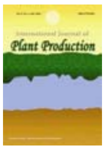

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Nitrogen effects on yield, quality and K/Na selectivity of sugar beets grown on clays under semi-arid, irrigated conditions

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Abstract

In a four-year experiment, five nitrogen rates (0, 60, 120, 180 and 240 kg N ha^{-1}) were tested over irrigated sugar beets grown on clays, under Mediterranean conditions, in central Greece. There, sugar beets are commonly grown under water shortages, high temperatures and high soil Na concentrations. Contrary to previous reports, N rates did not affect significantly population density (as assessed by root number at harvest) and sucrose content in fresh and dry root weight (SC and SCD, respectively). Yield response to N was year dependent and only in one out of four seasons, was there a positive effect of N on sugar yield and white sugar yield. In that case, the estimated optimum N dose was high (220 kg N ha^{-1}). Increasing N rates increased significantly N assimilation (as assessed by petiole NO_3-N and root α-amino N) and water content in root (WCR) but decreased biomass partitioning to root (lower harvest index). Selective absorption (SA, the preferential uptake of K over Na in roots) decreased with increasing N rates and it was negatively correlated with sugar beet N nutrition indices (petiole NO_3-N and root α-amino N). A negative correlation between SA and petiole NO_3-N was also evident when data combined over years, indicating that strong Na exclusion was associated with poor N nutrition, a contradiction to previous reports. The higher the SA, the lower the WCR indicating less dilution of sucrose in root and thus, the higher the SC. Moreover, high SA evoked sucrose accumulation in roots as it was shown by its positive correlation with SCD.

Keywords: *Beta vulgaris*; Fertilization; Root quality; Salinity; Sodium.

Introduction

Nitrogen (N) is the most limiting nutrient in sugar beet crop (*Beta vulgaris* L.), determining white sugar production by affecting both root yield and internal root quality (sucrose, K, Na, α-amino N concentrations). Excessive N promotes shoot growth at the expense of root growth and sucrose accumulation (Draycott and Christenson, 2003).

The variability of N use efficiency, due to environmental effects (de Koeijer et al., 2003), along with fertilizer cost and environmental pollution concerns (Herlihy and Hagarty, 1994), make N fertilization recommendations a challenging effort in sugar beet agronomic practice. Models based on the determination of soil properties (e.g. NO_3-N) before seeding have been proposed as accurate and reliable predictors of optimum N dose in sugar beets (Bilbao et al., 2004; Martín-Olmedo et al., 1999). These findings were revised by a meta-analysis authorized by Jaggard et al. (2009), who reported that on inorganic soils of England, no soil trait can predict reliably the optimum N dose in sugar beets. These authors proposed an amount of 100-110 kg N ha^{-1} as a rate equilibrating between fertilizer prices and beet values. This amount is within the range of 100-125 kg N ha^{-1} suggested by Märländer et al. (2003) as adequate for maximum sugar beet yield in Germany. In Greece, where sugar beets are grown mainly on inorganic soils, previous works have reported variable responses to N fertilization but when a positive response was evident, yields (fresh root weight-FRW, sugar yield-SY) were maximized at N rates > 200 kg N ha^{-1} (Tsialtas and Maslaris, 2005). In accordance to those findings, Neeteson and Wadman (1987) and Stevens et al. (2008) had reported optimum N doses higher than 200 kg N ha^{-1} in the Netherlands and USA.

In Thessaly Plain, central Greece, where irrigated sugar beets are grown on clays and under Mediterranean conditions, a dose of 150 kg N ha^{-1} is commonly recommended to growers. In this region, irrigation water shortages usually limit the supplemental irrigation to levels lower than the optimum (550 mm) for maximum yield (Analogides, 1993). The deficit water budgets put this region on a long-term threat of salinity. Stress conditions under which sugar beets are grown in central Greece are actually a combination of water, osmotic and salinity stresses (Munns, 2002).

Sugar beet, a semi-halophytic member of Chenopodiaceae, is considered as tolerant to both drought and salinity (Francois and Maas, 1994). However, deficit irrigation reduces significantly crop productivity and profitability (Morillo-Velarde and Ober, 2006; Tsialtas et al., 2009). Mild salinity could be beneficial for sugar beets grown on Na-poor soils (25 mg Na kg^{-1} soil). Thus, Na additions affected positively sugar beet physiology and yield (Durrant et al., 1978; Draycott and Christenson, 2003; Hajiboland et al., 2009). Sodium can substitute for K in its osmotic role being a better osmoticum (Subbarao et al., 2003). However, under semi-arid conditions, large amounts of Na are accumulated in plant tissues even under non-saline conditions (Wang et al., 2004; Tsialtas and Maslaris, 2006). Excessive Na affects negatively leaf morphology, physiology, yield and quality of sugar beets being the major root impurity under the semi-arid conditions (Koyro, 2000; Tsialtas and Maslaris, 2005; 2006; Wakeel et al., 2009).

Selective absorption of K over Na (SA), meaning the preferential absorption of K over Na, is a potential mechanism of Na tolerance in many species (Hester et al., 2001; Hafsi et al., 2007; Grieve et al., 2004; Zeng, 2005). In sugar beets, SA has been identified under controlled conditions and ascribed to root biochemical differences among genotypes (Stuiver et al., 1981). Under field conditions, locations and cultivars significantly affected SA, which was related with yield and sucrose content (Tsialtas and Maslaris, 2009). However, we are unaware of any work on the effect of N fertilization on SA of sugar beets grown under irrigated, Mediterranean conditions.

The aim of this work was to study the N fertilization effects on K/Na selectivity, yield and quality of sugar beets grown on clays under irrigated, Mediterranean conditions.

Materials and Methods

Site and experimentation

Sugar beet cv Rizor (SESVANDERHAVE NV/SA, Tienen, Belgium) was grown in adjacent sites for four growing seasons (2002, 2004, 2005 and 2006), on inorganic soils of eastern Thessaly Plain (39º 33’ N, 22º 27’ E, 98 m asl), Greece. Some soil properties of the experimental sites, before seeding, are given in Table 1. Agronomic information on the four-year experimentation is presented in Table 2.

The experiment was arranged as Randomized Complete Block (RCB) design with N rates being the main factor and with six replications. Seeds were mechanically drilled in plots of eight rows (8 m long), at 0.50 m apart and at 0.15 m spacing in the row. Five N rates (0, 60, 120, 180 and 240 kg N ha^{-1} encoded as N_0, N_{60}, N_{120}, N_{180} and N_{240}, respectively) were applied at 2/3 as basal [$(NH_4)_2SO_4$] and 1/3 as top-dressing (NH_4NO_3) before canopy closure. Adequate amounts of P and K fertilization (200 kg P_2O_5 ha^{-1} and 320 kg K_2O ha^{-1}, respectively) were incorporated into the soil before sowing. Supplemental irrigation was applied according to the needs and the availability of irrigation water (Table 2). Weeds, insects, Cercospora and powdery mildew were suppressed by chemical sprayings.

Table 1. Soil traits determined before seeding (0-60 cm) for the four years of experimentation. Each mean is the average of six samples.

Sand	Silt	Clay	pH	$CaCO_3$	Org. C	Total N	NO_3-N	P-Olsen	K	Na	CEC
	g kg^{-1}		1:1		g kg^{-1}			mg kg^{-1}			cmol kg^{-1}
						2002					
285.0	175.0	540.0	8.12	9.3	12.3	1.19	6.82	15.83	319.2	151.8	41.9
						2004					
268.3	216.7	515.0	8.20	12.0	14.0	1.33	8.25	14.58	364.7	272.2	40.9
						2005					
236.7	336.7	426.6	7.83	13.5	13.2	1.25	8.62	19.60	288.3	147.2	39.1
						2006					
363.3	260.0	376.7	8.28	81.8	17.2	1.39	10.43	7.13	331.2	271.2	32.9

CEC: Cation exchange capacity.

Table 2. Agronomic information on the four experiments.

Year	Previous crop	Seeding date	Harvest date	Mean temperature (ºC)*	Rainfall (mm)*	Irrigation (mm)
2002	Cotton	19 March	3 October	20.47	260.3	214
2004	Cotton	23 March	24 September	20.62	225.5	260
2005	Winter wheat	19 March	23 September	21.42	137.1	509
2006	Winter wheat	24 March	19 September	21.39	131.4	273

*During the growing season.

Analyses and determinations before harvest

Before seeding, soil samples at two depths, (0-30 and 30-60 cm) were taken with a core from the center of N_0 plots. After air-drying, soil properties were determined according to Bigham (1996). Table 1 presents the mean values of the two depths for each soil trait determined.

At early July, petioles of 12 healthy, fully-expanded leaves per plot were randomly selected, separated from blades, sliced and oven-dried at 75 ºC for 48 h. Petiole NO_3-N analysis was conducted on an Orion Meter (Model 920A) using an Orion Nitrate electrode 9307 ionplus (Thermo Scientific, Nijkerk, The Netherlands).

Analyses and determinations at harvest

Three rows per plot, at a length of 7 m (10.5 m^2), were harvested by hand, sugar beets were topped and the root number (RN) was counted. After root cleaning, fresh root (FRW) and top weights were measured. For each plot, fresh weight per root (FWR) was estimated as the FRW/RN ratio. From each plot, a randomly selected sub-sample of roots (25-30 roots) was transferred to factory's tare house for quality measurements (% sucrose content in fresh root-SC, K, Na, α-amino N concentration). Root quality was assessed using a Venema automatic beet laboratory system (Venema Automation, Groningen, the Netherlands) connected with a Betalyser system (Dr Wolfgang Kernchen, GmbH, Seelze, Germany). Sugar yield (SY) was estimated by combining FRW and SC. Molasses sugar (Z_m, %) was calculated according to Reinefeld et al. (1974) and used to correct SC for white sugar yield (WSY) estimation as the combination of FRW and SC-Z_m.

Two typical sugar beets per plot were topped, the roots were sliced and a sub-sample of ~200 g fresh root weight was dried at 75 ºC for 48 h. The water content in root (WCR) was estimated by comparing fresh and dry weights and it was used to estimate the sucrose content (%) in dry weight (SCD). The harvest index (HI) was estimated by the ratio of root dry weight to total dry weight per plot.

From the center of each harvested plot, soil samples were taken with a core at two depths (0-30 and 30-60 cm) for soil K and Na determinations. After air-drying, soil K and Na were extracted with 1 M CH_3COONH_4, pH 7.0 and measured on a flame photometer (Jenway PFP 7, Gransmore Green, UK).

Estimations and calculations

The selective absorption (SA) of K over Na was estimated using an adapted formula given by Wang et al. (2002):

$$SA = (\text{soil Na/K at 0-60 cm depth})/(\text{Na/K in root dry weight})$$

where soil Na and K are the sum of the soluble and the exchangeable fractions of the elements at harvest. The higher the SA, the stronger the root excludes Na and absorbs K indicating greater SA capacity.

Statistical analysis

Data were analyzed as a combined over years RCB design with six replications, with N rates as the main factor. Means were compared with the least significant difference (LSD) test at $P<0.05$ using the M-STAT statistical package (MSTAT-C, version 1.41, Crop and Soil Sciences Department, Michigan State University). Best-fitted curves of the relationships between determined traits were estimated using SPSS software (version 15.0, SPSS Inc., IL, USA).

Results

Quantitative and qualitative traits

Root number at harvest was affected significantly by years. It was highest in 2002 and 2005 and lowest in 2006 (Table 3).

Both years and N rates affected significantly FRW and FWR. Nitrogen rates ≥ 120 kg N ha^{-1} increased significantly FRW and a quadratic curve was the best-fitted to data (Figure 1). Using the first derivative of the quadratic function, optimum N rate was predicted at 335.5 kg N ha^{-1}, out of the range of N application doses. Amongst years, FRW was highest in 2002 (118.40 kg ha^{-1}) but no significant difference was found among the other years (Table 3). Nitrogen additions increased FWR compared to control (N_0) but no significant differences were found among N addition rates (N_{60}, N_{120}, N_{180} and N_{240}). Fresh weight per root was highest in 2002 and 2006.

Despite a descending trend of SC with increasing N doses, no significant effect of N was revealed. The highest SC was recorded in 2004 (15.85%), the lowest in 2002 and 2006 (12.42% and 12.90%, respectively) while in 2005, SC was moderate (14.93%). Accordingly, no effect of N rates on SCD was found (Table 3), with the highest values to be recorded in 2004 (73.11%).

Years, N rates and their interaction had a significant effect on SY. Higher N application rates (N_{120}, N_{180} and N_{240}) showed higher SY. All years but 2006 did not differ significantly for SY (Table 3). The year × N rate interaction was actually derived from the positive response of SY to N in 2004 since no significant effect was evident in the other years (data not shown). From the quadratic functions best-fitted data, SY was predicted to become maximum at 252.5 kg N ha^{-1} for combined data over years and at 218.6 kg N ha^{-1} in 2004 (Figure 1). Years and year × N rate interaction had a significant effect on WSY, with the lowest value to be recorded in 2006 (Table 3). Like SY, the significant interaction was derived from the response of WSY to N rates in 2004 while no response was evident in the other years (data not shown). In 2004, the quadratic function best-fitting data predicted the optimum N rate for maximum WSY at 220.8 kg N ha^{-1} (Figure 1).

Years but not N rates had a significant effect on WCR (Table 3). The lowest WCR values were recorded in 2004 and 2005 (0.781 g g^{-1}and 0.785 g g^{-1}, respectively) when SC and SCD were highest.

Both years and N rates affected significantly HI. A significant decrease of HI was evident only at the highest N rates (N_{180}, N_{240}) while the lowest HI was recorded in 2006 (Table 3).

Table 3. Comparison of means over N rates and years for root number (RN), fresh root weight (FRW), fresh weight per root (FWR), sucrose content in fresh root (SC), sucrose content in dry root (SCD), sugar yield (SY), white sugar yield (WSY), water content in root (WCR) and harvest index (HI).

	RN	FRW	FWR	SC	SCD	SY	WSY	WCR	HI
	×1000 root ha^{-1}	t ha^{-1}	kg root^{-1}	% sucrose	% sucrose	t ha^{-1}	t ha^{-1}	g g^{-1}	kg kg^{-1}
					N rates				
0	92.34^{a}	91.65^{c}	0.995^{b}	14.19^{a}	66.61^{a}	12.82^{b}	10.58^{a}	0.793^{c}	0.778^{a}
60	87.06^{b}	94.32^{bc}	1.089^{a}	14.02^{a}	70.01^{a}	13.04^{ab}	10.73^{a}	0.798^{abc}	0.774^{a}
120	88.97^{ab}	98.07^{ab}	1.111^{a}	14.25^{a}	69.67^{a}	13.84^{a}	11.32^{a}	0.795^{bc}	0.763^{a}
180	91.37^{a}	100.20^{ab}	1.099^{a}	13.85^{a}	68.91^{a}	13.74^{a}	10.94^{a}	0.800^{ab}	0.755^{bc}
240	90.15^{ab}	100.90^{a}	1.137^{a}	13.82^{a}	70.00^{a}	13.83^{a}	10.97^{a}	0.801^{a}	0.740^{c}
					Years				
2002	96.51^{a}	118.40^{a}	1.232^{a}	12.42^{c}	67.17^{b}	14.65^{a}	10.76^{a}	0.818^{a}	0.793^{a}
2004	84.95^{b}	87.43^{b}	1.033^{b}	15.85^{a}	73.11^{a}	13.80^{a}	11.81^{a}	0.781^{b}	0.801^{a}
2005	99.43^{a}	91.62^{b}	0.924^{b}	14.93^{b}	69.10^{ab}	13.67^{a}	11.72^{a}	0.785^{b}	0.777^{a}
2006	79.04^{c}	90.60^{b}	1.157^{a}	12.90^{c}	67.02^{b}	11.68^{b}	9.35^{b}	0.806^{a}	0.677^{b}
CV (%)	7.45	10.82	12.58	5.60	10.05	10.51	11.98	2.48	4.25

For the same column and the same factor, means labeled with the same letter did not differ significantly. CV, coefficient of variation.

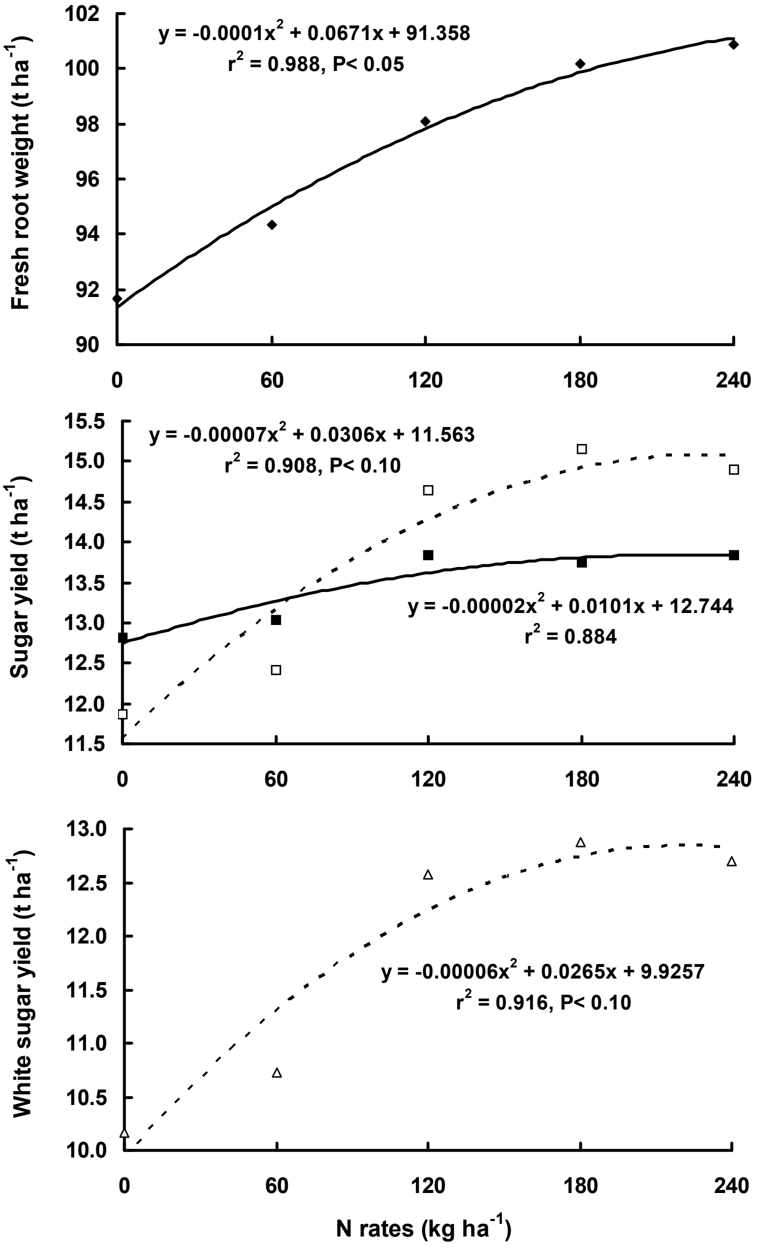

Figure 1. Quadratic functions relating N application rates and sugar beet yields. Each point is the mean of 24 measurements (four years × six replications). Filled points are for data combined over years and open points for 2004 data.

Selective absorption, petiole NO_3-N, soil K and Na and root impurities

The years affected significantly all the traits while N rates did not affect K concentration in both soil and roots and Na in soil (Table 4).

Table 4. Mean comparison over N rates and years for petiole NO_3-N, soil K and Na concentrations, root impurities (K, Na, α-amino N) and selective absorption (SA).

	Petiole NO_3-N	K soil	Na soil	K root	Na root	α-amino N	SA
	mg kg^{-1}	mg kg^{-1}	mg kg^{-1}	mg g^{-1}	mg g^{-1}	mg g^{-1}	
N rates							
0	2407^{c}	318.4^{a}	339.7^{a}	8.23^{a}	3.45^{b}	1.49^{d}	3.07^{a}
60	2512^{c}	315.6^{a}	328.0^{a}	8.48^{a}	3.56^{b}	1.63^{cd}	3.04^{a}
120	4612^{b}	319.0^{a}	332.1^{a}	8.34^{a}	3.86^{b}	1.78^{bc}	2.84^{ab}
180	5436^{b}	318.9^{a}	331.8^{a}	8.50^{a}	4.60^{a}	1.96^{ab}	2.47^{bc}
240	7059^{a}	316.0^{a}	320.6^{a}	8.53^{a}	4.74^{a}	2.04^{a}	2.30^{c}
Years							
2002	8223^{a}	325.0^{b}	317.0^{b}	9.25^{a}	6.66^{a}	2.82^{a}	1.49^{c}
2004	2462^{c}	354.8^{a}	374.6^{a}	8.48^{ab}	2.36^{c}	1.47^{b}	4.16^{a}
2005	1491^{c}	253.6^{c}	260.0^{c}	7.86^{b}	2.58^{c}	1.17^{b}	3.30^{b}
2006	5444^{b}	337.0^{ab}	370.1^{a}	8.07^{b}	4.57^{b}	1.66^{b}	2.04^{c}
CV (%)	44.82	8.88	13.53	12.39	25.78	23.18	26.82

For the same column and the same factor, means labeled with the same letter did not differ significantly. CV, coefficient of variation.

Petiole NO_3-N concentration increased with increasing N rates and was highest at N_{240} (7059 mg kg^{-1}), lowest at N_0 and N_{60} (2407 mg kg^{-1} and 2512 mg kg^{-1}, respectively) and moderate at N_{120} and N_{180} (4612 mg kg^{-1} and 5436 mg kg^{-1}, respectively). The lowest petiole NO_3-N concentration was recorded in 2004 and 2005 (2462 mg kg^{-1} and 1491 mg kg^{-1}, respectively) and the highest in 2002 (8223 mg kg^{-1}) while moderate concentration was found in 2006 (5444 mg kg^{-1}).

Both soil K and Na concentrations were highest in 2004 and 2006, moderate in 2002 and lowest in 2005 (Table 4). It is noteworthy that, at harvest, concentrations of soil Na were higher compared to the respective of soil K, a finding not evident before the establishment of the experiments (Table 1).

Root K concentration was highest in 2002 (9.25 mg kg^{-1}) and lowest in 2005 and 2006 (7.86 mg kg^{-1} and 8.07 mg kg^{-1}, respectively). For root Na concentration, the highest values were recorded in 2002 (6.66 mg kg^{-1}) followed by 2006 (4.57 mg kg^{-1}) while both 2004 and 2005 had the lowest values (2.36 mg kg^{-1} and 2.58 mg kg^{-1}, respectively). Only the highest N rates (N_{180}, N_{240}) had a significant effect on root α-amino N concentration (Table 4).

Increasing N rates increased root α-amino N concentration while correspondingly reduced SA (Table 4). In 2002, α-amino N concentration (2.82 mg kg^{-1}) was higher compared to the other years (Table 4). Selective absorption was highest in 2004 (4.16) followed by 2005 (3.30) and the lowest values were found in both 2002 and 2006 (1.46 and 2.04, respectively).

Relationships of SA with the other traits over N rates and years

Figure 2 presents the significant correlations between SA and the traits determined when data combined over years. Negative correlations related SA with petiole NO_3-N ($y= -5580.8x + 19719$, $r= -0.970$, $P<0.01$, $n=5$), FRW ($y= -10.61x + 126.14$, $r= -0.926$, $P<0.05$, $n=5$) and root α-amino N ($y= -0.6389x + 3.5332$, $r= -0.969$, $P<0.01$, $n=5$) whereas SA and HI were strongly and positively correlated ($y=0.0432x + 0.6434$, $r=0.975$, $P<0.01$, $n=5$).

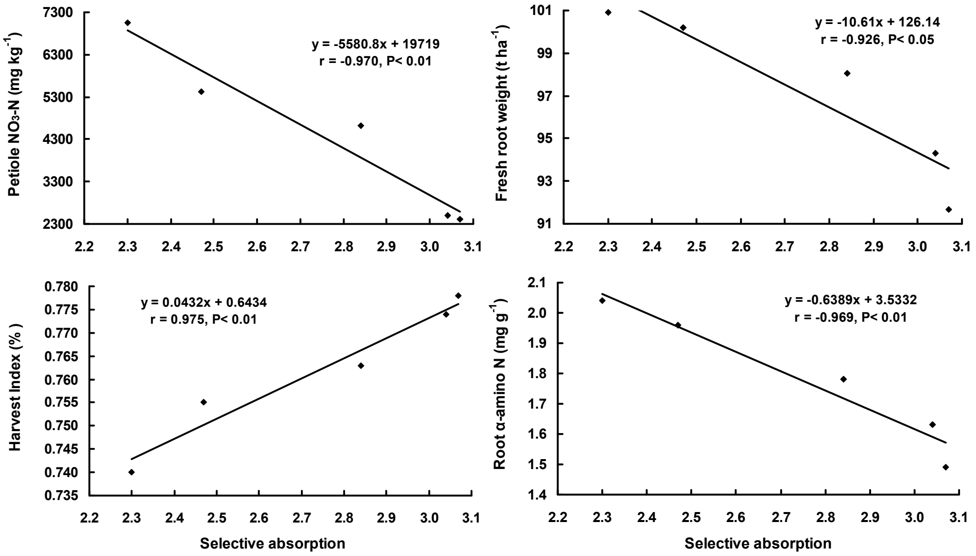

Figure 2. Significant correlations between selective absorption and the determined traits for the combined data over years. Each point is the mean of 24 measurements (four years × six replications).

Combining data over N rates, year means of SA were positively related with SC (linearly) and SCD (curvilinearly). A negative, curvilinear function was the best-fitted one between SA and WCR (Figure 3). Also, curvilinear, with high r^2 but marginally insignificant ($P=0.07$) were the relationships between SA and petiole NO_3-N or root Na concentration (Figure 4).

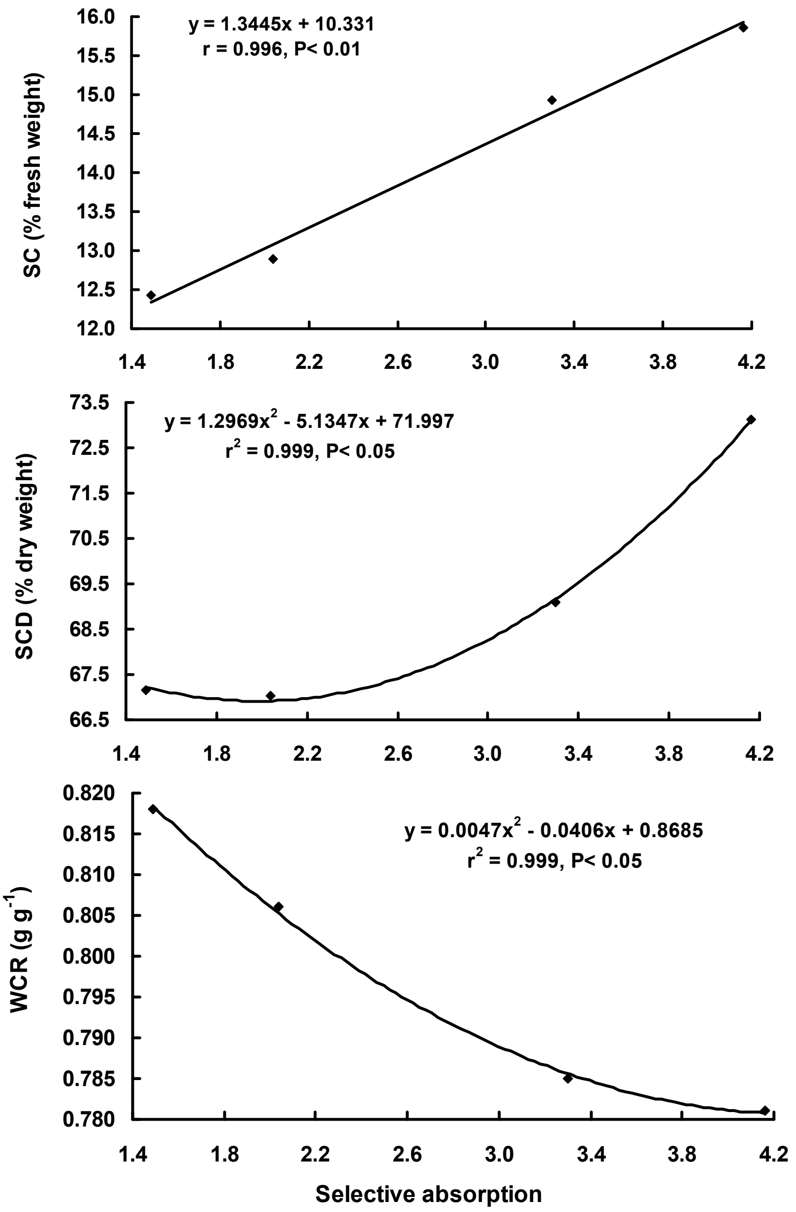

Figure 3. Significant relationships between selective absorption and sucrose content in fresh or dry weight (SC and SCD, respectively) and water content in root (WCR) for the combined data over N rates. Each point is the mean of 30 measurements (five N rates × six replications).

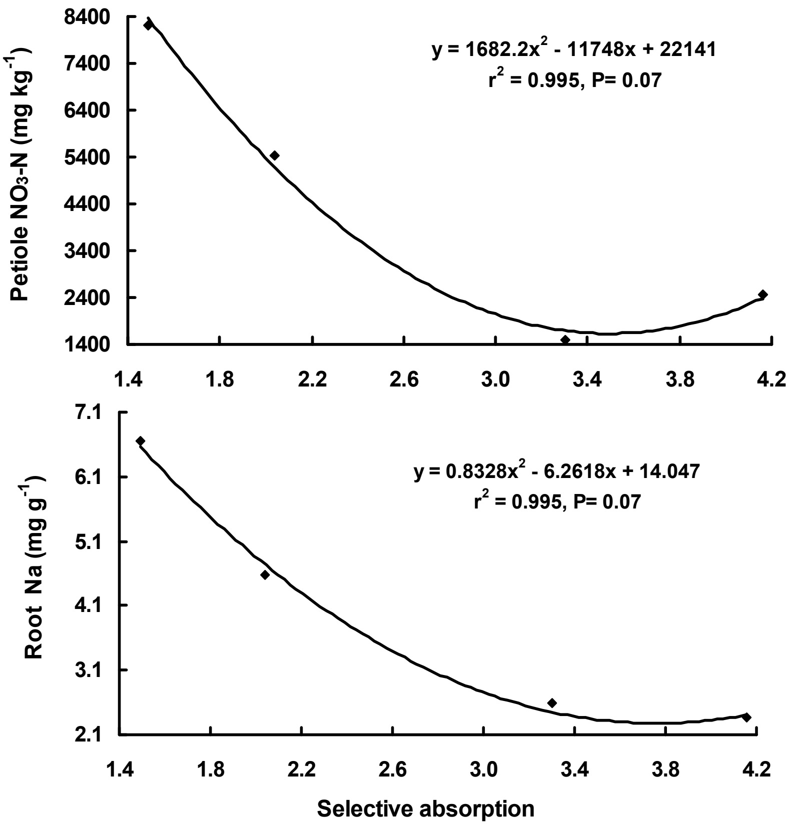

Figure 4. Quadratic functions between selective absorption and petiole NO_3-N and root Na concentration for the combined data over N rates. Each point is the mean of 30 measurements (five N rates × six replications).

Discussion

Balanced N fertilization of sugar beets is a highly important agronomic practice with implications on both growers' revenue and factory processing. However, reliable prediction models of sugar beet N needs, based on soil traits before sowing, are difficult to be built (Jaggard et al., 2009), as a consequence of the year effect on sugar beet response to N (de Koeijer et al., 2003). Thus, Jaggard et al. (2009) suggested that the application of 100-110 kg N ha^{-1} compromise for crop N needs, fertilizer prices and beet value. This rate is similar to that given by Märländer et al. (2003) as adequate to meet the N needs of sugar beets in Germany.

In Greece, where sugar beets are grown on various soils, from light-textured ones to clays, 120-150 kg N ha^{-1} is an average dose suggested as adequate. According to Jaggard (1977), soil density is a determinant factor of sugar beet N requirements. Experimental data combined over the main growing areas in Greece revealed high N demands for maximum yields (Tsialtas and Maslaris, 2005), in accordance with other researchers who reported optimum N rates higher than 200 kg N ha^{-1} (Neeteson and Wadman, 1987; Stevens et al., 2008). On the heavy soils of central Greece, these findings were confirmed only for FRW. For both SY and WSY, positive response to N fertilization was found only in one out of four growing seasons, predicting an optimum dose of ca 220 kg N ha^{-1}. These findings confirmed that sugar beet response to N is highly dependent on year (de Koeijer et al., 2003).

On clays of central Greece, increased N rates did not decrease RN at harvest (an assessment of plant density), contrary to the findings for the light-textured soils in northern Greece (Maslaris et al., 2010). An apparent explanation is that the high clay content restricted, by its fixing ability, the toxic effects of N on sugar beet germination (Draycott and Christenson, 2003).

Despite a declining trend, increasing N rates did not have a significant negative effect on SC, contrary to previous works (Tsialtas and Maslaris, 2005; Stevens et al., 2008; Maslaris et al., 2010; Hergert, 2010). Decreased SC at high N rates was ascribed to a dilution effect of sucrose in a greater fresh root volume (Follett et al., 1991) but this was not the case in the present work since no consistent effect of N on both WCR and SCD was evident.

Sugar beet N nutrition was responsive to rates ≥ 120 kg N ha^{-1} as it was revealed by the significant increase of both petiole NO_3-N and root α-amino N; two indices of sugar beet N adequacy (Oliveira et al., 1993; Pocock et al., 1990). High N supply (N_{180}, N_{240}) altered photo-assimilates and consequently biomass partitioning in favor of aboveground plant parts (Tsialtas and Maslaris, 2008). In the present work, this was shown by the significant reduction of HI at the highest rates.

The highest N doses (N_{180}, N_{240}) had detrimental effects on SA. Both negative and positive correlations were found to associate SA with N nutrition indices and HI, respectively. Since no significant effects of N fertilization on soil K and Na concentrations at harvest and on root K concentration were evident, the detrimental effect of N on SA was due to root Na concentration increases. Apparently, higher accumulation of both Na and α-amino N in roots at the higher N rates conferred osmotic regulation in sugar beet roots which had higher WCR (Ghoulam et al., 2002; Pakniyat and Armion, 2007; Tsialtas and Maslaris, 2009).

Based on the limits given by Milford et al. (2008), soils cropped with sugar beets in central Greece are usually adequately supplied with K but they also contain excessive of Na. Moreover, a great increase of soil Na concentrations from seeding to harvest was revealed when the data combined over N rates. Two explanations could be given for this; Na was added by irrigation water but more possibly, leached Na by winter precipitation to deeper soil layers was raised to the upper layers via capillary lift. Since rain water in central Greece is not enough for sugar beet crop, supplemental irrigation along with high soil Na levels, make the area prone to salinity threat (Munns, 2002), with serious implications on crop physiology and yield (Koyro, 2000; Tsialtas and Maslaris, 2006). Thus, the exploitation of the existing variation of SA in sugar beet genotypes is of high importance under these conditions (Stuiver et al., 1981; Pakniyat and Armion, 2007; Tsialtas and Maslaris, 2009). However, in this study where only one cultivar was grown, a possible explanation for the variation of SA between years could be the differences in the sum of the finer particles of soil (silt and clay); higher SA was associated with higher sum of silt and clay in 2004 and 2005.

Strong SA was associated with lower N uptake as revealed by the negative relationship between SA and petiole NO_3-N. Although N supply has been reported to reduce K uptake in grasses (Barhoumi et al., 2010), this was not evident in the present study. It was Na that showed increased concentrations in roots at the highest N rates (N_{180}, N_{240}). This is contrary to the findings of Tsialtas and Maslaris (2009) who reported that cultivars with higher SA showed a better N nutrition as it was indirectly assessed by root α-amino N concentration.

An interesting finding of the present study was the strong positive relationships between SA and SC and SCD. This further supported the findings of Tsialtas and Maslaris (2009) who reported a positive correlation between SA and SC across 14 cultivars when grown under stressful conditions (water shortage, high soil Na). In both studies, the negative influence of low SA on SC was ascribed to a dilution effect of sucrose due to the higher WCR in roots having low SA. The increased WCR when SA was low resulted possibly from the effective osmotic action of Na (Subbarao et al., 2003). The new addition of the present study was that low sucrose in low SA sugar beet roots was only partially attributable to a dilution effect since low SA was also related with low SCD, indicating that sucrose accumulation was retarded by Na in roots.

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