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TOWARDS HIGHER CROP WATER PRODUCTIVITY USING A SIMULATION BASED CONTROLLED DEFICIT IRRIGATION STRATEGY
(UNE STRATÉGIE D´IRRIGATION DÉFICTAIRE BASÉE SUR SIMULATIONS POUR ATTEINDRE UNE MEILLEURE PRODUCTIVITÉ D´EAU DES CULTURES)

This study proposes a simulation based optimal irrigation scheduling strategy which adapts to the actual weather conditions for maximizing crop water productivity (WP) as well as yield stability and reliability based on observed long term climate characteristics throughout the whole growing season. For achieving a given crop yield a stochastic optimization framework for adaptive irrigation scheduling together with a crop model is employed consisting of (i) a weather generator for simulating long term climate characteristics; (ii) a tailor-made evolutionary optimization algorithm for optimal irrigation scheduling with limited water supply (GET-OPTIS); and (iii) a crop growth model for simulating water balance and crop growth (PILOTE). At the beginning of the growing season an irrigation schedule which maximizes WP and achieves at the same time the given yield with a reliability of 95% was provided by the stochastic optimization framework. During the growing season this irrigation schedule was adapted weekly according to actual weather data using the stochastic optimization framework. Complying with the optimization framework, an experimental setup was established in 2009: Corn (*Zea mays L.*) was grown on a loamy soil under a Mediterranean semiarid climate at the CEMAGREF Institute of Montpellier, France. Optimal adaptive irrigation scheduling was applied on two plots which were subsurface drip irrigated (SDI) with drip lines buried at distances of 120 cm and 160 cm, respectively. The study showed that the higher drip line distance of 160 cm can be employed without loss in WP when an optimal irrigation control is used. This is confirmed by the experimental results which show mean grain yields of 11.8 t ha^{-1} for both SDI treatments. WP's of 3.7 kg m^{-3} (SDI120) and 3.5 kg m^{-3} (SDI160) were achieved for the adapted irrigation scheduling treatments which were higher compared to the WP of 3.3 kg m^{-3} of the full irrigated treatment. Thus, the field study confirmed that using a simulation-optimization approach for optimal irrigation scheduling can significantly increase WP and at the same time yield stability and reliability. In addition, the higher drip line distance is economically more beneficial when the investment costs are taken into account.

Cette recherche propose une stratégie d'irrigation déficitaire basée sur des simulations adaptées au temps actuel avec mission de maximaliser la productivité de l'eau. Le cadre de l'optimisation d' irrigation consiste en un algorithme de l'optimisation (GET-OPTIS), un modèle des plantes (PILOTE), un générateur du temps (LARS-WG) et le météo actuel. En 2009, le cadre a été employé en deux champs de maïs irrigué goutte à goutte enterré à CEMAGREF, France. En tout, il y avait cinq traitements: Deux irrigués goutte à goutte enterré (SDI120 avec une distance des gaines de 120 cm et une distance de rangs de 60 cm, et SDI160 avec et une distance des gaines de 160 cm et une distance de rangs de 75 cm), un traitement d'irrigation nécessaire à surface (FULL), et deux traitements non irrigués (RF60 avec une distance des rangs de 60 cm, et RF75 avec une distance des rangs de 75cm). Les rendements reçus sont 16.0 Mg ha^{-1} (FULL), 11.8 Mg ha^{-1} (SDI160 et SDI120), 3.2 Mg ha^{-1} (RF75) et 2.5 Mg ha^{-1} (RF60); les productivités d'eau sont de 3.7 kg m^{-3} (SDI120), 3.5 kg m^{-3} (SDI160) et 3.5 kg m^{-3} (FULL), respectivement. Les simulations avec Hydrus2D ont montré que les hautes données de l'éau tout d'un coup améliorent la distribution de l'eau irriguée au champ. L'optimisation d'irrigation adaptée a rehaussée la productitivé de l'eau d`au moins 10%. La conception du champ du SDI160 avec la distance des gaines plus large semble plus économique que la conception du SDI120, parce que les coûts du matériel et d'installation diminuent de 25% sans reduire le rendement.

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1. INTRODUCTION

With increasing municipal and industrial demands for water, irrigation water allocation for agriculture is decreasing steadily. To increase yields and/or to produce more revenue from less water (increase of water productivity WP) poses a great challenge for the agricultural sector. One irrigation strategy to maximize WP is the deficit irrigation strategy where water is applied mainly during drought-sensitive growth stages of a crop. Outside these periods, irrigation is limited or even unnecessary if rainfall provides a minimum supply of water (English 1990).
Furthermore, increasing concerns about water conservation and water quality protection requests irrigators to use more efficient irrigation systems. Subsurface drip irrigation (SDI) enables the application of small amounts of water to the soil through drip lines placed below the soil surface and hence increases the application efficiency. SDI offers many advantages over the surface drip irrigation such as reduction in evaporation and deep percolation, improved water and nutrient management, potential for improved yields and crop quality, and reduced total water requirements (Camp 1998). Many study results indicated that crop yields for subsurface drip irrigation was greater than or equal to that for other irrigation methods, and required less water in most cases (Camp 1998; Camp, Lamm et al. 2000; Lamm and Trooien 2003). However, SDI is hardly suitable for sandy soils and has higher investment costs than other pressurized irrigation systems (e.g. center pivot sprinkler). Cost reducing proper field design and management of SDI systems need a good understanding of the infiltration process around a buried point source, the equitable combination of drip line spacing, discharge rates, irrigation duration and irrigation frequency (Provenzano 2007). Surprisingly little attention has been paid to estimate the optimal soil water distribution under SDI resulting in sub-optimal management and low water productivity. Garcia et al. (2009) propose that further work should focus on the impact of the intra-seasonal weather variability and soil moisture conditions during different crop stages to determine critical periods that affect yield.
Increasing the spacing of the drip lines is one of the most important factors in reducing the high investment costs of SDI (Lamm and Trooien 2003). Optimum drip line spacing is related to the crop and its rooting pattern, the soil texturing and layering, and how soil water is redistributed, in-season precipitation and the comparative costs of drip lines, yields and possible off-site hazards caused by deep percolation. Camp (1998) published a comprehensive review of several publications with drip line spacings of SDI ranging from 0.25 to 5 m for different soils where most results indicated that alternate-row spacing of about 1.5 m would be appropriate for most uniformly spaced row crops like corn. Darusman and Khan et al. (1997) and Camp and Bauer et al. (1998) reported that subsurface placement of drip lines at wider spacings has significant potential for profitable irrigation. Stone and Bauer et al. (2008) found that the distance of the corn rows from the SDI drip lines greatly influenced the crop growth and grain yield, both decreasing significantly with distance from the drip lines. Concerning irrigation frequency, Camp (1998) reported in his review that frequencies ranging from

one to seven days had no effect on corn yield when soil water storage was managed within acceptable stress levels. However, Ayars, Phene et al. (1999) refer to reduced deep percolation using high frequency irrigation.

For optimal management of irrigation systems, the problem of intra-seasonal irrigation scheduling under limited seasonal water supply is of primary importance. An optimal distribution of the limited irrigation water during the growing season adapted to the actual weather conditions and the drought susceptibility of the crop may reduce the applied irrigation water amount achieving high yields. Until now, the simultaneous optimization of the irrigation schedule and the irrigation control in SDI systems has been insufficiently studied, both theoretically and experimentally. Thus, the objective of this study is to increase WP of deficit irrigated corn in a SDI system at CEMAGREF in Montpellier, France. A simulation based approach was applied to optimize the intra-seasonal adaptive deficit irrigation schedule.

2. OPTIMAL SCHEDULING FRAMEWORK

Two components are necessary for simulation based irrigation scheduling: an optimization algorithm for optimal irrigation scheduling and a crop growth model. In this study, the stochastic optimization framework consists of a tailor-made evolutionary optimization algorithm for optimal irrigation scheduling with limited water supply GET-OPTIS (Schmitz et al. 2007) and of the crop growth model PILOTE (Mailhol et al. 1997, Mailhol et al. 2004). The stochastic weather generator LARS-WG (Semenov et al., 1998) was used to generate long term climate characteristics based on CEMAGREF historical climate data from 1991-2008. Observations and statistics based on GET-OPTIS and PILOTE simulation/optimizations, actual weather forecasts and long term climate pattern were used to determine the irrigation schedule (see Figure 1). The generated crop water production functions (CWPFs) represent the maximum yields which can be achieved with a given amount of water for the generated site specific weather series. The statistical characteristics of the CWPFs, called SCWPF, are used as a decision support tool. A simulation based deficit irrigation schedule to reach a target grain yield of 14 Mg ha^{-1} with a reliability of 95% which maximizes WP was provided for two plots and adapted weekly according to actual weather by the stochastic optimization framework. The weather data of the current growing season since the sowing at the experimental site was used once a week to rerun the optimization algorithm and adapt the irrigation schedule to the actual weather (see Figure 2). The quantiles of cumulative irrigation depth were used as the tool for irrigation decision; by subtracting occurring rainfall from the one weeks´ estimated irrigation depth, a manual adaption to the precipitation took place.

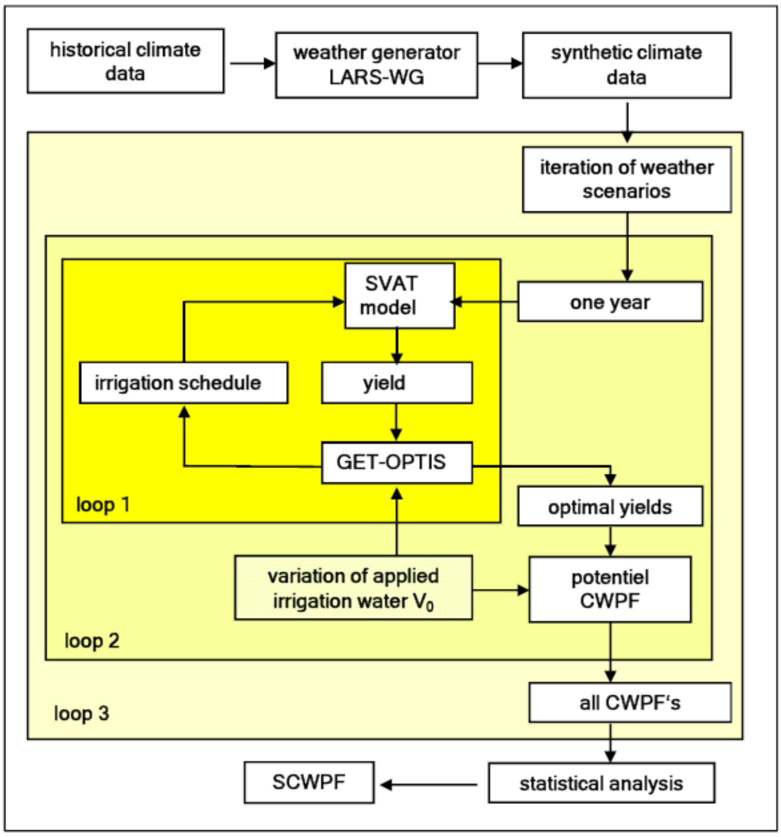

Figure 1. Framework for optimal scheduling (schéma de l` optimisation d` irrigation)

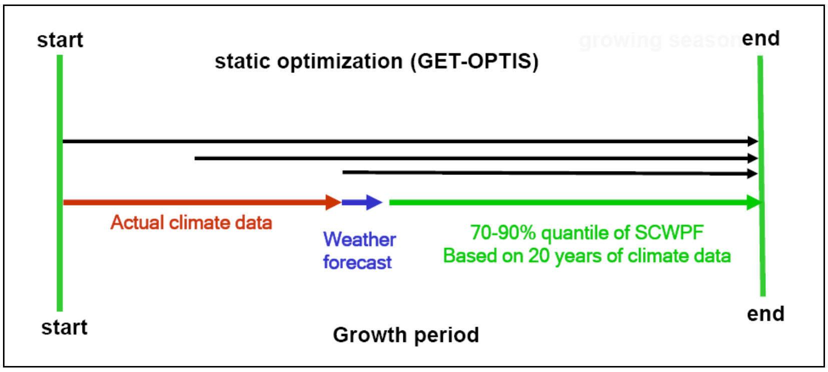

Figure 2. Scheme for the adaptive stochastic scheduling related to yield (schéma du plan de l' horaire adapté)

2.1 PILOTE crop growth model

PILOTE is an operative crop model for simulating the soil water balance at a daily time step and for predicting yield. The model is based on simulations of the leaf area index (LAI) and on a water balance module on a reservoir concept. For further model descriptions and applications see Mailhol et al. (1997) and Khaledian et al. (2008).

2.2 GET-OPTIS optimization algorithm

For determining the best irrigation schedule for a given amount of irrigation water, the tailor-made global optimization technique GET-OPTIS (Global Evolutionary Technique for OPTimal Irrigation Scheduling) for optimal irrigation scheduling with limited water supply and the crop growth model PILOTE were applied. The algorithm starts with a set of solutions – called population – which is, in our case, a random set of schedules. Every member of the set has a fitness value assigned to it which is directly related to the objective function, its crop yield. The fitness, i.e. the grain yield, is calculated by running PILOTE with the specified irrigation schedule of the member. In sequential steps, the population of schedules is modified by applying four steps, aiming to imitate biological evolution: selection, crossover, mutation, and reconstruction. The procedure is then repeated until a convergence criterion is reached, or the maximum value of steps is exceeded. The details of the algorithm are presented in Schmitz et al. (2007).

3. IRRIGATION CONTROL FOR DIFFERENT DRIP LINE SPACINGS

Determining the appropriate irrigation time for a given drip line spacing and discharge rate involves the consideration of the soil parameters (e.g. soil texture, retention curve) and initial soil moisture. In order to optimize the irrigation control, we applied the widely used model HYDRUS2D (Simúnek et al. 1996) where the subsurface water flow is modeled by the numerical solution of the 2D Richards equation. Since the arrangement of the crop rows and drip lines is non-uniform (e.g. for SDI160 the row spacing is 75 cm and the drip line spacing is 160 cm, see experimental setup below), some crop rows are remote to irrigation drip lines. HYDRUS2D was utilized to derive characteristic functions for the determination of optimal irrigation times and doses in order to provide a uniform distribution of the irrigation water supplying adequate irrigation water amounts to all crop rows. Meanwhile, deep percolation provoked by heavy water application amounts and/or elevated initial soil moisture contents had to be minimized. Using the HYDRUS2-Code, a soil column with four sections was generated for SDI120 and SDI160 (Figure 3). The mass balance of sections I to IV was calculated after an irrigation event for three and six simulation days. The water flowing from section II to section I equals the amount of irrigated water available for the left row. The aim was that 20-25% of the irrigation volume reaches the left row as just 50% of the root is modeled.

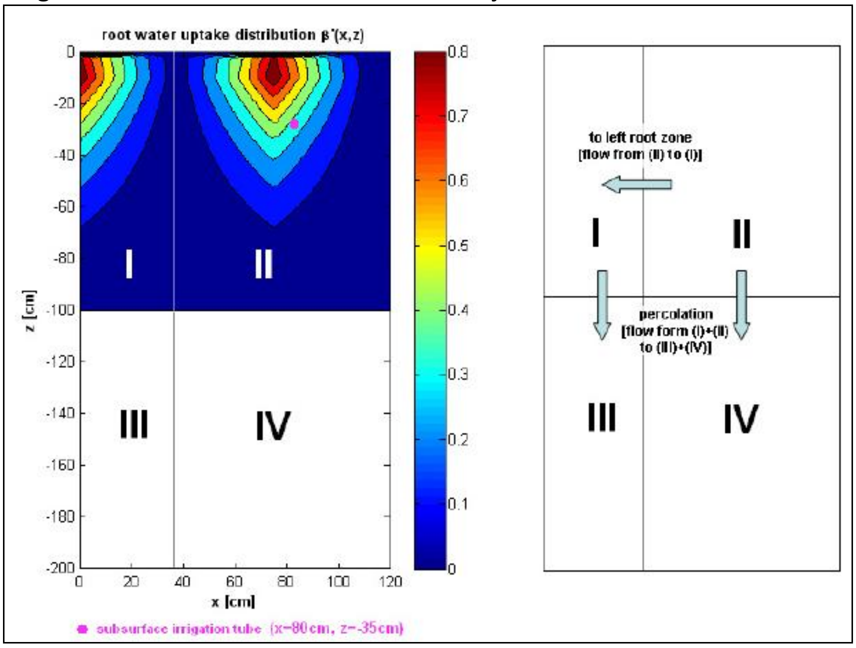

Figure 3. Model setup for calculating distribution of irrigated water for SDI160. The distance of the crop rows and the drip lines is 75 cm and 160 cm, respectively. The emitter (pink dot) is located at a lateral depth of 35 cm (z = -35 cm) and 5 cm from the root center of the right row (x = 80 cm) (le setup du modèle pour calculer la distribution de l´eau irriguée (SDI160). Les distances des rangs et des gaines sont de 75 cm et de 160 cm, respectivement. L` émetteur de l`eau (point rose) est localisé à 35 cm (z = -35 cm) et à 5 cm du centre des racines de la plante à droite (x = 80 cm))

4. EXPERIMENTAL DATA AND SETUP OF THE CROP MODEL PILOTE

4.1 Site description and experimental design

In an annual field experiment in 2009, a high yielding corn variety (Zea mays L., hybrid Pioneer 36K67) was cultivated at the CEMAGREF Institute of Montpellier, France (43°40'N, 3°50'E and altitude 30 m). The experimental site, located in the Mediterranean climate, shows an average annual rainfall of 767 ± 404 mm (1991-2008) average. The region has erratic and limited in-season rainfall and a high water deficit during summer of around 350 mm between potential evapotranspiration and rainfall. Daily normal (1991 - 2008 average) maximum and minimum air temperatures are 20.9 and 8.6 °C, respectively. The soil of the experimental site is of loamy sandy to loamy clayey sandy texture (about 18% clay, 44% silt, 38% sand). It is from both colluvial and alluvial origin being very deep, with a water table which is deeper than 5 m in summer and does not contribute to water supply of crops. The soil water storage capacity is high and ranges from 120 to 180 mm m^{-1}.

Optimal adaptive irrigation scheduling was applied on two plots which were subsurface drip irrigated (SDI) with a drip lateral depths of 0.35 m below the soil surface underneath tilling. Drip line spacings were 120 cm (plot here called SDI120, row distance: 60 cm, plot size: 0.12 ha) and 160 cm (plot here called SDI160, row distance: 75 cm, plot size: 0.093 ha), respectively. The dripper discharge rate for the SDI system was about 2.5 l h^{-1} per meter drip line length, depending lightly on the initial water content of the soil. Moreover, two non irrigated (rainfed) treatments with row distances of 60 (here called RF60) and 75 cm (here called RF75, both plot sizes about: 0.02 ha) and a surface drip irrigated full irrigation treatment were no water stress occurred (here called FULL, row distance: 75 cm, drip line distance: 150 cm, plot size: 0.05 ha) were established as control treatments. For the full irrigation treatment, a soil water balance approach (based on FAO-56) was used to estimate Etc and hence the irrigation water amount (for further explanations see Khaledian et al., 2008). An automatic meteorological station (CIMEL Enerco 411) located nearby provided hourly data of average temperature, radiation, wind speed, air pressure, relative humidity and precipitation, amongst others.

4.2 Farming practices

The selected Pioneer corn hybrid 36K67 was indicated as a high yielding, above-average drought tolerance with 3100 heat units and with potential grain yields varying from 15.5 to 21.9 t ha^{-1} in a study by Pioneer Hi-Bred International, Inc. Corn was grown using conventional production practices. At the beginning of October 2008, disc harrow was used to chop and bury the residues of the precedent crop. At the end of November, tillage with plough was performed until a depth of 25 cm. Corn was sown at a seeding depth of 5 cm on 23th of April (SDI160, FULL, RF75, row distances: 0.75 m) and on 7th May (SDI120, RF60, row distances: 0.60 m), respectively. Fertilizers (N, P, K) were applied at sowing and during the season on the basis of soil analysis in order to fully satisfy plant requirements.

4.3 Yield sampling, plant data and soil water measurements

Soil water content was monitored during the cropping season on plant rows, between two plant rows next to a drip line and between two plant rows remote to a drip line using aluminum neutron probes (Vectra CPN type 503) which were read regularly from 0 to 2 m at a 0.1 depth interval. Moreover, mercury tensiometer (SDEC, France) were installed 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 soil depths next to a row and at a distance of 0.4 m of a neutron probe and were monitored every morning. Around weekly leaf area index (LAI) measurements were obtained using a LI-COR LAI 2000 apparatus. About seven subsamples per treatment of about 3 m^2 were harvested on 17/09/2009, 133 (SDI120, RF60) and 147 (SDI160, FULL, RF75) days after seeding, respectively. Grain yield (expressed at 15 % moisture content) and leaf and stem weight (oven dried at 78 °C) of representative subsamples (two rows x 2.5 m and 7 replicates) were determined for all treatments, respectively. For all measured plant variables, we calculated treatment means and standard deviations and water productivity WP in kg per m^{-3} (see Equation 1):

$$WP = \frac{\text{grain yield (irrigation)} - \text{grain yield (rainfed)}}{\text{irrigation water applied}} \qquad \text{(Equation 1)}$$

where (irrigation) stands for the irrigated treatment and (rainfed) for the non-irrigated one.

4.4 Setup of the crop model PILOTE

PILOTE validation has been carried out for different crops under different environmental contexts (Mailhol et al., 1997; Mailhol, et al., 2004; Khaledian et al., 2009, Taky et al., 2009). For SDI systems, a specific model option was developed (Mailhol et al., 2009). PILOTE was used to simulate the grain yield, LAI and soil water reserve at the CEMAGREF experimental site. For calibration and validation of the model PILOTE, data of two precedent years (2007/08) at the same experimental site (five treatments) and the same corn variety were used (for further explanation see Khaledian et al., 2008). Exemplary in 2008, PILOTE simulated well the grain yield for two SDI treatments (simulation results vs. measured grain yields): 14.7 vs. 15 t ha^{-1} and 15.2 vs. 15.1 t ha^{-1}, respectively. The results of Khaledian et al. (2008) indicate that Pilote satisfactorily simulates LAI, soil water reserve, grain yield and dry matter yield. The setup of the PILOTE crop model is based on the field experiment in 2009 described in the experimental setup. The management description consisted of the sowing dates of 23th of April (SDI160) and 7th of May (SDI120). During the irrigation events a constant flow rate of 2.5 l h^{-1} per meter length is employed. The soil parameters (zero initial water deficit, field capacity FC = 0.32) and plant parameters (Pioneer maize) used in Khaledian et al. (2008) are applied.

5. RESULTS

5.1 Crop yields, water productivity and irrigation control

The entire growing season in 2009 can be characterized as dry: precipitation from sowing to harvest was only 96 mm, and for the later sowing date (SDI120, RF60) only 63 mm, respectively. The highest yield, 16.0 Mg ha^{-1}, was obtained by the full irrigated treatment. As expected, comparing the controlled deficit irrigated SDI treatments to the full irrigated control (FULL), total grain yield and grain yield per plant is higher for the control. Compared to SDI160 with almost the same drip line and row distances than the control, FULL showed higher 1000-seed weight and plant density resulting in higher yields. For both SDI treatments, grain yield was 11.8 Mg ha^{-1}, showing a higher variability for the SDI160 with the broader drip line and row distances. The higher 1000-seed weight (TSW) of SDI160 compensated the lower plant density and led to higher grain yield per plant compared to SDI120 (167 vs. 130 g per plant). The two rainfed treatments resulted in very low grain yields due to high drought stress where RF75 yielded higher than RF60 (3.28 vs. 2.5 Mg ha^{-1}) with a lower plant density but higher 1000-seed weight. The maximum values of LAI were 3.5 and 4 for SDI160 and SDI120, respectively. For SDI160, the values were lower due to lower plant density. Growth durations were 133 (SDI120, RF60) and 147 days (SDI160, FULL, RF75). Plant data and applied water amounts for all treatments are shown in Table 1.

Table 1. Water received and plant data (value ± standard deviations): Amount of irrigated water irr (mm), precipitation P (mm), total applied water TAW (in mm, sum of applied irrigation water and precipitation during the growth period), grain yield (Mg ha^{-1}), total dry matter (Mg ha^{-1}), WP (kg m^{-3}), 1000-seed weight TSW (g), plant density (plants per ha), grain yield per plant (g per plant) and maximum leaf area index (LAI_{max}) for corn in Montpellier, 2009. SDI120 stands for the subsurface drip irrigated treatment with a drip line spacing of 1.2 m, SDI160 stands for the subsurface drip irrigated treatment with a drip line spacing of 1.6 m, respectively. FULL means the surface drip irrigated treatment receiving full irrigation (no water stress). RF60 and RF75 stand for the rainfed treatment (no irrigation) with row spacings of 60 and 75 cm, respectively.(L´eau reçue et des données des cultures (donnée ± écart-type): L´eau irriguée irr (mm), pluie P (mm), l´eau appliqué totale TAW (mm), rendement (Mg ha^{-1}), matière seche totale (Mg ha^{-1}), productivité d´eau WP (kg m^{-3}), poids de 1000 grains TSW (g), dénsite des plantes (pl ha^{-1}), rendement pour plante (g pour plant) et LAI maximale (LAImax) de maïs cultivé à Montpellier, 2009. SDI120 est le traitement irrigué goutte à goutte enterré avec la distance entre des gaines de 120 cm et SDI160 de 160 cm respectivement. FULL est le traitement d´irrigation nécessaire à surface, et RF60 et RF75 sont des traitements sans irrigation avec la distance entre les rangs de 60 et 75 cm, respectivement)

	irr (mm)	**P (mm)**	**irr + P (mm)**	**grain yield (Mg ha^{-1})**	**dry matter (Mg ha^{-1})**	**WP (kg m^{-3})**	**TSW (g)**	**plant density (pl ha^{-1})**	**grain yield (g) per plant**	**LAI_{max}**
SDI120	249	63	312	11.8 ± 1.4	19 ± 4.1	3.7	278	90,824	130	4
SDI160	243	96	339	11.8 ± 1.9	20 ± 5.7	3.5	323	70,801	167	3.5
FULL	382	96	478	16.0 ± 1.2	25 ± 2.2	3.3	365	75,090	213	
RF60		63	63	2.5 ± 0.3	7.5 ± 0.6		165	84,302	30	
RF75		96	96	3.2 ± 0.8	8.4 ± 0.8		221	69,444	47	

In general, yields increased with increasing total applied water (see Figure 4). Irrigation, ranging from 0 to 382 mm, significantly affected yield, especially as precipitation was very low. The water productivities reached were 3.7 (SDI120), 3.5 (SDI160) and 3.3 kg m^{-3} (FULL).

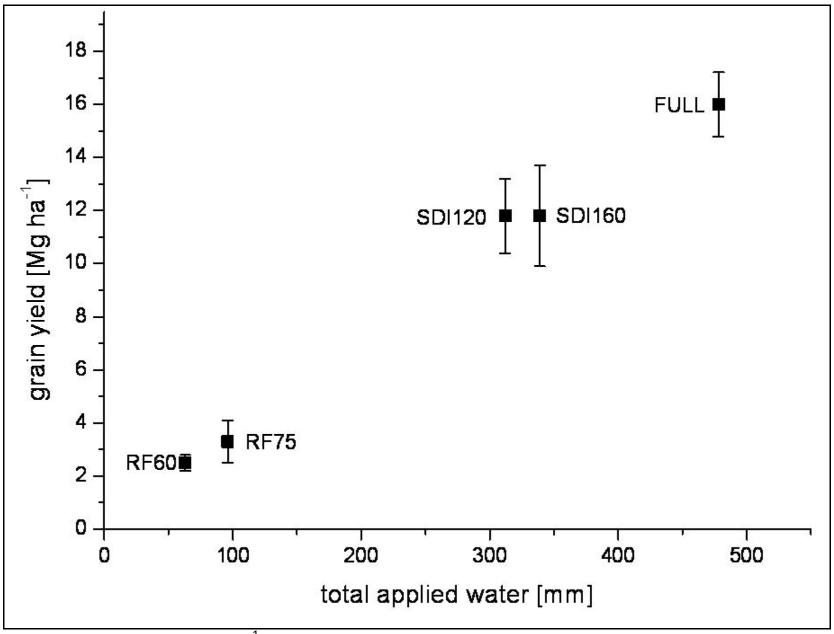

Figure 4. Grain yield (Mg ha^{-1}) and total water applied (mm) for corn in Montpellier, 2009. SDI120 stands for the subsurface drip irrigated treatment with a drip line spacing of 1.2 m, SDI160 stands for the subsurface drip irrigated treatment with a drip line spacing of 1.6 m, respectively. FULL means the surface drip irrigated treatment receiving full irrigation (no water stress). RF60 and RF75 stand for the rainfed treatment (no irrigation) with drip line spacings of 60 and 75 cm, respectively. (l´eau appliquée totale (mm) et rendement (Mg ha^{-1}) de maïs cultivé en Montpellier, 2009. SDI120 est le traitement irriguée goutte à goutte enterré avec la distance entre des gaines de 120 cm et SDI160 de 160 cm, respectivement. FULL est le traitement d´irrigation nécessaire à surface, et RF60 et RF75 sont des traitements sans irrigation avec la distance entre les rangs de 60 et 75 cm, respectivement)

The simulations with HYDRUS2D showed that increasing duration of subsurface drip irrigation and higher initial soil moisture both increase the amount of water reaching the left root zone (see Figure 3). Percolation decreases with lower initial soil moisture and, at the beginning, with increasing duration of irrigation, while the amount of water percolating out of the root zone increases after reaching a threshold, which depends on the initial soil moisture. Ordinarily high frequented (e.g. daily) irrigation with little irrigation water amounts per application may result in low percolation but highly non uniform water distribution and thus yield reduction in undersupplied rows. The application of HYDRUS2D confirmed that an irrigation duration of at least 15 h (low initial soil moisture preconditioned, discharge rate = 2.5 l $h^{-1}m^{-1}$) should be a good basis for distributing the water uniformly in a satisfactory manner restricting deep percolation at the same time. These findings were applied within the irrigation scheduling described below.

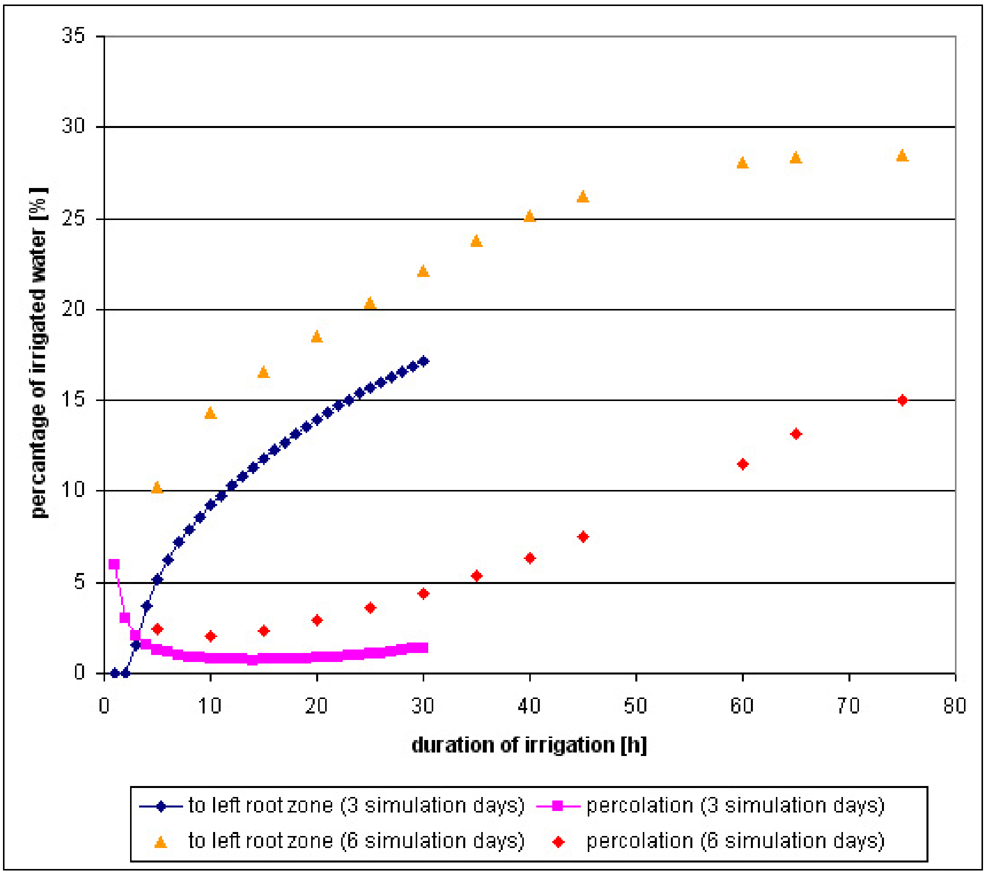

Figure 5. This figure shows the percentage of irrigation water reaching the left row depending on the duration of irrigation (h) after 3 (blue dots) and 6 simulation days (orange dots); and the percentage of percolated water depending on the duration of irrigation (h) after 3 (pink dots) and 6 simulation days (red dots). 29 and 12 simulations were performed for 3 and for 6 simulation days, respectively. The initial relative soil moisture was Θ_{rel} (t = 0) = 0.6. Further explanations are given above (l`illustration montre le pourcentage de l`eau irriguée qui arrive a la plante à gauche selon la duration d´irrigation (h) après 3 (points bleus) et 6 (points oranges) jours de simulation; et le pourcentage de l´eau percolée selon la duration d´irrigation (h) après de 3 (points roses) et 6 (points rouges) jours de simulation. 29 et 12 simulations ont été exécuté pour 3 et 6 jours de simulation, respectivement. L` humidité initiale relative était Θ_{rel} (t = 0) = 0.6)

6. DISCUSSION

The crop model performance was evaluated by comparing the previous simulated target value and harvested values. The target grain yield of 14 Mg ha^{-1} compared moderate with the harvested grain yields of 11.8 Mg ha^{-1}. The differences in the measured and simulated yields (11.8 and 14 Mg ha^{-1}) may not be statistically different at 5% due to the high yield variability between the rows (Cv > 20%). Nevertheless, the field study confirmed that using the simulation-optimization approach for optimal irrigation scheduling can significantly increase WP up to more than 10%, and at the same time provide a certain yield stability and reliability.

6.1 Yields and water productivity

Row spacing had a high impact on yields, resulting in higher 1000-seed weights and lower plant densities in case of 75 cm compared to 60 cm row distance (comparing SDI and RF treatments). In the case of the SDI treatments, the higher 1000-seed weight compensated the lower plant density (wider row distance) of SDI160 resulting in the same grain yield of 11.8 Mg ha^{-1} as SDI120.

The results show that higher WP were achieved by applying the controlled deficit irrigation and adapted irrigation schedule. WP was highest for SDI120, mainly caused by the lower grain yield of the referring rainfed treatment RF60 comparing it to SDI160, and caused by the high irrigation water amount comparing it to FULL (see Equation 1). The study indicated that the simulation based optimal irrigation scheduling strategy may increase WP more than 10%.

6.2 Impacts of the drip line spacing and irrigation control on soil moisture distribution

The visual condition of the corn plants suggested that different drip line spacings result in different patterns of crop biomass distribution on the field (e.g. plant height, biomass) generally decreasing with distance from nearest emitter. The higher variability in grain yields and dry matter for SDI160 compared to SDI120 and FULL confirmed these field observations. The drip line spacing of SDI160 seems to be economically more beneficial, as the wider drip line spacing of 1.6 m lowers initial installation and material costs of about 25% compared to the 1.2 m drip line spacing while reaching the same grain yields.

7 SUMMARIES AND CONCLUSIONS

At the beginning of the growing season in 2010, a deficit irrigation schedule which maximizes WP and achieves a given yield of about 14 t ha^{-1} (with a reliability of 95%) was determined applying a stochastic optimization framework for two plots. The irrigation schedule was provided by the tailor-made evolutionary optimization algorithm for optimal irrigation scheduling with limited water supply (GET-OPTIS) and the crop growth model PILOTE. It was completed by scenario series generated by the parameterized weather generator LARS-WG for simulating long term climate characteristics and weather forecasts. During the growing season the irrigation schedule was adapted weekly according to actual weather data using the stochastic optimization framework.

In 2009, the optimization framework was applied at two subsurface drip irrigated (SDI) plots at an experimental site in Montpellier, France. Three control treatments were conducted, too. Corn yields were satisfactory for the full irrigated treatment (FULL) and both deficit irrigated SDI treatments. Grain yields of about 11.8 Mg ha^{-1} with total water amounts of 339 and 312 mm for SDI160 (row distance 75 cm, drip line distance 160 cm) and SDI120 (row distance 60 cm, drip line distance 120 cm) were reached. The control treatments yielded 16 Mg ha^{-1} with 478 mm total water applied for the surface drip irrigated treatment (FULL), and 3.2 (RF75, row distance 75 cm) and 2.5 Mg ha^{-1}

(RF60, row distance 60 cm) for the rainfed treatments. The water productivities were 3.7 (SDI120), 3.5 (SDI160) and 3.3 kg m^{-3} (FULL). The drip line layout of SDI160 seems to be more profitable, because the wider drip line spacing of 1.6 m lowered initial installation costs of about 25% compared to the 1.2 m drip line spacing without yield decline. The field study confirmed that using the simulation-optimization approach for optimal irrigation scheduling can significantly increase WP up to more than 10%. Simulations with Hydrus2D show that high irrigation water doses around 30 mm per application increase water uniformity on field (especially for high drip line distanced plot SDI160) with acceptable percolation. However, the approach applied in PILOTE soil water balance module does not adequately present the non-uniform soil moisture distribution of the experimental site.

REFERENCES

Ayars, J.E., Phene, C.J., Hutmacher, R.B., Davis, K.R., Schoneman, R.A., Vail, S.S., Mead, R.M. 1999. Subsurface drip irrigation of row crops: a review of 15 years of research at the Water Management Research Laboratory. Agricultural Water Management (42): 1-27.

Camp, C. R. 1998. Subsurface drip irrigation: A review. Transactions of the Asae 41(5): 1353-1367.

Camp, C. R., P. J. Bauer, et al. 1998. Subsurface drip irrigation for agronomic crops. 19th Annual Irrigation-Association Technical Conference, San Diego, Ca.

Camp, C. R., Lamm F. R., et al. 2000. Subsurface drip irrigation - Past, present, and future. 4th National Irrigation Symposium, Phoenix, Az.

Darusman, A., Khan H., et al. 1997. "Water flux below the root zone vs. drip-line spacing in drip-irrigated corn." Soil Science Society of America Journal 61(6): 1755-1760.

Garcia y Garcia A., Garcia, Guerra L., Hoogenboom, G. 2009. Water use and water use efficiency of sweet corn under different weather conditions and soil moisture regimes. Agricultural water management.96 (6): 912-916.

English, M. 1990. Deficit Irrigation. I: Analytical Framework. Irrigation and Drainage Engineering. 116 (3): 399-412.

Khaledian, M.R, Mailhol, J.C, Ruelle, P., Rosique, P. 2008. Adapting PILOTE model for water and yield management under direct seeding system (DSM). The case of corn and durum wheat in mediterranean climate. AGWAT. (96): 757-770.

Lamm, F. R., Trooien T. P. 2003. "Subsurface drip irrigation for corn production: a review of 10 years of research in Kansas." Irrigation Science 22(3-4): 195-200.

Mailhol, J.C., Ayorinde A. A., Ruelle, P. 1997. Sorghum and sunflower evapotranspiration and yield from simulated leaf area index. Agric. Water Manag. 35: 167-182

Mailhol, J.C., Olufayo, O., Ruelle, P. 1997. AET and yields assessments based on the LAI simulation. Application to sorghum and sunflower crops. Agricultural Water Management revue. 35. 167-182.

Mailhol, J.C., Zaïri, A., Slatni, A., Nouma, B., El Amani, H. 2004. Analysis of irrigation systems and irrigation strategies for durum wheat in Tunisia. Agric. Water Manag. 70: 19-37.

Provenzano, G. 2007. Using HYDRUS-2D simulation model to evaluate wetted soil volume in subsurface drip irrigation systems. Journal of Irrigation and Drainage Engineering-Asce 133(4): 342-349.

Schmitz, G.H., Woehling, T., de Paly, M. 2007. GAIN-P: A new strategy to increase furrow irrigation efficiency. Arabian Journal for science and engineering. 32 (12): 103-114.

Semenov, M.A., Barrow E.M.: LARS-WG - A stochastic weather generator for use in climate impact studies - User manual. 2002. URL - http://www.iacr.bbsrc.ac.uk/mas-models/larswg.html. (28.10.2009)

Simúnek, J., Sejna, M., van Genuchten, M. Th. 1996. Hydrus-2d. User Manual. Bouleds, Co: International Ground Water Modeling Center, Colorado School of Mines. IGWMC-TPS 53.

Taky, A., Bouarfa, S., Mailhol, J.C., Hamani, A., Ruelle, P., Bouaziz, A. 2009. The furrow irrigation system: a technique to improve water productivity in the Gharb valley (Morocco). Irrigation and Drainage. 58: 297-306.