation, although studies have shown that it is not generalizable depending on soil, crop type and its environmental context as for corn for instance (Lam and Trooien, 2003). On the favour of field experiments carried out on a loamy soil plot with corn during two contrasted climatic seasons in SE of France one can chow that RIS with SDI systems can give high irrigation water productivity. To analyse the pertinence of this results under less favourable pedo-climatic contexts, modelling appears as an interesting tool. Since the role of irrigation being to grow the plant, a modelling approach coupling a 2D water transfer model with a crop model is the required tool. In addition, such a modelling could be useful for identifying the optimal solution, from an economic point of view, regarding the choice of lateral spacings under a pedo-climatic context and for a given crop. Nevertheless, such a model according to our knowledge does not exist yet. The reference numerical code Hydrus-2D (Simunek et al., 1999), is widely used for simulating the 2D soil water transfer under bare or cropped soils (Skaggs et al., 2004; Assouline et al., 2006; Arbat et al., 2008; Patel and Rajput, 2008, Mubarak et al., 2010; Mailhol et al., 2011), only. One can also note that root progression is not simulated by the model. As a consequence, the simulation over a cropping cycle is not very convenient (Mubarak et al., 2010; Mailhol et al., 2011). More over, a solution proposed by Simunek and Hopmans 2009) to the compensated root water uptake phenomenon, is not integrated yet in the last Hydrus versions. As widely evoked in Mailhol et al., (2011), this is an important characteristic of the plant. This physiological phenomenon initiated by the plant to survive consists to transfer its uptake capabilities to soil regions where water is more available. It seems evident, that such a phenomenon has to be taken into consideration under an irrigation system having the specificity to generate a variable wetting pattern and more especially under restrictive irrigation.

Before considering a complex modelling approach based on a 2D soil water transfer process with a distributed rooting pattern, it appears necessary to see if a more operative one cannot be used. PILOTE (Mailhol et al., 1997; Khaledian et al., 2009), a crop model where the soil water obeys to a 1D water transfer process and the root water uptake is based on a lumped model, after a simple adaptation to the SDI system has shown noticeable capacities to predict actual evapotranspiration (AET) and corn yield under a loamy soil conditions in SE of France (Mailhol et al., 2011).But, even if good results were obtained in such soil conditions for lateral spacing of 1.2 m and acceptable for lateral spacing of 1.6 m, the application to other soil types is still questionable. The objective of this work is to present the basic concepts of a more generic modelling approach allowing the yield prediction of a SDI irrigated crop.

MATERIALS AND METHODS

Field experiments were carried out on a deep loamy soil (20% clay, 47% silt, 33% sand) with corn at the Cemagref institute of Montpellier (SE of France) during two contrasted climatic years. This soil type has a holding capacity of 180 mm/m. A complete meteorological station exists on the site for evaluating the reference evapotranspiration (Allen et al., 1994). Cumulative ETref was of 600 mm in 2008 and 680 mm in 2009 on the cropping cycle duration. Significant rainfall ceased at mid June in 2008 while at mid May in 2009 which was hotter than 2008.The SDI system was tested on two treatment namely SDI120 and SDI160 in reference to the spacing (1.2 and 1.6 m respectively) of the laterals buried at a 35 cm depth, using Chapin drip tapes (Jain Irrigation System Ltd, Jalgaon, India).Each treatment had an area of 1200 m2 (60 m length, 20 m width). Maïze (cv. Pioneer PR35Y65) was sown on April 24 for the two seasons except for SDI120 in 2009 which was sown on May 7th, at a density of 9 Plt/m^2 , the plant density being of 8 Plt/m^2 for SDI160. For evaluating irrigation water productivity under SDI, the experiment was completed by two rainfed treatments in 2009: R160 and R120, each one having the same planting characteristics of their homologous SDI treatments. Due to problems during seeding in 2009, the buried pipes are not located between two corn rows. That resulted in an asymmetric SDI system more especially for SDI160 where some corn row are far from the pipe while others are close. Irrigation was done at a discharge rate of 2.8 Lh^{-1}m^{-1}, and at a pressure of 0.7 bar. The irrigation strategy was applied in order to reach approximately 70% of the maximum water requirements. But, it was different for the two years. That of 2008 consisted to irrigate at low dose and high frequency while that of 2009 consisted to irrigate at high dose and low frequency, the objective being also to apply a same water amount for the two SDI treatments. Accounting for climate and plant growth irrigation doses were around 5 to 12 mm every two days and 10 to 30 mm once a week, for the two years respectively. The water application depths (WAD) do not differ a lot between the two years: 235, and 250 mm in 2008 for SDI120 and SDI160 respectively and 240 mm for the two SDI treatments in 2009.

For each treatment an access tube (T1) for the neutron probe was installed to a depth of 150 cm at the vertical of the crop row in 2008 and a second (T2) near the pipe and at the inter-row (T3) in 2009. The periodicity of measurements was approximately one week. A series of mercury tensiometers were installed at 10, 20, 30, 45, 60, 75, 90, 110, 130 and 150 cm depth on a crop line of each treatment. The latter were useful to eventually update the irrigation dose in order to mitigate drainage risks. For analyzing the evolution of the wetting pattern under irrigation, two capacitance sensors placed in access tube (EnviroSMART) were vertically installed, a first under row and, a second at 15 cm from the buried dripper line.

Leaf area index (LAI) was monitored each week using the LAI2000 (LI-COR Plant Canopy Analyser). Plant samples were collected after maturity for evaluating total dry matter and grain yield according to the protocol described in Mailhol et al., (1997) and Khaledian et al., (2009).At harvest a soil profile was dug by a backhoe to analyse the root distribution perpendicularly to the drip lines. Root repartition was described on a grid of 5 cm x 5 cm (Fig. 1) using a qualitative root index varying between 0 and 5 as explained in Mubarak et al., (2009). For more details the reader can refer to Mailhol et al., (2011).

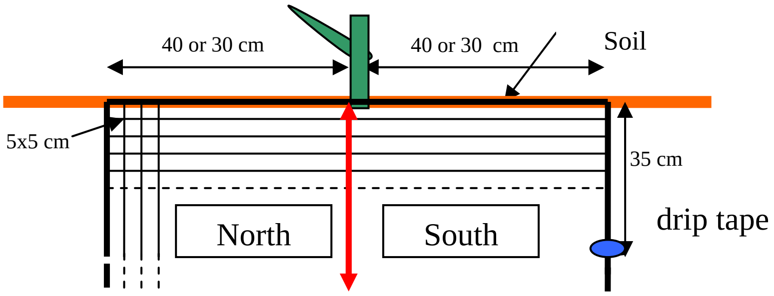

Figure 1. Position of the grid in the soil profile for analyzing root repartition

RESULTS

The root system under SDI

The root system pattern plays a major role in the water uptake process under SDI. A mean value of the index was calculated for each depth and on the North side and

South side of the profile to examine possible effect of drip tape and its wet bulb on root repartition. We can see that maximum rooting depth is around 1.2 m and most of the roots are observed in the first 40 to 50 cm whatever the case. In the asymmetric case, root density is much higher under pipe (35 cm at the vertical of the row) than in 2008 where the pipe is more or less exactly between the rows.

The map of the root index (RI) indicates that the roots are present in the whole of the domain even far from the buried pipe. High RI values often coincide with the local presence organic matter (crop residues). That still underlines the existing difficulty to model the root system distribution for simulating the plant water uptake process. For instance, the presence of roots more especially in the vicinity of the soil surface does not mean that they remained active along the cropping cycle as further seen. The high RI values close to soil surface is probably due to the fact that rainy events at the end of April (33 mm) and at mid May (17 mm) have contributed to a good installation of the root system of the SDI160 treatment. A same configuration of RI can be noticed for SDI120, but with lower RI values, maximal RI not exciding 3.5, due to a later sowing date than SDI160. After observations done on other sites, when the drip line is under a corn row, a high increase of root density can be seen under the drip line for a depth of 40 cm or more. A same effect existed for SD120 with a drip line 15 cm apart the corn row. It can be concluded that drip line has a noticeable effect on root development when the distance drip line-crop is short. Such root density configuration was not observed in 2008 with laterals placed at mid distance from crop rows.

Analysis of soil water content profile from neutron probe measurements and tensiometer readings.

In 2008, soil contribution to plant water supply is particularly well highlighted on SDI160 confirming that soil participation to the plant water supply legitimates strategies at low irrigation frequencies such as those applied in 2009. For both treatments corn uptakes water until 1.20 m at least while tensiometer monitoring for both SDI treatment in 2008 do not reveal drainage losses. At the opposite, SDI treatments in 2009 revealed drainage losses under pipe (case where the pipe is under crop) during short periods corresponding to a WAD > 20 mm delivered at the beginning of the irrigation season when the plant water uptake rate is low yet.

In 2009, water storages calculated on a thickness of 30 cm, from the soil surface to 150 cm, were continuously decreasing on T1 and T2 for both treatments and are similar under 120 cm at the end of the cropping cycle. The fact that a comparable trend is not observable for T3 of SDI160 results from the lateral spacing, a spacing of 1.2 m only, would allow the maintain of a root activity much greater in the vicinity of SDI120 T2 than in the vicinity of SDI160 T3. On SDI120, under deficit irrigation, crop is also more able to use a high amount of the soil water than on SDI160.

Analysis of the Soil moisture evolution from Envirosmart sensors

SDI160 case in 2008

The analysis of the sensor responses to irrigation events shows that irrigation water reached only a depth of 45 cm: and there is no increase of the signal of the deeper layers. The highest sensor response was obtained at 33 cm depth. For the deeper layers, there was a small decrease of the signal meaning that crop took up water from soil storage. The analysis of sensor responses installed under the corn row shows that lateral diffusion did not reach the corn row, meaning that lateral diffusion is lower than 30 cm.

SDI120 in 2009: an asymmetric case (row at 45 cm from pipe instead of 30 cm for a symmetric case)

Under SDI120 the irrigation impact is not perceptible at the vertical of the crop between 0.1 to 0.6 m depth. That seems logical with such high distances from the dripper line: 45 cm for this asymmetric configuration. In the inter-row (13 cm from pipe) the water front reaches 1 m depth but does not seem to go deeper. The first irrigation (11,6 mm) does not inverse the decreasing trend of the soil water content under row at the opposite of the inter-row where the water variations can be seen down to 0,5 m deep. The second irrigation stops the decreasing trend under row and even generated a sensitive increase of the soil water content at a depth of 0.7 m at the opposite of 2008 due to high WADs delivered at a low frequency. That is interesting in term of horizontal water diffusion even at a depth greater than 0.65 m, when assuming this water amount will be profitable to plant and will not contribute to eventual drainage losses. Indeed, the water diffusion process, enhanced by the soil water deficit before irrigation (Philip, 1984), would reach parts of the root system at deeper layers. These effects resulted in a wetting zone display at around 0.7 m depth as schematized by Fig.2, the lateral extension of the wetted zone being maximum around 45 cm from the drip line at 70 cm depth

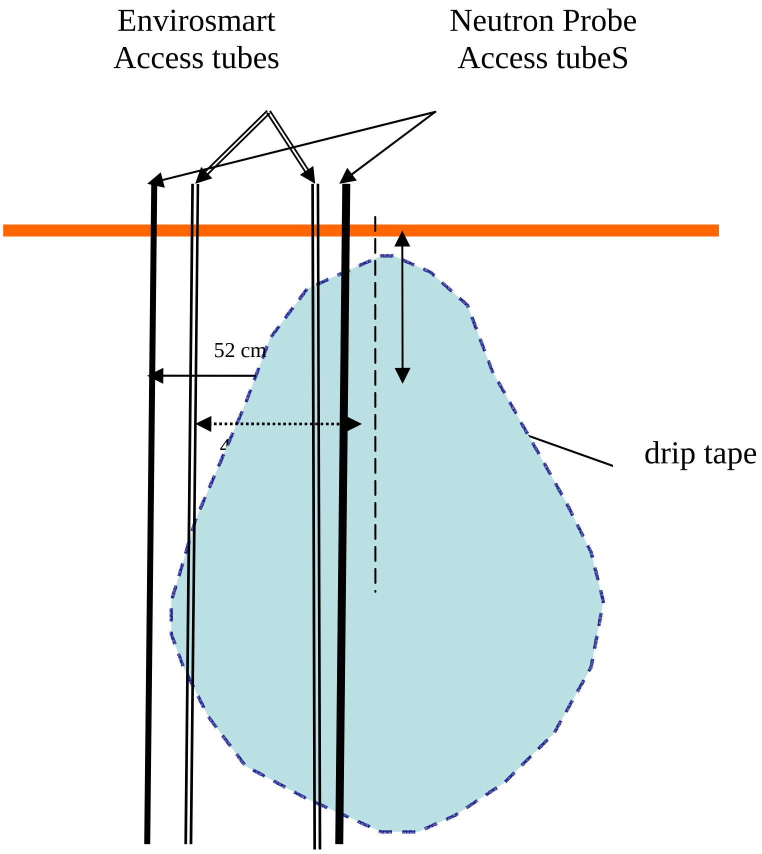

Figure 2. Approximate shape of the wetted area after an irrigation of 34mm on the 30th of June on SDI 120

Yield results in 2009

Due to the asymmetry problems the yields present a high variability the latter being a little higher for SDI160 than for SDI120. The averaged deviation between yield row N and yield row S is the lowest (3.6 vs 5 Mg/ha) for this treatment. For SDI120, averaged yields are 19 Mg/ha and 11.8 Mg/ha for total dry mater (TDM) and grain yield (GY at15% humidity) with a coefficient of variation Cv =21%. These values are of 20 and 11.8 Mg/ha respectively for TDM and GY for a same water amount of 250 mm. Note that averaged yield for SDI120 would have probably been higher than which of SDI160 if both were sown at the same date. As confirmed by the two no irrigated treatments the yields are higher for the maize sown earlier: 8.4 vs 7.5 T/ha for TDM and 3.3 Vs 2.5 T/ha for GY. For the full irrigated treatment (the surface drip system) TDM and GY are 16 and 25 Mg/ha respectively for a water amount of 350 mm. For these three treatments, the Cv value is lower than 10%.

Modelling

For a linear source, with a distance between two emitters is of 30 cm water transfer can be assumed to be ruled by a 2D process (Skaggs et al., 2004; Patel and Rajput, 2008; Mubarak et al., 2009b). This multidirectional water transfer rise questions about the interest of a 1D model such as PILOTE for SDI even adapted to this irrigation system (Maihol et al., 2011). This adaptation consists in delivering the dose directly to the second reservoir avoiding thus evaporation. However, when PILOTE applications to SDI are limited to AET and yield simulations this model is an interesting alternative to other models much more complex for identifying irrigation strategies under a water scarcity context. LAI and the soil water reserve (SWR) evolution are amongst the main PILOTE outputs. SWR on the maximal root depth Px ($SWR = \int_0^{Px} \theta(z)dz$), where □ is soil water content.

Hydrus-2D is particularly well adapted to this 2D water transfer. It is used here for dealing with the problem of the plant water uptake process under severe water stress conditions in comparison with PILOTE on the basis of AET and SWR simulations. In Hydrus-2D, SWR is simulated both under crop and under pipe at the opposite of PILOTE which can only give a lumped formulation of the soil water balance illustrated by the evolution of SWR.

Note that a narrow relationship exits between AET and yield (Howell and Musick, 1985; Jones, 1992). The latter is confirmed by the following relationship:

$$TDM(Mg/ha) = 0.056AET - 6.75 \quad (1)$$

With a coefficient of determination $R^2 = 0.983$. It is derived from PILOTE simulations for the two corn varieties studied at Lavalette (Khaledian et al., 2009) between 1998 and 2007 irrigated with different irrigation systems. The Hydrus-2D implementation under our experimental context is described in Mubarak et al., (2009) and Mailhol et al., (2011). A correct LAI simulation is a required condition to simulate well SWR. One can say that PILOTE gives acceptable LAI simulations for the two SDI treatments Fig.3. Note that when LAI is greater than 3.5 maximal evapotranspiration is not affected by a LAI fluctuation, due to the exponential function linking the crop coefficient to LAI used in PILOTE.

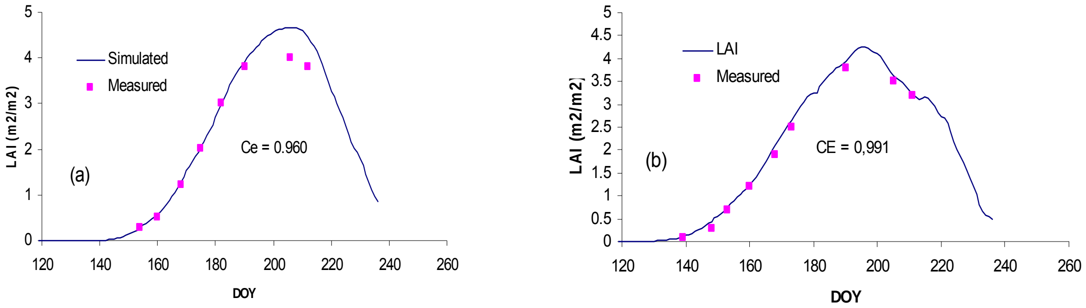

Figure 3. Simulated LAI by PILOTE under SDI120 (a) and SDI160 (b) with Ce, the efficiency criterion of Nash-Sutcliffe (ASCE, 1993)

An example of SWR simulations on the SDI120 case can be seen on Fig.4. PILOTE, a lumped root water uptake model does not gives substantial gaps with measured SWR compared with Hydrus-2D under the asymmetric context of 2009. SWR simulations for SDI160 present similar results. One can see that at the beginning of the cropping cycle SWR under pipe and under crop differ very significantly from DOY165 to DOY180 due to frequent and substantial water application depths and a water demand still low for this period. But they converge at the end of the cropping cycle because pipe is close to the plant rows and irrigation is less frequent. Note that, slight adjustments of the Hydrus-2D rooting pattern have been performed in order to fit as well as possible observed SWR's. The yields are well enough simulated by PILOTE (Table 1) with regard to measured yield variability in 2009. Since Hydrus is not a crop model and consequently does not simulate the crop yields. However, it is possible to use Eq(1) for estimating TDM yields then GY when assuming a harvest index of 0.5 for corn, (Mailhol et al., 2004; Khaledian et al., 2009). Table 2 presents the TDM estimations obtained by E(1). Under severe water stress conditions this Hydrus-2D version which does not simulated the root compensated water uptake process (CRWUP) yet, underestimated AET and consequently TDM, at the opposite of PILOTE. In a lumped root water uptake model such as PILOTE, CRWUP is conceptually integrated to the capacitive approach since the water uptake process is completely confined in the soil reservoir, the water of which governs the stress function.

Water productivity (WP) of irrigation: the ratio of the gain yield resulting from irrigation by the water amount applied is higher for SDI120 (3.76 kg/m3) than for SDI160 (3.41 kg/m3). Such a result could have been obtained using PILOTE for the loamy soil context. Far from these environmental conditions, PILOTE would not be so accurate. For instance it could not be recommended to test different lateral spacing associated to irrigation strategies on a coarser soil type. Associating Hydrus-2D to a relationship such as which proposed by Eq(1) could be a solution to compensate the lack of a predictive crop model adapted to SDI.

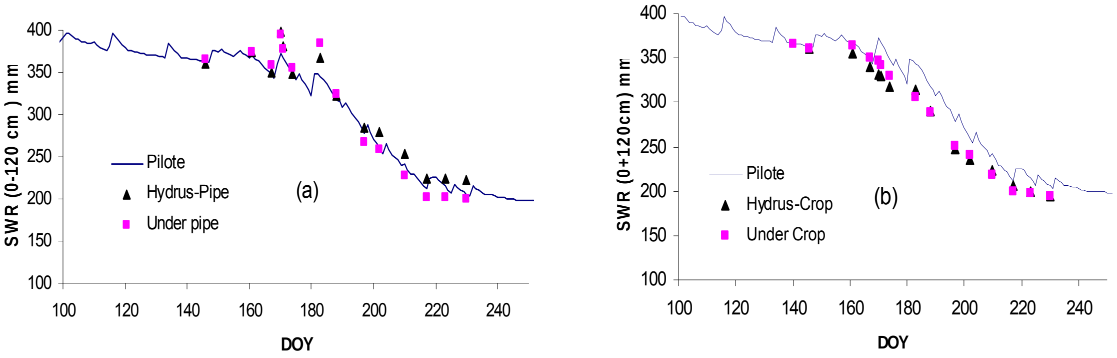

Figure 4. Soil Water Reserve (SWR) simulation by PILOTE and Hydrus on SDI120 under pipe (a) and under crop row (b) in 2009.

Table 1. Yields (TDM and GY) measured and simulated by PILOTE in 2008-2009 with water application depth (WAD)

Year	Treatments	Measured Mg/ha)	Simulated (Mg/ha)	WAD (mm)
2008	SDI160	24	24	238
		15	14.7	
	SDI120	26	25.6	250
		15	15.2	
2009	RF60	7.5	7.0	0
		2.5	2.5	
	RF75	8.4	8.0	0
		3.3	3.1	
	SDI160	19.7	20.5	249
		11.8	12.5	
	SDI120	19	19.7	247
		11.8	11.7	

Table 2. Cumulative seasonal AET (mm) and TDM (Mg/ha) evaluated by Hydrus-2D and PILOTE from Eq (1).

Year	Treatment	AET(Hyd)	TDM(Hyd)	AET(Pil)	TDM(Pil)	TDM(Measured)
2008	SDI120	545	23.8	585	26.1	26
2008	SDI160	526	22.8	561	24.7	24
2009	SDI120	395	15.5	449	18.5	19
2009	SDI160	435	17.5	480	20.2	19.7

CONCLUSION

SDI can be a solution to save water under limited resource conditions, with relative high WP values. On the loamy soil case even with moderate rainfalls during Spring, SDI160 is a solution to the problem of water scarcity that would merit to be economically analysed on the corn case. The different apparatus used in our loamy soil plot revealed the wetted zone is far to concern the whole of the rooting pattern more especially under an asymmetric context with some rows far from the drip line. Undoubtedly, under restrictive irrigation plant removes its capabilities of water uptake from stressed regions to unstressed region of the soil domain. This compensated root water uptake phenomenon (CRWUP) has to be taken into account when modelling the 2D soil water transfer for improving the crop yield predictions. At the opposite of distributed root water uptake model, a lumped water uptake model which integrates this CRWUP can accurately predict AET and yield under peculiar soil conditions. But, the domain of validity regarding a simple model such as PILOTE must be well identified. Indeed, due to its operative character this model can be easily used for identifying irrigation strategies that optimize yield under limited water conditions. Assuming that it is possible to establish a relationship such as Eq(1) whatever the considered crop, associating PILOTE to a generic 2D soil water transfer model such as Hydrus-2D would allow an expansion of the restrictive domain of application of PILOTE.

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