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Growth Responses of Eggplant and Soybean Seedlings to Mechanical Stress in Greenhouse and Outdoor Environments

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Additional index words. *Solanum melongena, Glycine max*, seismic stress, thigmic stress, plant conditioning

Abstract. **Eggplant (*Solanum melongena* L. var. *esculentum* 'Burpee's Black Beauty') and soybean [*Glycine max* (L.) Merr. 'Wells II'] seedlings were assigned to a greenhouse or a windless or windy outdoor environment. Plants within each environment received either periodic seismic (shaking) or thigmic (flexing or rubbing) treatments, or were left undisturbed. Productivity (dry weight) and dimensional (leaf area and stem length) growth parameters generally were reduced more by mechanical stress in the greenhouse (soybean) or outdoor-windless environment (eggplant) than in the outdoor windy environment. Outdoor exposure enhanced both stem and leaf specific weights, whereas mechanical stress enhanced only leaf specific weight. Although both forms of controlled mechanical stress tended to reduce node and internode diameters of soybean, outdoor exposure increased stem diameter.**

Controlled mechanical stress in the form of shaking (seismic stress) or stem flexing or rubbing (thigmic stress) generally inhibits growth in mass and dimensions of major plant parts (2, 8, 11, 15, 16) relative to undisturbed control plants. Mechanical stress also has been used to strengthen stems (9) and to control height of greenhouse bench crops (2).

Wind and precipitation are important sources of mechanical stress experienced by plants in nature (14). Wind action often results in plants with shorter stems and smaller leaves than wind-protected plants (22). Plant responses to wind may reflect changes in tissue temperature and water status, as well as boundary layer CO_2 level. However, seismic disturbance per se has been implicated as a factor that alters plant growth (1), and is a major component of wind action (6). Field-grown soybeans sheltered by windbreaks had increased leaf area, dry matter production, and seed yield relative to unprotected plants (19). Outdoor-grown soybeans were unresponsive to additional, controlled mechanical stress under cool temperature conditions (20).

Temperature and light level are among the environmental variables known to modify the responsiveness of plants to mechanical stress. Garden bean has characteristic minimum, optimum, and maximum temperatures for growth inhibition by thigmic stress (12), as does chrysanthemum for seismic stress (2). Furthermore, the progressive decrease in sensitivity to shaking with increasing light intensity may explain why shaking was ineffective in the greenhouse during summer but effective during winter for tomato (8) and soybean (20). The present study was designed to elucidate the effectiveness of controlled mechanical stress to limit the outdoor summer growth of eggplant and soybean seedlings in wind-protected or unprotected environments, as well as in an unshaded greenhouse.

Materials and Methods

Plant culture. Plants were grown in 12.7-cm-diameter plastic pots in a medium consisting of 1 soil : 2 peat : 2 perlite (by volume), amended as follows ($g \cdot m^{-3}$): 597 KNO_3, 597 $MgSO_4$, 896 superphosphate, and 75 trace element mix. The medium was adjusted to pH 6.2 with $CaCO_3$. To promote uniform seed-

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ling emergence, disinfested eggplant seeds were germinated in darkness at 30°C and transplanted 3 per pot in the greenhouse. Ungerminated seeds of soybean were sown 4 per pot. Seedlings of both species were thinned to one per pot and selected for treatment at the 2-leaf stage based on uniformity of stem length and leaf area. Eggplant and soybean seedlings were assigned randomly to treatments, and plants were harvested after 10 or 13 days of treatment, respectively.

Environments. Plants were treated simultaneously at 3 locations providing different types or levels of environmental stress. An unshaded greenhouse provided relative protection from wind and UV radiation. A "windless" outdoor environment was provided by surrounding each of 2 benches adjacent to the greenhouse with clear, 10-mil vinyl sheets secured to framework from 15 to 100 cm above the bench top. A double layer of cheesecloth below the vinyl permitted lateral ventilation but muffled air currents. The "windy" environment consisted of 2 unmodified outdoor benches. Reference to "outdoors" or "outdoor environment" applies to either location outside the greenhouse. Daily solar flux ($\pm$SE) averaged 9.61 $\pm$ 2.83 $MJ \cdot d^{-1} \cdot m^{-2}$ outdoors and 7.30 $\pm$ 2.15 $MJ \cdot d^{-1} \cdot m^{-2}$ in the greenhouse, as measured with an Eppley pyranometer. Average max/min ($\pm$SE) greenhouse temperatures were 37° $\pm$ 2°C day/24° $\pm$ 2° night, while those in the windless environment averaged 38° $\pm$ 2° day/22° $\pm$ 2° night, and in the windy environment 35° $\pm$ 2° day/22° $\pm$ 2° night. Outdoor wind speed averaged 2 $\pm$ 1 $m \cdot s^{-1}$.

Mechanical stress treatments. Seismic stress involved mounting plants from each environment on a gyratory platform shaker and agitating at 240 to 260 rpm for 5 min twice daily (0830 HR and 1630 HR). Thigmic stress consisted of rubbing and flexing the uppermost 5 cm of soybean stem between the thumb and forefinger 20 times twice daily (0830 HR and 1630 HR). Since eggplant was easily damaged by rubbing, thigmic stress involved flexing only the uppermost 5 cm of stem back and forth 20 times twice daily. The term "mechanical stress" as used refers to either seismic or thigmic treatment. Control plants were not intentionally disturbed.

Growth and data analysis. Measured growth responses included stem and first internode length, leaf area (LI-3000 area meter, LI-COR), and diameters of the first internode and node above the cotyledonary node. Dry weights of leaves, stems, and roots were measured after drying for 3 days at 70°C in a forced-air oven. All treatments consisted of 10 to 13 replicate plants. Growth data were subjected to analysis of variance and mean separation was tested by Tukey's honestly significant difference (HSD) procedure at the 5% level of significance. Mean separation was tested for control treatments across environments and for all treatments within environments.

Results and Discussion

Plant dry weight. Plant dry weight for both species grown in the outdoor-windless environment was 13% greater than in the greenhouse (Table 1). We attribute much of this difference to the 24% greater solar flux outdoors than in the greenhouse. Soybean dry weight was greater in the windy than in the windless environment, likely due to less stressful day temperatures in the windy environment.

Mechanical stress reduced eggplant dry weight in the outdoor windless environment and soybean dry weight in the outdoor windy environment relative to undisturbed controls (Table 1). For example, seismic and thigmic stresses reduced eggplant dry weight by 18% and 21%, respectively, in the outdoor windless environment.

Table 1. Effect of environment and mechanical stress on mean dry weight of eggplant and soybean seedlings after 10 and 13 days of treatment, respectively.

Environment treatment	Plant dry wt (g)	
	Eggplant	Soybean
Greenhouse		
Control	3.97 a[z]A[y]	2.50 bA
Seismic	3.81 a	2.14 a
Thigmic	3.43 a	2.45 b
Outdoors − wind		
Control	4.48 bB	2.82 aB
Seismic	3.65 a	2.57 a
Thigmic	3.54 a	2.74 a
Outdoors + wind		
Control	4.35 aAB	3.23 bC
Seismic	4.08 a	2.92 a
Thigmic	3.87 a	2.89 a

[z]Different lowercase letters within columns indicate mean separation of treatments within environments, Tukey's HSD, 5% level.

[y]Different uppercase letters within columns indicate mean separation of control treatments across environments, Tukey's HSD, 5% level.

Leaf growth response. Seismic stress reduced leaf area of soybean 15% in the greenhouse but only 7% in the windy environment relative to undisturbed controls (Fig. 1). Thigmic stress reduced leaf area of eggplant in all environments, but of soybean only in the windy environment.

Outdoor exposure increased specific leaf weight (SLW) 27% for eggplant and 24% for soybean (Fig. 1). Thigmic stress increased SLW 6% to 9% for both species in the greenhouse and outdoor windy environments. Seismic stress tended to increase SLW for soybean but not for eggplant.

Specific leaf weight may reflect changes in leaf morphology because, as leaf thickness increases, the ratio of mesophyll cell area to total leaf area increases (17). Specific leaf weight may be increased by high levels of photosynthetically active radiation (17), starch accumulation (22), wind (5, 7, 21), or seismic stress (1). Increased SLW also may enhance photosynthetic rate (18). Although total leaf area was less for outdoor-grown plants of both species relative to greenhouse controls, leaf dry weight was not reduced outdoors (Fig. 1), and whole-plant dry weight actually increased (Table 1). Because early stages of leaf development are important in determining SLW (18), mechanical stress of young greenhouse plants may improve eventual growth outdoors by increasing SLW.

Stem growth responses. Outdoor exposure depressed stem elongation for soybean but enhanced stem dry weight and specific stem weight (SSW) for both species, whereas controlled mechanical stress generally decreased growth in length and dry weight (Fig. 2). Stem dry weight of soybean increased 13% to 17% outdoors while stem length decreased 17%, resulting in a 35–40% increase in SSW. Seismic stress decreased soybean stem length 14% in the greenhouse but had no effect in the windy environment. Stem length of eggplant was reduced 10% to 13% by seismic stress and 26% to 29% by thigmic stress across environments. Mechanical stress also tended to reduce stem dry weight of both species. Specific stem weight was not consistently affected by mechanical stress.

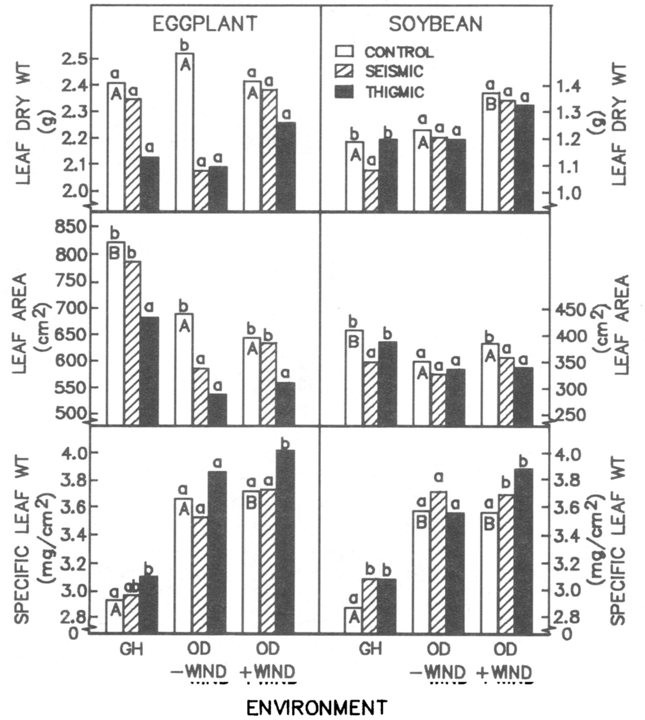

Fig. 1. Effect of seismic (5 min at 240–260 rpm) or thigmic (20 strokes) stress applied twice daily on leaf dry weight, area, and specific weight for eggplant and soybean plants after 10 or 13 days of treatment in a greenhouse (GH) or outdoors (OD) ± wind. Bar groups for each growth response within an environment with different lowercase letters are significantly different at the 5% level, Tukey's HSD. Different uppercase letters indicate mean separation of control treatments (within species) across environments, 5% level, Tukey's HSD.

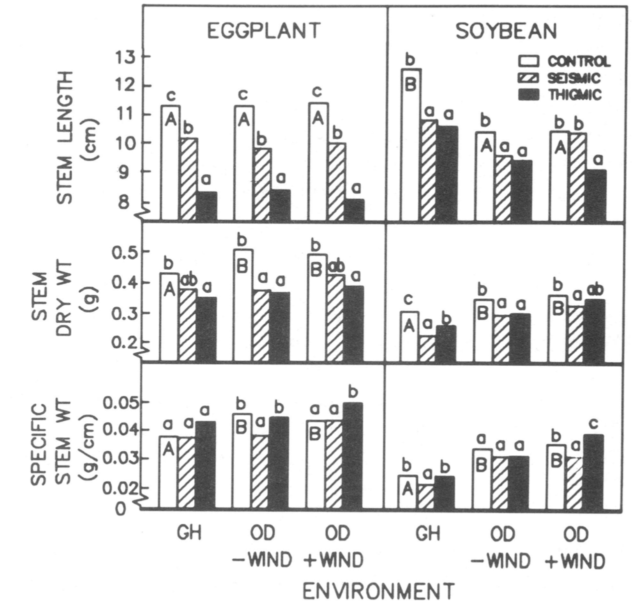

Fig. 2. Effect of mechanical stress on stem length, dry weight, and specific weight for eggplant and soybean plants grown in a greenhouse (GH) or outdoors (OD) ± wind. Statistical analyses were as for Fig. 1.

Soybean internode and node diameters generally were reduced by mechanical stress but increased by outdoor exposure (Fig. 3). There was no change in relative internode thickness (diameter : length ratio) with respect to environment, but thigmic stress decreased relative internode diameter of greenhouse and wind-exposed soybean plants. The ratio of node to internode diameter was increased slightly by mechanical stress treatment in the greenhouse. Node and internode diameters of eggplant responded to environment in a manner similar to soybean but were unaffected by mechanical stress (data not shown).

In contrast to reports that thigmic stress enhances stem diameter (4, 10), we found reductions in stem diameter of soybean by thigmic stress across environments (Fig. 3). In the windy environment, where node diameter of control plants increased 15% over that of greenhouse controls, thigmic stress reduced node diameter 12% relative to undisturbed controls. Previous reports of stem swelling in response to thigmic stress have implicated a role for ethylene (4, 10). Perhaps our thigmic treatment was not severe enough to cause production of wound ethylene. Alternatively, soybean may not be as sensitive to ethylene as species used in other studies, or the warm summer conditions occurring during this study may have modified the response (2, 8, 20).

Dry weight distribution. Outdoor exposure caused a proportionate dry weight shift from leaves to roots, as noted previously (21), and an increase in proportion of dry weight in lateral growth (Table 2). Mechanical stress affected dry weight partition in greenhouse eggplant only by decreasing the proportion of dry weight in petioles. On the other hand, the proportion of dry weight in soybean lamina increased at the expense of petiole and stem dry weight in response to mechanical stress in the greenhouse, and of roots in the outdoor windy environment. Seismic stress of soybean actually reduced the partition of dry weight into lateral growth in the greenhouse, whereas thigmic stress tended to increase lateral growth in the greenhouse and outdoor windless environments.

Water content responses. Outdoor exposure decreased specific water content of leaves and stems for both species (Table 3). Leaf specific water content (LSWC) and stem specific water content (SSWC) of soybean were the least in the windless (but warmer) outdoor environment. Mechanical stress had no effect

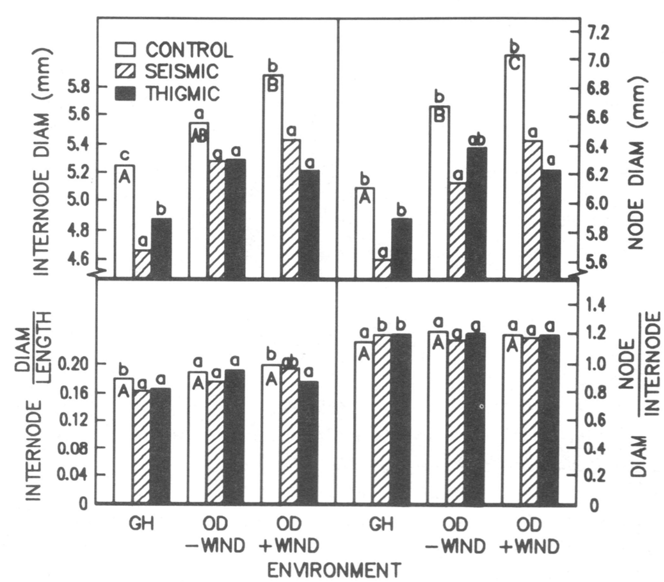

Fig. 3. Effect of mechanical stress on node and internode diameters, and ratios of internode diameter : length and node diameter : internode diameter for soybean plants grown in a greenhouse (GH) or outdoors (OD) ± wind. Statistical analyses were as for Fig. 1.

Table 2. Effect of mechanical stress and environment on the distribution of dry weight (as percentage of whole plant dry weight) for eggplant and soybean seedlings after 10 and 13 days of treatment, respectively.

Environment treatment	Eggplant Lamina	Eggplant Petioles	Eggplant Lateral growth	Eggplant Stem	Eggplant Roots	Soybean Lamina	Soybean Petioles	Soybean Lateral growth	Soybean Stem	Soybean Roots
	Dry wt distribution (%)									
Greenhouse										
Control	60.4 a[z]B[y]	10.3 bB	1.3 aA	10.9 aA	16.7 aA	47.8 aB	9.4 bB	4.3 bA	16.5 bB	23.4 aA
Seismic	61.6 a	9.1 a	1.6 a	10.4 a	16.9 a	50.9 c	8.3 a	2.6 a	14.7 a	24.2 a
Thigmic	61.7 a	8.6 a	1.6 a	10.5 a	17.0 a	49.4 b	8.5 a	5.3 b	14.5 a	24.0 a
Outdoors −wind										
Control	56.2 aA	10.1 cAB	2.4 aB	11.6 bA	19.1 aAB	43.8 aA	8.6 bA	5.0 aA	16.7 bB	27.6 abB
Seismic	56.8 ab	9.1 b	2.4 a	10.6 a	20.5 a	46.8 b	8.1 b	3.9 a	15.7 ab	26.8 a
Thigmic	58.2 b	8.4 a	2.5 a	10.2 a	19.7 a	43.6 a	7.2 a	7.8 b	15.1 a	28.6 b
Outdoors +wind										
Control	55.6 aA	9.7 bA	3.2 aB	11.6 bA	19.4 ab	42.5 aA	8.4 bA	9.4 aB	15.1 aA	27.2 bB
Seismic	58.2 b	9.3 b	2.8 a	10.7 ab	18.4 a	45.9 b	8.5 b	9.0 a	15.0 a	25.4 a
Thigmic	58.5 b	8.3 a	3.8 a	10.4 a	18.4 a	45.7 b	7.8 a	9.0 a	15.6 a	24.5 a

[z]Different lowercase letters within columns indicate mean separation of treatments within environments, Tukey's HSD, 5% level.
[y]Different uppercase letters within columns indicate mean separation of control treatments across environments, Tukey's HSD, 5% level.

on LSWC of eggplant in any environment, but it decreased SSWC in the greenhouse and outdoor windy environments. Thigmic stress tended to be more effective than seismic stress in this regard. For soybean, only thigmic stress decreased SSW in greenhouse and outdoor windy environments. These effects were largely attributable to increased specific (dry) weights of stems and leaves, due in turn to smaller dimensions of those plant parts (Figs. 1 and 2).

Eggplant growth outdoors generally did not vary with respect to presence or absence of wind, whereas soybean growth did. The wind load prevailing throughout the experiment displaced stems and leaves of soybean more than those of eggplant, which may explain why additional, controlled seismic stress reduced stem growth of outdoor eggplant more than that of outdoor soybean. Soybean exposed to wind has been reported to "harden off" to additional seismic stress (20). However, in the present study, soybean remained responsive to both seismic and thigmic stress outdoors. This discrepancy probably was due to the high intensity of shaking used and the warm temperatures that prevailed during this study.

Table 3. Effect of environment and mechanical stress on leaf specific water content (LSWC) and stem specific water content (SSWC) of eggplant and soybean seedlings after 10 and 13 days of treatment, respectively.

Environment treatment	Eggplant LSWC	Eggplant SSWC	Soybean LSWC	Soybean SSWC
	($g\ H_2O/g$ dry wt^{-1})			
Greenhouse				
Control	10.05 a[z]B[y]	11.52 cB	5.30 aC	7.55 bC
Seismic	10.16 a	9.94 b	5.12 a	7.64 b
Thigmic	10.30 a	8.73 a	5.22 a	6.98 a
Outdoor −wind				
Control	8.69 aA	9.47 aA	4.56 aA	6.34 aA
Seismic	9.32 a	9.30 a	4.40 a	6.56 a
Thigmic	9.35 a	8.73 a	4.89 b	6.25 a
Outdoors +wind				
Control	9.12 aA	9.80 bA	4.91 bB	7.06 bB
Seismic	9.01 a	8.78 a	4.66 a	6.64 b
Thigmic	9.10 a	8.31 a	4.74 ab	5.25 a

[z]Different lowercase letters within columns indicate mean separation of treatments within environments, Tukey's HSD, 5% level.
[y]Different uppercase letters within columns indicate mean separation of control treatments across environments, Tukey's HSD, 5% level.

Seismic stress has been reported to strengthen stems of tomato seedlings (9), and thigmic stress to strengthen stems of bean (13). Mechanical stress does mimic some aspects of the outdoor environment and has been suggested as a pretreatment for conditioning plants prior to outdoor transfer (3). A role for mechanical stress in physiological hardening remains to be determined.

The variation in plant growth responses obtained between environments, as well as between treatments within environments, reinforces the concept that environmental conditions control or modify the extent and direction of plant response to controlled mechanical stress (2, 8, 12, 20). Variation in species responsivity to mechanical stress may be due to differences in growth form or habit, or other inherent characteristics.

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Influence of Nutritional Conditioning on Muskmelon Transplant Quality and Early Yield

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Abstract. **Pretransplanting nutritional conditioning (PNC) regimes were evaluated for their effects on improving tolerance to transplant shock and increasing early fruit production. Muskmelon seedlings (*Cucumis melo* var. *reticulatus* L. 'Magnum 45') were fertilized twice weekly with solutions containing N, P, and K to determine nutrient needs required to produce high-quality transplants. Seedling height, stem diameter, leaf area, shoot and root dry weights, leaf number, and shoot : root ratios of 27-day-old transplants increased as N rates increased from 10 to 250 mg·liter^{-1}. These growth variables also increased with P from 5 to 25 mg·liter^{-1} but decreased as P increased from 25 to 125 mg·liter^{-1}. Increasing K rates from 10 to 250 mg·liter^{-1} increased seedling height, stem diameter, and leaf area. Nine PNC regimes ranging from low to high N–P–K status were tested under field conditions to determine any long-term advantage. Generally, as PNC levels increased, transplant shock (percentage of necrotic leaves) increased as measured 12 days after transplanting. However, vining, female flowering, fruit set, and early yields increased as PNC levels increased. A high level of PNC (250N–125P–250K, mg·liter^{-1}) conditioned transplants to overcome shock and to resume growth sooner and yield earlier than those at lower PNC levels.**

Most muskmelon production fields in the lower Rio Grande Valley of Texas are established by direct seeding, but transplanting also is used to improve stands, reduce seed usage, and improve earliness relative to direct seeding. However, transplant shock induced by wind, water, and temperature stresses may reduce transplant survival and negate any benefit of earliness. Therefore, techniques must be developed to enhance recovery of transplants from shock. Techniques developed to reduce field stresses of various crops may involve acclimatization of the transplants by hardening (14), application of abscissic acid (10, 12), antitranspirants (2, 13, 15), root antidesiccants (7), or pruning (6, 16).

It was hypothesized that certain fertilization practices occurring during the propagation of transplants, referred to here as pretransplanting nutritional conditioning regimes (PNC), condition seedlings to tolerate and recover from transplant shock and to promote early yields. Development of vigorous seedlings is a prerequisite to successful transplanting, and optimization of fertilization contributes greatly to the production of vigorous seedlings (9).

The use of PNC on improving yield in the field has been shown with other vegetable crops. Yields of pepper (8), lettuce (9), and cabbage (3) were improved with PNC regimes. Humates used in a plug-mix medium increased tomato seedling

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