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Yield Traits and Water and Nitrogen Use Efficiencies of Bell Pepper Grown in Plastic-Greenhouse

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Abstract

We report the results of a two-year study assessing the effects of nitrogen fertilization and irrigation regimes on yield traits and on water and nitrogen use efficiency of greenhouse-grown bell pepper (*Capsicum annuum* L.). The trials involved the combination of four N doses (0, 100, 200, 300 kg ha^{-1}) with two irrigation regimes (100% restitution of ETc; repeated cycles of water stress starting from fruit set). In the second year, the crop was transplanted one month earlier than in the first year and was mulched with plastic sheeting.

The highest yield in both years was obtained by associating 100% restitution of ETc and the N dose of 200 kg ha^{-1}. The marketable yields were 37 and 72 t ha^{-1} in 1998 and 1999, respectively. Doubling of the yield in the second year was probably due to the earlier transplantation and mulching, confirming the numerous benefits of the latter technique. The water deficit imposed during the late flowering-early fruit set phase had negative effects on the crop, with declines of the marketable yield of up to 44% due to the reduced number and weight of the fruit and the increased waste, mainly peppers with blossom-end rot, cracking, sun-burn and malformations. The peppers grown under water stress were richer in dry matter and soluble solids. The yield declines due to water deficit varied in relation to the N dose, as confirmed by the numerous interactions recorded between irrigation regime and nitrogen level. Without nitrogen fertilization, the quantity and quality of the fruits remained unchanged, while the maximum dose (300 kg ha^{-1}) enhanced the negative effects of the water deficit on the number (-52%) and weight (-161%) of marketable peppers. Moreover, the waste peppers reached 31% of the total production (by weight), with over 21% affected by blossom-end rot. Water stress led to a drastic reduction of the total above-ground dry biomass (40%) and a significant decrease of nitrogen absorption by the plant (54%) with preferential translocation towards stems and leaves, as shown by lower Harvest Index (HI) values.

Regarding the water use efficiency (WUE), the above-ground dry matter WUE (AGWUE) remained unchanged while the total yield WUE (TYWUE) and marketable yield WUE (MYWUE) decreased.

The N dose of 200 kg ha^{-1} maximized the yield and quality of the peppers, with and without water stress, and the values of water and nitrogen use efficiency were maximal in these conditions.

Key-words: *Capsicum annuum* L., yield, quality, water deficit, nitrogen, water use efficiency.

1. Introduction

Protected cultivations are an agricultural sector in constant growth and rapid expansion worldwide (Enoch and Enoch, 1999; von Eslner et al., 2000; Orgaz et al., 2005), while open-field vegetable growing generally shows a static trend. Bell pepper is an economically valuable crop grown in the open field and in the greenhouse. In the former case, the yield goes mainly to the processed food industry, while in the second it is destined almost exclusively for fresh consumption, which provides higher incomes because of deseasonalized production.

Greenhouse crops have been described in terms of technical characteristics and constraints, of (in)efficiencies of the use of resources involved in the production process (Castilla et al., 2004; De Pascale et al., 2006), of the environmental impact and related political and socio-economic aspects. In this sector, there

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is great interest in reconciling maximum yields (Castilla et al., 2004) with optimization of resource use efficiency through careful monitoring of environmental parameters and the improvement of cultivation techniques; the aim is to avoid both excesses or wastes and deficits or stresses, particularly of water and nitrogen which are notoriously among the production factors that can most seriously limit vegetable crop yields. The single effects of water stress and nitrogen deficit on the growth, development and yield of bell pepper are fairly well known, while information about their interaction, e.g. which stresses are combined with each other, is limited.

Irrigation management is a very critical topic in southern Italy because of the shortage of water resources, which strongly penalizes vegetable productions. Nevertheless, research on water demands and irrigation management of vegetable crops in Mediterranean greenhouse cultivation is limited, and irrigation management is often based on the grower's personal experience (Orgaz et al., 2005). For bell pepper, correct irrigation control is essential to obtain high yields, since this species is susceptible to both an excess and a deficit of water (Doorenbos and Kassam, 1986). Pepper is classified as sensitive to water stress, especially in the blossom phase during which a lack of water at the beginning and during the first flowering negatively affects the number of fruits (Bruce et al., 1980). However, a correct water supply is extremely important in all developmental stages of the plant, particularly influencing the rooting, growth, setting, fruit quality and susceptibility to some fungal diseases (Dalla Costa and Gianquinto, 2002; Sezen et al., 2006). According to different authors, water stress has negative effects on pepper yields, which vary according to the phenological stage in which the deficit occurs (Katerji et al., 1993) and severity of the stress (Delfine et al., 1990). A reduced water supply during the growth period has an unfavourable effect on yields, specially if the lack of water is continuous and extends from the beginning of setting to the first harvest (Dalla Costa and Gianquinto, 2002; Sezen et al., 2006), a period during which soil water should be maintained between 65% and 80% of field capacity.

Irrigation management also influences the nitrogen input to crops, with important effects on yields. Various studies have shown the positive effects of nitrogen fertilization on bell pepper productivity associated with increased chlorophyll content and photosynthesis and improved light use efficiency (Tei et al., 1993). In nitrogen deficit condition, the reduced photosynthetic activity leads to decreased leaf surface, dry biomass and pepper yields (Perniola et al., 1996; Miccolis et al., 2002). In water deficit, nitrogen is less available to the plant and, in this case, the symptoms of water stress are the consequence of the interaction between the water and nitrogen deficits (Frederik and Camberato, 1995; Perniola et al., 1996; Miccolis et al., 2002). Insufficient nitrogen input can also reduce the efficiency of water use by the crop (Hsiao, 1993). On the other hand, an excessive or inadequate use of water and nitrogen fertilization (with respect to the real needs of the plant) should be avoided because of possible losses due to leaching and negative consequences for the environment (Giardini, 1989; Ceccon et al., 1995; Zhu et al., 2005; De Pascale et al., 2006; Gercek et al., 2009). Nitrate leaching occurs in many vegetable-growing areas because N application rates often exceed crop demand. In addition, plants do not make use of all N applied and farmers incur economic loss by applying more N than is required to obtain a positive yield response (Zhu et al., 2005).

The aim of the present study was to assess the effects of irrigation regimes and nitrogen levels on the yield traits and efficiency of water and nitrogen use of greenhouse-grown bell peppers.

2. Materials and methods

2.1 Experimental protocol and treatments

The trials were conducted in 1998 and 1999 on bell pepper (*Capsicum annuum* L., 'Vidi' F_1 of Vilmorin seed company) grown in an unheated plastic-greenhouse (200 μm PE) on the "Pantanello" Experimental Farm (40° 00' N, 16° 48' E, 20 m a.s.l.) in Metaponto (South of Italy). The sandy-clayey soil (Table 1) has a field capacity of 21% and a wilting point of 11.3%, and an bulk density of 1.27 kg dm^{-3}.

Two irrigation regimes (WW, 100% restitution of the maximum crop evapotranspiration [ETc] for the whole cycle; WS, three cycles of water stress starting from the early fruit set

Table 1. Main chemical and physical characteristics of soil.

Chemical characteristics		
Total nitrogen (g kg^{-1})		0.5
Assimilable P (Olsen's method) (mg kg^{-1})		16
Exchangeable K (Merwin and Peach's method) (mg kg^{-1})		253
Organic matter (g kg^{-1})		5.0
Total calcareous (g kg^{-1})		77
Reaction (pH in water)		7.7
Electrical conductivity (dS m^{-1})		0.5
Particle size		
Corse sand	2> ∅ >0.2 mm (g kg^{-1})	376
Fine sand	0.2> ∅ >0.02 mm (g kg^{-1})	240
Silt	0.02> ∅ >0.002 mm (g kg^{-1})	178
Clay	<0.002 mm (g kg^{-1})	206
Hydrological constants		
Field capacity (-0.03 MPa) (% dry weight)		21.0
Wilting point (-1.5 MPa) (% dry weight)		11.3
Bulk density (kg dm^{-3})		1.27

phase) and four levels of nitrogen fertilization (0, 100, 200 and 300 kg ha^{-1} of N, indicated as respectively N0, N100, N200 and N300) were compared. We adopted the split-plot experimental design with three replicates, positioning the irrigation regimes in the main plots and the fertilization doses in 40-m^2 sub-plots.

Nitrogen was applied by fertirrigation in four phenophases (transplantation, taking root, flowering and fruit set), using a liquid fertilizer with 30% nitrogen in a 1:1:2 nitric, ammoniac, ureic ratio. In the second year, the soil along the rows was mulched with black low density polyethylene (LDPE) sheeting 50 μm thick and 60 cm wide.

The crop was transplanted on April 18, 1998 and March 15, 1999, with a density of 3.2 plants m^{-2} (35 cm apart along the rows and 90 cm between rows), using seedlings at the 3rd-4th true leaf stage, grown in 91-hole polystyrene trays.

Drip irrigation lines were laid with drip holes (1.5 L h^{-1}) every 20 cm along the rows. Watering was carried out with a constant irrigation limit (15 mm until a soil coverage index of 50%, and then 30 mm) and with variable irrigation intervals. The ETc was estimated by the evapotranspirometric method (Doorenbos and Pruitt, 1977), using the daily reference evapotranspiration data (ETo), measured with an atmometer (cat. ET, Gage, Turin), and the crop coefficients (Kc) of greenhouse-grown bell pepper (Tarantino and Onofrii, 1991) (1.1 at the beginning of the cycle, up to 2.3 during the phase of maximum LAI). The water stress (WS) treatment was regularly irrigated until the beginning of early fruit set, after which watering was suspended until the mean leaf water potential (Ψ_t), measured with a Scholander pressure chamber, was less than 0.5 MPa with respect to the plants maintained in optimal water conditions. When this limit was reached, the crop was regularly irrigated again in order to bring the Ψ_t to approximately the same value recorded in the regularly irrigated crop; this procedure was repeated so as to create three water stress cycles.

Phospho-potassium fertilization (150 kg ha^{-1} of P_2O_5 and 200 kg ha^{-1} of K_2O) was carried out over the entire experimental area during preparation of the transplantation bed. Other cultivation operations were those ordinarily performed by vegetable growers in the Metaponto area, including support of the plants with wooden stakes and nylon thread.

There were five harvests per year, starting respectively on 10/7 and 18/6 and finishing on 19/8 and 26/7 in the first and second year. Peppers were picked in 3.2 m^2 trial areas when they had the typical red colour.

2.2 Recorded parameters and equipment used

At each harvest, the peppers were counted, weighed and classified as marketable or waste; the waste fruits were divided into those with sun-burn, with blossom-end rot, with irregular shape, broken and rotten. In samples of five marketable peppers, we determined the mean weight, proximal and distal diameters, length and thickness of the mesocarp, and soluble solids content (°Brix) with a digital refractometer. The peppers were then desiccated in a ventilated stove (70 °C) to measure the dry matter (DM) content (%).

At the end of the crop cycle, the plants in each 3.2 m^2 sampling area were separated into stems, leaves and fruits to determine the dry matter of each part. The samples were then finely ground (2 mm) and used to determine the N contents (Kjieldhal method). To study the partitioning of photosynthates and nitrogen among the different parts of the plant, we calculated the Harvest Index (HI) (ratio between the DM of the fruits and the total above-ground DM) and the Nitrogen Harvest Index (NHI) (ratio between the N removed from the fruits and the N removed from the plants). The Water Use Efficiency (WUE) indexes were the Above Ground dry biomass WUE (AGWUE), the Total Yield WUE (TYWUE) and the Marketable Yield WUE (MYWUE), respectively as the ratio between the above-ground dry biomass, dry weight of all peppers and dry weight of marketable peppers with respect to the consumed water.

To describe nitrogen use efficiency, we calculated the following indexes (Florenzano, 1986; Giardini et al., 1989): the Nitrogen Agronomic Use Efficiency (NAUE), ratio between the difference in yield between each fertilized and unfertilized crop (expressed both as marketable yield and as total dry matter) and the dose of nitrogen fertilizer applied; the Apparent Nitrogen Recovery (ANR), ratio between the difference in nitrogen absorbed by the fertilized and unfertilized crops and the nitrogen supplied to the soil; the Nitrogen Uptake Efficiency (NUE), percentage ratio between the absorbed nitrogen and the supplied nitrogen.

Analysis of variance was applied to the recorded and calculated parameters, and the differences between means were evaluated with the least significant difference test (LSD).

3. Results and discussion

3.1 Climatic trend and irrigation variables

The 1998 was a particularly hot year. Except for some days in April and May, the maximum daily temperatures inside the greenhouse (Fig. 1) were over 30 °C, often exceeding 35 °C even in April. After the middle of June, the temperature was well over 40 °C on many days. The minimum temperatures varied from around 11 °C in the initial phase to 22-24 °C in the second half of the cycle. The daily ETo, dependent on the temperature trend, varied from 1.5-2.5 mm in the initial phases of the crop cycle to values oscillating around 4.5 mm, with peaks of between 7 and 9 mm on some days in July. In 1999, the earlier transplantation (by one month) than in the preceding year meant that daily temperature values and the ETo were lower on average, particularly in the first 30 days of the crop cycle when the minima dropped few times below 10 °C. The maximum daily temperatures exceeded 35 °C less often than in 1998 (Fig. 1).

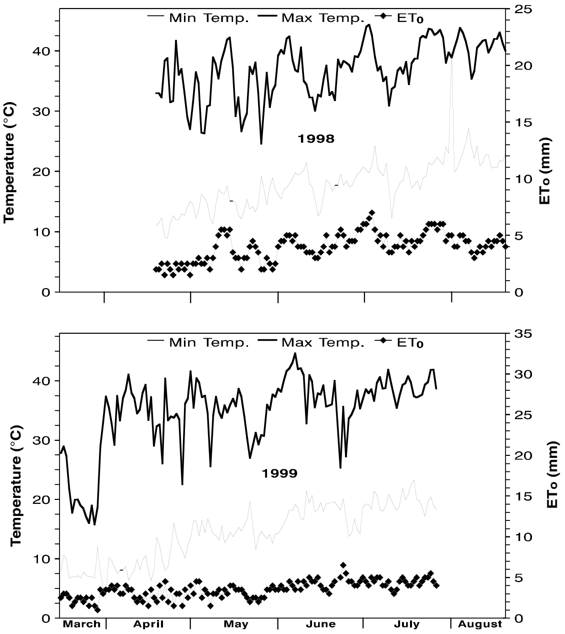

Figure 1. Daily trend of minimum and maximum temperatures and reference evapotranspiration (ETo) measured during pepper crop cycle in two years.

During the crop cycle, the seasonal irrigation volumes were 8617 and 8128 m^3 ha^{-1} for WW and 4907 and 4403 m^3 ha^{-1} for WS in the first and second year, respectively.

3.2 Yield traits

The total pepper yield was, on average, 30.8 and 49.6 t ha^{-1} in 1998 and 1999, respectively, while the marketable yield was 74 and 85% in the two years. The irrigation regime and nitrogen dose significantly influenced most of the yield traits, when both the main effects and the interaction were considered (Tab. 2).

The marketable yield was 44 and 51% lower for WS than WW in the first and second year, respectively. The decrease can be attributed mainly to the smaller number of marketable fruits per plant, the thinner mesocarp and lower mean weight (Tab. 2). This confirms reports by other authors that bell pepper is particularly sensitive to water deficit during flowering and fruit development, with negative repercussions on yields (Dalla Costa and Gianquinto, 2002), both in the open field and in the greenhouse

Table 2. Yield and qualitative traits of pepper related to irrigation regimes and N levels in two years.

Years/ Treatments		Total yield		Marketable yield		Fruit mean weight (g)	Mesocarp tickness (mm)	Soluble solids (°Brix)	Dry matter (%)	Waste fruits (% in weight)		
		(n. fruits plant^{-1})	(t ha^{-1})	(n. fruits plant^{-1})	(t ha^{-1})					Sun burn	Blossom end	Total waste$^{(2)}$
1998	*WW*	12.0	38.9	6.1	28.6	149	3.9	6.9	7.5	15.2	3.6	26.4
	WS	11.3	22.7	4.1	16.2	122	3.5	7.7	8.6	14.9	5.5	28.6
	(1)	n.s.	**	**	**	**	**	**	**	n.s.	n.s.	n.s.
	N0	12.8 a	24.7 c	4.6 b	14.6 c	94 c	3.5 b	7.7 a	8.0 b	24.0 a	5.0 a	40.8 a
	N100	10.4 b	28.2 c	5.1 a	21.7 b	131 b	3.3 b	7.1 b	8.3 a	11.3 b	4.6 a	23.0 b
	N200	11.6 b	38.4 a	5.5 a	30.4 a	172 a	4.2 a	7.1 b	8.1 ab	12.2 b	3.1 b	20.9 b
	N300	11.7 b	31.9 b	5.1 a	23.9 b	145 b	3.7 ab	7.1 b	7.9 b	12.7 b	5.6 a	25.2 b
	(1)	**	**	**	**	**	**	*	**	**	**	**
Inter.	*W x N*	**	**	**	**	**	*	*	*	**	n.s.	**
1999	*WW*	12.7	64.8	9.7	56.6	191	4.9	6.8	7.4	2.9	5.5	11.1
	WS	11.6	34.5	6.9	28.0	139	3.7	8.3	8.8	3.1	11.7	18.8
	(1)	n.s.	**	*	**	**	**	**	**	n.s.	*	*
	N0	7.3 b	27.9 c	6.4 b	26.5 c	138 b	4.0	7.2 a	8.2	0.3 b	3.7 b	5.2 b
	N100	13.1 a	50.8 b	8.2 a	41.1 b	165 a	4.5	7.5 ab	8.3	6.1 a	10.8 a	19.1 a
	N200	14.7 a	62.1 a	9.6 a	50.3 a	175 a	4.3	7.8 a	8.1	3.5 ab	9.9 a	19.0 a
	N300	13.5 a	57.7ab	8.9 a	48.2 a	183 a	4.6	7.7 a	7.9	2.3 ab	10.2 a	16.4 a
	(1)	**	**	**	**	**	n.s.	**	n.s.	**	*	**
Inter.	*W x N*	n.s.	**	**	**	*	*	**	n.s.	n.s.	n.s.	n.s.

(1) The values in the columns not having the same letters are significantly different; * = Significant at $\alpha \leq 0.05$; ** = Significant at $\alpha \leq 0.01$; n.s. = Not significant.difference.

(2) Cracked, rotten and irregularly shaped fruits are included.

(Katerji et al., 1993), and that the lower yield in water shortage conditions is generally due to a smaller number of fruits (Dalla Costa and Gianquinto, 2002; Sezen et al., 2006).

As expected, in both years, the water deficit increased the soluble solids content and the dry matter percentage of the peppers, which were respectively 10 and 13% higher in 1998 and 18 and 16% higher in 1999 with respect to the well irrigated crop. In 1998, the irrigation regime did not affect the total waste (including rotten and irregularly shaped fruits), which was 28% for both regimes, of which 4.4% blossom-end rot and 15% sun-burned peppers. Instead in 1999, the water stress caused an increase of 53% of blossom-end rot and 40% of total waste.

The total number of peppers and the number of marketable peppers per plant were not affected by the amount of nitrogen applied, with the exception of the unfertilized crop. However, there were significant variations in fruit weight among the different N doses (Tab. 2). In particular, in the first year, the marketable yield progressively increased from 14.6 t ha^{-1} for N0 to 30.2 t ha^{-1} for N200, and then dropped to 23.9 t ha^{-1} for N300. N200 produced peppers with the highest mean weight and mesocarp thickness. The unfertilized peppers had the highest soluble solids content. The yields in the second year were double those in the first year, independently of the level of applied nitrogen. This can be attributed to the earlier transplantation (by one month) and, especially, to the use of plastic mulch, known to positively influence the thermal and water regime of the soil as well as its structure, thus providing more favourable growth conditions (Gercek et al., 2009). The positive effects of mulching are enhanced when it is combined with fertirrigation, increasing yields and optimizing the efficiency and sustainable use of water and fertilizers thanks to lower losses due to leaching (Bowen and Frey, 2002; Romic et al., 2003). As clearly shown by Kirnak et al. (2003), mulching mitigates the negative effects of water stress on plant growth and fruit yield of pepper, particularly in the open field and in semi-arid conditions, and also increases the N availability to the plants.

In 1999, the total and marketable yields increased respectively from 27.9 and 26.5 t ha^{-1} for

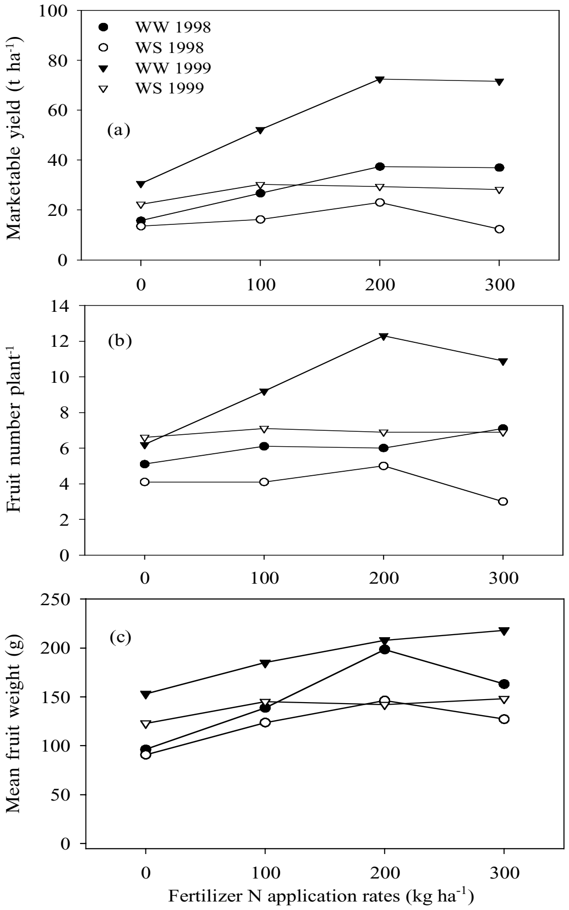

Figure 2. Interactive effect between N levels and water supplies on marketable yield (a), fruit number per plant (b) and mean fruit weight (c).

N0 to 62.1 and 50.3 t ha^{-1} for N200, and then dropped for N300. Therefore, the highest N fertilizer application rate tested (300 kg N ha^{-1}) can be regarded as excessive in terms of fruit yield and quality responses.

In the first year, the percentage of waste peppers was higher for N0 (41%) than for the other three doses (on average 23%); a large proportion of the waste for N0 consisted of peppers with sun-burn (24%) and blossom-end rot (5%). The waste percentage was lower in the second year than in the first, independently of the amount of nitrogen applied; moreover, N0 produced the lowest percentage of unmarketable fruits. The interaction between irrigation regime and N level was significant for most of the morpho-yield traits (Tab. 2). In both years, the plants subjected to periods of water shortage exhibited a significant reduction of the number and yield of marketable peppers with respect to the regularly watered plants, but only when N fertilizer was applied; this reduction tended to increase with the increasing N dose (Fig. 2a, 2b).

The reduction of the mean fruit weight due to water deficit (Fig. 2c) was more marked with N200 and N300 than with the minimum N dose; however, in the absence of N fertilization, the irrigation regime had little (1999) or no (1998) influence on this parameter. In the first year only, the water deficit caused a significant increase of the total number of peppers per plant in the unfertilized crop (data not shown) because of the higher percentage of waste, consisting mainly of fruits with blossom-end rot and, to a lesser degree, with sun-burning; however, since the waste fruits were affected by the pathologies in the initial developmental stage, they did not contribute to the total yield weight. An uniform supply of soil water throughout the growing season is needed to prevent poor fruit size and shape and to increase yield (Sezen et al., 2006; Shao et al., 2008). A reduced water supply during the growing period generally has adverse effects on yield and the greatest yield reduction occurs when there is a continuous water shortage until the first picking. Water stress in bell pepper also causes fruit drop, sun-burn and blossom-end rot. According to several authors (Dalla Costa and Gianquinto, 2002; Sezen et al., 2006), the critical period for water is between the beginning of fruit set and first maturing fruits, when soil water should be maintained between 65% and 80% of field capacity.

Our results confirm that water deficit and reduced N availability, especially during the reproductive phase, are very harmful for bell pepper, whether grown in the greenhouse or in the open field (Katerji et al., 1993), as observed also for tomato (Pulupol et al., 1996).

3.3 Accumulation and partitioning of dry matter and water use efficiency

In the first year, water stress caused significant variations of the accumulation and partitioning of DM and of WUE. Total above-ground DM varied from 570 g m^{-2} with regular watering to 461 g m^{-2} with water stress (Tab. 3). The WW plants accumulated a higher amount of DM in the fruits (both marketable and total), whereas

Table 3. Production and partitioning of dry matter (DM), water use efficiency (WUE), and uptake, partitioning and N use efficiency (NUE) in greenhouse pepper pepper related to irrigation regimes and N levels in two years.

Years / Treatments		Dry biomass		Harvest Index		Water Use Efficiency			N uptake		NHI	Nitrogen use efficiency			
		marketable yield (g m^{-2})	above ground (AG) (g m^{-2})	marketable yield (g g^{-1})	total yield (g g^{-1})	MY (kg of DM m^{-3} H_2O)	TY (kg of DM m^{-3} H_2O)	AG (kg of DM m^{-3} H_2O)	TY (kg ha^{-1})	AG DM (kg ha^{-1})	(kg kg^{-1})	NAUE (MY) (kg kg^{-1})	NAUE (AG) (kg kg^{-1})	NUE (kg kg^{-1}) *100	ANR (kg kg^{-1})
1998	*WW*	218	570	0.38	0.50	0.25	0.33	0.66	58	104	0.56	96.5	13.5	65.4	27.4
	WS	139	461	0.30	0.41	0.28	0.38	0.94	40	85	0.47	23.3	2.2	52.2	8.3
	(1)	**	**	**	**	n.s.	*	**	**	**	**	**	**	**	**
	N0	116 c	401 b	0.29 b	0.48 a	0.18 c	0.31 b	0.65 c	35 c	66 b	0.54 a	-	-	-	-
	N100	174 b	467 b	0.37 a	0.47 a	0.26 b	0.33 b	0.73 bc	44 bc	78 b	0.55 a	63 a	6.6 b	78 a	11 b
	N200	239 a	636 a	0.38 a	0.47 a	0.37 a	0.46 a	0.99 a	66 a	123 a	0.52 a	75 a	11.7 a	62 b	28 a
	N300	185 a	558 a	0.33 a	0.40 b	0.26 b	0.33 b	0.83 b	51 b	109 a	0.45 b	33 b	5.2 b	36 c	14 b
	(1)	**	**	**	**	**	**	**	**	**	**	**	**	**	**
Inter. W x N		**	**	n.s.	**	**	*	**	**	**	*	n.s.	n.s.	n.s.	n.s.
1999	*WW*	440	837	0.52	0.56	0.54	0.58	1.03	95	150	0.62	187	28	100	62
	WS	248	737	0.34	0.43	0.56	0.69	1.68	64	166	0.51	44	23	87	51
	(1)	**	**	*	n.s.	n.s.	*	**	*	*	*	**	n.s.	*	n.s.
	N0	215 c	444 c	0.48	0.51 a	0.36 b	0.39 b	0.77 c	34.4 c	61.7 c	0.55 ab	-	-	-	-
	N100	345 b	788 b	0.44	0.52 a	0.57 a	0.69 a	1.34 b	75.5 b	125.4 b	0.60 a	147 a	34 a	125 a	64 a
	N200	426 a	966 a	0.44	0.49ab	0.66 a	0.77 a	1.64 a	110.2 a	184.1 a	0.58 a	122 ab	26 b	92 b	61 a
	N300	391 ab	950 a	0.41	0.46 b	0.61 a	0.72 a	1.63 a	100.9 a	195.8 a	0.51 b	78 b	16 c	65 c	45 b
	(1)	**	**	n.s.	*	**	**	**	**	**	**	**	**	**	**
Inter. W x N		**	**	**	**	**	*	n.s.	*	*	**	n.s.	n.s.	n.s.	n.s.

(1) The values in the columns not having the same letters are significantly different; * = Significant at $\alpha \leq 0.05$; ** = Significant at $\alpha \leq 0.01$; n.s. = Not significant difference.

the dry weight of the stems and leaves showed no variation (data not shown). A similar trend was observed in 1999, even though there was an increase of around 52% of total DM with respect to the previous year, probably due to the earlier transplantation and mulching.

Regarding the effect of nitrogen fertilization, the total above-ground DM varied from a minimum of 434 (mean of N0 and N100) and 444 g m^{-2} (N0) to a maximum of 597 and 958 g m^{-2} (as a mean of N200 and N300) in the first and second year, respectively. For the DM of marketable fruits, the highest levels in the two years were achieved with the two highest N doses; in addition, the DM of the stems and leaves was, on average, around 50% of the total above-ground DM in both years, independently of the N level (data not shown). Similar results have been reported by various authors; in similar conditions, they concluded that the decreased accumulation and partitioning of DM in pepper could be attributed to a lower photosynthetic rate due to reduced stomatal conductance (Shao et al., 2008) and to decreased leaf area and chlorophyll content (Perniola et al., 1996; Miccolis et al., 2002).

Under water stress, the HI for marketable and total berries was reduced by, respectively, 21 and 18% in the first year and 35 and 23% in the second year, since the translocation of elaborates to stems and leaves was favoured (data not shown).

The HI for marketable fruits in the first year was lower for N0 (0.29) than for the other three N doses, which did not differ from each other (on average 0.36); in the second year, there were no differences among the N levels (on average 0.44). The HI for total fruits was lowest with the highest N level in both years (Tab. 3).

The MYWUE was not influenced by the irrigation regime (mean 0.27 and 0.55 kg DM m^{-3} H_2O respectively in the first and second year); instead, the TYWUE and AGWUE increased with water stress in both years. In the first year, the WUE increased from N0 to N200 and then significantly decreased as the N dose increased to 300 kg ha^{-1}. In the second year, excepting N0 which again had the lowest values for this pa-

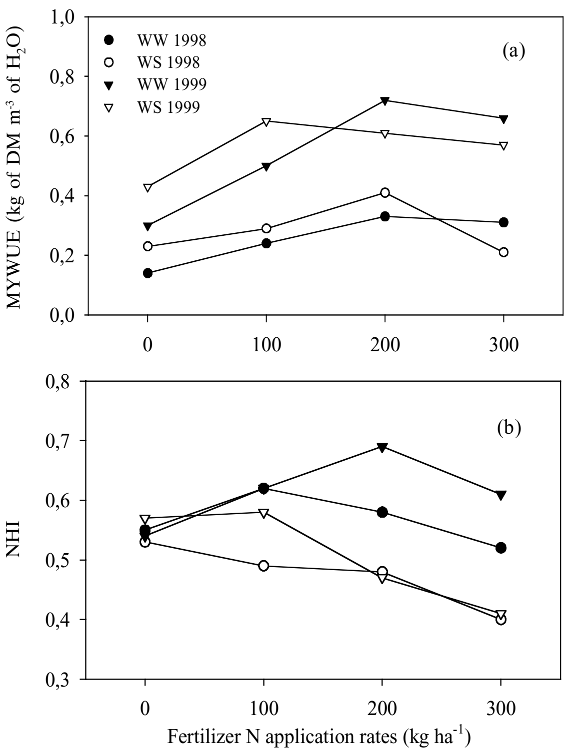

Figure 3. Interactive effect between N levels and water supplies on marketable yield WUE (MYWUE) (a) and nitrogen harvest index (NHI) (b).

rameter, there were no significant differences among the three N doses (N100-N300), whose values tended to be higher than in the previous year (Tab. 3). The interaction between irrigation regime and nitrogen fertilization was significant, except for the AGWUE in the second year (Tab. 3). In particular, there was an appreciable reduction of the WUE indexes with the decreased water supply and with the highest N doses, i.e. with N300 in 1998 or already with N200 in 1999 (Fig. 3a); with that dose, the MYWUE was significantly lower in the water stress crop than in the regularly irrigated one, while the TYWUE and AGWUE remained the same with the two irrigation regimes (data not shown). The above-ground dry biomass, total dry biomass and the marketable and total yields were also decreased by the reduced water supply in both years (data not shown); the effects of the water deficit were more marked with the maximum N dose. This was more evident for the marketable peppers whose decrease of dry weight was about 55% on average in the two years.

3.4 Nitrogen absorption, partitioning and use efficiency

Nitrogen absorption, partitioning and translocation were affected by water availability (Tab. 3). In both years, the well irrigated crop absorbed around 20 units of N more than the water stressed crop, considering only the fruits and the whole plant. The water deficit caused an increase of the percentage of N translocated to the stems and leaves (data not shown) and a significant reduction of the NHI due to decreased N translocation to the fruits. This is confirmed by the higher indexes of NUE in optimal irrigation conditions. Considering the marketable yield, the NAUE values were 76% lower for the well irrigated crop than the stressed one in both years; the difference was even more evident for the total number of fruits, in which the use efficiency for the stressed crop was negative (data not shown). The ANR dropped from 27.4% for the well watered plants to 8.3% for the water stressed ones in 1998, while there was no difference in the second year (Tab. 3).

The WW treatment absorbed 65 and 100% of the applied nitrogen in the first and second year respectively, while N absorption decreased to 52 and 87% with water stress (Tab. 3). The different amounts of nitrogen applied to the crop were absorbed by the plants in different measure, with a direct effect on the use efficiency of the element. In particular, the greatest absorption by the total above-ground biomass was recorded for N200 and N300 (on average around 116 and 190 kg ha^{-1} of N respectively in the first and second year, with no significant difference between the two); in contrast, 80 kg ha^{-1} of the N were absorbed for N0 and N100. Nitrogen accumulation in the fruits varied from a maximum of 66 and 110 kg ha^{-1} for N200 in 1998 and 1999, respectively, to a minimum of 35 kg ha^{-1} for the unfertilized crop. Accordingly, the NHI, i.e. the percentage of N absorbed by the crop and translocated to the fruits, decreased as the N dose increased, from 56% (mean of the three lower N doses) to 48% for N300; however, the proportion of N translocated to the stems and leaves was highest with the maximum N dose (data not shown).

The highest values of the NAUE (for marketable yield and total above-ground DM) and the ANR were obtained with the intermediate

N dose. Moreover, the NUE, i.e. the proportion of nitrogen absorbed with respect to that supplied, decreased as the N dose increased, from 78 to 36% in the first year and from 125 to 65% in the second year. Water stress had different effects on N absorption and partitioning according to the amount of N applied. In both years, the N accumulation in the fruits remained unchanged in N0 treatment but it significantly decreased with water stress as the supply of nitrogen fertilizer increased (data not shown); this is confirmed by the similar pattern of the NHI (Fig. 3b).

4. Conclusions

For unheated greenhouse-grown bell pepper with a spring-summer cycle, the best yields were obtained by associating full restitution of the water consumed with nitrogen fertilization at a dose of 200 kg ha^{-1} of N: the marketable yields were 37 and 72 t ha^{-1} in 1998 and 1999, respectively. Independently of the N dose and the irrigation regime, the yields were approximately doubled in the second year due to earlier transplantation and mulching, thus confirming the beneficial effects of the latter technique. Water stress applied repeatedly to pepper plants from the beginning of fruit set had a significant effect on the morpho-yield traits and on the accumulation and partitioning of DM and nitrogen in the different plant organs, influencing the water and nitrogen use efficiency of the crop; the magnitude of these effects varied according to the dose of nitrogen fertilizer supplied.

As in previous studies, water deficit compromised the bell pepper yields, with decreases of 44% due to the reduced number and weight of the fruits and the increased percentage of waste. Waste was caused mainly by blossom-end rot, cracking, sun-burn and malformations, although in such circumstances, the berries were richer in dry matter and soluble solids. The yield decreases due to water stress varied according to the amount of N supplied, as confirmed by the interactions recorded between the water regime and nitrogen level. In fact, the fruit quality and quantity remained the same in the absence of nitrogen fertilization, while the negative effects of the water deficit were enhanced at the highest N dose (300 kg ha^{-1}), leading to a 52% reduction of the number and a 161% reduction of the weight of marketable peppers, with a significant increase of waste and blossom-end rot. In these conditions, there was a drastic reduction of the total above-ground DM (-40%), as well as decreased nitrogen absorption by the plant (-54%) and increased partitioning and translocation of N to the stems and leaves with respect to the fruits, as shown by the lower HI values. The AGWUE remained unchanged, while both the TYWUE and MYWUE decreased. With the dose of 200 kg ha^{-1} of N, the yield and fruit quality of pepper crop were optimal, with and without water stress, and the water and nitrogen use efficiency improved.

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