PHYSIOLOGICAL EFFECTS OF SILICA ON GROWTH AND PROTEIN CONCENTRATION IN WHEAT (*Triticum aestivum* L.)

by

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INTRODUCTION

Silicon is the second most abundant element on earth and comprises approximately 28% by weight of the earth's crust. It is one of the primary elements involved in soil genesis. Soil weathering and soil composition are, in part, controlled by silicon. Most soils of the great wheat and corn belts of the world are composed of silicate clays. The importance of silica in plant growth and yield has yet to be established. The present study attempted to explore some aspects of the role of silicon in the growth and nutrition of wheat.

REVIEW OF LITERATURE

Silicon is generally not regarded as an essential element for higher plants. It has been assumed to play certain functions in grasses and, in some cases, it was reported to meet some criteria for essentiality (Lipman, 1938; Sommer, 1926). One function assigned to silicon relates to resistance to certain pathogens in cereals. Increasing silicon content in rice leaves appeared to increase resistance to brown spot, stem rot, and blast disease (Ota, Kobayahi, and Kawaguchi, 1957; Yoshida, Ohnishi, and Kitagishi, 1962). A relationship also seemed to exist between the silicon content of a plant and its resistance to certain insect pests. Some examples are resistance of wheat to Hessian fly (Mitler, et al., 1960; Refai, Jones, and Mitler, 1955) and resistance of rice to stem borer (Ota, Kobayah, and Kawaguchi, 1957).

Plants absorbed differing amounts and proportions of silicon from a soil according to their species. Typically, gramineous species contained ten to twenty times as much silica as leguminous species (Baker, Jones, and Wardrop, 1961). Individual plants of the same species absorbed different amounts of silicon when grown in different soils (Jones and Handreck, 1965; Islam and Saha, 1969).

In solution, silicon was present at pH 9 and below as monosilicic acid ($Si(OH)_4$) (Alexander, et al., 1954). Saturated solutions of monosilicic acid contained 130-140 ppm SiO_2. In pure aqueous solutions, solubility was independent of pH between 2 and 9 (Alexander, et al., 1954). However, in soil solutions, monosilicic acid solubility decreased with an increase in pH from 4 to 9 (Beckwith and Reeve, 1964). This was attributed to increased adsorption of monosilicic acid by iron and aluminum oxides with increasing pH (McKeague and Cline, 1963b). Thus, the concentration of monosilicic acid in soil solutions was dependent upon pH-controlled adsorption reactions.

Soil solutions contained as little as 7 ppm SiO_2 and as much as 80 ppm SiO_2 (Jones and Handreck, 1965; McKeague and Cline, 1963a). Soil solution extraction procedures affect the final concentration of SiO_2 in solution. Extracting soils at field capacity, either by the use of a pressure cell device (Jones and Handreck, 1965) or by displacement with water (McKeague and Cline, 1963a), were effective procedures for obtaining consistent results. Soils extracted repeatedly maintained a steady concentration of silica in solution (Jones and Handreck, 1965).

Silica was taken up by the plant as monosilicic acid and transported in the transpirational stream in that form (Handreck and Jones, 1965; Hartley and Jones, 1972; Jones and Handreck, 1967; Lewin and Reiman, 1969). As water was transpired, the concentration of silica increased until it polymerized and eventually deposited as solid opal ($SiO_2 \cdot nH_2O$) (Jones and Handreck, 1965; Smithson, 1958). The greatest deposition of silica occurred in those plant parts from which the greatest quantity of water transpired. Lanning et al. (1958) determined that the wheat leaf sheath contained five times the silica concentration of the stem. Numerous other studies found the largest portion of deposited silica in the leaves and inflourescences of a number of cereal grasses. Within the leaf, silica impregnated the cell walls of epidermal cells and all parts of the stomata (Jones, Milne, and Wadham, 1963). Specialized silica cells almost completely filled with silica were observed in the leaves of several grasses (Parry and Smithson, 1957, 1958).

Silica and manganese interact in wheat and other Gramineae. When silica was added to culture solutions, manganese concentration in the roots and vegetation decreased (Vlamis and Williams, 1967). Cereal grasses normally show a narrow range of manganese tolerance. When Vlamis and Williams (1967) varied the concentration of manganese in nutrient solutions from 0 to 5 ppm, toxicity symptoms appeared as brown lesions on the leaves at high manganese levels with barley but not with wheat. Addition of silica to the nutrient solution increased the yield of wheat and barley 50% and 150%, respectively. Toxicity symptoms were no longer present; silica apparently eliminated the toxic effects of manganese in barley. The increased yield of wheat was caused by an alleviation of toxic effects, though toxicity symptoms were not present, or it was a direct beneficial effect of silica.

MATERIALS AND METHODS

Experiment 1A

Seeds of a spring wheat (*Triticum aestivum* L. var. 'Chris') and a high protein selection of winter wheat (*Triticum aestivum* L. 'Triumph x Atlas 50') were planted in vermiculite. The spring wheat seedlings were transplanted to nutrient solutions one week after germination. The winter wheat seedlings were placed in vernalization chambers at 4 C for six weeks. After vernalization, the winter wheat seedlings were transplanted to nutrient solutions.

Treatments were three $MnSO_4 \cdot H_2O$ levels, 5, 50, and 500μM, and two $NaSiO_3 \cdot 9H_2O$ levels, 0 and 5mM. Six seedlings were secured in 2-liter polystyrene containers holding nutrient solution and one Si:Mn treatment. The nutrient solution (Hoagland and Arnon, 1950) provided 5mM KNO_3, 5mM $Ca(NO_3)_2$, 2mM $MgSO_4$, and 1mM KH_2PO_4. Micronutrients were supplied at the levels suggested by Johnson et al. (1957). Iron was supplied by twice weekly additions of 1 ml of 0.6% $FeSO_4 \cdot 7H_2O$-0.4% tartaric acid solution to each container. The nutrient solutions were adjusted twice weekly to pH 5.0 with HCl and NaOH. Nutrient solutions for all treatments were replenished weekly. The six Mn x Si treatments were replicated three times in a randomized complete block experimental design.

Plants were grown to maturity in growth chambers maintained at 25$\pm$ 1 C and 15 $\pm$ 1 C day-night temperature with a 16-hour light period and an 8-hour dark period. Light intensity was 30,000 lux and relative humidity was approximately 40%.

Plasticware was used in all procedures to avoid Si contamination. All items were cleaned successively in 0.1 N EDTA, 1.5 N HNO_3, and deionized distilled water. Reagent grade chemicals were used for preparing the nutrient solutions.

Plants were harvested at maturity and separated into grain, vegetation (leaves, stems, and chaff), and roots. All parts were dried to constant weight at 70 C, weighed, and ground to 20-mesh size. Grain nitrogen concentration was determined by the Kjeldahl procedure. A nitrogen -to- protein conversion factor of 5.7 was used. Silica content was determined by a modified NaOH fusion procedure described by Kilmer (1969). A 500-mg sample of plant material was wet-ashed in a 1:1:1 mixture of nitric acid, perchloric acid, and water. Manganese concentration was subsequently determined by atomic absorption spectrophotometry.

Experiment 1B

A separate experiment was conducted with three $MnSO_4 \cdot H_2O$ levels of 5, 0.5, and 0.0 μ*M*. All other procedures, conditions, and analyses were as described for Experiment 1A.

Experiment 2

Seeds of eight winter wheat varieties (Table 1) were germinated in moist vermiculite. One week after germination, the winter wheat seedlings were placed in a vernalization chamber kept at 4 C. Five weeks later, seeds of four spring wheat varieties (Table 1) were planted in polystyrene pots containing silica sand. After a six-week vernalization period, the winter wheat seedlings were transplanted to similar containers.

Treatments were three silica levels, 0, 80, and 400 ppm Si as $NaSiO_3 \cdot 9H_2O$. These levels of silica were based on the amount of silica sand contained in each pot and were considered to be control, medium, and high concentrations, respectively.

Two or four seedlings were grown in each pot, depending upon the number of seedlings available per variety. The thirty-six Si x variety treatments were replicated three times in a randomized complete block experimental design.

Table 1. High and low protein wheat varieties used in Experiment 2.

Variety	Protein Type
Winter Wheat Varieties	
Triumph x Atlas 50	Low
Triumph x Atlas 50	High
Atlas 66	High
Lancota	High
T. aestivum x *A. elongatum*	High
Atlas 50	High
White Wheat*	High
Sage	Standard
Spring Wheat Varieties	
Chris	Standard
Turgidum	High
Durum	High
Spring Wheat x Turgidum	High

*The white wheat was not completely vernalized. Consequently, the data obtained for this variety was not used in the analysis.

Nutrient solutions containing the three silica treatments were added to each pot three times at two-week intervals beginning two days after transplanting the winter wheat. The pH of all the sand cultures was adjusted weekly with H_2SO_4 to pH 5.0. Iron was supplied as 0.6% $FeSO_4 \cdot 7H_2O$-0.4% tartaric acid added to the water supplied to the plants daily.

Plants were grown to maturity in a greenhouse maintained at approximately 25-30 C day temperature and 15-20 C night temperature. Plants were harvested at maturity and separated into grain, vegetation (leaves, stem, and chaff), and roots. The stems and roots were rinsed in distilled water to remove any adhering particles of silica sand. All parts were dried to a constant weight at 70 c and weighed. Twelve vegetation samples (for Si analysis) and all grain samples were ground to 20-mesh size. Analysis of Kjeldahl nitrogen and silica content were by methods described in Materials and Methods for Experiment 1.

Experiment 3

Soil samples were taken during June 1975 at the Kansas locations listed in Table 2 where the 1975 Kansas Winter Wheat Performance Tests were growing. At each location four soil samples were taken to a 15 cm depth randomly from each of four replications. The four samples from each replication were combined and mixed to constitute one soil sample from each replication. All soil samples were analyzed for total silica content, available profile nitrogen and silica concentration in the soil solution. Total silica was determined by the NaOH fusion method described by Kilmer (1969). Available profile nitrogen analysis was performed by the Kansas Agricultural Experiment Station Soils Testing Laboratory. Silica concentration in the soil solution was determined by the colorimetric procedure of Morrison and Wilson (1963). Soil

Table 2. Areas and locations in Kansas where soils were sampled in Experiment 3.

Area	Location
North-east	Manhattan
	Powhattan
South-east	Parsons
North-central	Hays
	Belleville
South-central	Hutchinson
	St. John
North-west	Colby
West-central	Tribune
South-west	Garden City
	Minneola

solutions were extracted from each soil three times (except soil samples from Belleville and Powhattan which were extracted once). Soil solutions were extracted by placing 40 or 60 g of oven dry soil in vertical 1.25-cm. diameter plexiglass cylinders. A measured quantity of deionized distilled water was added to the top of each cylinder. Excess water which had passed through the soil was collected and measured. The difference between the quantities added and collected from the soil in each cylinder was considered to be the water holding capacity of the soil. This quantity of water was then added to each cylinder containing soil and allowed to displace the soil water which was then collected and analyzed for silica concentration.

Experiment 4

A high protein winter wheat (var. 'Atlas 66') was grown in sand cultures in a greenhouse (Materials and Methods, Experiment 2). Treatments were three levels of SiO_2, 0, 80, and 400 ppm, added as $NaSiO_3 \cdot 9H_2O$. Leaf and glume samples were removed from the plants grown at the three silica levels. Samples were taken at maturity and air dried. Leaf and glume surfaces were examined for anatomical differences caused by silica nutrition using a scanning electron microscope.

Experiment 5

Seeds of spring wheat (var. 'Chris') were germinated for one week in moist vermiculite. The seedlings were transplanted to polystyrene containers holding nutrient solution (Experiment 1). Seedlings were removed from the nutrient solution after one week and the roots were severed 2.5 cm below the mesocotyl with a razor blade. The seedlings were then sealed in a Fischer

Brand potometer containing nutrient solution plus the following levels of Si as $Na_2SiO_3 \cdot 9H_2O$: 0.0, 8.25, 17.5, 35.0, 70.0, and 140.0 ppm. Transpiration rates of the cut seedlings were then measured in mlH_2O/hour. Electrical conductivity of the nutrient solutions containing the various levels of Si was measured using a conductivity bridge.

RESULTS

Experiment 1A

Small brown lesions appeared as toxicity symptoms on the leaves of both the spring and winter wheat plants grown in nutrient solutions containing the medium and high levels of manganese. The symptoms were more severe at the higher level. The winter wheat showed less pronounced toxicity symptoms than the spring wheat. Addition of silica reduced but did not eliminate the appearance of the toxicity symptoms on both wheats.

Plant height was less with increasing manganese levels (Table 3). Silica in the nutrient solution partially offset the reduction in plant height due to the higher manganese levels.

Silica in the nutrient solution significantly increased the grain yield of the winter wheat variety at all manganese levels (Table 4). Grain yield of the spring wheat variety was significantly increased by silica at the 50μ<u>M</u> and 500μ<u>M</u> levels of manganese, but Si decreased grain yield at the lowest manganese level.

The yield of vegetative material also increased when silica was added to the nutrient solution (Table 5). The yield of vegetation and the increase in vegetative yield in response to silica was greatest in the winter wheat. The differences in vegetative yields among treatments parallel the differences in grain yield.

Table 3. Effect of Si on plant height in spring wheat and winter wheat grown at three Mn levels.

	Si level (mM)	Mn level (μM) 5	50	500
		-------------	cm	-------------
Spring Wheat	0	93	86	68
	5	91	105	85
Winter Wheat	0	86	77	46
	5	105	95	87

Table 4. Effect of Si on grain yields of spring wheat and winter wheat grown at three Mn levels.

	Si level (mM)	Mn level (μM)		
		5	50	500
		g/6 plants		
Spring Wheat	0	20.86	12.56	3.35
	5	17.72	31.35	8.52
Winter Wheat	0	8.73	3.92	0.49
	5	20.90	18.36	17.71

Table 5. Effect of Si on vegetative growth in spring wheat and winter wheat grown at three Mn levels.

	Si level (m*M*)	Mn level (µ*M*) 5	50	500
		-----------g/6 plants----------		
Spring Wheat	0	40.2	30.0	12.6
	5	33.2	52.8	20.1
Winter Wheat	0	47.5	21.6	17.1
	5	92.5	84.5	61.7

Root growth also increased with added silica (Table 6). Root growth is considered to be a function of shoot growth. This is reflected in a vegetative weight/root weight ratio. This ratio did not change greatly for any treatment of the spring wheat (Appendix Table I). This ratio for the winter wheat diminished greatly as the amount of manganese in the nutrient solution increased.

Silica in the nutrient solution increased the number of heads produced by the winter wheat (Appendix Table II). No distinction was made between filled and unfilled heads. However, in the winter wheat treatments containing silica the number of late tillers increased with increasing manganese level. That accounted for the differences in grain yields although the number of heads did not differ appreciably.

Grain protein concentration was not greatly altered by the addition of silica (Table 7). Wheat grains from plants grown at the highest level of manganese with no added silica in the nutrient solution were shrunken and shriveled in appearance. A large proportion of the grains were green and immature.

Silica concentrations in the vegetative plants parts were generally higher in the spring wheat than in the winter wheat (Appendix Table III). The effect of manganese on the silica content in the vegetation of spring wheat closely followed the effect of manganese on vegetative yield. This was reflected in Appendix Table IV, where differences in the total silica content are small. The percentage of silica in the vegetation of the winter wheat changed little among manganese levels (Appendix Table III).

The effect of manganese on the concentration (Appendix Table V) or total content (Appendix Table VI) of silica in the roots followed no consistent pattern over all treatments for either wheat variety.

Table 6. Effect of Si on root growth in spring wheat and winter wheat grown at three Mn levels.

	Si level (m$\underline{M}$)	Mn level (µ$\underline{M}$) 5	50	500
		------------g/6 plants------------		
Spring Wheat	0	4.32	3.00	1.57
	5	3.97	5.81	2.47
Winter Wheat	0	3.14	1.79	1.62
	5	5.96	6.16	9.08

Table 7. Effect of Si on grain protein concentration in spring and winter wheat grown at three Mn levels.

	Si level (m$\underline{M}$)	Mn level (μ$\underline{M}$) 5	50	500
		-----------% protein------------		
Spring Wheat	0	17.4	17.2	19.5
	5	20.1	17.1	17.0
Winter Wheat	0	16.7	17.7	19.9
	5	16.1	18.4	15.9

Silica in the nutrient solution decreased the level of manganese in the vegetative portions (Appendix Table VII). The manganese level decreased approximately 25, 40, and 50 percent for the low, medium, and high manganese treatments, respectively, when silica was added. Silica decreased the manganese concentration in roots at only the medium level treatment of manganese in spring wheat and the low level in winter wheat (Appendix Table VIII). Silica increased the manganese content of the roots in all other treatments. The greatest increase was in the roots of plants grown in the nutrient solution containing the high level of manganese.

Experiment 1B

Manganese deficiency appeared as a slight chlorosis and yellowing of the upper leaves. Reduced growth also occurred in plants grown without manganese in the nutrient solution. Deficiency symptoms were less at the medium level of manganese. Addition of silica did not alter the appearance of the deficiency symptoms.

Plant height was less with decreasing manganese levels (Table 8). This occurred regardless of the silica level in the nutrient soltuion.

Silica had no significant effect on the grain yield, vegetative yield, or root growth of plants grown at the three manganese levels (Table 9). There was, however, a slight increase in all three parameters in response to silica.

Silica did not affect the number of heads produced (Table 9). The disparity between number of heads produced and grain yield was due to a large proportion of immature heads and unfilled grains in deficient plants.

Low levels of manganese in the nutrient solution resulted in a higher protein concentration in the grain (Table 9). Wheat kernels from plants grown

Table 8. Effect of Si on plant height grain protein concentration and number of heads in winter wheat grown at three Mn levels.

	Si level (m*M*)	Mn level (μ*M*) 0.0	0.5	5.0
Plant Height (cm)	0	34	77	85
	5	44	81	93
% Protein	0	23.5	18.2	17.4
	5	21.3	19.7	17.3
# of Heads/6 Plants	0	17	30	30
	5	19	28	27

Table 9. Effect of Si on grain yield, vegetative growth, and root growth of winter wheat grown at three Mn levels.

	Si level (m$\underline{M}$)	Mn level (μ$\underline{M}$)		
		0.0	0.5	5.0
		----------g/6 plants----------		
Grain	0	0.7	8.2	12.6
	5	0.8	9.2	13.6
Vegetation	0	14.7	28.6	39.3
	5	19.8	29.8	39.1
Roots	0	1.6	3.2	3.8
	5	2.1	2.7	3.0

at the lower manganese levels were shrunken and shriveled. Silica had no effect on grain protein concentration at any of the manganese levels.

Silica concentration in the vegetation increased with decreasing levels of manganese in the nutrient solution (Appendix Table IX). The total silica content in the vegetation differed little among manganese treatments (Appendix Table IX). There was no consistent effect of manganese on the silica concentration in the roots (Appendix IX).

Silica decreased the manganese concentration in the vegetation (Appendix Table X). This effect was apparent at all three manganese levels. Manganese concentration in the roots was not affected by silica (Appendix Table X).

Experiment 2

Treatment means in Table 10 indicate that grain yield response to silica was favorable at the 80 ppm level and unfavorable at the 400 ppm level. Addition of 80 ppm silica to the sand cultures significantly increased the grain yield of six wheat varieties (Table 11). Three of the remaining five varieties also responded favorably to the medium silica level, though the response was not significant at the 5% level of significance. Two varieties, Atlas 50 and Turgidum, had slight but not significant decreases in grain yield at the same level. All varieties except Agrotriticum yielded significantly less grain when grown at the 400 ppm silica level than when grown at the 80 ppm level. Furthermore, the maximum silica level in the nutrient supply decreased grain yield from the control treatment. No differences in response of grain yield to added silica could be determined between the high protein varieties and the low protein varieties.

Table 10. Treatment means for root growth, vegetative growth, grain yield, grain protein concentration, and plant height.

Mean	Si level (ppm) 0	80	400	LSD (.05)
Root growth (g/plant)	0.81	0.82	0.37	0.13
Veg. growth (g/plant)	3.11	3.45	1.83	0.40
Grain yield (g/plant)	1.80	2.19	1.22	0.29
Protein percent	10.1	10.0	10.2	N.S.*
Plant Height (cm)	77.0	71.2	57.6	4.7

*Not Significant

Table 11. Effect of Si on grain yield of twelve wheat varieties.

Variety	Si level (ppm) 0	80	400
	---------------g/plant---------------		
T x A 50 Low	1.93	2.12	1.20
T x A 50 High	1.25	1.67	0.86
Atlas 66	1.96	2.14	1.00
Lancota	1.41	2.01	0.86
Agrotriticum	1.88	2.52	2.52
Atlas 50	1.87	2.52	0.81
White Wheat	0	0	0
Sage	1.76	1.90	1.40
Chris	1.09	1.75	0.70
Turgidum	1.91	1.84	0.41
Durum	2.07	2.74	2.19
Sp. x Turgidum	2.66	3.56	2.24
LSD (.05 level)	Between varieties		0.56
LSD (.05 level)	Between treatments		0.29

Root growth was severely limited by large amounts of silica in the nutrient supply (Table 10). Within varieties, the maximum addition of silica adversely affected root growth of all varieties except the durum wheat (Table 12). However, 80 ppm silica in the nutrient supply significantly increased the root growth of the durum wheat, the Triumph x Atlas 50 selection, and the Agrotriticum variety. The same silica level had a significantly harmful effect of the root growth of the Triumph x Atlas 50 low protein selection and the Turgidum variety. There was no significant variety x treatment interaction for root growth.

Silica at the 80 ppm level increased the vegetative yield of the eleven wheat varieties as indicated by the treatment means, while the 400 ppm silica treatment had a definite negative effect on vegetative growth (Table 10). Vegetative yield of all varieties except Agrotriticum decreased significantly under the high silica application (Table 13). Vegetative growth of Agrotriticum was significantly enhanced by 80 ppm silica in the nutrient supply but was not significantly depressed by 400 ppm silica. Vegetative growth of three other varieties, Triumph x Atlas 50 high protein, durum wheat, and Spring Wheat x Turgidum, also responded favorably to 80 ppm silica, while only one variety, Lancota, responded unfavorably.

Silica had no effect on the grain protein concentration means for the eleven wheat varieties tested (Table 10). As would be expected, the varieties differed in their protein concentration (Table 14). The three "low" protein varieties, Triumph x Atlas 50 low protein, Sage, and Chris showed no positive grain protein response to either the 80 or 400 ppm levels of silica. Five of the "high" protein varieties, Triumph x Atlas 50 high protein, Atlas 66, Agrotriticum, Turgidum, and Spring Wheat x Turgidum, had a significant increase

Table 12. Effect of Si on root growth of twelve wheat varieties.

Variety	Si level (ppm) 0	80	400
	----------------g/plant	------------------	
T x A 50 Low	0.63	0.38	0.17
T x A 50 High	1.06	1.22	0.19
Atlas 66	0.80	0.90	0.27
Lancota	0.66	0.54	0.20
Agrotriticum	2.02	2.26	1.61
Atlas 50	0.84	0.77	0.21
White Wheat	7.34	9.57	3.66
Sage	0.80	0.89	0.44
Chris	0.25	0.34	0.12
Turgidum	0.48	0.27	0.09
Durum	0.47	0.64	0.44
Sp x Turgidum	0.89	0.83	0.32
LSD (.05 level)	Between Varieties		0.24
LSD (.05 level)	Between Treatments		0.13

Table 13. Effect of Si on vegetative growth of twelve wheat varieties.

Variety	Si level (ppm) 0	80	400
	---------------g/plant---------------		
T x A 50 Low	2.72	2.50	1.29
T x A 50 High	2.74	3.26	1.21
Atlas 66	2.96	3.17	1.40
Lancota	3.60	3.09	1.24
Agrotriticum	5.45	7.16	5.47
Atlas 50	3.41	3.08	1.19
White Wheat	7.24	7.71	5.32
Sage	2.99	3.11	2.02
Chris	1.46	2.04	1.02
Turgidum	2.16	2.12	0.77
Durum	2.69	3.42	1.67
Sp. x Turgidum	4.07	5.07	2.86
LSD (.05 level)	Between Varieties		0.76
LSD (.05 level)	Between Treatments		0.40

Table 14. Effect of Si on grain protein concentration of twelve wheat varieties.

	Si level		
Variety	0	80	400
	------------------% Protein----------------		
T x A 50 Low	10.9	10.4	11.0
T x A 50 High	9.9	9.6	11.1
Atlas 66	10.7	9.7	12.3
Lancota	9.8	8.4	9.7
Agrotriticum	9.9	12.2	12.9
Atlas 50	10.5	10.2	10.7
White wheat		No grain yield	
Sage	8.7	9.2	7.7
Chris	13.7	10.0	10.5
Turgidum	8.4	9.9	11.1
Durum	10.7	11.1	8.4
Sp. x Turgidum	8.1	9.5	10.4
LSD (.05 level)	Between varieties		1.6
LSD (.05 level)	Between treatments		N.S.*

*Not significant

in grain protein concentration when 400 ppm silica was supplied in the nutrient solution. Two high protein varieties, Lancota and Atlas 50, showed no increase in protein concentration at either silica level. The durum wheat had a lower protein content when it was grown on 400 ppm silica than when it was grown without silica.

Plant height generally decreased with increasing silica in the nutrient solution (Table 10). The decrease in plant height between the minimum and medium silica levels was significant for six varieties (Table 15). Plant height never increased significantly when silica was added.

Silica uptake increased with an increasing content of silica in the nutrient solution. However, the uptake of silica was not proportional to the supply (Table 16). The approximately 1% silica concentration in the vegetation of plants grown without added silica was attributed to contamination in the silica sand.

Experiment 3

Available profile nitrogen in individual soil samples ranged from 6.0 ppm N (as ammonia plus nitrate) at Tribune to 69.9 ppm N at Powhattan (Table 17). Location means of available profile nitrogen ranged from 7.4 ppm N to 62.1 ppm at Tribune and Powhattan, respectively. Grain yields of winter wheat varieties tested at Powhattan were among the highest yields reported at all locations (Winter Wheat Performance Tests Results, 1975). The lowest grain yields were found at Tribune. Yields of four of the seventeen varieties, Triumph 64, Danne, Trison, and Buckskin, were significantly correlated (10% level of significance) with available profile nitrogen (Appendix Tables XI, XII, XIII, and XXIII). Yields of the other thirteen varieties were not related to available profile nitrogen.

Table 15. Effect of Si on plant height of twelve wheat varieties.

Variety	Si level (ppm) 0	80	400
	-----	cm	-----
T x A 50 Low	76.0	66.3	56.7
T x A 50 High	90.3	82.7	47.0
Atlas 66	76.3	77.7	56.7
Lancota	76.0	72.7	50.3
Agrotriticum	104.7	96.7	92.7
Atlas 50	79.0	73.7	61.3
White wheat	13.0	12.7	99.0
Sage	75.7	71.7	66.0
Chris	66.7	47.7	53.0
Turgidum	61.3	54.7	39.0
Durum	59.3	61.3	44.0
Sp. x Turgidum	81.7	78.0	61.0
LSD (.05 level)	Between varieties		9.0
LSD (.05 level)	Between treatments		4.7

Table 16. Effect of silica in the nutrient supply on the silica content of wheat vegetation.

	Si level (ppm)		
Variety	0	80	400
	----------------- % SiO_2 -----------------		
T x A 50 High Prot.	.86	1.9	8.3
Atlas 66	.64	2.8	8.8
Chris	1.1	4.3	9.6
Sp x Turgidum	1.1	3.8	6.8

Table 17. Available profile nitrogen and total silica content of Kansas soils sampled in Experiment 3.

Location	Sample	Available Nitrogen[1/] (ppm)	Total Silica (% SiO_2)
Belleville	1	46.3	67.9
	2	36.0	68.1
	3	44.5	67.3
	4	28.6	70.3
	Avg.	38.8	68.4
Colby	1	36.2	66.2
	2	23.9	65.1
	3	24.8	66.2
	4	24.3	71.4
	Avg.	27.3	67.2
Garden City	1	10.4	72.4
	2	12.0	71.8
	3	15.4	69.6
	4	15.1	71.4
	Avg.	13.2	71.3
Hays	1	23.4	70.7
	2	17.1	56.1
	3	12.4	67.9
	4	17.6	69.4
	Avg.	17.6	66.0
Hutchinson	1	31.6	73.9
	2	41.6	73.9
	3	36.8	71.1
	4	37.0	73.1
	Avg.	36.8	73.0
Manhattan	1	45.5	74.1
	2	42.6	73.5
	3	53.1	71.9
	4	54.8	74.1
	Avg.	49.0	73.4
Minneola	1	18.1	71.6
	2	9.5	65.8
	3	12.4	67.7
	4	12.4	74.8
	Avg.	13.1	70.0

Table 17 continued

Location	Sample	Available Nitrogen[1/] (ppm)	Total Silica (% SiO_2)
Parsons	1	43.7	81.6
	2	32.6	77.1
	3	48.8	79.7
	4	48.0	81.2
	Avg.	43.3	79.9
Powhattan	1	69.9	75.6
	2	62.0	66.6
	3	61.9	73.1
	4	54.5	69.6
	Avg.	62.1	71.2
St. John	1	17.2	81.2
	2	22.2	75.6
	3	21.0	81.2
	4	15.7	82.3
	Avg.	19.0	80.1
Tribune	1	6.5	70.1
	2	6.0	66.0
	3	9.0	72.0
	4	8.1	66.0
	Avg.	7.4	68.5

[1/] ppm nitrogen as nitrate plus ammonium in the two-foot profile

A relationship between grain protein concentration and available profile nitrogen was significant at the 5% level for the variety Sentinel. Grain protein concentration and available profile nitrogen were not related at the 5% or 10% level in any of the other varieties. In addition, the protein values for Sentinel wheat were available from only four locations (Appendix Table XXIV).

Total silica concentration in the soil samples ranged from 56.1 to 82.3% SiO_2 for samples from Hays and St. John, respectively (Table 18). The majority of the soil samples had a silica content of approximately 70%. There were no significant relationships between the total silica content of a soil and the winter wheat grain yields of any of the varieties used in this experiment.

The grain protein concentration of the variety Turkey was positively correlated with total silica content of soil samples. Grain protein concentration of all other varieties tested was not related to the total silica content of the soil.

Silica concentrations in the first, second, and third soil water extracts varied significantly among soil samples from different locations (Table 18). There was no consistent increase or decrease in silica concentration in the soil water from the first to the third extracts of all soils analyzed. Variation in silica concentration was less between the second and the third extracts than between the first and second extracts.

Grain yields of the winter wheat varieties in this study were not correleated with the silica concentrations in the soil water extracts. No correlation was found between grain protein concentration and the level of dissolved silica in the first soil water extract. However, the silica concentration in the second and/or third extracts varied inversely with the

Table 18. Silica concentration in three successive soil water extractions.

Location	Sample	1st Extraction	2nd Extraction	3rd Extraction
		----------------	μg SiO_2/g dry soil	----------------
Belleville	1	7.1		
	2	11.8		
	3	16.5		
	4	11.6		
	Avg.	11.8		
Colby	1	15.6	15.6	14.6
	2	16.5	18.9	22.1
	3	18.6	21.0	25.7
	4	19.9	21.6	23.6
	Avg.	17.7	19.3	21.5
Garden City	1	11.8	12.6	18.0
	2	21.0	26.4	22.5
	3	13.9	13.9	18.2
	4	23.6	27.2	29.1
	Avg.	15.6	20.0	22.0
Hays	1	13.7	15.4	17.4
	2	16.3	19.5	23.1
	3	13.1	16.3	19.9
	4	22.5	23.8	23.4
	Avg.	16.4	18.8	21.0
Hutchinson	1	12.4	11.1	6.4
	2	6.6	8.4	9.0
	3	16.7	16.3	9.6
	4	10.7	9.6	15.6
	Avg.	11.6	11.4	10.2
Manhattan	1	15.6	9.2	3.9
	2	11.1	3.6	4.1
	3	19.7	9.2	4.7
	4	15.0	12.0	4.7
	Avg.	15.4	8.5	4.4
Minneola	1	14.6	17.4	14.6
	2	16.5	21.4	19.9
	3	18.0	21.6	27.2
	4	19.7	22.9	18.6
	Avg.	17.2	20.8	20.1

Table 18 continued

Location	Sample	1st Extraction	2nd Extraction	3rd Extraction
		----------------	$\mu g\ SiO_2/g$ dry soil	----------------
Parsons	1	4.5	3.0	4.3
	2	10.7	7.7	4.3
	3	5.8	4.1	2.8
	4	6.6	3.6	2.6
	Avg.	6.9	4.6	3.5
Powhattan	1	14.8		
	2	22.5		
	3	10.1		
	4	12.2		
	Avg.	14.9		
St. John	1	11.6	6.2	4.9
	2	11.4	8.8	5.6
	3	12.0	10.5	9.4
	4	13.1	9.9	6.9
	Avg.	12.0	8.9	6.7
Tribune	1	12.4	14.6	14.4
	2	11.4	10.8	11.4
	3	14.8	19.3	19.9
	4	12.9	15.2	18.2
	Avg.	12.9	15.0	16.0

grain protein concentration of eight of the seventeen varieties (Appendix Tables XVI, XVII, XVIII, XIX, XXII, XXIII, XXVI, and XXVII).

Experiment 4

Scanning electron photomicrographs of the surface of a leaf from a mature plant grown without silica show the stomata to be approximately 50 u long and 30 u wide (Figures 1 and 2). The particulate structure on the leaf surface is probably the dried cuticle layer. The dimensions of a stomate from a plant grown with 400 ppm silica supplied in the nutrient solution were 50 u x 15 u (Figure 3). The dried cuticle layer is significantly less apparent in Figure 4 than in Figure 2. In the upper portion of Figure 4 there appears to be specialized silica cells in the shape of a thick rod. Two silicified hooks are present in the center of Figure 4.

Figures 5-8 are SEM's of the glumes. There are no apparent differences in stomate size or tissue surface appearance between silica treatments.

Figures 9-11 are similar to Figures 1-4 except the silica treatment was 80 ppm silica. The stomates in Figure 9 are approximately 50 u long and 10 u wide, which was very similar to the stomate size in the other SEM's. The amount of dried cuticle material visible in Figure 11 appears to be midway between the amounts seen in Figures 2 and 3.

Experiment 5

Transpiration rates of the wheat seedlings changed little with varying amounts of silica in the nutrient solution (Table 19). All seedlings were in the third leaf stage of development and were approximately 15 cm tall. The seedling with the lowest rate of transpiration had the 0 ppm silica treatment.

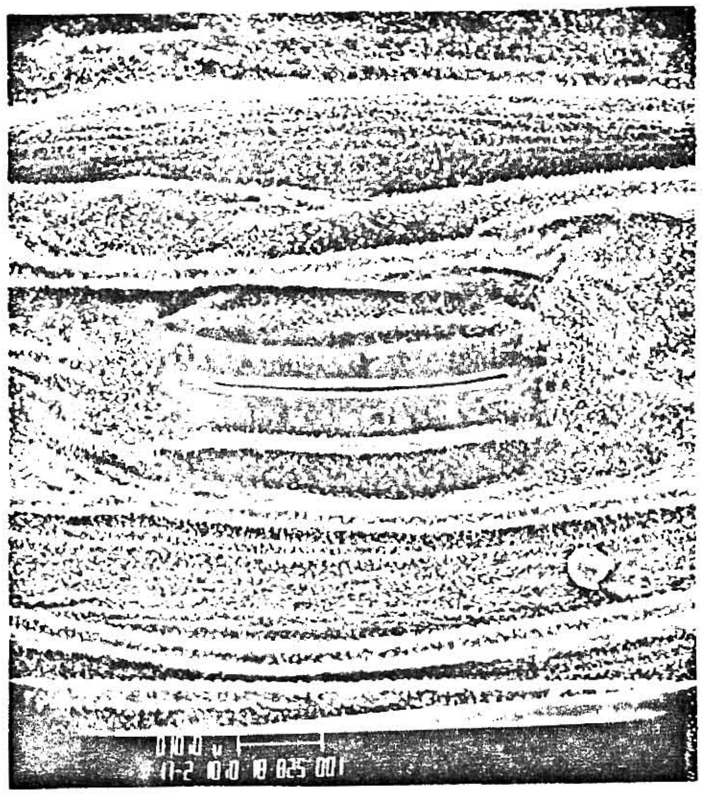

Figure 1. Scanning electron photomicrograph (SEM) of the outside surface of a leaf blade from wheat grown with no silica.

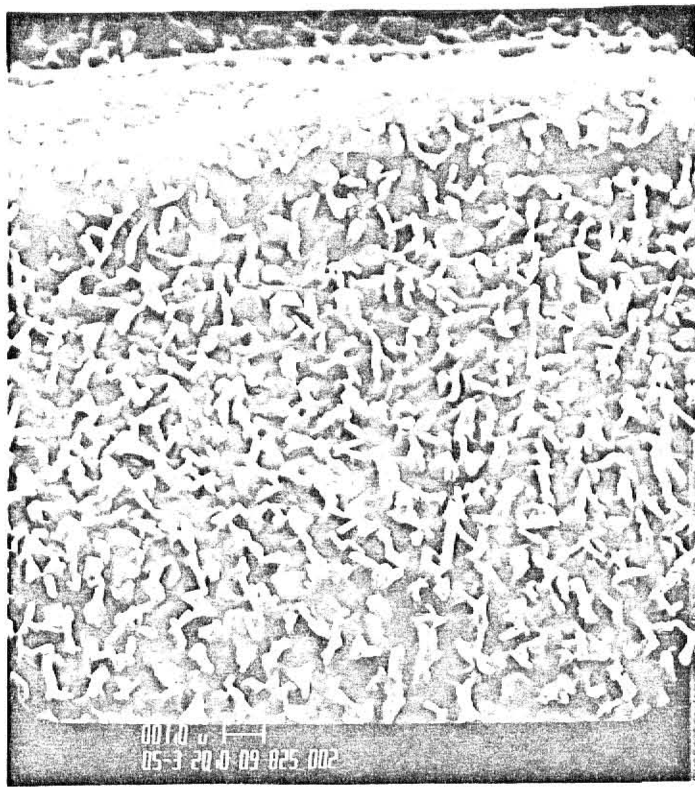

Figure 2. SEM of the outside surface of a leaf blade from wheat grown with no silica.

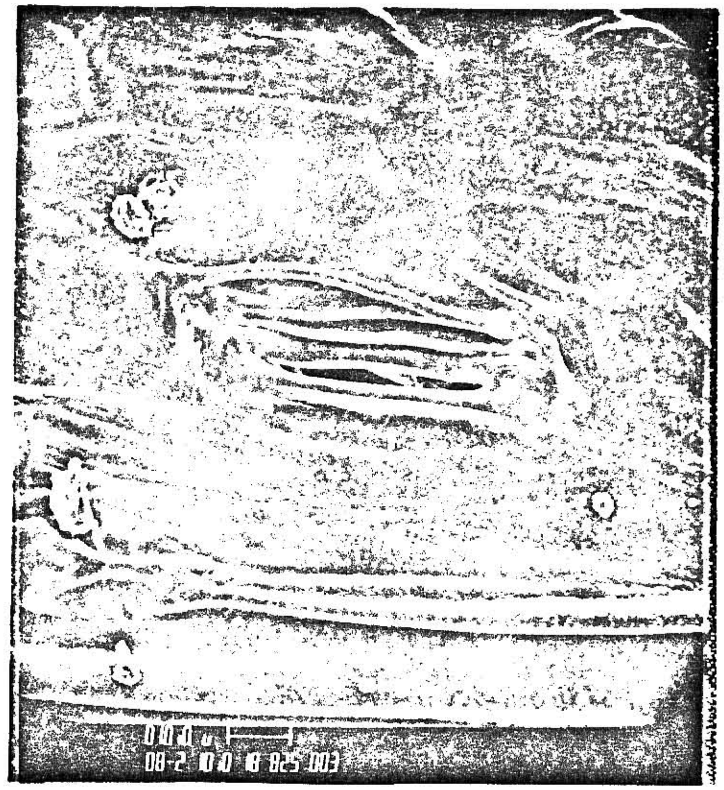

Figure 3. SEM of the outside of a leaf blade from wheat grown with 400 ppm silica.

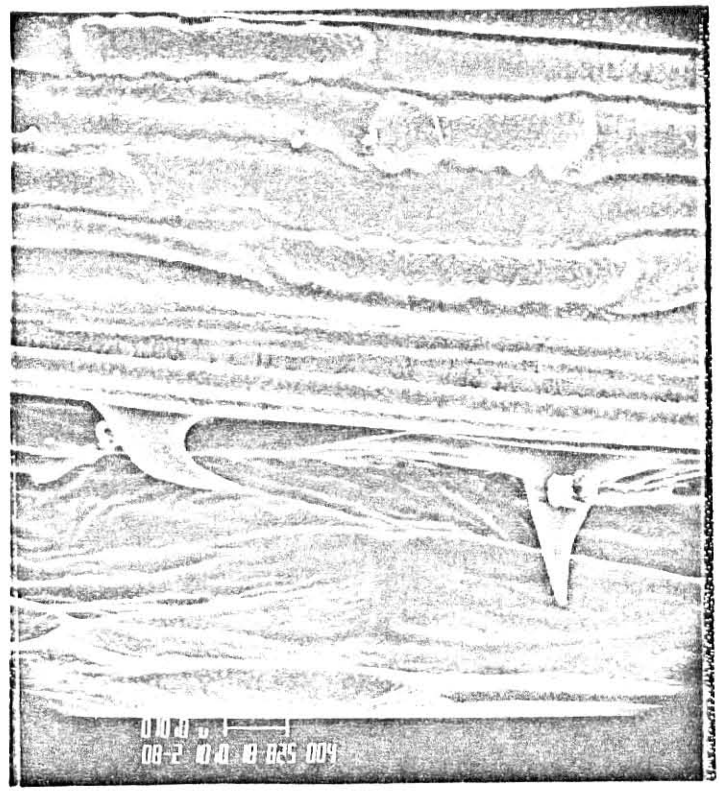

Figure 4. SEM of the outside of a leaf blade from wheat grown with 400 ppm silica.

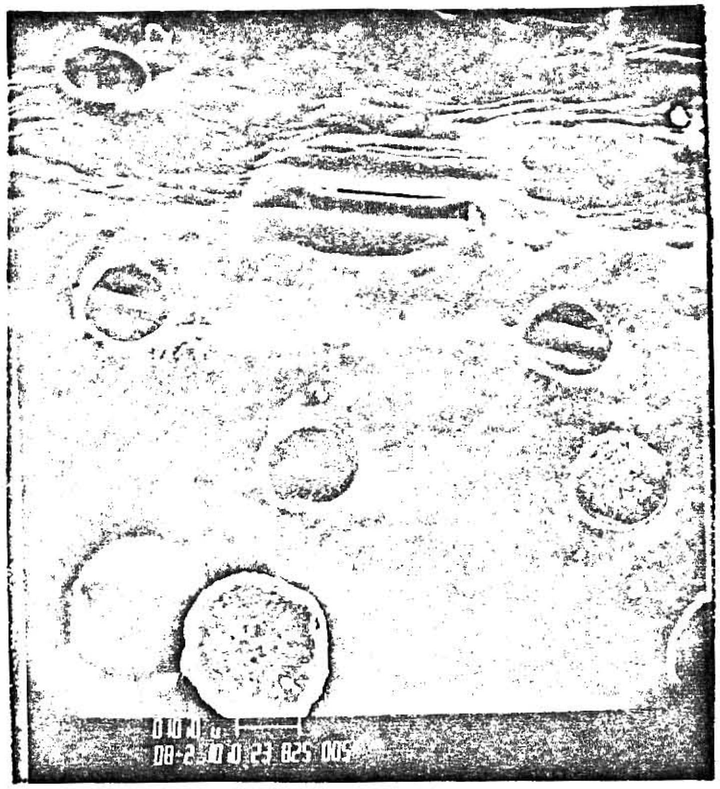

Figure 5. SEM of the outside surface of a glume from wheat grown with no silica.

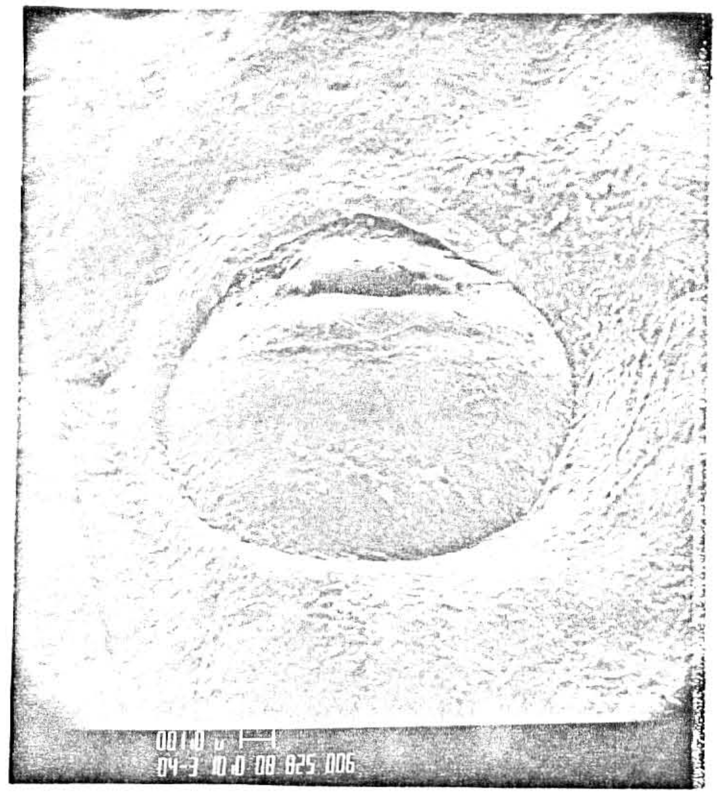

Figure 6. SEM of the outside surface of a glume from wheat grown with no silica.

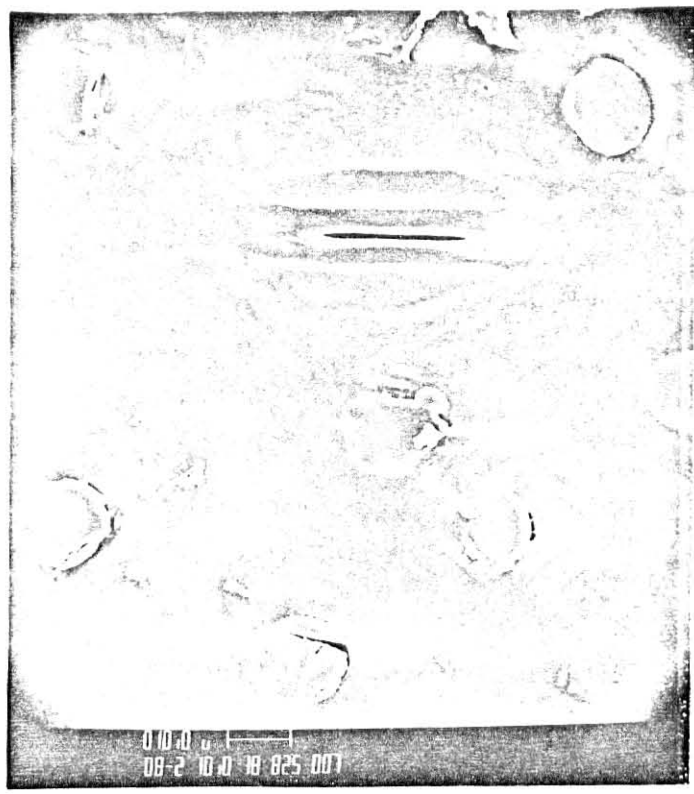

Figure 7. SEM of the outside surface of a glume from wheat grown with 400 ppm silica.

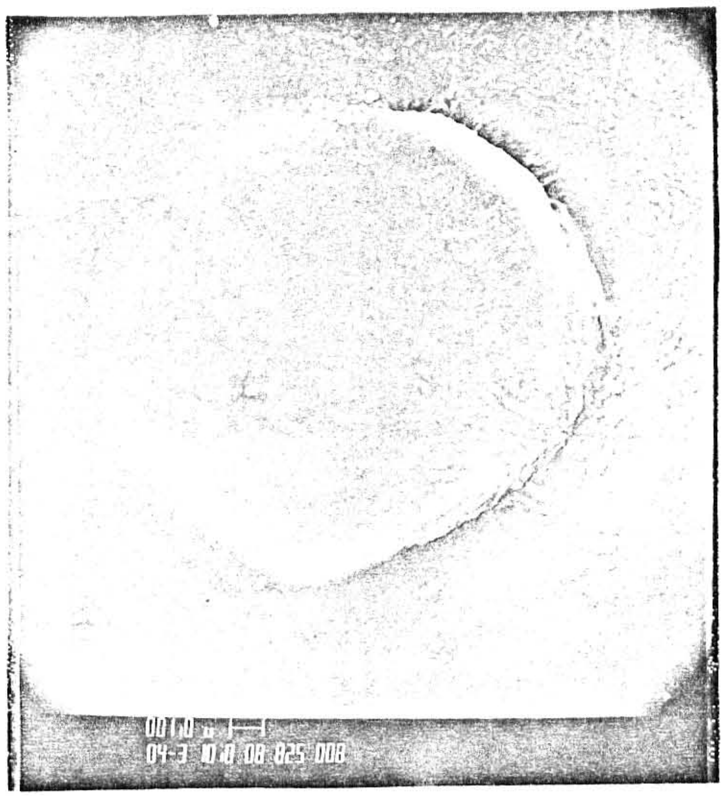

Figure 8. SEM of the outside surface of a glume from wheat grown with 400 ppm silica.

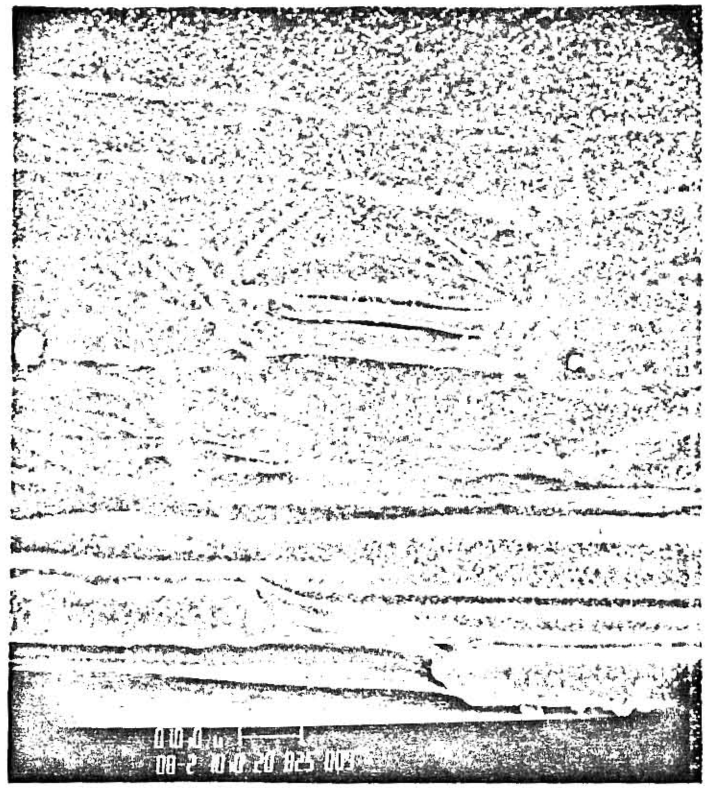

Figure 9. SEM of the outside surface of a leaf blade from wheat grown with 80 ppm silica.

Figure 10. SEM of the outside surface of a leaf blade from the wheat grown with 80 ppm silica.

Figure 11. SEM of the outside surface of a leaf blade from the wheat grown with 80 ppm silica.

Table 19. Effect of silica on transpiration rates of 14-day-old wheat seedlings.

Si level ppm Si	Transpiration rate ml H_2O/hour
0.0	0.20
8.25	0.22
17.50	0.22
35.00	0.23
70.00	0.21
140.00	0.21
	mean 0.215

The maximum rate of transpiration was recorded at the 35 ppm silica level. The range from the lowest to the highest rate of transpiration was 0.20 ml H_2O/hour to 0.23 ml H_2O/hour. The transpiration rate of the seedling kept in the nutrient solution with the highest level of silica (140 ppm) was 0.21 ml H_2O/hour or approximately the mean rate of transpiration for all seedlings.

Electrical conductivity rose from 1.39 to 2.00 millimhos with increasing silica levels from 0 ppm to 140 ppm, respectively (Table 20). Compared with soils, all conductance values were within the range considered to be low for salt concentration.

DISCUSSION

Silica appeared to be effective in decreasing manganese toxicity in wheat grown in nutrient solution. Grain yield, vegetation yield, and root growth increased in response to silica. However, toxicity symptoms were not eliminated by silica. That observation disagrees with that by Vlamis and Williams (1967) for barley. Silica lowered, but did not prevent accumulation of toxic levels of manganese in the vegetation. Therefore, the increased growth was probably a direct beneficial effect of silica rather than alleviation of the toxic effects of manganese. This was confirmed by the winter wheat yield response to silica at toxic manganese levels, which was greater than the yield of the control treatment.

Silica restricted translocation of manganese from the roots to the vegetation regardless of the manganese concentration in the nutrient solution. This also was in contrast to the report by Vlamis and Williams (1967), which stated that at low manganese levels silica affected the microdistribution of

Table 20. Effect of silica on electrical conductivity of nutrient solutions.

Si level ppm Si	Conductance millimhos/cm at 25 C
0.0	1.39
8.25	1.45
17.50	1.47
35.00	1.59
70.00	1.69
140.00	2.00

manganese in barley leaves but did not exclude it from the plant. Greatest restriction of manganese translocation apparently occurred in plants grown at toxic manganese levels, where silica increased uptake and/or accumulation of manganese in the roots.

Silica had no significant effect on growth of plants at very low levels of manganese. Possible manganese contamination in the unpurified silica stock solution could have caused the small nonsignificant increase in growth in response to silica. However, silica decreased the manganese concentration in the vegetation. Consequently, silica might have accentuated manganese deficiency by stimulating vegetative growth.

High levels up to 400 ppm silica had a definite harmful effect on the growth of wheat. The high levels of silica might have created an unfavorable osmotic gradient and limited the normal uptake of water of other nutrients. However, that was unlikely in view of the fact that silica did not greatly alter the salt level, as measured by electrical conductivity, of the nutrient solution. Beckwith and Reeve (1963) found that silica added to soils is adsorbed on the surface of soil particles. That type of adsorption phenomena might have occurred on the roots of plants grown at the 400 ppm level of silica and limited water and nutrient uptake. Since silica concentration was based upon the weight of silica sand contained in each pot, the nutrient solution was probably saturated at the 80 ppm level of silica. Water and nutrient uptake were also probably limited at this silica level. This may have been further illustrated by the small difference in silica concentration in the vegetation of plants grown at the widely separated levels of silica in the nutrient solution. Water uptake might have been limited at the highest level of silica, as transpiration rates and silica concentrations in the vegetation have been well correlated (Jones and Handreck, 1965). The positive yield response to silica, shown by some wheat varieties to the 80 ppm level, might have been greater if lower levels of silica had been used.

All varieties analyzed had different silica concentrations when grown at different levels of silica. Silica concentrations of approximately 1% in plants grown at the 0 ppm silica level were attributed to dust or contaminating silica sand particles. These results correspond to those of Jones and Handreck (1965) and Islam and Saha (1969), who reported variations in silica uptake within a species on soils or nutrient solutions with different levels of silica. However, silica concentrations in the vegetation also varied between varieties grown at the same level of silica in the nutrient solution.

Information on genetic differences in response to silica and the relationship of silica nutrition to protein potential in wheat was obtained in the present study. Several low and high protein wheat varieties provided the differential genetic material. Two of the standard protein wheat varieties, 'Sage' and 'Triump x Atlas 50 low protein' did not respond favorably to silica. Some, but not all, of the high protein wheat varieties showed an increased yield in response to silica. These results did not show any conclusive relationship between grain protein concentration and the plants' ability to respond to silica. Therefore, grain protein concentration and the silica response did not appear to be genetically or physiologically related.

It is well known that winter wheat responds well to nitrogen application. However, the yield of all varieties and available profile nitrogen were not correlated in this study. This could have been caused by the June soil sampling date. In Kansas during early June, winter wheat has usually reached its maximum vegetative growth stage. The majority of the required nitrogen has been removed from the soil at this date. Consequently, available profile nitrogen values probably reflected residual nitrogen and did not directly influence the 1975 wheat grain yields.

Silica analyses of the soil samples showed a trend, which was consistent with the reports in the literature (Jones and Handreck, 1965), that sandy soils contained more total silica. The concentration of silica in the soil solution tended to vary inversely with the sand fraction of the soils. These results corresponded well with those of McKeague and Cline (1963), who reported that sandy soils have fewer adsorption sites than clay soils and a subsequent smaller capacity to release adsorbed monosilicic acid. The levels of silica in the soil solutions were considerably less than the levels used in the growth chamber or greenhouse studies. The lack of any significant correlations between silica concentration in the soil solution and grain yield can probably be attributed to the failure of low levels of silica to elicit a favorable grain yield response.

Scanning electron photomicrographs of winter wheat leaf surfaces did not reveal any silica induced ultrastructural changes in the leaf surface. Silica did not affect stomata size or shape. Rod-shaped cells in the photomicrographs were assumed to be specialized silica-containing cells. These specialized cells have been reported by Jones et al. (1963) and Parry and Smithson (1958) and are assumed to have no detrimental effect on plant growth. Silica appeared to decrease the cuticle layer on the leaf surface. However, this can only be inferred by comparing the photomicrographs as no quantitative determination was made. Air drying the plant samples was clearly an unsatisfactory method of preparing the samples for scanning electron photomicrography. Any in-depth study of the effect of silica on leaf surface ultrastructure should employ preparation methods that preserve the characteristics of fresh tissue samples.

Transpiration rates were unaffected by silica. Though the salt concentration, as measured by electrical conductance, increased slightly with increasing silica, the effect probably was not great enough to alter transpiration rates. The data suggest that silica is carried passively in the transpirational stream and does not affect transpiration rates. Silica concentration in the soil solution and vegetation has been proposed as a measure of transpiration rates (Jones and Handreck, 1965). The results of these studies present no evidence to dispute this proposal.

Further investigations should be carried out to determine the effect of added silica on soil chemistry and soil fertility. Field studies should be conducted to determine the effect of additional silica on wheat growth under normal field conditions and in areas where manganese toxicity is a problem.

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APPENDICES

Appendix Table I. Effect of Si on the foliar wt./root wt. ratio of spring wheat and winter wheat grown at three Mn levels.

	Si level (m$\underline{M}$)	Mn level (μ$\underline{M}$) 5	50	500
		------g vegetation/g roots------		
Spring Wheat	0	9.3	10.0	8.1
	5	8.4	9.1	8.1
Winter Wheat	0	15.1	12.1	10.6
	5	16.0	13.7	7.1

Table II. Effect of Si on number of heads of spring wheat and winter wheat grown at three Mn levels.

	Si level (mM)	Mn level (µM) 5	50	500
		---------Heads/6 plants---------		
Spring Wheat	0	39	31	22
	5	29	42	23
Winter Wheat	0	26	12	2
	5	35	32	34

Table III. Effect of Mn on the concentration of SiO_2 in vegetation of spring wheat and winter wheat grown at three Mn levels.

	Si level (m$\underline{M}$)	Mn level (μ$\underline{M}$)		
		5	50	500
		----------% SiO_2----------------		
Spring Wheat	0	0	0	0
	5	6.2	3.3	8.3
Winter Wheat	0	0	0	0
	5	4.2	4.6	4.5

Table IV. Effect of Mn on total SiO_2 content in vegetation of spring wheat and winter wheat grown at three Mn levels.

	Si level (m_M_)	Mn level (μ_M_) 5	50	500
		-------g SiO_2/6 plants--------		
Spring Wheat	0	0	0	0
	5	2.1	1.7	1.7
Winter Wheat	0	0	0	0
	5	3.7	3.8	2.8

Table V. Effect of Mn on the concentration of SiO_2 in roots of spring wheat and winter wheat grown at three Mn levels.

	Si level (mM)	Mn level (μM) 5	50	500
		----------% SiO_2-------------		
Spring Wheat	0	0	0	0
	5	1.3	0.5	1.8
Winter Wheat	0	0	0	0
	5	0.8	1.1	0.8

Table VI. Effect of Mn on total SiO_2 content in roots of spring wheat and winter wheat grown at three Mn levels.

	Si level (m$\underline{M}$)	Mn level ($\mu\underline{M}$) 5	50	500
		--------SiO_2/6 plants--------		
Spring Wheat	0	0	0	0
	5	52.8	26.7	43.2
Winter Wheat	0	0	0	0
	5	46.5	67.1	76.3

Table VII. Effect of Si on Mn concentration in vegetation of spring wheat and winter wheat grown at three Mn levels.

	Si level (m$\underline{M}$)	Mn level (μ$\underline{M}$) 5	50	500
		------------ppm Mn------------		
Spring Wheat	0	83.3	419.0	1335.0
	5	64.0	274.0	689.9
Winter Wheat	0	96.2	433.7	1921.0
	5	65.3	258.3	839.0

Table VIII. Effect of Si on Mn concentration in roots of spring wheat and winter wheat grown at three mn levels.

	Si level (m$\underline{M}$)	Mn Level ($\mu\underline{M}$) 5	50	500
		----------ppm Mn----------		
Spring Wheat	0	38.2	441.0	1493.0
	5	53.0	296.7	3394.7
Winter Wheat	0	98.5	282.2	1417.0
	5	40.7	1324.0	9717.0

Table IX. Effect of Mn on concentration of Si in vegetation and roots, and total Si content in vegetation of winter wheat grown at three Mn levels.

	Si level (mM)	Mn level (μM) 0.0	0.5	5.0
Vegetation	0	0	0	0
% SiO_2	5	1.0	0.6	0.5
Roots	0	0	0	0
% SiO_2	5	0.2	0.1	0.3
Vegetation	0	0	0	0
g SiO_2/6 plants	5	0.2	0.2	0.2

Table X. Effect of Si on Mn concentrations in vegetation and roots of winter wheat grown at three Mn levels.

	Si level (mM)	Mn level (μM)		
		0.0	0.5	5.0
		----------ppm Mn----------		
Vegetation	0	4.2	9.5	28.5
	5	3.5	4.1	17.8
Roots	0	5.3	5.4	14.2
	5	4.3	6.1	13.3

Table XI Correlation coefficients for

Triumph 64 grown at 6 locations.

	Yield	Protein
Available Profile Nitrogen (APN)	0.75*	-0.22
% SiO_2	-0.59	0.74*
ppm SiO_2 in Extract #1	0.37	0.40
ppm SiO_2 in Extract #2	-0.41	-0.34
ppm SiO_2 in Extract #3	-0.36	-0.30

*Significant at the .10 level
**Significant at the .05 level

Table XII. Correlation coefficients for the winter wheat variety Danne grown at 8 locations.

	Yield	Protein
Available Profile Nitrogen	0.81**	-0.27
% SiO_2	0.14	0.75*
ppm SiO_2 in Extract #1	0.14	-0.37
ppm SiO_2 in Extract #2	-0.57	-0.17
ppm SiO_2 in Extract #3	-0.60	-0.11

Table XIII. Correlation coefficient the

variety Trison grown at 11 locations.

	Yield	Protein
Available Profile Nitrogen	0.58*	0.04
% SiO_2	0.14	0.53
ppm SiO_2 in Extract #1	-0.20	-0.26
ppm SiO_2 in Extract #2	-0.45	-0.35
ppm SiO_2 in Extract #3	-0.43	-0.31

Table XIV. Correlation coefficients for the winter wheat variety Parker grown at 8 locations.

	Yield	Protein
Available Profile Nitrogen	0.23	0.05
% SiO_2	-0.64	-0.39
ppm SiO_2 in Extract #1	0.21	-0.32
ppm SiO_2 in Extract #2	-0.43	-0.54
ppm SiO_2 in Extract #3	-0.22	-0.52

Table XV. Correlation coefficients for the winter wheat variety Satanta grown at 6 locations.

	Yield	Protein
Available Profile Nitrogen	0.26	0.26
% SiO_2	0.05	0.72
ppm SiO_2 in Extract #1	0.44	-0.53
ppm SiO_2 in Extract #2	0.36	-0.66
ppm SiO_2 in Extract #3	0.19	-0.54

Table XVI. Correlation coefficients for the winter wheat variety Scout grown at 11 locations.

	Yield	Protein
Available Profile Nitrogen	0.36	0.25
% SiO_2	-0.27	0.37
ppm SiO_2 in Extract #1	0.22	0.38
ppm SiO_2 in Extract #2	-0.32	-0.59*
ppm SiO_2 in Extract #3	-0.29	-0.56*

Table XVII. Correlation coefficients for the winter wheat variety Eagle grown at 11 locations.

	Yield	Protein
Available Profile Nitrogen	0.40	0.15
% SiO_2	-0.33	0.42
ppm SiO_2 in Extract #1	0.24	-0.43
ppm SiO_2 in Extract #2	-0.30	-0.57*
ppm SiO_2 in Extract #3	-0.27	-0.55*

Table XVIII. Correlation coefficients for the winter wheat variety Sage grown at 11 locations.

	Yield	Protein
Available Profile Nitrogen	0.34	0.34
% SiO_2	-0.33	0.39
ppm SiO_2 in Extract #1	-0.27	-0.50
ppm SiO_2 in Extract #2	-0.29	-0.71**
ppm SiO_2 in Extract #3	-0.25	-0.68**

Table XIX. Correlation coefficients for the winter wheat variety Homestead grown at 11 locations.

	Yield	Protein
Available Profile Nitrogen	0.43	0.18
% SiO_2	-0.25	0.27
ppm SiO_2 in Extract #1	0.25	-0.30
ppm SiO_2 in Extract #2	-0.33	-0.55*
ppm SiO_2 in Extract #3	-0.31	-0.51

Table XX. Correlation coefficients for the winter wheat variety Kirwin grown at 11 locations.

	Yield	Protein
Available Profile Nitrogen	0.48	0.20
% SiO_2	0.13	0.43
ppm SiO_2 in Extract #1	-0.06	-0.23
ppm SiO_2 in Extract #2	-0.47	-0.50
ppm SiO_2 in Extract #3	-0.47	-0.50

Table XXI. Correlation coefficients for the winter wheat variety Gage grown at 5 locations.

	Yield	Protein
Available Profile Nitrogen	-0.28	-0.11
% SiO_2	-0.87*	-0.11
ppm SiO_2 in Extract #1	0.46	-0.43
ppm SiO_2 in Extract #2	-0.06	-0.52
ppm SiO_2 in Extract #3	0.08	-0.43

Table XXII. Correlation coefficients of the winter wheat variety Cloud grown at 11 locations.

	Yield	Protein
Available Profile Nitrogen	0.35	0.41
% SiO_2	-0.22	0.53
ppm SiO_2 in Extract #1	0.26	-0.49
ppm SiO_2 in Extract #2	-0.25	-0.69**
ppm SiO_2 in Extract #3	-0.25	-0.71**

Table XXIII. Correlation coefficients for the winter wheat variety Buckskin grown at 11 locations.

	Yield	Protein
Available Profile Nitrogen	0.52*	0.36
% SiO_2	-0.11	0.50
ppm SiO_2 in Extract #1	0.18	-0.35
ppm SiO_2 in Extract #2	-0.38	-0.65**
ppm SiO_2 in Extract #3	-0.37	-0.65**

Table XXIV. Correlation coefficients for the winter wheat variety Sentinel grown at 5 locations.

	Yield	Protein
Available Profile Nitrogen	0.48	0.97**
% SiO_2	-0.12	-0.35
ppm SiO_2 in Extract #1	-0.16	-0.49
ppm SiO_2 in Extract #2	-0.21	-0.83
ppm SiO_2 in Extract #3	-0.23	-0.80

Table XXV. Correlation coefficients for the winter wheat variety Turkey grown at 11 locations.

	Yield	Protein
Available Profile Nitrogen	0.36	0.16
% SiO_2	-0.30	0.76
ppm SiO_2 in Extract #1	0.47	-0.36
ppm SiO_2 in Extract #2	0.13	-0.39
ppm SiO_2 in Extract #3	-0.11	-0.43

Table XXVI. Correlation coefficients for the winter wheat variety KS70H210 grown at 9 locations.

	Protein
Available Profile Nitrogen	0.47
% SiO_2	0.42
ppm SiO_2 in Extract #1	-0.30
ppm SiO_2 in Extract #2	-0.73**
ppm SiO_2 in Extract #3	-0.76**

Note: Yield values for this variety were not available.

Table XXVII. Correlation coefficients for the winter wheat variety Centurk grown at 11 locations.

	Yield	Protein
Available Profile Nitrogen	0.36	0.38
% SiO_2	-0.12	0.44
ppm SiO_2 in Extract #1	-0.21	-0.37
ppm SiO_2 in Extract #2	-0.26	-0.64**
ppm SiO_2 in Extract #3	-0.26	-0.66**

PHYSIOLOGICAL EFFECTS OF SILICA ON GROWTH AND PROTEIN CONCENTRATION IN WHEAT (*Triticum aestivum* L.)

by

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Physiological effects of silica on growth and yield of wheat were studied in laboratory, growth chamber, and greenhouse experiments. Effect of silica on manganese toxicity in two wheat varieties, a spring wheat and a high protein winter wheat, was studied in a growth chamber. Plants were grown in nutrient solution containing 5, 50, or 500 µM manganese and 0 or 5 mM silica. A separate experiment was conducted with the winter wheat at three Mn levels, 0, 0.5, and 5 µM, and two Si levels, 0 and 5 mM. Grain yield, grain protein concentration, plant height, vegetative yield, root growth, and Mn and Si concentrations in the vegetation and roots were determined. The greenhouse experiment had twelve high and low protein wheat varieties grown in sand cultures containing 0, 80, and 400 ppm Si as SiO_2 added with the nutrient solution. In the first of three laboratory experiments, soil samples from eleven Kansas locations where the 1975 wheat performance tests were conducted were analyzed for available profile nitrogen and total and water-extractable silica. Relationships between the wheat performance results and soil analyses were determined by statistical analysis. In the second laboratory experiment, scanning electron photomicrographs were taken of leaf surfaces of plants grown with and without silica in the greenhouse experiment. The third experiment determined transpiration rates of two-week-old wheat seedlings maintained in nutrient solutions containing various silica levels.

Silica alleviated effects of managanese toxicity in wheat by stimulating growth, but did not eliminate appearance of manganese toxicity symptoms. Silica increased grain yield and plant growth at all manganese levels. Translocation of manganese from roots to vegetation was limited by silica. Effects of manganese deficiency in wheat were not affected by silica.

High levels of silica in sand cultures were detrimental to growth of wheat. That was probably caused by silica adsorbed on the root surface that interfered with uptake of water and nutrients. Some varieties responded favorably to 80 ppm Si, but this level was too high for most varieties. No conclusive evidence of differential responses of high and low protein wheat varieties to silica was found.

Grain yield and protein concentration of field-grown wheat were not related to available profile nitrogen, total soil silica, or extractable soil silica.

Scanning electron photomicrographs of wheat leaf surfaces showed no ultrastructural changes caused by silica. Specialized silica cells and hooks were visible, but they had no apparent beneficial or detrimental effects. Transpiration rates were unaffected by silica concentration. Silica apparently was transported passively and had little direct influence on transpiration rates.