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ORIGINAL ARTICLE

Growth, Carbon Isotope Discrimination and Nitrogen Uptake in Silicon and/or Potassium Fed barley Grown under Two Watering Regimes

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The present pot experiment was an attempt to monitor the beneficial effects of silicon (Si) and/or potassium (K) applications on growth and nitrogen uptake in barley plants grown under water (FC1) and non water (FC2) stress conditions using ^{15}N and ^{13}C isotopes. Three fertilizer rates of Si (Si_{50}, Si_{100} and Si_{200}) and one fertilizer rate of K were used. Dry matter (DM) and N yield (NY) in different plant parts of barley plants was affected by Si and/ or K fertilization as well as by the watering regime level under which the plants have been grown. Solely added K or in combination with adequate rate of Si (Si_{100}) were more effective in alleviating water stress and producing higher yield in barley plants than solely added Si. However, the latter nutrient was found to be more effective than the former in producing higher spike's N yield. Solely added Si or in combination with K significantly reduced leaves $\Delta^{13}C$ reflecting their bifacial effects on water use efficiency (WUE), particularly in plants grown under well watering regime. This result indicated that Si might be involved in saving water loss through reducing transpiration rate and facilitating water uptake; consequently, increasing WUE. Although the rising of soil humidity generally increased fertilizer nitrogen uptake (Ndff) and its use efficiency (%NUE) in barley plants, applications of K or Si fertilizers to water stressed plants resulted in significant increments of these parameters as compared with the control. Our results highlight that Si or K is not only involved in amelioration of growth of barley plants, but can also improve nitrogen uptake and fertilizer nitrogen use efficiency particularly under water deficit conditions.

Key words: Barley; Silicon; Potassium; 15Nitrogen; ∆13Carbon; water stress.

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Key words: Barley/ Silicon/ Potassium/ 15Nitrogen/ Δ13Carbon/ water stress.

Water deficit is the principal abiotic factor affecting crop yield in arid and semiarid areas and considered as one of the major limitations to the agricultural productivity worldwide (Farooq et al., 2009). Barley (*Hordeum vulgare* L.) is a crop of major economic importance and is grown in a wide geographical range with varied agroclimatic conditions. In the Mediterranean basin, barley is cultivated on a large scale under rain-fed conditions, where drought represents a major limitation to crop nutrition and production. The management of plant nutrients is very useful to develop plant tolerance to drought. Better plant nutrition can effectively alleviate the adverse effects of drought by a number of mechanisms (Farooq et al., 2009; Waraich et al., 2011). Potassium (K) is reported to improve plant's resistance against drought stress and can alleviate water shortages in many plants species (Marschner 1995; Moinuddin and Imas, 2007). Potassium has been shown to play a significant role in the opening and closing of leaf stomates which control the movement of CO_2 into the plant and water out into the air, and would therefore have an effect on stomatal conductance (Bednarz et al., 1998). Moreover, numerous reports indicate that silicon (Si) improves growth parameters of plants growing under water stress. Although silicon is not considered to be an essential nutrient for most terrestrial plants, it plays an important role in protecting plants from abiotic and biotic stresses (Ma 2004, Epstein 2009; Liang et al., 2007). Sacala (2009) reported that the beneficial effects of Si may result from better and more efficient osmoregulation, improved plant water status, reduction in water loss by transpiration, maintenance of adequate supply of essential nutrients, restriction in toxic ions uptake and efficient functioning of anti-oxidative mechanisms. Furthermore, the role of Si in plants is not restricted to formation of physical or mechanical barrier in cell wall, lumens and intercellular voids, but it can also modulate plants' metabolism and alter physiological activity. Liang *et al*., (1999) suggested that silica-cuticle double layer formed on leaf epidermal tissue is responsible for higher water potential in plants received Si. Carbon isotope discrimination ($\Delta^{13}C$) of C3 plant leaves is related to photosynthetic gas exchange, because $\Delta^{13}C$ is in part determined by C_i/C_a, the ratio of CO_2 concentration in the leaf intercellular spaces (C_i) to that of the atmosphere (C_a), (Farquhar and Rishards, 1984). Foliar $\Delta^{13}C$ values have been used as an integrated measure of the response of photosynthetic gas exchange to environmental variables such as water availability (Gondon et al., 2002). Low $\Delta^{13}C$ has been proposed as an indicator of high water use efficiency (WUE) in C3 plants (Farquhar and Richards, 1984). Although the relationship between water uptake, transpiration rate and Si deposition or K status in the plant is well established, there seems to be a distinct lack of work on the effects of these two nutrients on $\Delta^{13}C$, and consequently on water use efficiency. Moreover, applied Si seems to interact favorably with other nutrients (N, P, and K) and offers the potential to improve efficiency in terms of yield response (Singh et al., 2005). Ashraf et al., (2009) reported that potassium and silicon improve yield and juice quality in sugarcane under salt stress. Since potassium and silicon have been noted for their particular role in enhancing drought tolerance of crops, very little is known about their beneficial effects on growth and N-uptake of barley plants in response to drought tolerance particularly, when they are added separately or altogether. Hence, a better understanding of the interactions between silicon and other nutrient applications and plant responses will contribute to more efficient fertilizer practices, particularly under water stress conditions. The present pot experiment aimed at investigating the effects of potassium and /or silicon fertilizer on dry matter production, N uptake, and carbon isotope composition in barley plants subjected to different soil moisture levels at the beginning of anthesis stage, using ^{13}C and ^{15}N isotopes.

MATERIALS AND METHODS

Soil properties, experimental design & treatments

Seeds of barley (*Hordeum vulgare* L., c.v. Arabi-Abiad) were grown in pots, each one containing 5 kg of thoroughly mixed soil. The main physical and chemical soil properties are: pH 7.7; Ec_e 0.83 dS /m; organic matter 0.91%; cations mmol (e) /L (Ca^{2+} 1.1, Mg^{2+} 0.47, K^+ 0.14, Na^+ 1.27); anions mmol (e) /L (SO_4^{2-} 1.27, HCO_3^- 0.97, Cl^- 0.74); available P (Olsen) 6.8 µg/ g; total N 0.07%; NO_3^- 42µg/g; NH_4^+ 26.1µg/g; clay 30.85%; Loam 17.99% and sand 51.26%. After germination, barley seedlings were thinned to 2 plants per pot. The pots were set outdoors under natural climatic conditions. The design was a split plot factorial, with irrigation regimes being the two main plots and the factors potassium and silicon fertilizers randomized within each irrigation regime as a 3 factorial (2x2x4) design. The irrigation regimes constitute two watering levels: water stress (FC1, 45-50% of field capacity) and well watered (FC2, 75-80% of field capacity). Within these two irrigation regimes, the first treatment was potassium fertilizer (K) which was applied in the form of K_2SO_4, at two levels: K^- and K^+ (equivalent to 150 K_2O/ha). Within each of the K treatment, silicon fertilizer (Si) was applied in the form of sodium metasilicate ($Na_2SiO_39H_2O$) at four levels: no fertilizer (Si^-) versus application of 50, 100 and 200 µg Si/g air-dried soil (abbreviated as Si_{50}, Si_{100} and Si_{200}, respectively. All treatments were replicated four times. Total number of pots was 64 (i.e. 2 water regimes x 2 K levels x 4 Si levels x 4 replicates). Soil water content in all pots was maintained at around 75% of field capacity from planting up to the beginning of anthesis stage. Thereafter, plants were subjected to the two above-mentioned soil moisture regimes, starting from anthesis to physiological maturity stage. Pots were weighed every 3 days and water was added to maintain the soil moisture levels previously described. For estimating the fractional contribution of nitrogen derived from soil (Ndfs) and from fertilizer (Ndff), an equivalent rate of 20 kg N/ha of ^{15}N labeled urea (10%^{15}N atom excess) was applied at planting**.** Nitrogen fertilizer use efficiency (%NUE) was calculated as fertilizer N recovery in the whole plant using the ^{15}N isotopic data.

Plant sampling and isotopic composition analyses

Plants were harvested 12 weeks after planting. Leaves and spikes were oven dried at 70 °C, weighed and ground to a fine powder. Concentration of total N and C, and isotopic composition of ^{15}N and ^{13}C were determined on sub-samples (7 and 2 mg dry weight for N and C determination, respectively) of different plant parts using the continuous-flow isotope ratio mass spectrometer (Integra-CN, PDZ Europea Scientific Instrument, UK). Isotopic compositions are expressed using delta notation (δ) in parts per thousand (‰): $\delta\ (‰) = [(R_{sample}/R_{standard}) - 1]\ 1000$, where R is the ratio of $^{15}N/^{14}N$ or $^{13}C/^{12}C$.

Carbon isotope discrimination ($\Delta^{13}C$) was calculated according to Farquhar et al. (1982):

$$\Delta^{13}C = (\delta\ ^{13}C_{air} - \delta\ ^{13}C_{sample}) / (1 - \delta\ ^{13}C_{sample}/1000),$$

where $\delta\ ^{13}C_{air}$ is the $\delta\ ^{13}C$ value in air (-8‰) and $\delta\ ^{13}C_{sample}$ is the measured value in the plant.

Statistical analysis

The data were subjected to analysis of variance (ANOVA) test, and means were compared using the Least Significant Difference (Fisher's PLSD) test at the 0.05 level of confidence.

RESULTS

Dry matter yield

Both soil moisture levels and fertilizers had significant effects on dry matter yield (DM) in leaves and spikes of barley plants (Table 1). For leaves, the lowest dry matter yield (6.13 g/pot) was observed in plants grown without fertilization (S^-K^-) under water stress treatment (FC1). Low and mild rates of solely applied silicon ($Si_{50}K^-$ and $Si_{100}K^-$) significantly increased DM of leaves by 11 and 8%, respectively. However, leave's DM in plants receiving higher rate of Si ($Si_{200}K^-$) was similar to that of the control. Sole application of K increased leave's DM by 9%. Moreover, addition of Si along with K fertilizers ($Si_{50}K^+$ and Si_{200} K^+) improved DM by 12 and 6%, respectively, as compared with the control (S^-K^-). However, no significant difference was observed between $Si_{100}K^+$ and the control.

Generally, increasing soil water level from FC1 to FC2 had no impact on leaf DM regardless of fertilizer treatments. In well watered plants, low and mild rates of solely applied silicon ($Si_{50}K^-$ and $Si_{100}K^-$) significantly increased DM of leaves by 10 and 7%, respectively. However, application of Si at a higher rate ($Si_{200}K^-$) did not significantly differ from that of the control. Although, the sole application of K significantly increased leave's DM (9% over the control), dual applications of Si and K did not result in significant increases of leaf DM.

In almost all cases, dry matter yield of spikes was not positively affected in response to fertilization. The only positive and significant impact of fertilizers were observed for plants grown under water stress in the Si^-K^+ and $Si_{100}K^+$ treatments (3 and 8% over S^-K^-, respectively). Increasing soil moisture content from FC1 to FC2 had generally positive impact in enhancing spike's DM where the highest percent increment (28%) was observed in the $Si_{200}K^+$.

For the whole plant (leaves and spikes), slight but significant increase of total DM (about 6% over S^-K^-) was observed in the Si^-K^+ and $Si_{50}K^+$ treatments under water stress conditions.

Nitrogen yield

The effect of Si and/or K fertilizers on N yield is shown in Table 2. Under water stress conditions (FC1), nitrogen yield (NY) in leaves of plants grown without fertilization (S^-K^-) was 32.62 mg N/pot. Sole or dual applications of Si and K did not markedly affect leaf NY. A significant decrease of the leaf NY was observed in plants received higher rate of silicon (K^-Si_{200}). Increasing soil water level from FC1 to FC2 had generally no impact on leaf NY. Under well watering regime (FC2), the Si^-K^+ treatment showed higher leaf NY than that in $Si_{100}K^-$ and $Si_{200}K^-$.

The beneficial effect of Si fertilizer on NY was more pronounced in spikes than in leaves. Under water stress conditions (FC1), nitrogen yield (NY) in spikes of barley plants grown without fertilization (S^-K^-) was 99 mg N/pot. Low and mild rates of solely applied silicon ($Si_{50}K^-$ and $Si_{100}K^-$) significantly increased NY of spikes by 17 and 27%, respectively. However, spike's NY in plants received higher rate of Si ($Si_{200}K^-$) did not significantly differ from that of the control. Moreover, the sole application of K significantly increased spike's NY (14% over the control). However, dual applications of Si and K had smaller effects on spike's NY than single fertilizer applications (10% over the control in the $Si_{50}K^+$ and Si_{100} K^+). Under well watering regime (FC2), NY of spikes was not significantly affected in response to fertilization. In contrast to FC1, sole application of K in FC2 significantly decreased spike's NY (10% less than the control). Overall, it is worth to mention that spike's NY in the FC1-$Si_{100}K^-$ was the highest among the other treatments subjected to both watering regimes.

The pattern of whole plant nitrogen yield (leaves and spikes) was relatively similar to that of spike's NY. Total nitrogen yield (TNY) of barley plants grown without fertilization (S^-K^-) was 132 mg N/pot. Low (Si_{50}) and mild (Si_{100}) rates of solely applied silicon significantly increased TNY by 13 and 20%, respectively. However, TNY in plants received higher rate of Si ($Si_{200}K^-$) did not significantly differ from that of the control one. Sole application of K significantly increased TNY (12% over the control); whereas, dual applications of Si and K did not result in significant increases of TNY. Under well watering regime (FC2), TNY did not significantly differ among fertilizer treatments.

Nitrogen derived from soil and fertilizer

The effect of Si and/or K fertilizers on soil N-uptake was more pronounced in plants grown under water stress than those grown under non-stress conditions (Fig.1). In water stressed plants, amount of N derived from soil (Ndfs) in the Si^-K^- was 112 mg N/pot. Low and mild rates of solely applied silicon ($Si_{50}K^-$ and $Si_{100}K^-$) significantly and gradually increased total N-uptake by 9 and 17%, respectively. At a higher rate of Si ($Si_{200}K^-$), a reduction in this parameter was observed relative to the above mentioned treatments, where its value was relatively similar to that of the control. Sole application of K increased soil N-uptake by 10%. Lower rate of Si in combination with K ($Si_{50}K^+$) increased Ndfs by 9% which was similar to that observed in solely added Si. A gradual reduction in Ndfs, relative to the control, was observed beyond the Si_{50} level. Total Ndfs in $Si_{100}K^+$ and $Si_{200}K^+$ did not significantly differ from that of the control.

The effect of Si and/or K fertilizers on nitrogen derived from fertilizer (Ndff) is shown in Figure 1. In water stressed plants, low and mild rates of solely applied Si ($Si_{50}K^-$ and $Si_{100}K^-$) significantly increased Ndff by 30 and 37%, respectively. However, Ndff in plants receiving higher rate of Si (Si_{200}) with or without K did not significantly differ from that of the control. Sole application of K increased total N-uptake by 23%. Also, low and mild rates of Si in combination with K ($Si_{50}K^+$, $Si_{100}K^+$) increased Ndff by 10 and 13%. Under well watered conditions, low rate of Si in combination with K ($Si_{50}K^+$) significantly increased Ndff by 15% relative to the control; whereas, no significant differences were observed between the control and the other fertilizer treatments.

Nitrogen fertilizer use efficiency (%NUE) was calculated as fertilizer N recovery in the whole plant using the ^{15}N isotopic data (Table 3). In water stressed plants, %NUE in the control treatment was 49.4%. Sole or dual applications of silicon and potassium enhanced %NUE. The highest NUE values were observed following single additions of low ($Si_{50}K^-$) and mild ($Si_{100}K^-$) rates of silicon (64.6 and 68%, respectively). %NUE in plants received higher rate of Si (Si_{200}) with or without K did not significantly differ from that of the control. In potassium fed plants (Si^-K^+), %NUE (60.9%) was significantly higher than that of the control. Although, a positive impact of dual applications of silicon and potassium on NUE in the $Si_{50}K^+$, $Si_{100}K^+$ treatments, their values (54.5 and 55.8%, respectively) were significantly lower than those corresponding to the solely added K. Under well-watered conditions, the highest %NUE value (70.7%) was observed in $Si_{50}K^+$. However, no significant increments were observed for %NUE in the other fertilizer treatments, relative to the control.

Carbon isotope discrimination (‰$\Delta^{13}C$)

Data presented in Figure 2 showed that carbon isotope discrimination (‰$\Delta^{13}C$) in barley's leaves was affected by the rate of fertilizers and soil water levels. The effect of Si and/or K fertilizers on (‰$\Delta^{13}C$) was more pronounced in plants grown under non-stress than those grown under water stress conditions. Under water stress conditions (FC1), only $Si_{100}K^+$ showed a lower $\Delta^{13}C$ value compared with the other treatments. In well watered plants, $\Delta^{13}C$ in plants grown without fertilization (S^-K^-) was 20.42‰. Low and mild rates of solely applied silicon ($Si_{50}K^-$ and $Si_{100}K^-$) significantly reduced $\Delta^{13}C$ relative to the control. However, $\Delta^{13}C$ in plants receiving higher rate of Si ($Si_{200}K^-$) and those receiving only K did not significantly differ from that of the control. Nevertheless, Dual applications of Si and K significantly reduced $\Delta^{13}C$ in all the fertilizer combinations (i.e. $Si_{50}K^+$ $Si_{100}K^+$ and $Si_{200}K^+$), with no significant differences being observed from each others. Moreover, $\Delta^{13}C$ values in $Si_{50}K^-$, $Si_{100}K^-$, $Si_{50}K^+$ and $Si_{200}K^+$ treatments were significantly lower in well watered plants than those in plants grown under water stress conditions.

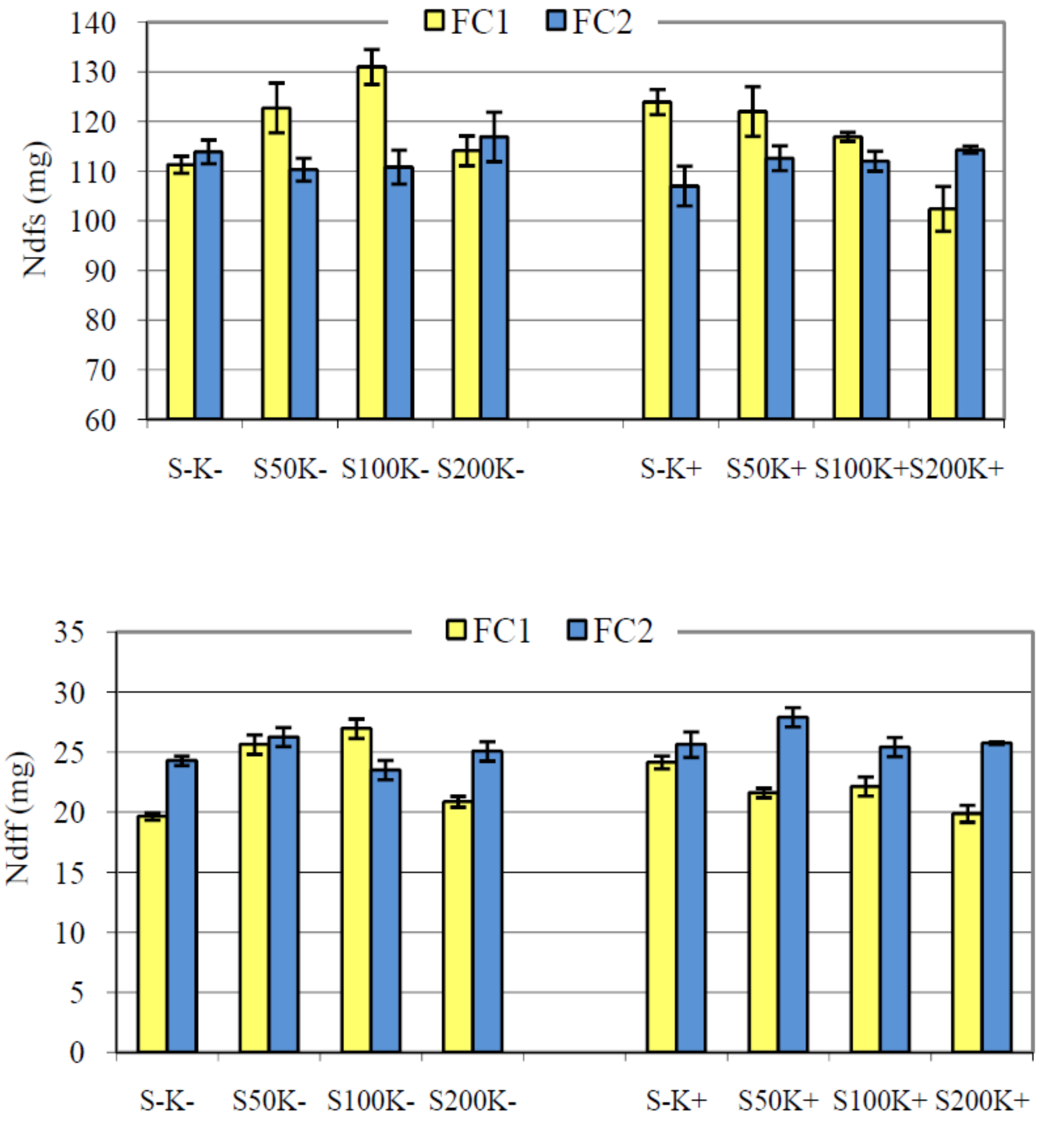

Figure 1. Amounts of nitrogen derived from soil (Ndfs) and fertilizer(Ndff) in the whole plant of barley grown under two watering regimes (FC) as affectedby silicon (Si) and potassium (K) fertilizers.

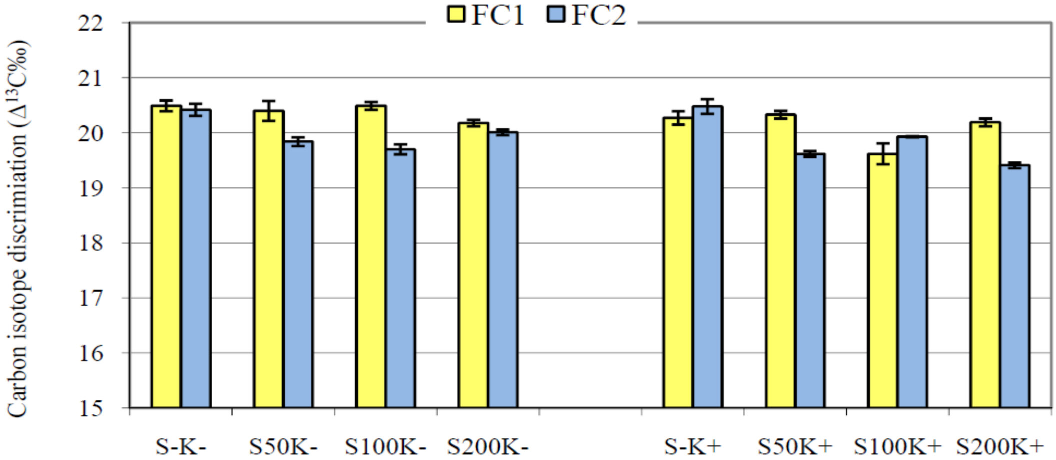

Figure 2. Carbon isotope discrimination ($\Delta^{13}C$‰) in leaves of barley grown under two watering regimes (FC) as affected by silicon (Si) and potassium (K) fertilizers.

Table 1. Dry matter yield (g/ pot) in different plant parts of barley grown under two watering regimes (FC) as affected by silicon (Si) and potassium (K) fertilizers

Treatment	**Leaves**			**Spikes**			**Whole plant**		
	FC1	**FC2**	*LSD*	**FC1**	**FC2**	*LSD*	**FC1**	**FC2**	*LSD*
Si^-K^-	6.13c,A	6.13e,A	*N.S*	7.80bc,B	8.58a,A	*0.47*	13.93bc,B	14.70ab,A	*0.67*
$Si_{50}K^-$	6.78ab,A	6.73a,A	*N.S*	7.43d,B	8.33bc,A	*0.50*	14.20abcB	15.05a,A	*0.66*
$Si_{100}K^-$	6.60ab,A	6.53abc,A	*N.S*	7.60c,A	8.25c,A	*N.S*	14.20abcA	14.78ab,A	*N.S*
$Si_{200}K^-$	6.13c,A	6.33cde,A	*N.S*	7.58cd,A	8.08d,A	*N.S*	13.70cd,B	14.40b,A	*0.68*
Si^-K^+	6.68ab,A	6.70ab,A	*N.S*	8.05a,A	7.98e,A	*N.S*	14.73a,A	14.68ab,A	*N.S*
$Si_{50}K^+$	6.88a,A	6.43bcdeA	*N.S*	7.73c,B	8.25c,A	*0.24*	14.60a,A	14.68ab,A	*N.S*
$Si_{100}K^+$	6.05c,B	6.48bcdeA	*0.1*	8.45a,A	8.40b,A	*N.S*	14.50ab,A	14.88ab,A	*N.S*
$Si_{200}K^+$	6.50b,A	6.20de,A	*N.S*	6.68e,B	8.58a,A	*0.40*	13.18d,B	14.78ab,A	*0.77*
LSD	*0.36*	*0.30*		*0.28*	*0.10*		*0.58*	*0.56*	

Means within a column (small letters) and within a row (capital letters) followed by the same letter are not significantly different (P > 0.05).

Table 2. Nitrogen yield (mg N/ pot) in different plant parts of barley grown under two watering regimes (FC) as affected by silicon (Si) and potassium (K) fertilizers

Treatments	**Leaves**			**Spikes**			**Whole plant**		
	FC1	**FC2**	*LSD*	**FC1**	**FC2**	*LSD*	**FC1**	**FC2**	*LSD*
Si^-K^-	32.6ab,A	27.7ab,A	*N.S*	99.4cd,B	110.5a,A	*7.9*	131.8cd,A	138.2a,A	*N.S*
$Si_{50}K^-$	33.3ab,A	29.9ab,A	*N.S*	115.0b,A	106.7ab,A	*N.S*	148.3ab,A	136.6a,A	*N.S*
$Si_{100}K^-$	32.1ab,A	25.9b,A	*N.S*	125.9a,A	108.4ab,B	*14.0*	158.0a,A	134.3a,B	*14.8*
$Si_{200}K^-$	27.6c,A	25.8b,A	*N.S*	107.3bc,A	117.0a,A	*N.S*	135.0c,A	142.8a,A	*N.S*
Si^-K^+	34.3a,A	32.8a,A	*N.S*	113.8b,A	100.0b,A	*N.S*	148.0ab,A	132.6a,B	*14.7*
$Si_{50}K^+$	34.3a,A	27.0b,B	*4.0*	109.3bc,A	113.4a,A	*N.S*	143.6,bc,A	140.5a,A	*N.S*
$Si_{100}K^+$	29.3bc,A	29.9ab,A	*N.S*	109.7b,A	107.5ab,A	*N.S*	139.0bc,A	137.4a,A	*N.S*
$Si_{200}K^+$	29.8abc,A	29.1ab,A	*N.S*	92.4d,B	110.9aA	*9.6*	122.2d,B	140.0a,A	*12.8*
LSD	*4.49*	*5.38*		*9.94*	*10.5*		*11.9*	*N.S*	

Means within a column (small letters) and within a row (capital letters) followed by the same letter are not significantly different (P > 0.05).

Table 3. Nitrogen use efficiency of added fertilizer (%NUE) in the whole plant of barley grown under two watering regimes (FC) as affected by silicon (Si) and potassium (K) fertilizers

	FC1	**FC2**	*LSD*
Si^-K^-	49.4d,B	61.2bc,A	*3.0*
$Si_{50}K^-$	64.6ab,A	66.2ab,A	*N.S*
$Si_{100}K^-$	67.9a,A	59.2c,B	*6.7*
$Si_{200}K^-$	52.6cd,B	65.2ab,A	*5.8*
Si^-K^+	60.9b,A	64.6bc,A	*N.S*
$Si_{50}K^+$	54.5c,B	70.7a,A	*5.7*
$Si_{100}K^+$	55.8c,B	64.1bc,A	*5.2*
$Si_{200}K^+$	50.1d,B	64.2bc,A	*4.4*
$LSD_{0.05}$	*0.016*	*0.012*	

Means within a column (small letters) and within a row (capital letters) followed by the same letter are not significantly different (P >0.05).

DISCUSSION

The present experiment was an attempt to monitor the beneficial effects of Si and/or K applications on growth and nitrogen uptake in barley plants grown under water and non-water stress conditions. Regardless of Si and K fertilizer treatments, no significant impact of watering regime on leaf DM was observed under prevailing experimental conditions. However, applications of Si, particularly at low and mild rates, or K significantly increased leaf dry matter production when grown under both watering regimes. Moreover, the beneficial effect of dual fertilizer applications on leaf dry matter production was more pronounced in plants grown under stress than those grown under non stress conditions. Although, the lower rate of Si (Si_{50}) in combination with K (K^+) had a positive impact on leaf DM, the sole application of potassium or silicon (at the afore-mentioned level) could be considered an optimal treatments in increasing leaf DM of barley plants grown under water stress conditions. However, taking into account that spikes are the most important plant part from productivity standpoint, sole applications of potassium (Si^-K^+) or in combination with silicon ($Si_{100}K^+$) could be considered optimal treatments for increasing dry matter yield of spikes as well as the whole plant of barley grown under water stress conditions.

Potassium has been reported to improve plant's resistance against drought stress and can alleviate water shortages in many crops (Marschner 1995; Moinuddin and Imas 2007; Kurdali et al., 2002; Kurdali and Al-Chammaa 2010). This is attributed to the K role in cell turgor control and metabolic activity (Beringer et al., 1983). Surya Kant and Kafkafi (2001) reported that drought tolerant plants try to accumulate K in plant parts before initiation of the stress to the extent of "luxury consumption" which is the insurance strategy of plants to withstand the forthcoming stress (Moinuddin and Imas 2007). Such plant adaptive strategy to water stress may serve to formulate plant management approach adapted to semi-arid environmental conditions (e.g., K fertilizer amendment before planting). On the other hand, the increased dry matter yield in silicon-fed barley is consistent with findings of other studies which show that silicon can promote growth, and even increase yields of several agricultural crop plants including rice (Chen et al., 2011), wheat (Mali and Aery 2008), maize (Kaya et al., 2006) and sugarcane (Savant et al., 1999). Many studies suggest that Si exerts its effect on certain metabolic processes in plants. Agarie et al., (1992) reported that the beneficial effect of Si on leaf dry matter yield in rice was attributed to maintenance of water status and photosynthesis along with protection of chlorophyll from destruction. On the light of dry matter data, the undertaken study indicated that the solely added K or in combination with adequate rate of Si were more effective in alleviating water stress and producing higher yield in barley plants than the solely added Si.

Leave's carbon isotope discrimination ($\Delta^{13}C$) in barley plants was affected by Si and or K fertilization as well as by the watering regime level under which the plants have been grown. In contrast to leaf DM yield, the effect of solely added Si or in combination with K on $\Delta^{13}C$ was more pronounced in plants grown in well watering regime than those grown under water stress conditions. It has been reported that $\Delta^{13}C$‰ is linearly related to the ratio (C_i/C_a) of intercellular to ambient CO_2 partial pressure in C3 plants. The C_i/C_a ratio is determined by leaf stomatal conductance and photosynthetic capacity (Farquhar et al., 1982). Farquhar et al., (1989) concluded that low $\Delta^{13}C$ is generally associated with low stomatal conductance. In this study, sole application of silicon ($Si_{50}K^-$ and $Si_{100}K^-$) or in combination with K ($Si_{50}K^+$, $Si_{100}K^+$ and $Si_{200}K^+$) to well watered barley significantly reduced leave's $\Delta^{13}C$. Such decrease reflects lower C_i/C_a ratios which result either from stomatal closure or from higher rates of photosynthetic capacity or a combination of both (Condon et al., 2002). For sole Si fed plants, lower C_i/C_a ratios could be resulted from lower stomatal conductance (i.e. lower $\Delta^{13}C$) and, from higher rates of photosynthetic capacity (i.e. higher dry matter yields). In dual fertilization treatments, such decreases could be resulted mainly from lower stomatal conductance (i.e. lower $\Delta^{13}C$) and, to a lesser degree from photosynthetic capacity (no significant increments in dry matter yields).

Low $\Delta^{13}C$ has been proposed as an indicator of high water use efficiency (WUE) in C3 plants (Farquhar and Richards, 1984), since a negative correlation between $\Delta^{13}C$ and WUE has been reported for wheat (Farquhar and Richards 1984), rice (Dingkuhn et al., 1991), barley (Isla et al., 1998) and various other crops (Knight et al., 1994). Therefore, it can be suggested, that sole applications of silicon or in combination with K to well watered barley had bifacial effects on WUE. Agarie et al., (1998) have shown that the transpiration from leaves of rice plants is considerably reduced by the application of silicon. Gao et al., (2004) also observed that the WUE in Si fed maize plants was significantly higher than that of non Si fed plants. The passive accumulation of Si through the xylem in barley grown under field conditions may be also related to WUE (Walker and Lance, 1991). As Si is deposited beneath the cuticle of the leaves forming a Si-cuticle double layer, the transpiration through the cuticle may be decreased by Si deposition (Ma, 2004). Therefore, the undertaken study may suggest that the beneficial effect of Si on WUE (i.e. lower $\Delta^{13}C$) in barley plants could be resulted from saving water loss by reducing transpiration rate and facilitating water uptake; consequently, increasing its use efficiency. On the other hand, the lower $\Delta^{13}C$ values in well watered plants compared with water stressed plants in $Si_{50}K^-$, $Si_{100}K^-$, $Si_{50}K^+$ and $Si_{200}K^+$ treatments were not associated with significant increments of leaf DM. Thus, such decreases could be mainly resulting from lower stomatal conductance which might be involved in reducing water loss and, consequently increasing WUE. Moreover, since no significant increment in leaf DM was observed in the $Si_{100}K^+$ grown under water stress conditions, its lower $\Delta^{13}C$ value might be also resulting from a lower stomatal conductance. Additional studies are needed to determine how silicon affects hydraulic resistance in barley as well as to clarify the mechanisms for inter-species differences in response to silicon application (Hattori et al., 2007).

Applied Si has been reported to interact favorably with other nutrients (N, P, and K) and offers the potential to improve efficiency in terms of yield response (Singh et al., 2005). There are many reports indicating that Si is beneficial for crops under drought stress through adjustment of the mineral absorption in many plant species including rice (Chen et al.,2011), sunflower (Gunes et al.,2008), maize (Kaya et al.,2006) and pigeonpea (Owino-Gerroh et al. 2005). In this study, NY in barley plants was affected by Si and/ or K fertilization as well as by the watering regime level under which the plants have been grown. The beneficial effect of Si and or K fertilizers on NY was more pronounced in spikes than in leaves, particularly under water stress conditions. Despite the beneficial effect of rising soil humidity on spike's NY enhancement in the non fertilized plants, applications of K or Si fertilizers to water stressed barley plants had relatively similar or even more positive effects on the afore-mentioned parameter as compared with well watered plants. In contrast to spike's DM, a mild rate of solely added Si (Si_{100}) was more effective in alleviating water stress and producing higher NY in barley plants than those of solely added K or than dual fertilizer application. The latter obtained data may indicte that K had a more beneficial effect than Si in enhancing seed yield (i.e spike DM) of barley plants grown under water stress conditions; while, Si seemed to be more effective than K in terms of seed quality improvement (i.e. spike's N). Although, addition of K along with a mild rate of Si resulted in a significant increase of spike's DM, the dual applications of K and Si, however, did not give rise to substantial increments of spike's NY. Considering that water is infrequently available for irrigation in semi-arid areas, our result would illustrate the importance of applying K or Si fertilizers to alleviate water stress occurring during growth period of barley grown under rain fed conditions.

Although the rising of soil humidity generally increased fertilizer nitrogen uptake (Ndff) and its use efficiency (%NUE) in barley plants, applications of K or Si fertilizers to water stressed barley induced significant increments in these parameters as compared with the control. The highest values were observed following single addition of silicon (Si_{50} and Si_{100}). Moreover, single addition of K also showed an elevated value of Ndff as well as NUE. Dual applications of Si and K, however, did not induce any substantial increments in these parameters compared with solely added fertilizers. Moreover, the effect of Si and/or K on soil N-uptake (Ndfs) was more pronounced in plants grown under water stress than those grown under non-stress conditions. Such an effect was relatively similar to that observed in fertilizer nitrogen uptake. These results highlight that Si or K is not only involved in amelioration of growth of barley plants, but can also improve nitrogen uptake and fertilizer nitrogen use efficiency particularly under water deficit conditions. Although barley is considered to be a relatively high drought tolerant crop, where it can grow with lesser soil moisture (Khalil et al., 2007), our findings may have important implications in the agronomic practice of improving nutrient efficiency in plants grown under water deficit conditions (Waraich et al., 2011), particularly by the application of Si and K fertilizers.

CONCLUSIONS

- Solely added K or in combination with adequate rate of Si were more effective in alleviating water stress and producing higher yield in barley plants than solely added Si.
- Silicon was found to be more effective than K in producing higher spike's N yield, particularly under water stress conditions.
- Silicon might be involved in increasing water use efficiency (i.e. lower $\Delta^{13}C$) through reducing transpiration rate from leaves and facilitating water uptake.
- Applications of K or Si fertilizers to water stressed plants resulted in significant increments of fertilizer nitrogen uptake and its use efficiency.

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