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in

Lamaddalena N. (ed.), Bogliotti C. (ed.), Todorovic M. (ed.), Scardigno A. (ed.).
Water saving in Mediterranean agriculture and future research needs [Vol. 1]

Bari : CIHEAM
Options Méditerranéennes : Série B. Etudes et Recherches; n. 56 Vol.I

2007
pages 277-289

DEFICIT IRRIGATION SCHEDULING IN PROCESSING TOMATO

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SUMMARY - An increasingly reduction in water availability, especially in arid and semi-arid regions, has induced new criteria in water management and the application of innovative irrigation strategies.
In order to save water, a reduced crop irrigation regime is to be undertaken and the scheduling of irrigation becomes a crucial facet of the overall irrigation technique. Deficit irrigation can be applied regularly along the whole cropping season or according to the crop sensitivity to water with respect to different crop stages. In this latter case a "regulated" deficit irrigation is carried out, converging watering in the most sensitive stages so to optimize crop productivity.
Crop yield response to water can be synthetically stated by means of the k_y coefficient (FAO, 1979), defined as the relative reduction in crop yield corresponding to a relative crop evapotranspiration deficit.
Tomato, according to the FAO classification, is considered a moderately sensitive crop and its k_y value is estimated equal to 1.05 over the total cropping season. Trials worked out from different authors in the same Mediterranean conditions, generally exhibited contrasting k_y values, lower or higher than FAO, without discriminating from the different crop phenological stages. The aim of the paper, after two years of experimental trial, is to derive tomato k_y values with respect to the whole crop cycle as well as to different crop stages. Interesting considerations are suggested as regard to tomato irrigation strategy.

Key words: water saving, irrigation deficit, k_y, tomato.

RESUME *- Une accrue réduction de la disponibilité d'eau, particulièrement dans les régions arides et semi-arides, a induit des nouveaux critères dans la gestion de l'eau et l'application des stratégies innovatrices d'irrigation.*
A fin de sauver l'eau, un régime réduit d'irrigation doit être entrepris et la programmation de l'irrigation devient un facteur crucial pour la technique entière d'irrigation. Le déficit d'irrigation peut être appliqué régulièrement pendant l'entier cycle de la culture ou en accord avec la sensibilité de la culture à l'eau respect à différents stades du cycle. Dans ce dernier cas un déficit d'irrigation "réglée" est effectué, avec l'application d'eau aux stades plus sensibles pour optimiser la productivité de la culture. La réponse du rendement de la culture à l'eau peut être synthétiquement établie avec le coefficient k_y *(FAO, 1979), défini au moyen de la réduction relative du rendement dans la correspondance du déficit relative d'évapotranspiration de la culture. En accord avec la classification de la FAO, la plant de tomate est considère une culture modérément sensible et son valeur de* k_y *est 1,05 pour l'entier cycle. Épreuves établies de différents auteurs en même conditions méditerranéennes, généralement ont exhibé valeurs plus élevées que la FAO, sans distinguer pour les différents stades du cycle. L'objectif de l'article, après deux ans d'épreuve expérimentale, est de dériver les valeurs de* k_y *de la tomate pour trois stades suivants et pour l'entier cycle. Considérations intéressantes sont suggérées pour la stratégie de l'irrigation de la tomate.*

Mots-clés: *conservation de l'eau, déficit d'irrigation,* k_y*, tomate.*

INTRODUCTION

Water is an essential resource used for civil, industrial and, above all, agricultural uses; on a world scale, indeed, about 70% of the overall water consumption is utilized by this last sector. Irrigation allows several advantages, especially in the areas with scarce rainfall and elevated evapotranspiration demand: a yield increase and its stabilization over the years, an improvement in the production quality, the cultivation of more profitable crops (Mannini, 2004).

Nevertheless, in the last years, a worrying quantitative and qualitative reduction in water supplies for agriculture is taking place at world-wide level (Postel, 1996; Kirda, 2002); the future expectations don't seem to be positive for a lot of geographical areas (Fereres, 2004).

There are several causes that limit water availability for agriculture: an increasing demand by the civil users; a greater requirement by the industrial sector; climatic changes that cause a rise in the air temperature and an irregular distribution of rainfall, producing more intense precipitations and run-offs and limiting water infiltration in the soil as well as the refill of the aquifers; a scarce maintenance of the water distribution network (Hamdy and Lacirignola, 1999; Kirda, 2002; Mannini, 2004; Giuliani *et al.*, 2005; Giuliani *et al.*, 2006).

In addition to a quantitative decrease in water availability, in the last few years a further limiting factor in the use of water for irrigation purposes is to be considered: that is the qualitative degradation due to serious processes of salinization and pollution of the surface- and ground-water (Mannini and Gallina, 1995; Saint-Cruz *et al.*, 2002).

The Mediterranean area is one of the most important basins for agricultural production but, at the same time, is also seriously involved in the processes of general decrease and degradation of water resources. Specific pedo-climatic features support these critical processes; the Mediterranean area is characterized by an arid or semi-arid climate: a long warm, dry period in the summer months and mild temperatures in association with most of the annual rainfall in winter (Shahin, 1996). Besides, the soil nature is frequently clay and is characterized by an elevated degree of 'weakness' caused by different factors: a high pedological aridity; a scarce amount of humus due to the rapid oxidation of the organic matter in the mineralized forms; a scarce amount of total nitrogen; a deficiency in structure and in drainage and a high exposure to the risk of salt accumulation in the soil (Fierotti *et al.* 1999).

The climatic changes, especially in this area, could play a negative role for agriculture. In Capitanata, an area of great agricultural importance, situated in Southern Italy (Apulia), there has been a rise in the annual mean temperatures (especially in the minimum temperatures) and a reduction of the annual total rainfall in the fifty-year period 1951-2000 (Monteleone *et al.*, 2004).

For a better use of water recourses in agriculture, at the farm level it is essential to apply a criterion of irrigation scheduling, in order to water the crop at the right time and in the right volume; on condition of limited water supply, a so called "regulated water deficit" or "deficit irrigation" can be conveniently applied (English *et al.*, 1990). Deficit irrigation consists in supplying lower irrigation volumes compared to those actually required by the crop during the whole crop cycle but in coincidence with some particular stages that are the most sensitive to water stress (Kirda, 2002); a consequent increase in the water use efficiency (WUE) is obtained. In other words, deficit irrigation is an optimization strategy that aims to avoid irrigation when it has a scarce influence on yield, in this way maximizing the productive result with smaller water amounts (Mannini, 2004).

An important information on the productivity behaviour of the crop with respect to deficit irrigation is expressed by the 'crop yield response to water' (k_y). Such a factor represents the angular coefficient of the following linear equation (Stewart *et al.*, 1977):

$$1 - Y_a / Y_m = k_y \, (1 - ET_a / ET_m) \qquad [1]$$

Where:

Y_a (t ha^{-1}): the expected yield consequent to a deficit irrigation,
Y_m (t ha^{-1}): the maximum attainable yield on condition of full water availability,
ET_a: the actual crop evapotraspiration (mm)
ET_m : the maximum crop evapotraspiration (mm).

The yield response factor (k_y) connects the relative yield reduction ($1-Y_a/Y_m$) to the relative evapotranspiration deficit ($1-ET_a/ET_m$) and its specific value varies according to the crop species and cultivar, the irrigation method and the cropping management; it also greatly depends on the stage of crop growth and development along the crop cycle (i.e. transplanting, vegetative growth, flowering, fruit-setting or ripening). A k_y value higher than one identifies the most sensitive crops to water stress;

this range of values points out that the yield reduction consequent to a sub-optimal irrigation regime, is more than proportional (in relative terms) to the corresponding evapotranspiration decrease (Kirda *et al.*, 1999). Of course, crops with a k_y value lower than one shows the opposite behaviour and are more tolerant to water deficit conditions.

Doorenbos and Kassam (1979), in the FAO paper n. 33, determined the k_y value for different crops, carrying out their classification according to their yield response to conditions of increasing water stress.

Tomato is a very important crop for the Mediterranean area, particularly in the Capitanata plain; it has a typical spring-summer crop cycle so that, in order to obtain good yields, it requires about 500-600 mms of water that are almost totally supplied with irrigation, considering the limited contribute of rains. For this crop, Doorenbos and Kassam (1979) have esteemed an overall k_y value equal to 1.05, therefore underlining a moderate sensitivity of tomato to water deficit. Moreover, the same Authors have reported k_y values according to the tomato crop stage. Such values correspond to 0.4, 1.1, 0.8 and 0.4 with regard to the following stage: vegetative growth, flowering, fruit-setting and ripening, respectively. For this crop, therefore, flowering is the stage with a higher k_y value.

Nevertheless, considerable differences about water deficit effects on tomato yield are reported by several Authors; Giardini and Giovanardi (1980), for example, in a first year of trial, derived a k_y value equal to 1.3, while, in a second year, they got k_y values varying from 0,5 to 1, showing, therefore, a reversal trend in comparison with the previous year.

Although from the beginning of ‘80s up today several genetically improved tomato varieties, more productive and tolerant to water deficit, have been introduced (Kassam and Smith, 2001), still limited information related to the tomato yield response factor k_y are available, and in several occasion different and discordant values are proposed. Perniola *et al.* (2005) have estimated, in fact, a k_y value for tomato equal to 1.4, referred to the yield dry matter. On the other hand, in a study carried out on tomato grown in a protected environment, Kirda *et al.* (2004) have determined a k_y value lower than one and, precisely, equal to 0.68, underlining, therefore, the possibility to undertake deficit irrigation for this crop, in order to save water without an elevated yield reduction.

Referring to the Mediterranean environmental conditions, representative of the Capitanata plain, the present paper was aimed at studying the yield response of the tomato crop, grown in open field, with respect to diverse irrigation regimes differently applied in the course of the consecutive stages of the crop cycle. Specific interest and consideration is addressed to the determination of both the yield water use efficiency (YWUE) and the yield response factor k_y, that are functionally related one each other and mutually dependent (Kirda, 2002). This evaluation is worked out with respect to the whole crop cycle as well as to particular crop phenological stages that are considered mostly sensitive to water deficit.

MATERIALS AND METHODS

Experimental layout

The trial was carried out in a two-year period (A1=2005 e A2=2006) at the Syngenta Experimental Station on Mediteranean Crops, located in Foggia (Apulia region, Southern Italy), 74 m above the sea level. The latitude and longitude of the experimental site are, 41°46’ N and 15°54’ E, respectively.

Four tomato processing hybrids: Ercole (E), Genius (G), Tania (T) and Ulisse (U), have been grown in open field, on a clay loam soil (U.S.D.A. classification) with the following main characteristics: sand 40%, silt 25%, clay 35%, pH 7.5, organic matter (Walkley-Black) 1.9%, field capacity (-0.03 MPa) 32.4% d.w. and wilting point (-1.5 MPa) 14% d.w.

A “strip-plot” experimental design was applied with four replications (blocks): the irrigation treatments were randomly arranged in vertical-strip plots while the tomato hybrids were randomly arranged in horizontal-strip plots. The resulting intersection plot was 30 m^2 in surface.

Irrigation treatments

Six experimental irrigation regimes have been applied as follows: (a) three 'fixed' water regimes, constant and regular over the whole crop cycle and (b) three 'variable' water regimes, with different water application criteria according to the crop phenological stages.

(a) The 'fixed' irrigation regimes were performed re-establishing 100, 75 and 50% of the maximum crop evapotranspiration (ET_m), respectively.
(b) The 'variable' irrigation regimes, always supplied a deficit amount of water as compared to ET_m, and were determined referring to a specific phenological stages (FC), elapsing from the flowering of the first clusters to the first fruit veraison (fruits breaking colours). The FC stage is normally considered more sensitive to water deficit as compared to other stages (FNC), both in the previous (FNC1) and in the following (FNC2) part of the crop cycle. Therefore, the three 'variable' irrigation regimes were performed re-establishing 100/75, 100/50 and 75/50% of ET_m in the FC and FNC stages respectively.

Each year, soon after transplanting and during the first two weeks or the crop cycle, three waterings of approximately 50 mm in total were performed indifferently with respect to all the experimental treatments; this procedure ensured a good establishment of the plants. This particular starting stage of the crop cycle is thereafter coded FNC0.

Cropping practices

Transplanting was carried out on 28 April in A1 and on 2 May in A2; the plants were placed on coupled-rows, 1.7 m apart one another and at a distance of 0.5 m between each single row; along the row the plant were 0.4 m apart; an overall plant density of approximately 28500 plants ha^{-1} was thus established.

During the crop seasons the ordinary agricultural practices were performed: the soil was ploughed to a depth of 0.45 m in winter of the previous year, fertilized with 48 kg ha^{-1} of N, 48 kg ha^{-1} of P_2O_5 and 68 kg ha^{-1} of K_2O, well harrowed at its surface a few days prior to transplanting. Ferti-irrigations were performed along the crop growth, supplying a total amount of 70.6 kg ha^{-1} of N, 30.5 kg ha^{-1} of P_2O_5, 12.5 kg ha^{-1} K_2O. Weeds and pests control was performed according to currently management practices.

Irrigation was scheduled on the basis of a soil water balance. Daily ET_m was estimated according to the "two steps approach" (ET_m=ET_0*K_c); reference evapotranspiration (ET_0) was calculated using the Monteith's equation (Jensen *et al.*, 1990; Allen *et al.*, 1998); the weather station of the Research Center, positioned 50 m apart from the experimental field, provided the meteorological data. The crop coefficients (K_c) detected by Tarantino and Onofrii (1991), in a similar environment, were used for the ET_m calculation. Watering was performed each time the depletion of the available water reached the threshold value of 40%. A drip irrigation system was used; one emitter line was available for each coupled-row and emitters of 4 L h^{-1} were placed 0.6 m apart along the line. A water flow meter was placed at the head of each plot to accurately measure the amount of irrigation water applied.

The harvest was performed on 4 August and on 17 August, in A1 and A2 respectively; a representative sample of 12 consecutive plants for each intersection plot was considered in order to derive the total and the marketable yield.

Statistical analysis

The analysis of variance (ANOVA) was initially performed with respect to each year of trial according with the field experimental design actually applied. The Bartlett test confirmed the homogeneity of variance between the years so that a combined statistical analysis was later processed, this time applying the analysis of covariance (ANCOVA).

The tomato crop performance was interpreted with reference to the total yield (Y_{tot}, t ha^{-1}) that included also the weight of the unmarketable, discarded fruits (affecting, on average, approximately the 15% of the total yield). The three following statistical analysis were performed:

(a) first of all, Y_{tot} was interpreted as a function of the overall water W (m^3 ha^{-1}) supplied to the crop and equal to the amount of irrigations and rainy precipitations recorded along the crop cycle;
(b) in the next stage, the total yield Y_{tot} was valued with respect to the fraction F (ET_a / ET_m) of the maximum crop evapotraspiration that was actually supplied to the crop over the its cycle;
(c) finally, using the interpretative model reported in the equation [1], the yield decrease ($1–Y_a / Y_m$) was accounted with respect to the relative crop evapotraspiration deficit R corresponding to the expression: ($1–ET_a / ET_m$).

Under the three analysis conditions, the effect of the irrigation treatments (in the form of *W, F* or *R*) were considered in reference both to the whole crop cycle and to its *FC* and *FCN* (previously defined) phenological stages.

The crop yield data have been processed stating a general model whose coefficients were solved with the ANCOVA, each time using the variable *W, F,* or *R* as a regressor (continuous numerical variable). Categorical variables were also considered in the same model; they were: the years of the trial (*A1* and *A2*), the tomato hybrids (*E, G, T* and *U*) and the experimental blocks (*B1, B2, B3* and *B4*).

This linear model ($Y=a+b*X$) can predict the yield (dependent variable *Y*) as a function of the irrigation amount (regressor *X*) and through the statistic values assigned to the intercept *a* and to the angular coefficient *b*, both depending on each considered categorical variable.

The yield water use efficiency (*YWUE*, t m^{-3}) and the crop yield response factor k_y (-), are both expressed by the angular coefficient *b* of the model on condition that the regressor *X* is represented by the variable *W* in the former case and by the variable *R* in the latter.

RESULTS AND DISCUSSION

Meteorological data

The thermo-pluviometric pattern of the two years of trial (Fig. 1), clearly shows that in the first year the precipitations were scarce and sporadic rainy events took place especially in the second decade of July. Moreover, the season was quite often characterized by maximum temperatures superior to 32°C; those thermo conditions could have caused yield reductions due to a greater difficulty in the fruit setting stage (Casarini and Di Candilo, 1995).

In the second year of trial, the crop cycle was characterized by a different meteorological pattern. First of all, the intense rainfalls and the abrupt lowering of the mean temperatures in the first decade of June (the period in which flowering begins), determined a slowdown in the normal crop growth.

Then, in the third decade of June, maximum temperatures superior to 35°C occurred and they probably caused difficulties in the fruit setting stage. Finally, the abundant rainy precipitations occurred in the first and second decade of August, during the fruit ripening, negatively influenced the marketable yield probably causing a greater incidence in fruit discarding.

Actual irrigation volumes

The irrigation volumes supplied and the rainfall recorded over the two years of trial as well as in each stage of the tomato crop cycle is shown in *Table 1*. The complete restoration of the crop evapotraspiration demand required the supply of seasonal irrigation volumes between 480 and 500 mm (in *A2* and *A1* respectively) and 14-15 watering along the whole cultivation cycle. In both years, the FC phenological stage required a higher water amount, corresponding to about 45% of the overall quantity.

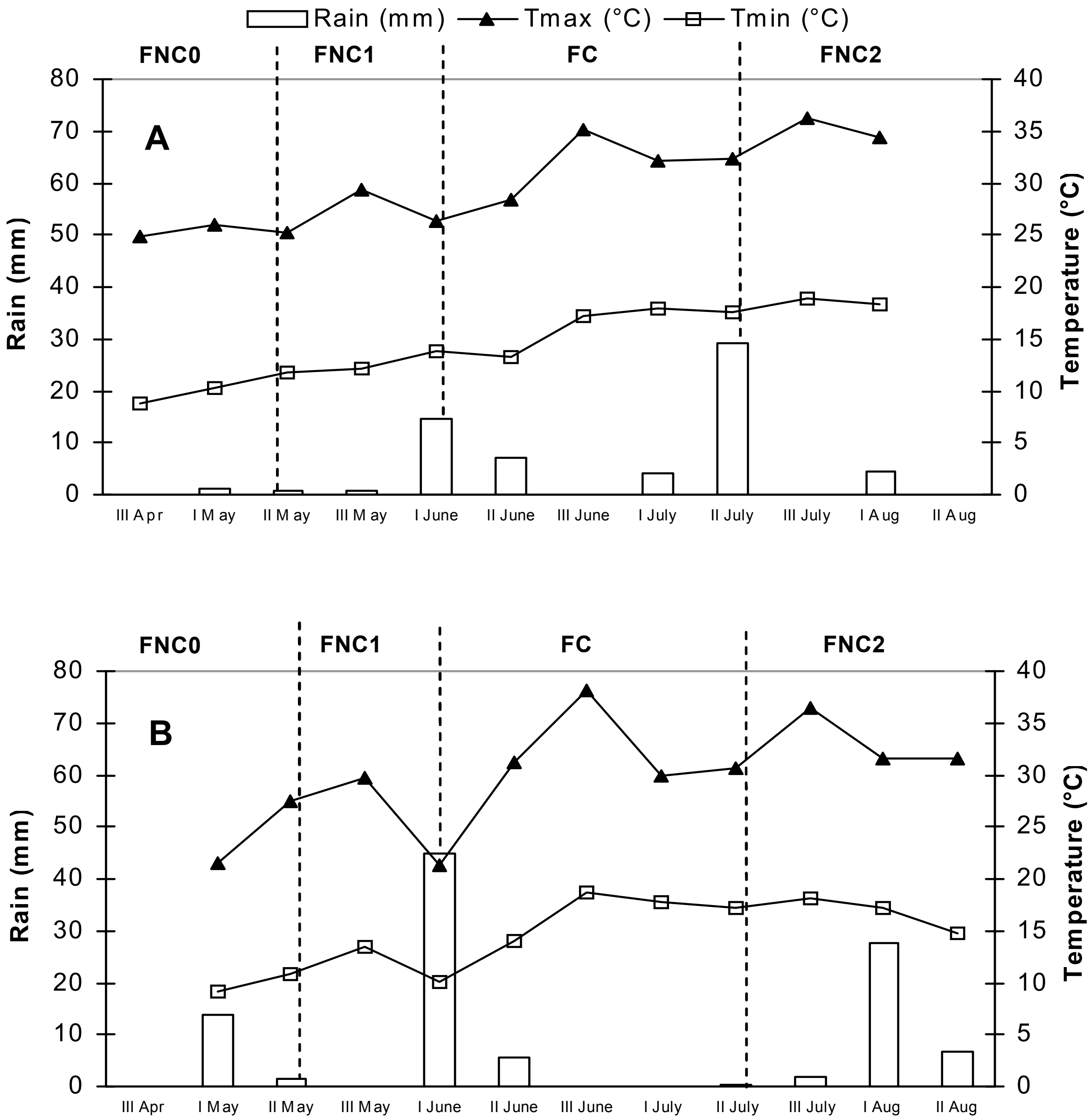

Fig. 1. Ten days average values of temperature and rain for each irrigation season. 2005 (A) and 2006 (B).

Table 1. Duration of the crop phenological phases, watering number and irrigation volumes (mm) according to the different experimental treatments in the course of the two experimental years (2005-06).

Year	Crop Phase	Duration	Rain	Watering	Irrigation volumes (**) *(mm)*					
	(*)	*(d)*	*(mm)*	*(N.)*	Constant irr. regimes			Variable irr. regimes		
					100	75	50	100/75	100/50	75/50
2005	FNC0	13	1.2	3	47.9	47.9	47.9	47.9	47.9	47.9
	FNC1	31	10.4	4	111.3	77.7	54.6	77.7	54.6	54.6
	FC	40	46.3	5	228.5	169.8	111.0	228.5	228.5	169.8
	FNC2	17	4.3	3	115.5	86.2	58.8	86.2	58.8	58.8
	Total	**99**	**62.2**	**15**	**503.2**	**381.6**	**272.3**	**440.3**	**389.8**	**331.1**
2006	FNC0	17	15.3	3	53.8	53.8	53.8	53.8	53.8	53.8
	FNC1	17	46.3	3	63.0	44.1	31.5	44.1	31.5	31.5
	FC	44	8.8	5	213.5	158.0	97.1	213.5	213.5	158.0
	FNC2	30	56.1	3	146.7	108.7	67.7	108.7	67.7	67.7
	Total	**108**	**126.5**	**14**	**477.0**	**364.6**	**250.1**	**420.1**	**366.5**	**311.0**

(*) FNC0 = plant establishment, till two weeks after transplanting; FNC1 = after FNC0 up to the beginning of flowering; FC = after FNC1 up to fruits breaking colours of the first cluster; FNC2 = after FC till fruit maturation.
(**) Constant irrigation regimes = restoration of 100, 75 and 50% of maximum water consumption (ET_m) respectively; variable irrigation regimes = restoration of 100/75%, 100/50% and 75/50% of ET_m respectively with reference to FC and FNC crop phases.

Tomato yield with respect to the irrigation treatments

As a result of the ANOVA, the first year of trial was on average more productive than the second (83 vs. 76 t ha^{-1}). *Table 2* shows that this superiority was confirmed with respect to all irrigation treatments. Tomato-yield significantly decreased with a decreasing water supply but from the particular arrangement of the irrigation treatments (not balanced with respect to FC and FNC) was difficult to discern the specific effect of a water deficit in the FC phase from that in the FNC phase of the crop cycle. Therefore, a different statistical approach was required and, for this reason, the ANCOVA procedure was processed.

Table 2. Tomato yield (t ha^{-1}) as affected by the different irrigation treatments in both the experimental years, according to the ANOVA results.

Irrigation treatments		Experimental years	
FC	**FNC**	**A1**	**A2**
100	100	92.6	89.6
100	75	90.7	81.7
100	50	86.2	76.6
75	75	81.4	75.2
75	50	76.4	70.6
50	50	70.4	60.7
	Std Err	1.6	2.6
	D.F.	15	15
	LSD(0.05)	3.4	5.5
	LSD(0.01)	4.7	7.7
	Year average	83.0	75.7

Tomato yield with respect to the crop water supply

Table 3 shows the statistical significance of the ANCOVA model as a function of the amount of water (W) totally supplied to the crop. The effect of the “hybrids” was not significant, either referred to the intercept value or to the angular coefficient. On the contrary, the “year” significantly influenced both the intercept and the angular coefficient values, even tough this effect was limited to the FNC stages and did not involved the FC phenological stage of the crop cycle.
According to the results of the statistical analysis, is possible to define the following linear equation:

$$Y_{tot} = 24.88 + 12.55 * a + [11.46 - 1.27 * a] * 10^{-3} * W(Tot) \quad (1)$$

in which $a=1$ if the year=*A1* or $a=-1$ if the year=*A2*. The model interprets 81% of the overall data variability and a RMSE (Root Mean Square Error) equal to about 4.8 t ha^{-1} corresponded to it.

As regards the FC and FNC phenological stages, it is possible to write:

$$Y_{tot} = 24.82 + 12.05 * a + 13.58 * W(FC) + [9.27 - 3.18 * a] * 10^{-3} * W(FNC) \quad (2)$$

The model interprets 83% of the overall data variability and a RMSE equal to about 4.6 t ha^{-1} corresponds to it.

From the previous equations, it is possible to deduce that a yield increase equal to 11.46 kg m^{-3} of water supply was observed, on average, over the two-year period of the trial. This coefficient can be split to identify a higher yield water conversion efficiency in the FC phenological stage (13.58 kg m^{-3}) than in the other FNC stages of the crop cycle (9.27 kg m^{-3}). Moreover, it is worth to notice the significant influence of the year on the water use efficiency in the FNC stages (±3.18 kg m^{-3}).

Table 3. Results of the ANCOVA model applied to the tomato production data as a function of the water (W) supplied to the crop along the whole crop cycle (A) or with regards to different phenological stages FC and FNC respectively (B).

	A				**B**			
Term	**Estimate**	**Std Error**	**t Ratio**	**Prob>|t|**	**Estimate**	**Std Error**	**t Ratio**	**Prob>|t|**
Intercept								
mean value	24.88	2.29	10.9	<.0001	24.82	2.44	10.2	<.0001
year[A1 vs.A2]	12.55	2.29	5.5	<.0001	12.05	2.44	4.9	<.0001
angular coefficient	*(x 1000)*	*(x 1000)*			*(x 1000)*	*(x 1000)*		
W(Tot)	11.46	0.48	24.1	<.0001				
W(FC)					13.58	0.91	14.9	<.0001
W(FNC)					9.27	0.98	9.4	<.0001
year [A1 vs.A2]* W(Tot)	-1.27	0.48	-2.7	0.0087				
year [A1 vs.A2]*W(FC)					0.61	0.91	0.7	0.5023
year [A1 vs.A2]*W(FNC)					-3.18	0.98	-3.2	0.0015
	R^2 = 0.81; RMSE = 4.8				R^2 = 0.83; RMSE = 4.6			

Tomato yield with respect to the fraction of the crop ET_m restored

Table 4 shows the statistical significance of the ANCOVA model obtained with respect to the fraction (F) of crop ET_m actually restored along the crop cycle. Also in this case, the effect of the “hybrids” was not significant, either referred to the intercept value or to the angular coefficient. On the contrary, the “years” significantly influenced both the intercept and the angular coefficient value; in the same way as in the previous analysis, the effect related to the factor “years” was limited to the FNC stages and did not involved the FC phenological stage of the crop cycle.

According to the results of the statistical analysis, is possible to define the following linear equation:

$$Y_{tot} = 39.66 + 6.80 * a + [52.46 - 4.22 * a] * W(Tot) \qquad (3)$$

in which $a=1$ if the year=$A1$ or $a=-1$ if the year=$A2$. The model interprets 80% of the overall data variability and a RMSE equal to about 4.8 t ha^{-1} corresponded to it.

As regards the FC and FNC phenological stages, it is possible to write:

$$Y_{tot} = 39.66 + 6.13 * a + [31.78 + 1.10 * a] * W(FC) + [19.31 - 5.15 * a] * W(FNC) \qquad (4)$$

The model interprets 83% of the overall data variability and a RMSE equal to about 4.6 t ha^{-1} corresponded to it.

From the previous equations, it is possible to deduce that the complete re-establishing of the crop evapotraspiration requirement allowed to achieve, as an average value over the two experimental years, a yield increase of about 50 t ha^{-1} with respect to the reference yield value of about 40 t ha^{-1} that is supposedly achievable without any water supply (even though the latter is an extrapolated datum and it does not derive from a direct testing). Irrigation has a stronger effect in the FC stage than in the FCN stages, determining a yield increase of about 32 t ha^{-1} in comparison with about 19 t ha^{-1} in the other case. It is worth to note, again as previously, the significant interaction that irrigation displayed with the factor "years", particularly with respect to the FNC stages of the crop cycle (±5.15 kg m^{-3}).

Table 4. Results of the ANCOVA model applied to the tomato production data as a function of the fraction (F) of the crop ET_m restored along the whole crop cycle (A) or with regards to different phenological stages FC and FNC respectively (B).

	A				B			
Term	**Estimate**	**Std Error**	**t Ratio**	**Prob>|t|**	**Estimate**	**Std Error**	**t Ratio**	**Prob>|t|**
Intercept								
Mean value	39.66	1.70	23.37	<.0001	39.99	1.63	24.56	<.0001
Year [A1 vs.A2]	6.80	1.70	4.01	<.0001	6.13	1.63	3.76	0.0002
Angular coefficient								
F(Tot)	52.46	2.20	23.89	<.0001				
F(FC)					31.78	2.09	15.23	<.0001
F(FNC)					19.31	2.09	9.26	<.0001
year [A1 vs.A2]* F(Tot)	-4.22	2.20	-1.92	0.0561				
year [A1 vs.A2]*F(FC)					1.10	2.09	0.53	0.599
year [A1 vs.A2]*F(FNC)					-5.15	2.09	-2.47	0.015
	R^2 = 0.81; RMSE = 4.8				R^2 = 0.83; RMSE = 4.6			

Tomato relative yield decrease with respect to actual ET relative reduction

Table 5 shows the statistical significance of the ANCOVA model defined in accordance with the equation reported in the formula [1]. The response variable ($1-Y_a/Y_m$) represents the yield tomato decrease relative to its maximum annual value (Y_m); the latter is obviously related to the irrigation treatment characterized by a complete restoration of the crop water requirements (100% of ET_m). The independent variable (regressor X) is represented by the relative evapotraspiration deficit ($R=1-ET_a/ET_m$). In this case, the intercept of the linear equation is set equal to zero, in order to force the line that express the model to pass trough the origin of the axes.

Once again and definitely, the effect of the "hybrids" was not significant contrary to the effect of the "years" that significantly influenced the slope of the line (i.e. its angular coefficient); a significant interaction "years x irrigation treatments" was also detected with respect to the FNC stages.

According to the results of the statistical analysis, it is possible to define the following linear equation:

$$1\text{-}Y_a/Y_m = [0.55 - 0.06 * a] * R(Tot) \qquad (5)$$

in which *a=1* if the year=*A1* or *a=–1* if the year=*A2*. The model interprets 80% of the overall data variability and a RMSE equal to about 0.053 corresponded to it.

As regards the FC and FNC phenological stages, it is possible to write:

$$1\text{-}Y_a/Y_m = 0.35 * R(FC) + [\,0.21 - 0.06 * a] * R(FNC) \qquad (6)$$

in this case, the model interprets 83% of the overall data variability and a RMSE equal to about 0.051 corresponded to it.

From the previous equations, it is possible to deduce that, over the two-year period, the K_y coefficient was on average equal to 0.55, while it was equal to 0.35 and 0.21 in the FC and FNC phenological stages respectively. This last results support the indication, as already observed, that the FC stage is more relevant and sensitive, with respect to the water supply effect on yield, than the other FNC stages of the crop cycle; in fact, the K_y value is almost 70% higher in the former stage than in the latter. The "years" effect is still significant, confirming the same results of the preceding statistical analysis.

Table 5. Results of the ANCOVA model applied to the tomato relative production decrease data as a function of the crop deficit evapotranspiration (R) along the whole crop cycle (A) or with regards to different phenological stages FC and FNC respectively (B).

	A				**B**			
Term	**Estimate**	**Std Error**	**t Ratio**	**Prob>|t|**	**Estimate**	**Std Error**	**t Ratio**	**Prob>|t|**
Intercept	*Zeroed*				*Zeroed*			
angular coefficient								
R(Tot)	0.545	0.013	41.19	<.0001				
R(FC)					0.349	0.023	15.18	<.0001
R(FNC)					0.213	0.015	14.18	<.0001
year [A1 vs. A2]*R(Tot)	-0.060	0.024	-2.45	0.0153				
year [A1 vs. A2]*R(FC)					0.004	0.023	0.18	0.8586
year [A1 vs. A2]*R(FNC)					-0.061	0.023	-2.67	0.0083
	R^2 = 0.81; RMSE = 0.053				R^2 = 0.83; RMSE = 0.051			

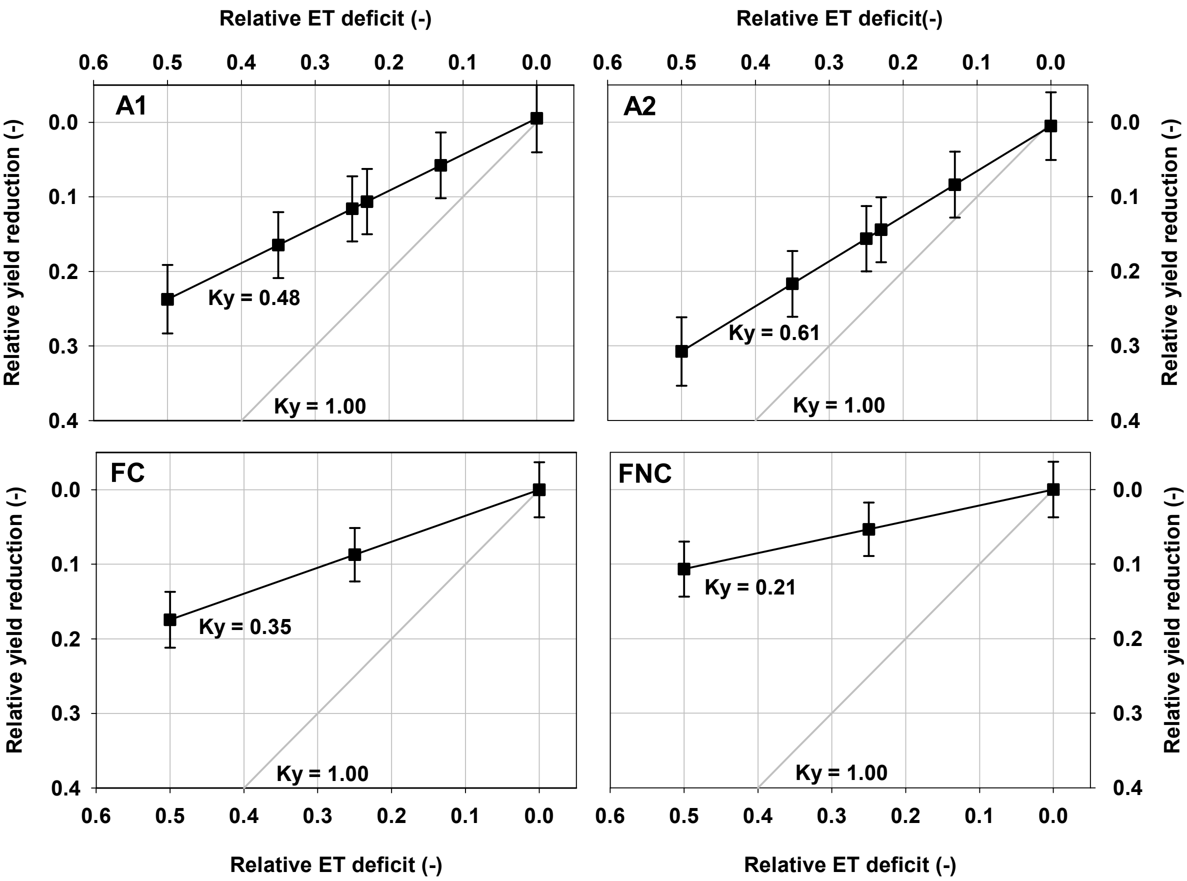

Fig. 2. Predicted values and regression lines of the functional relationship between the relative yield reduction ($1-Y_a/Y_m$) and the relative evapotranspiration deficit ($1-ET_a/ET_m$). A1 and A2 refer, respectively, to the whole 2005 and 2006 crop cycle, while FC and FNC refer to different phenologycal phases of the crop cycle. The error bars represent the individual standard error of the predicted values. K_y = 1 is shown as a reference line.

The Fig. 2 shows the values of the K_y coefficient according to a conventional scheme of graphical representation, as originally suggested by Doorenbos and Kassam (1979). The first two graphs (A1 and A2) display the K_y values obtained in the two experimental years, with reference to the whole crop cycle (0.48 and 0.61, respectively), while the other two graphs (A3 and A4) display the average K_y value over the two experimental year but with respect to the different phenological stages FC and FNC of the crop cycle (0.35 and 0.21, respectively).

CONCLUSIONS

The two-year experimental trial on tomato crop, grown in open field, was aimed at estimating the effect of different irrigation regimes with respect to the whole crop cycle and to a particular phenological stage that was expected to be more sensitive to water deficit than others.

Actually, the phenological FC stage, elapsing from the first cluster flowering to the first fruit veraison (fruits breaking colours), proved to be more relevant than the other stages (collectively coded FCN) in order to determine the yield; the FC stage, in other words, confirmed its high sensitivity to water shortage. This conclusion is supported by several experimental evidences that are summarized as follows:

a) The FC stage, on both years, was marked by the highest water requirements, approximately corresponding to about 45% of the overall water amount;
b) The FC stage showed the highest yield water use efficiency (YWUE) equal to about 13.58 kg m^{-3} in the two-year period in comparison with the mean value of 9.27 kg m^{-3} for the other stages (FNC) of the crop cycle;

c) The yield increase associated to the complete re-establishing of the crop evapotraspiration requirements was significantly higher in the FC stage than in the others (FNC); it was equal to about 32 t ha^{-1} in comparison with about 19 t ha^{-1} in the FNC stages.
d) The tomato k_y coefficient (crop yield response to water availability) was always significantly less than one in the present research and showed a higher values in the FC stage than in the FCN stages; average values equal to 0.35 and 0.21 have been estimated in the FC and FCN stages respectively over the two-year period.

Another consideration allows us to emphasize the different crop response to water supply as regard the FC stage in comparison with the other FNC stages. The YWUE and the k_y values displayed in the FC stages were always not significantly affected by the influence of the particular experimental year, showing a rather stable and constant value over the two-year period. Differently, the same parameters showed to be very sensitive to the effect of the experimental year when related to the FNC stages. This observation induces us to believe that critical phenological phases in strictly under the physiological control exerted by the crop and less subjected to external conditions or environmental circumstances. The FC phenological phase, indeed, is that particular stage of crop growth and development connected to the reproductive processes (particularly flowering and fruit setting) and, therefore, to the crop productivity.

Finally, the k_y coefficient (crop yield response to water availability) was either always inferior to the unity and exhibited values (0.55 for the whole crop cycle as an average value over the two-year period) lesser than those usually reported in literature, with a few exceptions.

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