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Interactions between Silicon and NaCl-Salinity in a Soilless Culture of Roses in Greenhouse

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Summary

In an experiment with roses grown hydroponically, a low (0.3 mM) and a high (2 mM) level of silicon were combined with a low (0.8 mM) and a high (40 mM) NaCl concentration in the nutrient solution supplied to the crop. The aim of the experiment was to detect possible beneficial effects of silicon on plant growth, yield and flower quality and to test whether the deleterious effects of NaCl-salinity on roses could be mitigated by increasing the Si concentration in the root zone. Silicon was added to the nutrient solution in form of a water-soluble potassium silicate compound. The electrical conductivity (EC) in the nutrient solutions with low and high NaCl concentrations was 1.8 and 6.1 dS m^{-1}, respectively, while the corresponding values in the drainage water, which indicated the salinity status in the root zone, were 2.3 and 8.2 dS m^{-1}, respectively.

The increase of the NaCl concentration in the root zone restricted the above-ground vegetative weight of roses, the number of flowers per plant and the mean flower weight and stem length. The increased supply of Si significantly enhanced the vegetative growth of roses at both salinity levels, improved the overall appearance of the plants and resulted in a higher number of marketable flowers per plant at the low salinity level. However, silicon was unable to ameliorate the adverse effects of NaCl-salinity on flower production and quality. The increased Si concentration in the root environment restricted the translocation of Na and Cl to the young leaves of roses. However, net photosynthesis, stomatal conductance and transpiration rate were not affected either by Si or by NaCl-salinity at the concentration levels tested in this study. This finding indicates that the stimulation of the vegetative growth of roses by Si under conditions of high external salinity was not due to mitigation of toxic Na or Si effects on the photosynthetic apparatus.

Key words. *Rosa×hybrida* – hydroponics – silicon – salt stress – beneficial elements – yield responses – flower quality

Introduction

Although silicon is not considered an essential nutrient for higher plants, its beneficial effects on plant growth and development have been proven by numerous studies concerned with its role in plant nutrition (MARSCHNER 1995; EPSTEIN 1999). The favourable effects of silicon on the growth of rice and various other *Poaceae* are unanimously recognized (MITSUI and TAKATOH 1963; SAVANT et al. 1997; EPSTEIN 1999), although the mechanisms underlying this response are not completely clear yet. However, not only *Poaceae* but also many dicotyledonous species seem to respond positively to an enhanced supply of Si (e.g. ADATIA and BESFORD 1986; LI et al. 1989; SAVVAS et al. 2002). One of the most known effects of Si on plants is the enhanced resistance to powdery mildew and presumably to several other fungal and bacterial pathogens (BLANGER et al. 1995). This effect has been ascribed to deposition of solid amorphous silica ($SiO_2.nH_2O$) in cell walls, which enhances the mechanical strength of the epidermal cell layers (JONES et al. 1967; BLAICH and GRUNDHÖFER 1998). Due to this effect, various natural Si forms are widely used as plant protection agents in organic agriculture (FRITZ and KÖPKE 2000).

In addition to the impact of Si on plant protection, various other beneficial effects of Si have been reported, such as amelioration of the adverse effects of Al and Mn toxicity to plants (WILLIAMS and VLAMIS 1967; JARVIS and JONES 1987; HODSON and EVANS 1995; MA et al. 1997), improvement of water use efficiency (GAO et al. 2004; HU and SCHMIDHALTER 2005), as well as enhancement of the salt tolerance (MATOH et al. 1986; SCHMIDHALTER and OERTLI 1993; LIANG et al. 1996). EPSTEIN (1999), implicates a possible effect of Si on plant water relations in the mitigation of salt damage by Si. Nevertheless, the reports on the interactions between Si and salinity are rather limited in the literature. LIANG (1999), examined possible interactions between Si and NaCl in barley with respect to the uptake of Na and the activity of some enzymes related to plant protection against stress conditions. The results indicated that Si is capable of diminishing the accumulation of Na in the plant tissue, but were rather not conclusive with respect to the responses of enzyme activity to Si. Nevertheless, ZHU et al. (2004) found that the addition of 1 mM Si to the nutrient solution was capable of ameliorating the adverse effects of NaCl-salinity on cucumber by enhancing the activity of antioxidant enzymes in leaves. In contrast, SAVVAS et al. (2002) did not observe any mitigating effect of Si (2 mM) on salinity imposed by increasing the concentration of major nutrients in a soilless culture of gerbera. However, in that experiment the nutrient solution supplied to the control plants was prepared using tap water, which contained 0.2 mM Si. Thus, the results were not conclusive as to whether the absence of any interaction between Si and salinity was due to the source of salinity (increased concentrations of major nutrients) or due to supply of some Si even in the control treatment.

In soil grown crops, an inadequate supply of Si is rather unusual, due to the abundance of Si in the earth's crust. However, in commercial hydroponics, plants are commonly grown on inert substrates and, therefore, their supply with Si depends mainly on the concentration of this element in the raw water used to prepare nutrient solution. On the other hand, if the response of plants to Si is quantitative, the external Si concentration may be more rapidly and effectively increased up to an optimal level in hydroponics. Currently, the inclusion of silicon to the nutrient solution is a standard recommendation in soilless cultures of some plant species, particularly roses, cucumber, and zucchini (DE KREIJ et al. 1999; SONNEVELD 2002). The positive role of Si on soilless-grown cucumber is well established (ADATIA and BESFORD 1986). However, in case of roses, this practice is based more on experience rather than on published research results. Therefore, this paper was designed to provide insight into the effects of Si, NaCl, and their interactions on soilless grown roses (*Rosa×hybrida*).

Materials and Methods

Rooted cuttings of rose (*Rosa×hybrida*) raised in jiffy pots were transferred to bags filled with pumice, which were placed into channels connected to fully a automated hydroponic installation. The experiment was conducted in a glasshouse located in Arta (lat. 39 ° 7 'N, long. 20 ° 56 'E), Greece. The channels were distributed over 12 independently operating hydroponic systems, which constituted the experimental units. Each experimental unit consisted of two channels, 5 m in length, and each channel accommodated 4 bags with 10 plants per bag. Two different rose cultivars were planted, particularly 'First Red' and 'Bianca' , which were planted in the two different channels of each experimental unit. The plants were pruned by pinching and bending down all weak stems to maximize the photosynthesizing leaf area. Excessively high summer temperatures were controlled by passive ventilation and shading screens. Trickle irrigation was automatically applied using a suitable computer program, at intervals depending on solar radiation intensity. The drainage water was left to run off freely.

Four different nutrient solution treatments were established in a randomized complete blocks design with three blocks, which differed in the Si and NaCl concentrations, while the levels of all nutrients was identical. In particular, a low (0.3 mM) and a high (2 mM) Si concentration were combined with a low (0.8 mM) and a high (40 mM) NaCl level in the nutrient solution supplied to the plants. The low Si and NaCl levels originated exclusively from the raw water. The increased NaCl and Si concentrations were attained by adding NaCl and a liquid potassium silicate compound ($SiO_2.2KOH$) (SONNEVELD 2002), respectively. The potassium silicate compound had a strong alkaline reaction and was, therefore, delivered from a separate stock solution tank. The nutrient concentrations in the basic nutrient solution are given in Table 1, while the pH was set at 5.6 in all treatments.

The rose cuttings were planted on January 21, 2004, and the experimental treatments were initiated on April 22, 2004. Harvesting of rose flowers started on April 19, 2004 and lasted up to September 22, 2004, when the experiment was terminated. During the entire growing period, the harvested flowers from all treatments were counted, weighed and graded. Furthermore, the length of all flower stems was measured throughout the experiment. The effects of Si and NaCl-salinity on the vegetative plant growth were investigated by sampling the entire shoot of two plants per experimental unit at crop termination and determining their fresh weight. Furthermore, samples of drainage solution and young leaves of 'Bianca' (upper three leaflets from mature leaves) were collected 15, 54, 98, and 147 days after treatment initiation and analysed to determine the Na and Cl concentrations. In the samples of drainage solution, the Si concentration was also determined.

Gas exchange measurements were conducted at 10 plants per experimental unit from 17 to 22 September 2004, using a LCi Portable Photosynthesis System (ADC BioScientific Ltd.). These measurements included net assimilation rate ($\mu mol\ CO_2\ m^{-2}\ s^{-1}$), transpiration rate ($mmol\ m^{-2}\ s^{-1}$) and stomatal conductance for CO_2 diffusion ($mmol\ m^{-2}\ s^{-1}$). All measurements were conducted in leaves of the same physiological stage (3rd or 4th node from the top of the stem) at the same daytime (10.00–11.30 a.m.) and under identical conditions (photon flux density incident on leaf surface $\approx 800\ \mu mol\ m^{-2}\ s^{-1}$ and leaf surface temperature ≈ 30 °C).

All leaf samples were dried at 65 °C to constant weight and ground. Sodium was extracted by means of 10 ml of HCl 2 M and 1 ml of HNO_3 6 N after dry ashing of 0,2 g of ground tissue at 550 °C for 5 h. The determination of Na in both the plant tissue extracts and the drainage solution as well as that of silicon in the drainage solution was performed using an atomic absorption spectrophotometer (Perkin Elmer AA100). For Na, an optimum mixture of air – C_2H_2 was used, whereas for Si determination the oxidant – fuel mixture was comprised of N_2O and C_2H_2. To extract chloride from the plant tissue samples, 1 g of dried and ground material was transferred into porcelain crucibles and 2 g of CaO were added. Minimum amount of distilled water was used in order to prepare a homogenized paste. The crucibles were then put in the oven (300 °C, 4 h). After cooling to room temperature, the dry material was processed with distilled water and transferred to a Whatman 41 filter. The crucible and the filter were washed several times with distilled water and all the filtrates were collected and diluted to a final vol-

Table 1. Nutrient concentrations in the basic nutrient solution.

Macronutrient	mM	Micronutrient	µM
K	4.70	Fe	25.0
Ca	3.15	Mn	10.0
Mg	1.50	Zn	4.0
NH_4^+	1.30	Cu	0.7
NO_3^-	11.20	B	25.0
SO_4^{2-}	1.10	Mo	0.5
P	1.20		

ume of 100 ml. Chloride was determined in both the plant tissue extract and the drainage solution following the Mohr method, which involves titration of each sample with a standard $AgNO_3$ solution (0.01 N) in the presence of K_2CrO_4, while using distilled water as blank. A calibration curve was constructed by titration of standard chloride solutions with the same $AgNO_3$ standard solution which was used for the samples.

The data were subjected to factorial analyses of variance using the PlotIT3.2® work package. The significance of differences between the treatment means in Fig. 1–4 is indicated by vertical bars depicting ± standard errors.

Results

As shown in Fig. 1, the actual concentration of Si in the drainage solution ranged between 0.18–0.41 mM in the treatments without Si addition, but was raised to 1.57–1.93 mM when potassium silicate was injected into the nutrient solution supplied to the plants (irrigation solution). Within each Si level in the irrigation solution, the concentration of silicon in the drainage solution tended to be lower at the high external NaCl level. The concentrations of Na and Cl in the drainage solution ranged between 51–77 mM and 59–74 mM, respectively, when the irrigation solution contained 40 mM NaCl (Fig. 2). The corresponding values in the low NaCl-salinity treatments were 0.5–4.1 mM Na and 1.4–8.5 mM Cl, respectively. The enrichment of the irrigation solution with Si had no effect on the Na and Cl concentrations in the root zone of roses, as indicated by the values measured in the drainage solution.

The increase of NaCl-salinity in the root zone of roses to the levels shown in Fig. 2 restricted significantly the above-ground vegetative weight of the plants, the total number of flowers and the number of marketable flowers per plant (Table 2). Both cultivars were affected nearly to the same degree by salinity. The increase of Si concentration in the solution supplied to the plants enhanced the above-ground vegetative growth of roses in both levels of external NaCl concentration but had no significant effect on the number of flowers per plant. However, the number of marketable flowers per plant was significantly enhanced when an elevated Si supply was combined with low NaCl-salinity. In contrast, the enhanced Si concentration in the root zone had no effect on the number of marketable flowers per plant when the high Si level was combined with exposure of the plants to high NaCl-salinity. This interaction between Si and salinity was significant at a confidence level of 0.05. In addition to the quantitative effects of Si on the vegetative growth of roses, the overall appearance of the plants was also influenced. Thus, the older leaves of the Si-treated plants were darker green, had an obviously rougher appearance and were less prone to the senescence process compared to those of the low-Si plants.

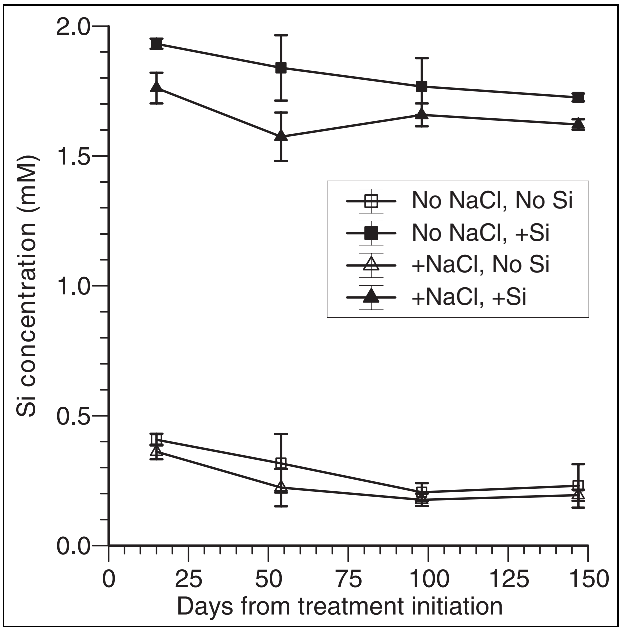

Fig. 1. Concentration of Si in the drainage solution at four sampling dates during the experiment. Vertical bars depict ± standard errors of means of 3 measurements.

With respect to quality characteristics, salinity restricted significantly both the length and the mean weight of the flower (Table 3). In contrast, the external Si level had no effect on any of these flower characteristics. The flowers of 'Bianca' had longer stems and a higher mean weight as compared to those of 'First Red' , regardless of salinity or Si treatments.

The concentration of Na in the leaf of roses increased as the external NaCl concentration was elevated but the increase was appreciably lower as the Si supply was enhanced (Fig. 3). The difference in the leaf Na concentration between the salinized plants supplied with extra silicon and those not receiving extra Si via the irrigation solution was highly significant in the last two sampling dates. Similar results were obtained also for the leaf Cl concentration, which increased to a noticeably lower level in the last two sampling dates when the elevation of the external NaCl-salinity was accompanied by an enhancement of the Si-supply (Fig. 3).

Neither salinity nor Si had a significant effect on gas exchange in roses, as indicated by the measurements of net assimilation rate, leaf transpiration rate and stomatal conductance (Fig. 4). The effects of salinity and Si on gas exchange were not depending on the cultivated variety.

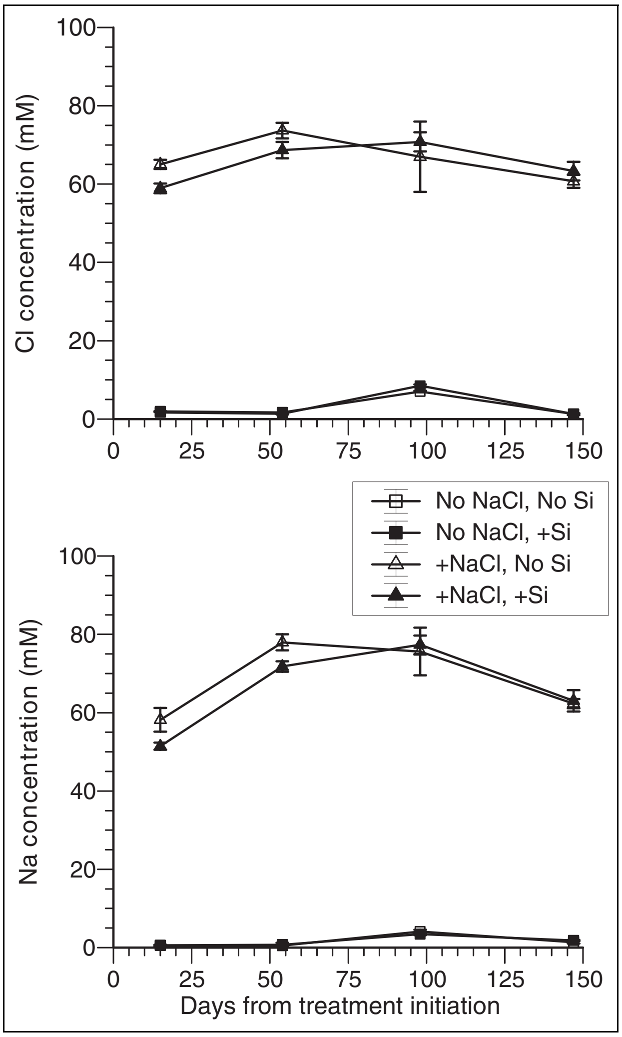

Fig. 2. Concentrations of Na and Cl in the drainage solution at four sampling dates during the experiment. Vertical bars depict ± standard errors of means of 3 measurements.

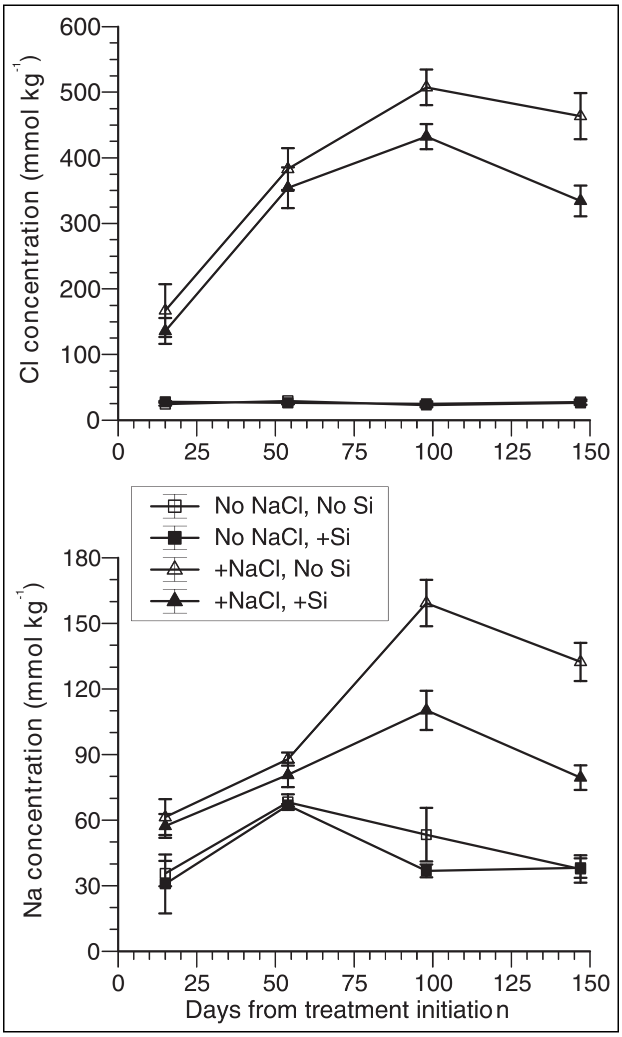

Fig. 3. Sodium and chloride concentrations in the leaf of roses as influenced by NaCl and Si supply via the nutrient solution. Vertical bars depict ± standard errors of means of 3 measurements.

Discussion

The results presented in this study suggest that an increase of silicon concentration up to 1.5–2.0 mM in the root zone of roses is capable of enhancing their vegetative growth, regardless of external salinity level. This finding is in agreement with previous reports that Si promotes the growth of various higher plant species (Mitsui and Takatoh 1963; Miyake and Takahashi 1978, 1983; Savant et al. 1997; Zhu et al. 2004). The simulation of growth by silicon may be either indirect, owing to the protective effects of Si against pathogens (Blanger et al. 1995; Blanger and Benyagoub 1997), or direct, originating from implications of Si to both morphological changes and physiological processes in plants. The impact of an elevated Si supply on morphological leaf attributes originate predominantly from its enhanced deposition to the cell walls in form of solid amorphous silica ($SiO_2.nH_2O$) and opal phytoliths (Hodson and Sangster 1988; Inanaga and Okasaka 1995). Such morphological alterations, which reinforce the cell walls, may result in enhanced leaf thickness, erectness and rigidity (Adatia and Besford 1983), and hence in better disposed leaves for light interception (Epstein 1999). This consideration is in agreement with the overall appearance of the rose plants receiving nutrient solution with enhanced Si concentration in the present study. The possible involvement of Si in physiological processes was indicated in our study by the darker leaf colour and the slackening of the senescence process in the older leaves, which agree with the observations of Adatia and Besford (1986) in cucumber treated with increased Si concentrations. Nevertheless, our knowledge regarding the physiological actions of Si in higher plants is still insufficient, although such indices are not lacking. Thus, for instance, the activity of RuBP-carboxylase was 50 % higher in the leaves of cucumber grown in recirculating nutrient solution enriched with Si (Adatia and Besford 1986). Carpita (1996) referred to incorporation of Si into cell walls of grasses but was unable to give any further information regarding the biochemistry of this process and the chemical interaction of Si with other constituents of cell walls. Epstein (1999) cited some more refer-

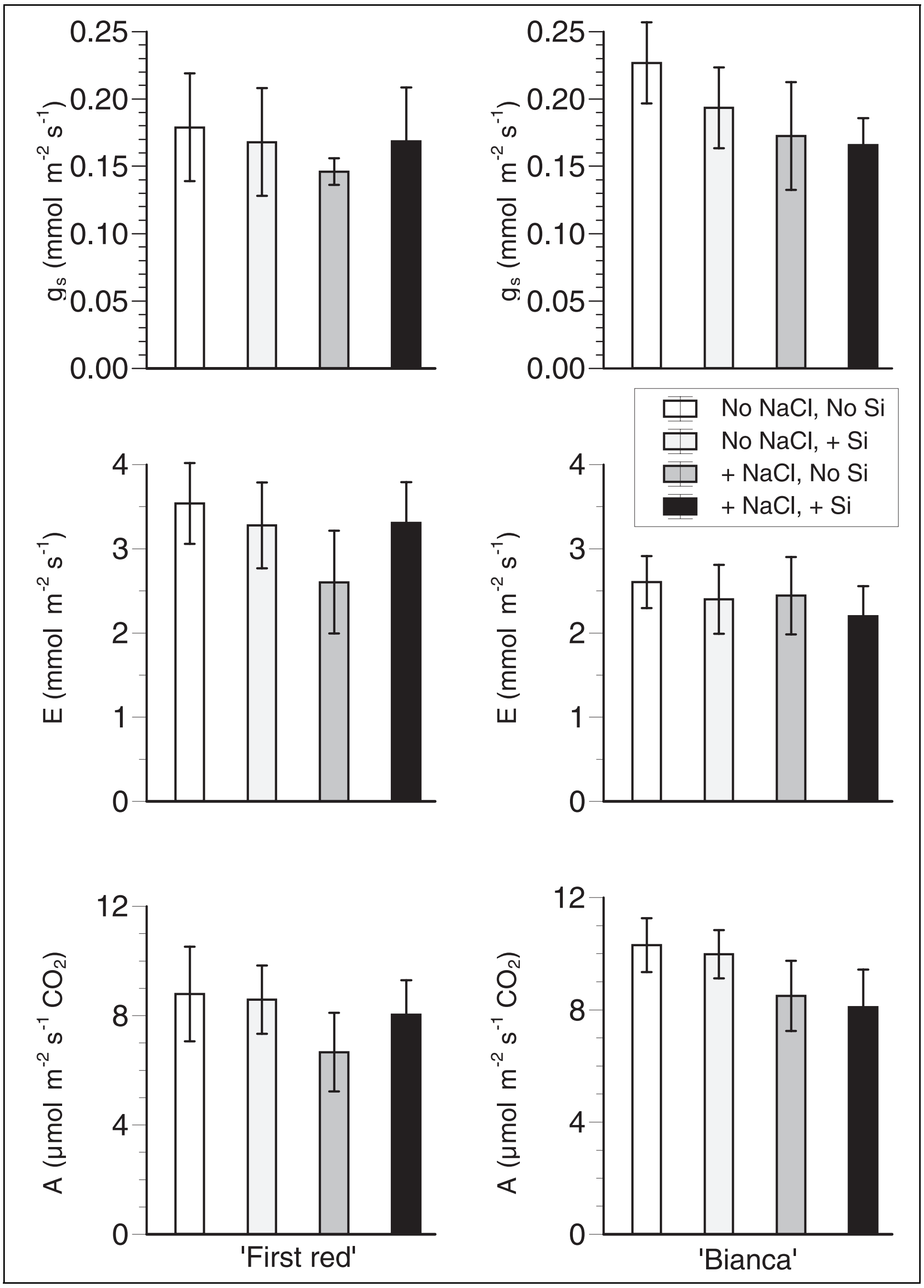

Fig. 4. Net assimilation rate, transpiration rate, and stomatal conductance in the leaf of two rose cultivars as influenced by NaCl and Si supply via the nutrient solution. Vertical bars depict ± standard errors of means of 12 measurements.

ences to research results indicating possible implications of Si to biochemical processes. However, the currently available knowledge is still insufficient to highlight the key role of Si to plant metabolism processes that are capable of retarding leaf senescence and promoting plant growth. The slow-down of leaf senescence may imply an involvement of Si in the metabolism and translocation of plant hormones such as cytokinin, but evidence supporting this consideration is still lacking. Alternatively, the retardation of the senescence process in plants treated with Si might be due to enhanced activity of antioxidant enzymes, as reported by Liang et al. (2003) and Zhu et al. (2004).

Despite the stimulation of the vegetative growth by Si, the number of flowers per plant, the length of the flower stem and the mean flower weight were not increased by the enhanced silicon supply. No convincing explanation can be found for the fact that the enhancement of the vegetative growth by Si was not reflected in an increased production of flowers. Adatia and Besford (1996) also report on stimulation of the vegetative growth of cucumber by Si which was not accompanied by enhanced fruit yield. Nevertheless, the elevated supply of Si improved the quality of the rose flowers when salinity was low. This interaction between Si and NaCl-salinity is similar to that reported by Savvas et al. (2002) for gerbera, although in the last case salinity was imposed by adding extra amounts of macronutrient fertilizers.

Our results clearly indicate that Si is capable of suppressing the uptake and translocation of Na and Cl to the

Table 2. Effect of cultivar, salinity, and silicon on above-ground vegetative growth and flower yield of roses grown hydroponically.

	Above-ground vegetative weight (g plant^{-1})	Flowers per plant (total)	Flowers per plant (marketable)
Low NaCl, low Si	259.4	74.4	49.1
Low NaCl, high Si	301.5	84.5	57.7
High NaCl, low Si	116.3	46.5	16.1
High NaCl, high Si	142.7	44.5	16.2
Variety	-	n.s.	n.s.
Salinity	***	***	***
Si	*	n.s.	*
Salinity×Si	n.s.	n.s.	*

n.s.: not significant at a confidence level of 0.05.

Table 3. Effects of cultivar, salinity, and silicon on qualitative characteristics of rose flower in soilless culture.

	Flower stem length (cm)	Mean flower weight (g)
Low NaCl, 'First red'	50.5	29.3
Low NaCl, 'Bianca'	55.2	36.2
High NaCl, 'First red'	44.0	26.8
High NaCl, 'Bianca'	49.9	32.5
Variety	***	***
Salinity	***	**
Si concentration	n.s.	n.s.
Variety×salinity	n.s.	n.s.

n.s.: not significant at a confidence level of 0.05.

photosynthetically active leaves of roses under conditions of high external NaCl-salinity. A similar effect of Si on Na uptake has been reported also by MATOH et al. (1986) for rice, LIANG (1999) for barley, and YEO et al. (1999) for rice, while STAMATAKIS et al. (2003) found that the addition of 2 mM Si in a conventional nutrient solution significantly reduced the Na and Cl concentrations in the leaf of tomato. The suppression of Na and Cl uptake by Si may be beneficial to horticultural plants responding to salinity by salt exclusion, if the efficiency of their exclusion mechanisms is low and the growth suppression caused by salinity is due to excessively high salt concentrations in the photosynthesising leaves. The modern rose cultivars are rated moderately sensitive to salinity in soilless culture (CABRERA and PERDOMO 2003) but their exclusion mechanism for Na and Cl seem to be highly efficient, as suggested by SONNEVELD et al. (1999) and indicated by our results. Hence, the reduction of rose growth imposed in our study by high salinity in combination with low Si supply was presumably not due to impairment of biochemical processes by excessive tissue Na and Cl concentrations. Consequently, although the uptake of Na and Cl was suppressed by silicon in the treatment combining high salinity with enhanced Si supply, this effect was presumably hardly beneficial to plant growth and yield. The above consideration is supported by the gas exchange data, which clearly show that the Na and Cl levels measured in the leaf of roses exposed to high external NaCl but low Si concentrations were not high enough to affect photosynthesis and stomatal conductance. It is well known that plant growth may be restricted by salt or drought stress as an adaptation to the adverse external conditions, without concomitant changes in net photosynthesis, stomatal conductance and transpiration rate (SCHMIDHALTER et al. 1998; MUNNS 2002).

In conclusion, the results presented in this study suggest that an enhanced Si supply is beneficial to roses grown in soilless culture, because it stimulates the vegetative growth and improves the flower quality. In soil-grown crops, the availability of Si to the plants is in most cases not a limiting factor, because silicon is abundant in the earth's crust. However, when the plants are grown on inert substrates, their supply with Si depends mainly on the concentration of this element in the raw water used to prepare the nutrient solution. Hence, to ensure a sufficient supply of silicon to roses grown on chemically inactive substrates, it is recommended to include this element to the nutrient solution supplied to the crop.

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