Effect of cropping strategies on the irrigation water productivity of durum wheat

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ABSTRACT

The importance of irrigation for durum wheat is often questionable because of possible spring rainfalls in the south-east of France. The cropping strategies i.e. plant density (PD), sowing date and irrigation management were analysed for improving irrigation water productivity (IWP). An experiment was carried out to calibrate and validate the PILOTE model. An adaptation of the potential harvest index to PD was implemented in PILOTE. The latter satisfactorily simulates different model outputs with coefficients of efficiency greater than 0.97. The model was employed for simulating the impact of cropping strategies on IWP for a long climatic series. According to model simulations, the necessity of irrigation is questionable under our conditions. IWP was notably lower under high PD than under low PD for the same sowing date. Under low PD and without irrigation it would be possible to obtain yield similar to that obtained under high PD with irrigation.

Keywords: water scarcity; plant density; harvest index; *Triticum turgidum*; crop model

Water demand growth in urban, industrial, agricultural and environmental sections creates more competition for the limited and degraded water resources. Hence, it is crucial to plan accurately water resources distribution and allocation to attain sustainable agriculture. 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. Crop models can help us to test different cropping strategies. Model simulations under various climatic conditions can help us to identify the best crop management (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 comparison to other crop models, PILOTE (Mailhol et al. 1997) requires a low number of input data to simulate the yield response to water.

Durum wheat is one of the main crops cultivated in the Mediterranean regions, but the interest of irrigation for this crop is often questionable. This is because of possible rainfalls during spring, the access to water and the irrigation costs. Whatever the specificity of the context, water scarcity is a characteristic of the Mediterranean regions that encourages the evaluation of cropping strategies which can improve the irrigation water productivity (IWP). Little studies dealt with the impact of plant density on the harvest index (HI) and on water consumption more especially for durum wheat. Water productivity of sweet sorghum was studied in relation to plant density (Dalianis et al. 1996). It was found that decreasing plant density increased water productivity in a Mediterranean climate. Lamm et al. (2009) found that increasing plant density from 66 300 to 82 300 plants/ha generally increased grain yield and water productivity of corn. The results of another study conducted on corn showed that HI decreased when plant density increased (Reddy et al. 1987), which is evidence that leaf area index (LAI) increases with plant density as attested by the studies on the architectural plant growth models (Cournède 2009, Mailhol et al. 2011). Recently, Jamaati-e-Somarin et al. (2010) conjointly analysed the role of fertilization and plant density on HI. Their findings attested a significant decrease of HI with plant density for N application level of 180 kg/ha, the dose generally applied by farmers in the south-east of France. The same results were obtained for sorghum by Ismail and Ali (1996). In contrast, Puckridge and Donald (1967) showed that plant density has little impact on the harvest index, the latter decreasing at a rate of 0.01 when doubling plant density. Many studies highlighted the great impact of water and fertilization on the total dry matter production and on HI (Merah 2001, Khaledian et al. 2009, 2010, 2011, Jamaati-e-Somarin et al. 2010). In cereals, low rate of seed is proposed to prevent high competition for light and water. With increasing plant density, delay in flowering, earring and decrease in reproductive period length is deserved (Daynard and Muldoon 1983, Panahyan-e-Kivi et al. 2010). Uhart and Andrade (1995) suggested that a decrease in soluble carbohydrates remobilization as a result of shading may be attributable to growth decrease and lower physiological demand for assimilates. Competition for light seems to be determinant in the allocation process of the energy capture to the different plant organs (Fisher and Wilson 1975). This problem can be analysed using appropriate model as functional and structural plant models although modelling efforts are still required (Cournède et al. 2007). Field experiments, however demonstrated a strong negative relationship ($r = –0.60$) of HI with both plant height and leaf length (Singh and Stoskopf 1971, Donald and Hamblim 1976). Such a statement suggests that HI is negatively correlated with LAI of an individual plant and by extension to LAI from a general point of view.

The objective of this study was to evaluate the impact of PD on IWP improvement for durum wheat in a Mediterranean climate, SE of France. For that, empirical relationships were established between HI and LAI and implemented in the crop model PILOTE for simulating the impact of sowing PD with sowing date and irrigation strategies on IWP. Optimizing cultural management practices will be a key factor in managing crop production.

MATERIAL AND METHODS

Field experiments. The field experiments were carried out on a loamy soil plots (20% clay, 47% silt, 33% sand) located at the Irstea research institute of Montpellier (SE of France). Soil water content at field capacity is in average of 0.29 cm^3/cm^3, and wilting point is taken at 0.12 cm^3/cm^3. The average annual rainfall is 780 mm. Evapotranspiration calculated by the Penman equation (1948) exceeds the whole year rainfall under the Mediterranean climate, being 870 mm/year. These climate data were monitored at a weather station situated in the experimental station. Some climatic data are presented in Figure 1. Durum wheat was sown at different dates and density (Table 1) for four contrasted climatic campaigns: 2004–2005; 2005–2006; 2008–2009; 2009–2010, the driest being that of 2005–2006 when total rainfall was 271 mm during the cropping season. Fertilization doses were adapted to plant requirements and initial soil N content. The average doses were of 180 kg N/ha. Nitrogen content in the plant was measured at harvest (Table 2). To determine the grain yield (GY) and dry matter yield (DM) ten 3 m^2 sub-plots were hand harvested (Table 1). LAI was measured using a LI-COR LAI 2000 (Lincoln, USA) approximately each week when possible. The evolution of the soil water content from 0 to 2 m was monitored using a neutron probe while mercury tensiometers installed at different depths allowed the monitoring of the zero flux plan positions, an indicator of the front root position during periods without water transfer trough the root zone which can be provoked by heavy rains or irrigations. Irrigation consisted into water applications depths of 25 to 30 mm delivered by a travelling rain gun system.

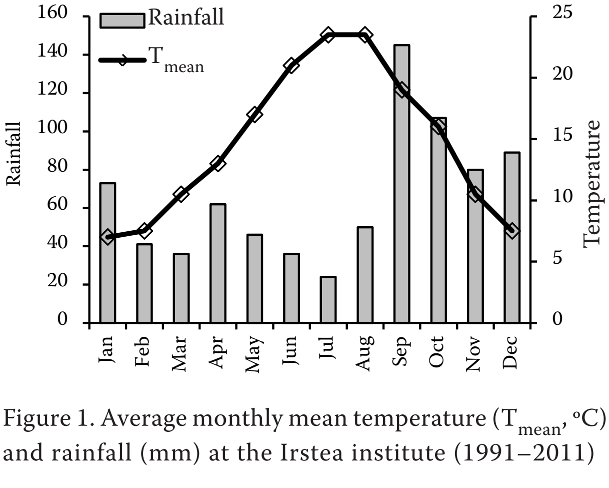

Figure 1. Average monthly mean temperature (T_{mean}, °C) and rainfall (mm) at the Irstea institute (1991–2011)

Table 1. Yields (the first line: dry matter, the second line: grain yield at 15% of humidity) for the different treatments with number of irrigation (I and I* for conventional tillage and direct seeding into mulch, respectively, in 2009–2010 season), sowing dates, plant density (plants/m^2) maximum LAI value (LAI_x) and potential harvest index (HI_{pot})

Crop seasons	Grain yield (t/ha)	Dry matter (t/ha)	Irrigation	Sowing dates (DOY)	Plant density (plants/m^2)	LAI_x (m^2/m^2)	HI_{pot}
2004–2005	4.7	9.6	0	321	250	3.9	0.47
	7.5	13.7	3I	321	300	3.9	0.47
	6.3	12.4	2I	321	300	3.9	0.47
	5.4	10.5	1I	321	250	3.9	0.47
2005–2006	3.7	6.7	0	321	200	3	0.5
	6	9.6	3I	321	200	3	0.5
	5.4	10.6	1I	321	250	3	0.5
2008–2009	5	8.8	0	305	225	3.6	0.5
2009–2010	5.8	13.6	0	312	400	5	0.37
	6.9	14.5	2I	312	400	5	0.37
	5.9	13.4	1I	312	400	5	0.37
	6.3	15	1I*	289	400	5	0.38

Modelling. PILOTE is an operative crop model that simulates soil water balance and crop yield at a daily time step by association of a soil module and a crop module, under the assumption of water being the only limiting factor affecting on crop growth and yield. The soil module consists of a 3-reservoirs system (Mailhol et al. 1997) covering a layer from the soil surface until the maximum rooting depth. A shallow reservoir, R_1 with a depth of 10 cm rules the water balance at the soil surface, in which evaporation is governed by current LAI acting on the partitioning coefficient between transpiration and evaporation. The following reservoir, R_2 accounts for root section, so its capacity increases with root growth. Before the potential root area is totally taken by the second reservoir, the third reservoir represents the remaining part. Water is first taken from the shallow reservoir until total depletion by evaporation and plant uptake then from the second one by plant only. On the basis of field capacity and wilting point, the soil water balance among reservoirs is thus calculated. Maximum evapotranspiration (MET) and actual evapotranspiration (AET) are involved in the water stress index (WSI) calculation. MET is derived from:

$$MET = K_c \times ET_0$$

Where: ET_0 – reference evapotranspiration; K_c – crop coefficient as a function of LAI.

Under water stress conditions, AET linearly decreases from MET with the depletion level of R_2. Then, WSI, obtained accordingly to this lumped plant uptake approach, is exported to the crop module as an environment coefficient.

The crop module is based on the LAI simulation and its response to WSI. The simulation involves two shape parameters and a vegetative stage parameter (T_m) corresponding to the temperature sum when the maximum LAI (LAI_x) reached. T_m and LAI_x can be derived from the literature or measured in the field. Dry mater is calculated based on Beer's law, RUE (radiation use efficiency) being affected by WSI. Grain yield is evaluated by the product of DM by a harvest index (HI). HI is set to a potential value (HI_{pot}) if average LAI (LAI_{av}) from the stage 'grain filling' (controlled by Ts_1) to the stage of 'pasty grain' (controlled by Ts_2) is greater than a threshold value (LAI_{st}), otherwise it linearly decreases (Mailhol et al. 2004, Khaledian et al. 2009). The required climatic data are precipitations, global radiation, average temperature and ET_0.

Table 2. Plant N content at harvest with measured harvest index (HI)

Crop season	N in the plant (kg/ha)	HI
2004–2005	141	0.47
2005–2006	143	0.5
2008–2009	130	0.5
2009–2010	140	0.37

PILOTE accounts for plant density impact on LAI_x and on HI_{pot} using empirical relationships. That concerning LAI was calibrated on corn and gave satisfactory results (Khaledian et al. 2009). The adapted maximum LAI value to a given plant density is:

$$LAI_x = LAI_{ref} (PD/PD_{ref})^{0.6} \quad (1)$$

Where: LAI_{ref} – maximum reference LAI value measured for reference plant density (PD_{ref}).

For the specificity of durum wheat, the following relationship is proposed for adapting potential harvest index of durum wheat (HI_{pdw}) to plant density:

$$HI_{pdw} = HI_{pot} \times (3.5/LAI_x) \times 0.6 \quad (2)$$

It was calibrated and validated from data of Table 1. This empirical formulation restricts the domain of application to the experimental conditions i.e.: a maximum LAI of 5 obtained for PD = 400.

According to data of Table 2, it seems that no link could be established between the N amounts in the plant and the HI values. Thus, attributing a significant link between LAI_x and HI_{pot} seems to be a realistic assumption, LAI_x in 2009 and 2010 have being measured in unstressed treatments.

At last to account for a water stress impact, the following equation, used in the classical PILOTE version model (Khaledian et al. 2009) is proposed:

$$HI = Min\ [HI_{pot}; (HI_{pot} - a_r \times (LAI_{st} - LAI_{av})] \quad (3)$$

Where: Min – minimum; HI_{pot} – potential harvest index; a_r – calibration parameter for simulating water stress impact on HI; LAI_{st} – LAI threshold value under which HI_{pot} is affected by water stress (m^2/m^2); LAI_{av} – averaged LAI values calculated between T_{s1} and T_{s2} (m^2/m^2), the beginning and the end of critic phase, respectively (°C day).

To obtain grain yield, HI should be multiplied in dry matter. HI is set to 0.5 or very close to 0.5 for many crops. It is correct for crops not sensitive to water stress, but not suitable for other crops e.g. wheat being sensitive to water stress. Hence, equation 3 can demonstrate the impact of water stress on HI.

Irrigation water productivity (IWP, kg/m^3) can be defined (Mailhol et al. 2011) as:

$$IWP = \frac{GY - GYr}{WAD} \quad (4)$$

Where: GY – grain yields (kg/ha) under irrigation; GY_r – grain yields (kg/ha) under under rainfed conditions; WAD – water application depth (m^3/ha).

The root mean squared error (RMSE) and the prediction efficiency of model (Ce) proposed by Nash and Sutcliffe (1970) were used to evaluate grain yield (GY) and soil water reserve (SWR) simulations in comparison with measured values.

To compare statistically model simulation results in different treatments, paired samples *t*-test in SPSS software package (Chicago, USA) was used.

RESULTS AND DISCUSSION

Model verification. The identified phenological stages were considered with base temperature $T_b = 0.0$: $T_m = 1700°C$, $T_{s1} = 1300°C$, $T_{s2} = 2100°C$ and $T_{mat} = 2400°C$. $LAI_x = 5$ was measured for plant density of 400 plants/m^2. The radiation use efficiency, RUE = 1 g/MJ/cm^2 was derived from previous findings (Mailhol et al. 2004, Khaledian et al. 2009) as well as $a_r = 0.15$ and $LAI_{st} = 2.5$, the parameters of Eq. (3) and those governing root growth. According to tensiometer readings plant uptakes water until $P_x = 1.2$ m, considered here as the maximum depth reached by roots.

As shown by Figures 2a–b, LAI and SWR i.e. the soil water reserve on P_x, calculated by:

$$SWR = \int_0^{Px} \theta(z)dz$$

are well simulated in 2008–2009 and 2009–2010 crop seasons with the LAI shape parameters calibrated in 2005.

In this study, to evaluate the performance of PILOTE model out of our experimental conditions, the results of 2010–2011 cropping season in two agricultural fields located at Montpellier are compared with model simulations (Figures 3c–d). All measurements and treatments were the same as in the experimental station.

The yields of the different treatments in the experimental station of Irstea (in 2004–2005, 2005–2006, 2008–2009 and 2009–2010 crop seasons) and in agricultural fields (in 2010–2011 crop season) are fairly well simulated by the model PILOTE as shown by Figure 3.

Model application. The model can now be used for simulating the impact of cropping strategies on IWP for a climatic series of 19 years. These cropping strategies refer to sowing date, plant density and irrigation management. The latter consists in delivering a WAD of 35 mm when the easily available water reserve is depleted. Regarding

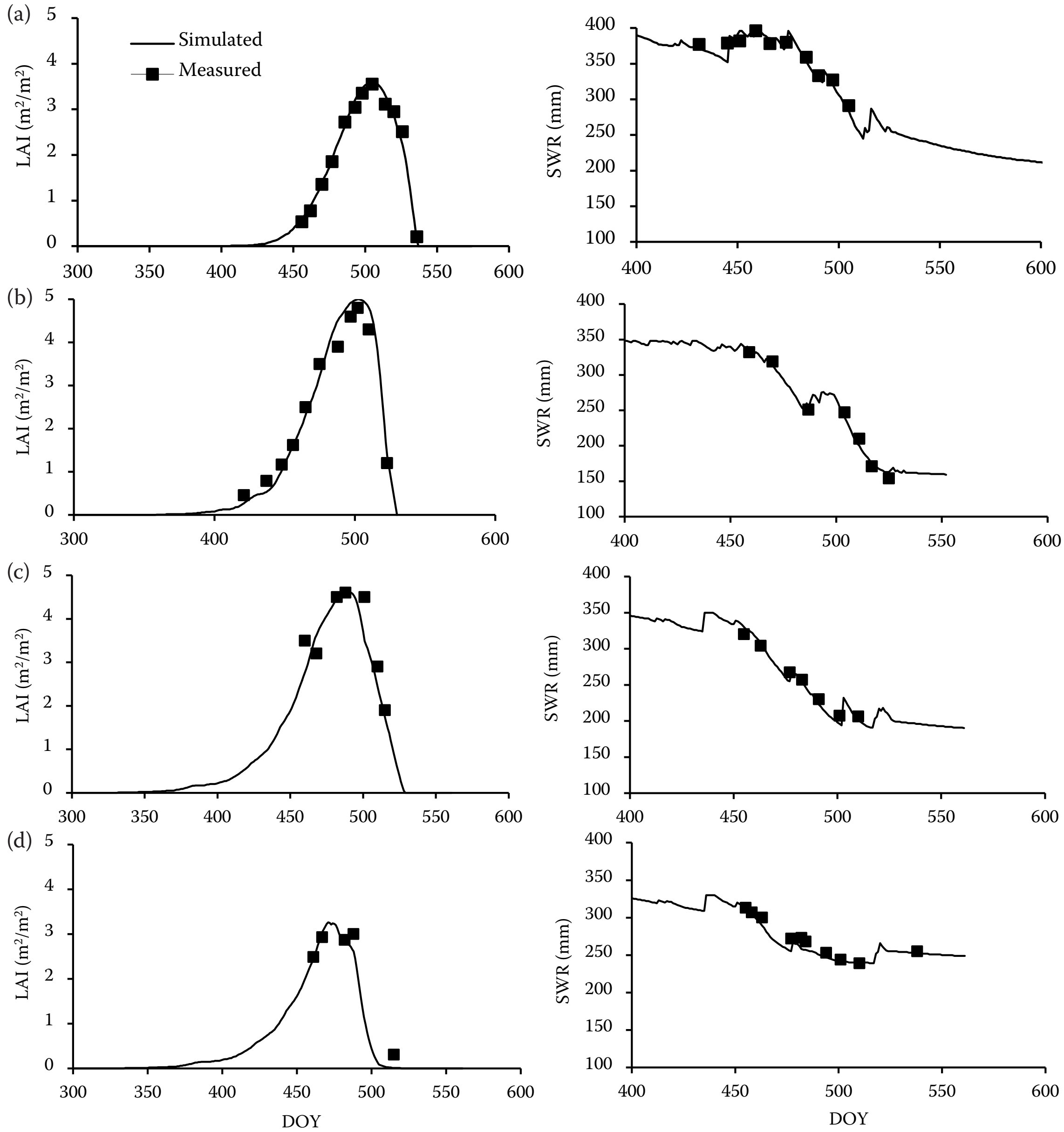

Figure 2. Simulation of leaf area index (LAI) and soil water reserve (SWR) in (a) 2008–2009 with the coefficient of model efficiency (Ce) and root mean square error (RMSE) criteria (LAI: Ce = 0.986 and RMSE = 0.13 m^2/m^2; SWR: Ce = 0.875 and RMSE = 11.47 mm); (b) the rainfed treatment in 2010 with the Ce and RMSE criteria (LAI: Ce = 0.962 and RMSE = 0.31 m^2/m^2; SWR: Ce = 0.988 and RMSE = 6.7 mm); (c) an agricultural field (water application depth, WAD = 43 mm on 18/05) in 2010–2011 crop season (LAI: Ce = 0.676 and RMSE = 0.53 m^2/m^2; SWR: Ce = 0.962 and RMSE = 8 mm); (d) in a rainfed agricultural field in 2010–2011 crop season (LAI: Ce = 0.952 and RMSE = 0.21 m^2/m^2; SWR: Ce = 0.870 and RMSE = 9 mm)

plant density, obviously it is assumed that all the seeds will emerge, our objective being mainly to highlight the role of a cropping practice and not to predict exactly a GY value for a given year.

Definitely, later sowing requires more water than the earlier one, which results in a lower IWP value. Consequently, assuming that water is the sole limiting factor from Table 3, the following statements can be established:

(1) According to model simulations the necessity of irrigation is indeed questionable under the pedo-climatic context of our experimental field. Yield under rainfed condition and low plant density is of 7.6 t/ha (coefficient of variation, *CV* = 11%). Every other year irrigation can be avoided under low density. In average, in 2 years out of 3 with WAD of 35 mm only it is possible to obtain a GY value of 8.3 t/ha (*CV* = 6.7%)

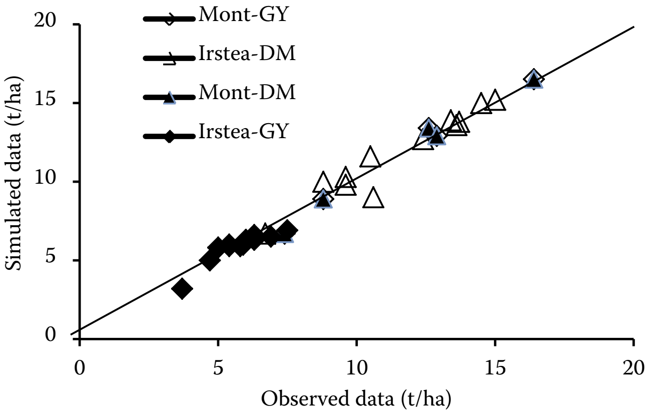

Figure 6. Dry matter at the Irstea institute (Irstea-DM), in Montpellier (Mont-DM), grain yield (GY) at the Irstea institute (Irstea-GY) and in Montpellier (Mont-GY) of durum wheat simulated by PILOTE in different treatments in four crop seasons at the Irstea institute as well as in two agricultural fields in Montpellier in 2010–2011 crop season (Ce = 0.997 and RMSE = 0.54 t/ha). Ce – coefficient of model efficiency; RMSE – root mean square error

at low density compared with GY of 7.3 t/ha (*CV* = 7.7%) obtained with high PD (the difference is very significant, or probability value *P* = 0.000). Whatever the cropping practices, irrigation secures the production since the *CV* values are lower than those obtained under rainfed condition.

(2) WP is notably lower under high density than under low density for the same sowing date (the difference is significant, or *P* = 0.027). This is due to the fact that water consumption increases with a PD increase and that HI_{pot} decreases when PD increases.

(3) In average, under high PD a supplementary WAD is necessary in one year out of 3.

(4) Under low PD (250 plants/m^2) and without irrigation, it would be possible to obtain a GY value similar to that obtain under high PD with

Table 3. Impacts of plant density on simulated grain yield (GY, t/ha), water application depth (WAD, m^3/ha), rainfed grain yield (GY_r) and irrigation water productivity IWP (kg/m^3) of durum wheat in Montpellier (SE of France), for the sowing date: October 15 or day of year (DOY): 288

Crop seasons	Plant density of 400 plants/m²				Plant density of 250 plants/m²			
	GY	WAD	GY_r	IWP	GY	WAD	GY_r	IWP
1992	6.9	1400	5	1.36	7.9	1050	5.9	1.9
1993	7.1	0	7.1	–	8	0	8	–
1994	6.8	700	5.8	1.43	7.8	700	6.8	1.43
1995	7.5	700	6.6	1.29	8.4	350	7.8	1.71
1996	6.4	0	6.4	–	7.4	0	7.4	–
1997	7	1050	5.8	1.14	8	700	6.8	1.71
1998	6.7	0	6.7	–	7.8	0	7.8	–
1999	7.6	1050	5.9	1.62	8.4	1050	6.4	1.9
2000	8	700	7.3	1	8.9	350	8.3	1.71
2001	6.6	0	6.6	–	7.7	0	7.7	–
2002	7.2	0	7.2	–	8.3	0	8.3	–
2003	7.6	350	7.2	1.14	8.7	350	8.4	0.86
2004	7.9	350	7.7	0.57	9.1	350	8.9	0.57
2005	8.6	1400	6.6	1.43	9.5	1050	7.5	1.9
2006	7.8	1750	5.2	1.49	9	1750	6	1.71
2007	6.5	0	6.5	–	7.5	0	7.5	–
2008	7.6	0	7.6	–	8.7	0	8.7	–
2009	7.5	0	7.5	–	8.4	0	8.4	–
2010	7.5	700	6.8	1	8.3	350	7.8	1.43
Mean	7.3	534	6.6	1.22	8.3	423	7.6	1.53
CV (%)	7.7	104	11.5	26	6.7	108	11.2	27

irrigation (the difference is not significant or $P = 0.185$).

(5) The sowing date plays an important role in water savings. Indeed, the highest WP (1.53 kg/m^3, $CV = 27\%$) values are obtained when durum wheat is sown on October 15 compared with durum wheat sown on November 15 (1.48 kg/m^3, $CV = 38\%$), which requires more frequent water applications.

(6) GY, GY$_r$ and IWP are significantly higher with 250 plants/m^2 than 400 plants/m^2, respectively, whereas WAD is significantly lower with 250 plants/m^2 ($P < 0.05$).

It is clear that DM under high PD is higher than DM under low PD for the same WAD and fertilization conditions. Regarding GY, it was assumed that nitrogen did not have an impact on the measured HI$_{pot}$ values, as attested by Table 2. Further field and model simulation studies are probably needed to reinforce this assumption. Model application on a climatic series allowed the evaluation of IWP gaps between cropping practices. It clearly appears that it is not recommended to grow durum wheat at high plant density in a water scarcity context. It is more suitable to sow at mid-October than past mid-November to save water in a Mediterranean climate with water deficiency.

In conclusion, PILOTE, an operative crop model has shown its capabilities to predict the yields of durum wheat for different plant densities. A limitation of this approach resides in the fact that plant density cannot be exactly predicted from the initial seed density adopted by the farmer although a good soil preparation insures a level of germination generally greater than 90%. Another limitation results from the empirical formulation adopted for predicting HI$_{pot}$. Yet, we have to point out that harvest index is not always accurately predicted for field crops by the Process Based Models (Marcelis et al. 1998, Nemeth 2001, Marcelis and Heuvelink 2007) a model category to which PILOTE belongs. Further works are required for improving the predictability of HI$_{pot}$ by integrating for instance new information from genetics (Hammer et al. 2010, Lizaso et al. 2011) or by coupling with other crop growth models such as functional structural plant models based on sophisticated allocation functions (Feng 2011).

The application of this adapted version of PILOTE was carried out to identify the best cropping strategy for a climatic series in the Mediterranean climate on a loamy soil. The results of this application showed that irrigation is far to be always necessary in the context of SE France. An average grain yield value of 7.6 t/ha can be obtained under rainfed conditions at low plant density (250 plants/m^2) and no nitrogen stress, and a similar value was obtained at high plant density by irrigation, the role of which being to reduce the inter-annual variability. In a perspective of irrigation profitability, irrigation can be avoided every other year under low plant density. Under such climate, sowing at mid-October instead of mid-November results in significant water savings. The highest irrigation water productivity (IWP = 1.53 kg/m^3, $CV = 27\%$) is obtained when durum wheat is sown on October 15 compared with durum wheat sown on November 15 (1.48 kg/m^3, $CV = 38\%$) which requires more frequent water applications. The role of direct seeding into mulch as realised in this experimentation have to be taken into account for early sowing. Similar studies could be performed under other environmental (soil and climate) contexts for improving durum wheat cropping and its irrigation management.

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