IMPACT OF PLANT DENSITY ON THE IRRIGATION WATER PRODUCTIVITY OF DURUM WHEAT IN A MEDITERRANEAN CLIMATE

IMPACT DE LA DENSITE DE LA PLANTE SUR LA PRODUCTIVITE DE L'EAU D'IRRIGATION DU BLE DUR DANS LE CLIMAT MEDITERRANEEN

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ABSTRACT

In this article cropping strategies comprising plant density, sowing date and irrigation management are analysed and evaluated with a view to improving WP in the water-scarce Mediterranean regions. An experimental loamy soil plot located at the Cemagref research institute of Montpellier (SE of France) was used for calibrating and validating the crop model PILOTE. Durum wheat was sown at different dates and density for four contrasted climatic campaigns: 2004-2005; 2005-2006; 2008-2009; 2009-2010. Fertilisation doses were according to the plant requirements and initial conditions, nitrogen in the plant being measured at harvest. The experimental results showed that LAIX (the LAI peak value) and HIpot, (the potential harvest index) were narrowly linked to plant density (PD). The empirical relationship between LAIX and plant density, previously established for corn and implemented in PILOTE, is found valid for wheat. An adaptation of HIpot to plant density was also proposed and implemented in PILOTE. The latter satisfactorily simulates LAI, soil water reserve (SWR), total dry matter (DM) and grain yield (GY) with coefficients of efficiency greater than 0.970. The model is therefore used for simulating the impact of cropping strategies on WP for a climatic series on a loamy soil. According to model simulations the necessity of irrigation is questionable under the pedo-climatic context of the experimental field. Yield under rainfed conditions and at low plant density is 7.6 T/ha (Cv = 11%). Every other year irrigation can be avoided under low density. In average, 2 years out of 3 with a water application depth (WAD) of 35 mm only, it is possible to obtain a GY value of 8.3 T/ha (Cv=6.7%) at low density compared with a GY of 7.3 T/ha (Cv=7.7%) at high PD. Whatever the cropping practices, irrigation secures the production since the Cv values are lower than those under rainfed conditions. WP is notably lower under high density than under low density for a same sowing date. This is due to the fact that water consumption increases with PD and that HIpot decreases when PD

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increases. In addition, the highest WP (1.53 kg/m^3, Cv = 27%) values are obtained when wheat is sown on October the 15th than if sown on November the 15th (1.48 kg/m^3, Cv = 38%) which requires more frequent water applications. Under low PD (250 Plts/m^2) and without irrigation it would be possible to obtain, in SE of France and for the cultivars used, a GY value similar to that obtain under high PD with irrigation. It is obvious that DM under high PD is higher than DM under low PD for a same WAD and fertilisation conditions. Regarding GY, it was assumed that nitrogen did not have any impact on the measured HIpot values. Further works are needed to reinforce this assumption. Modelling applied to a climatic series allowed the evaluation of WP gaps between cropping practices. It clearly appears that it is not recommended to grow wheat at high density in a water scarcity context.

Key words: *Durum wheat, water scarcity, plant density, water productivity, crop model*

RESUME

L'intérêt d'irriguer le blé dur, une des principales cultures des pays méditerranéens, est bien souvent discutable en raison de printemps relativement pluvieux et de l'investissement nécessaire. Cependant quelle que soit la spécificité du contexte, la rareté de l'eau n'en demeure pas moins une caractéristique propre au bassin Méditerranéen ; l'économiser est donc une nécessité. Cette constante milite en faveur de la mise en œuvre de stratégies de gestion des systèmes de cultures visant à améliorer la productivité de l'eau (WP) d'irrigation. Dans le cadre de ce travail, ces stratégies concernent la densité de plantation, la date de semis et la façon de gérer l'irrigation. La modélisation appliquée à une série d'années climatique est un outil intéressant pour identifier ces stratégies.

Des expérimentations ont été menées sur blé dur en sol limoneux au Cemagref de Montpellier en vue de calibrer et valider le modèle de culture PILOTE. Le blé dur a été semé à différentes dates et à différentes densités au cours de 4 campagnes climatiquement contrastées: 2004-2005 ; 2005-2006 ; 2008-2009 ; 2009-2010. L'apport en fertilisant est en général adapté aux besoins de la plante et aux teneurs initiales d'azote dans le sol, la teneur en azote dans la plante étant par ailleurs mesurée à la récolte. Outre la mesure des composantes du rendement, l'indice foliaire (LAI) et l'état hydrique du sol font l'objet d'un suivi tout au long du cycle de culture.

Les résultats expérimentaux font état d'une relation entre valeur maximale LAIX du LAI et indice de récolte potentiel (IRpot), LAIX étant de façon plus explicite lié à la densité de plantation (DP). Une relation empirique est alors proposée reliant IRpot et DP par l'intermédiaire de la relation LAIX = f(DP). Les rendements en grain varient de 7.5 Mg/ha en irrigué à 3.7 Mg/ha en sec. PILOTE simule de façon satisfaisante LAI, réserve en eau du sol, matière sèche (MS) et rendement en grain (RG). Le modèle est alors utilisé pour simuler, sur une série d'années climatique, l'impact de stratégies de culture sur WP dans le cas du blé dur en sol limoneux.

Selon le modèle, l'intérêt d'irriguer le blé dur est en effet discutable dans notre contexte environnemental. Le RG moyen en pluvial atteint 7.6 Mg/ha (Cv= 11%). Une année sur deux l'irrigation peut être évitée sous faible densité (250 plts/m^2). En moyenne, 2 années sur 3, une dose de 35 mm seulement permet d'atteindre un rendement de 8.3 Mg/ha (6.7%) sous fiable densité comparé à 7.3 Mg/ha (Cv = 7.7%) sous forte densité (400 plts/m^2). Cependant, *quelle que soit la stratégie l'irrigation sécurise la production dans la mesure où elle réduit la variabilité interannuelle. WP est notablement plus élevée sous faible densité pour une même date de semis. Cela est dû au fait que la consommation en eau augmente avec DP et que IRpot décroît lorsque DP augmente. Par ailleurs, WP est en moyenne plus élevée pour un semis précoce de mi Octobre (1.53 Kg/m^3, Cv = 27%) que pour un semis tardif de mi Novembre (1.48 kg/m^3, Cv = 38%) et présente surtout une variabilité interannuelle plus faible. Un semis précoce requiert en outre moins d'irrigations. En moyenne sous haute densité une dose supplémentaire s'avère nécessaire en moyenne une année sur trois. Sous faible densité, et sans irrigation il serait possible d'atteindre, dans le Sud-Est de la France pour les variétés utilisées, un rendement proche de celui obtenu avec irrigation sous forte densité, avec cependant une variabilité interannuelle plus forte. A l'évidence, la MS sous forte densité est plus élevée que sous faible densité pour une même quantité d'eau et de fertilisants apportée. A la faveur de ces simulations il paraît peu recommandable de cultiver du blé dur à forte densité dans un contexte de faible disponibilité en eau.*

Mots clés : *Blé dur, rareté de l'eau, densité de la plante, productivité de l'eau, modèle de culture*

1. INTRODUCTION

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 (WP). Limited studies have dealt with the impact of plant density on the harvest index (HI) and on water consumption, especially for durum wheat. Study conducted on corn showed that HI decreases when plant density increase (Reddy et al., (1987). There are evidences that LAI increases with plant density as found in studies using the architectural plant growth models (Lee et al.. Unpublished, Cournède, 2009 and Mailhol et al., 2011). Recently, Jamaati-e-Somarin et al. (2010) conjointly analysed the role of fertilisation and plant density on HI. Their findings revealed a significant decrease of HI with plant density for a Nitrogen application level of 180 Kg/ha generally applied by farmers in SE of France. Same results were obtained for Sorghum by Ismail and Ali (1996). Contrarily, 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 fertilisation on total dry matter production and on HI (Merah, 2001; Khaledian, et al., 2009; Khaledian et al., 2010; Jamaati-e-Somarin et al., 2010). But only limited studies deal with the difficult problem of competition for light, which seems to be determinant in the allocation process of the energy capture to the different plant organs (Fisher and Wilson, 1975). Such a problem can be analysed using appropriate model as functional structural plant model although further modelling efforts are still required (Cournède et al., 2007). Field experiments however corroborated a strong negative relationship (r = - 0.60) of HI with plant height and leaf length (Singh and Stoskopf, 1971; Donald and Hamblim, 1971). Such a statement suggests that HI is negatively correlated with LAI of an individual plant and by extension to LAI in general. The objective of this work is to show that plant density (PD) can play a major role in the WP improvement for durum wheat in a Mediterranean climate. For that, empirical relationships were established between HI and LAI and used in the crop model PILOTE for simulating the impact of sowing (PD with sowing date) and irrigation strategies on WP.

2. MATERIALS AND METHOD

The field experiments

The field experiments were carried out on a loamy soil plot (20% clay, 47% silt, 33% sand) located at the Cemagref research institute of Montpellier atSE of France). The average soil water content at field capacity is 0.29 cm^3/cm^3 and at wilting point is 0.12 cm^3/cm^3. The average annual rainfall is 750 mm. Evapotranspiration calculated by Penman equation (1948) for the year exceeds the annual. These climate data were monitored at a weather station situated in the experimental station.

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 where total rainfall was 271 mm during the cropping season. Fertilisation doses were in accordance to the plant requirements and initial conditions. The average doses are of 180 Kg of N/ha. Nitrogen 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). Leaf Area Index (LAI) was measured using a LI-COR LA1 2000 approximately each week when possible. The distribution of the soil water content $\theta(z,t)$ from $z = 0$ to $z = 2$ m was monitored using neutron probes while mercury tensiometers installed at different depths were used to monitor the zero flux plan position, an indicator of the front root position during periods without water transfer trough the root zone (caused by heavy rain or irrigation). Irrigation consisted of water applications depths of 25 to 30 mm delivered by a travelling rain gun system.

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. The soil module consists of a three 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 governs 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 evapotranspiratin (MET), and actual evapotranpiratoin (AET) are involved in the water stress index (WSI) calculation. MET is derived from MET = Kc.ETref, where ETref is the reference evapotranspiration and Kc, the crop coefficient as a function of LAI. Under water stress conditions, AET linearly decreases from MET with the depletion level of R2. 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 (the 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 (HIpot) if average LAI (LAIav) 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 (LAIst), otherwise it linearly decreases (Mailhol et al., 2004; Khaledian et al., 2009). The required climatic data are precipitations, global radiation, average temperature and ETref.

PILOTE accounts for plant density impact on LAI_X and on HIpot using empirical relationships. That concerning LAI was calibrated on corn and gave satisfactory results (Khaledian et al., 2009). The adapted maximal LAI value to a given plant density is:

$$LAI_X = LAI_{ref} \, (PD/PD_{ref})^{0.6} \qquad (1)$$

where LAI_{ref} is the maximum reference LAI value measured for the reference plant density (PD_{ref}).

Whatever the crop, the following empirical relationship is proposed to express the HIpot value as a function of plant density.

$$HIpot \; = HI_{ref}.(PD/\, PD_{ref})^{0.125} \qquad (2)$$

where HIpot is the potential value of HI, HIref is the potential value of the HI measured for $PD_{ref.}$. Eq (2) is valid for a low sensitivity of HI to PD as shown in literature. For the specificity of durum wheat, the followings relationships is proposed

$$HIpot = IRpot(3/LAI_X)^{*}0.6 \qquad (3)$$

It was calibrated and validated from data of Table 1.

According data of Table 2, it does not seem that any link could be established between the N amount in the plant and the HI value. Thus, attributing a significant link between LAI_x and HIpot seems to be more realistic. LAI_X in 2009 and 2010 were measured on unstressed treatments.

At last, to account for a water stress impact:

$$HI = Min \, [HIpot; \, (HIpot - a_r \, (LAIst - LAIav \,)] \qquad (4)$$

Table 1. Yields (DM, first line and GY at 15% of humidity, second line) for the different treatments with number of irrigation (I and I* for conventional tillage and direct seeding into mulch in 2009-2010, respectively), sowing dates, plant density (Pl/m²,) maximum LAI value (LAI_x) and potential harvest index HIpot,

Year	Yields (Mg/ha)	Irrigation	Sowing dates (DOY)	Pl/m²	LAI_x	HIpot
	9.6	0		250		
	4.7					
	13.7	3I		300	3.9	0.47
	7.5					
2004-2005	12.4	2I	321	300		
	6.3					
	10.5	1I		250		
	5.4					
	6.7	0		200	3	
	3.7					0.5
	9.6	3I		200		
2005-2006	6		321			
	10.6	1I		250		
	5.4					
2008-2009	8.8	0	305	225	3.6	0.5
	5			225		
	13.6	0		400	5	0.37
	5.8			400		
	14.5	2I	312	400		
	6.9			400		
2009-2010	13.4	1I	312	400		
	5.9			400		
	15	1I*	289	400	5	0.38
	6.3					

Table 2. Nitrogen in the plant at harvest with measured HI

Year	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

Model verification

The identified phenological stages give with base temperature t_b = 0.: Tm = 1700 °C, Ts_1 = 1300 °C, Ts_2 = 2100 °C and Tmat = 2400 °C. LAI_X = 5 was measured for a plant density of 400. The radiation use efficiency RUE = 1g/MJ/cm^2 was derived from (Mailhol et al., 2004; Khaledian et al., 2009) as a_r = 0.15 and LAIst = 2.5, the parameters of Eq(4) and which governing root growth. According to tensiometer readings plant uptakes water until Px = 1.2 m, considered here as the maximal depth reached by roots.

As shown by Fig.1 and Fig.2, LAI and SWR the soil water reserve on Px, calculated by, $SWR = \int_0^{Px} \theta(z)dz$ are well simulated with the LAI shape parameters calibrated in 2005.

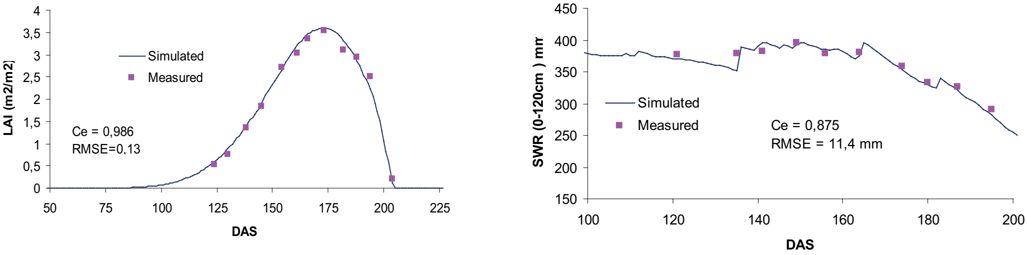

Fig.1. Simulation of LAI and SWR in 2009 with the Nash-Sutcliffe (ASCE, 1993) criterion.

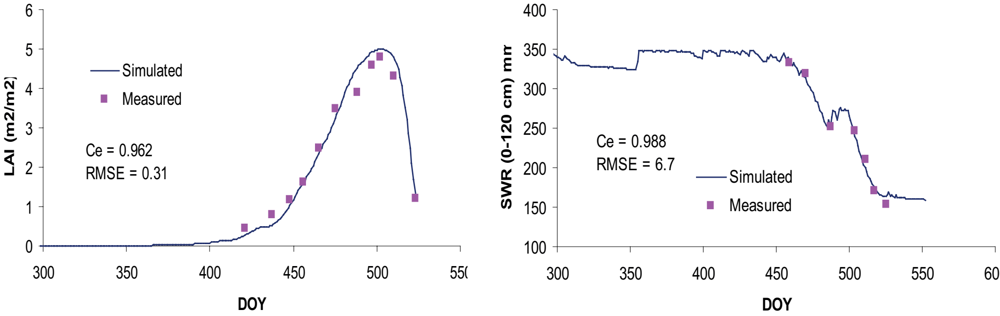

Fig.2. Simulation of LAI and SWR on the rainfed treatment in 2010 with the Nash-Sutcliffe (ASCE, 1993) criterion.

The yields of the different treatments are fairly well simulated by the model PILOTE as shown by Fig. 3.

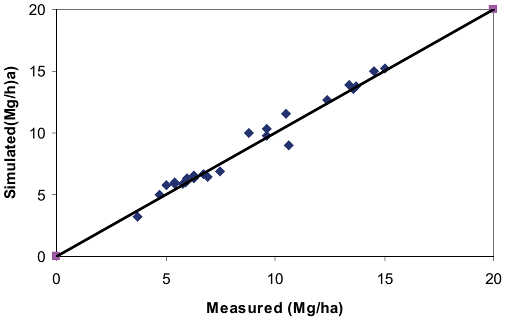

Fig.3. DM and GY of durum wheat simulated by PILOTE on the different treatments for four campaigns.

Model application

The model can now be used for simulating the impact of cropping strategies on WP for a climatic series of near 20 years. These cropping strategies refer to sowing date and plant density and irrigation management. The latter consists in delivering a water application depth of 35 mm when the easily available water reserve is depleted.

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

1-Accordingly to model simulations the necessity of irrigation is indeed questionable under the pedo-climatic context of our experimental field. Yield under rainfed conditions and low plant density is of 7.6 T/ha (Cv = 11%).Every other year irrigation can be avoided under low density. In average, 2 years out of 3 with a water application depth (WAD) of 35 mm only it is possible to obtain a GY value of 8.3 T/ha (Cv=6.7%) at low density compared with a GY of 7.3 T/ha (Cv=7.7%) obtained with high PD. Whatever the cropping practices, irrigation secures the production due to lower Cv values than under rainfed conditions.

2- WP is notably lower under high density than under low density for a same sowing date. This is due to the fact that water consumption increases with PD and that HIpot decreases when PD increases

3- In average, under high PD, a supplementary WAD is necessary 1/3 years.

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

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 wheat is sown on October the 15th compared with wheat sown on November the 15th (1.48 kg/m^3, Cv = 38%) which requires more frequent water applications.

Table 3. Impact of plant density on WP of durum wheat at Montpellier (SE of France), for the sowing date: October the 15th. (DOY288).

Years	**Density 400 plants/m²**				**Density 250 plants/m²**			
	GY (T/ha)	**WAD (m^3/ha)**	**GY_d (T/ha)**	**WP (kg/m^3)**	**GY (T/ha)**	**WAD (m^3/ha)**	**GY_d (T/ha)**	**WP (kg/m^3))**
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

It is obvious that DM under high PD is higher that DM under low PD for a same WAD and fertilisation conditions. Regarding GY, it was assumed that nitrogen did not have any impact on the measured HIpot value, as attested by Table 2. Further works are probably needed to reinforce this assumption. Modelling applied to a climatic series allowed the evaluation of WP gaps between cropping practices. It clearly appears that it is not suitable to grow wheat at high density when water is scarce and proper time to sow wheat at mid October that past mid November to save water in a Mediterranean climate.

3. CONCLUSIONS

PILOTE, an operative crop model for simulating soil water balance and yields has shown its capabilities to predict the yields of durum wheat for different plant densities. An application of the model for identifying the best cropping strategy have been carried out for a climatic series in a Mediterranean climate on a loamy soil plot. The results of these application show that irrigation is far to be always necessary in such a context of South of France. Indeed, an average grain yield value of 7.6 Mg/ha can be obtained under rainfed conditions at low plant density (250 plts/m^2) and no nitrogen stress, a similar value obtained at high density by irrigation the role of which being to reduce the inter-annual variability. In a perspective of irrigation profitability, every other year irrigation can be avoided under low plant density. Under such a climate sowing at mid October instead of mid November results in significant water savings. The highest irrigation water productivity (WP= 1.53 kg/m^3, Cv = 27%) is obtained when wheat is sown on October the 15th compared with wheat sown on November the 15th (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.

Such a work could be performed under other environmental (soil and climate) contexts for improving the durum wheat cropping and its irrigation management.

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