Communications in Soil Science and Plant Analysis, 36: 951–967, 2005

ISSN 0010-3624 print/1532-2416 online
DOI: 10.1081/CSS-200050280

Effects of Salinity, Imazethapyr, and Chlorimuron Application on Soybean Growth and Yield

Sharon K. Papiernik
United States Department of Agriculture, Agricultural Research Service, Soil Management Research, Morris, MN, USA

Catherine M. Grieve, Scott M. Lesch, and Scott R. Yates
United States Department of Agriculture, Agricultural Research Service, George E. Brown Jr. Salinity Laboratory, Riverside, CA, USA

Abstract: Soybean is an important crop worldwide. Soybean cultivars differ in their sensitivity to soil salinity and herbicide damage. In these experiments, we examined the impact of salinization and herbicide (imazethapyr and chlorimuron) application on the growth and yield of two soybean cultivars, Essex and Manokin. Experiments were conducted in small pots in the greenhouse, in outdoor sand cultures, and in drip-irrigated field plots. Plants were irrigated with non-saline water or saline water (electrical conductivity, EC = 7 dS/m) with a composition typical of those in areas affected by sulfate-dominated salinity. Morphological changes resulted from herbicide application, including leaf elongation and formation of large shoots at the cotyledonary node. Herbicide treatment significantly reduced main stem height, number of nodes on the main stem, and stem diameter relative to the controls (not treated with herbicide); responses from the two herbicides were not significantly different. Salinity had a significant effect on seed weight: yield for "Essex" (a Cl accumulator) was significantly higher when irrigated with fresh water, while yield for "Manokin" (a Cl excluder) was significantly larger for plants irrigated with saline water. Yield for "Essex" was greater than that for "Manokin" when the plants were irrigated with fresh water; but at the higher irrigation water salinity (7 dS/m),

Received 12 December 2003, Accepted 27 July 2004
Address correspondence to Sharon K. Papiernik, United States Department of Agriculture, Agricultural Research Service, Soil Management Research, 803 Iowa Avenue, Morris, MN 56267, USA. E-mail: papiernik@morris.ars.usda.gov

"Manokin" produced significantly greater yield than "Essex." Although herbicide application significantly impacted several growth variables, herbicide treatment had no significant impact on yield.

Keywords: Chlorimuron, *Glycine max* L. Merrill, height, herbicide, imazethapyr, nodes, salt stress, seed weight, soybean

INTRODUCTION

Soybean (*Glycine max* L. Merrill) is an important agronomic crop in the United States and worldwide. In 2001, more than 75 million acres of soybeans were planted in the United States (National Agricultural Statistics Service 2005). A significant proportion of this acreage is comprised of irrigated and/or salt-affected soils. Fertilization with potassium chloride (KCl) can result in soil chloride (Cl) concentrations that cause leaf scorch or other phytotoxic symptoms in soybeans (Parker, Gaines, and Gascho 1986; Parker et al. 1987). Soybean cultivars vary in their sensitivity to soil chloride concentrations (Parker, Gaines, and Gascho 1986; Abel and MacKenzie 1964). Soybean cultivars which are classified as chloride excluders tend to confine chloride to the roots while cultivars classified as chloride accumulators translocate chloride to the shoots and leaves (Abel and MacKenzie 1964). Chloride salinity has been shown to affect the rate of germination, nodulation, leaflet size, shoot height, root length, shoot and root dry weight, and seed size and weight in soybeans (Parker et al. 1987; Abel and MacKenzie 1964; Maftoun et al. 1982; Beecher 1993; Shalhevet, Huck, and Schroeder 1995; Wang and Shannon 1999; An et al. 2001). Most research on the salt-sensitivity of soybeans has been conducted using chloride salts (NaCl and $CaCl_2$). In prairie soils in the United States, Canada, and the San Joaquin Valley of California, salinity is comprised of both chloride and sulfate salts. Plants may demonstrate different responses to sulfate-dominated salinity than to chloride-based salinity at the same electrical conductivity (Curtin, Steppuhn, and Selles 1993). A larger decrease in soybean biomass production has been observed in soils salinized with chloride salts than with sulfate salts (Gupta and Gupta 1984).

Nearly all land planted to soybeans in the U.S. and Canada receives herbicide application. The herbicides imazethapyr, 2-[4,5-dihydro-4-methyl-4-(1-methylethyl)-5-oxo-1*H*-imidazol-2-yl]-5-ethyl-3-pyridinecarboxylic acid), and chlorimuron, ethyl-2-[[[[(4-chloro-6-methoxy-2-pyrimidinyl)amino]carbonyl]amino]sulfonyl]benzoate, are often used for the postemergence control of weeds in legumes, especially soybeans and peanuts. These compounds belong to the sulfonyl urea (chlorimuron) and imidazolinone (imazethapyr) herbicide classes, which cause phytotoxicity though the inhibition of acetohydroxy acid synthase and the synthesis of branched chain

amino acids. Selectivity of these herbicides is based on the rate and/or extent of metabolism (detoxification) of the active ingredient by the plant (Brown 1990; Shaner and Mallipudi 1991).

In the hours following imazethapyr application to soybeans, fresh weight of shoots and roots was increased, but dry weight was decreased, indicating higher water concentrations in imazethapyr-treated plants (Scarponi, Martinetti, and Alla 1996). Enzyme activities and glucose and starch contents were also affected within hours after imazethapyr application (Scarponi, Martinetti, and Alla 1996; Scarponi, Alla, and Martinetti 1995). Both imazethapyr and chlorimuron have been shown to decrease protein and branched-chain amino acid contents of legumes (Scarponi et al. 1997). Some studies have indicated no growth (Adcock and Banks 1991) or yield response to soybean treatment with chlorimuron or imazethapyr (Krausz, Kapusta, and Knake 1992).

Soybean cultivars show different susceptibility to chlorimuron applied either pre-plant or post-emergence (Newsom and Shaw 1992; Mian et al. 1997). Varying degrees of soybean tolerance to an imadazolinone herbicide have also been reported (Newsom and Shaw 1995; Wixson and Shaw 1991). More plant damage resulting from pre-emergence application of sulfonyl urea and imidazolinone herbicides occurs in moist soils, most likely because of the increased bioavailability of the compounds in soils with increased water content (Newsom and Shaw 1992; Newsom and Shaw 1995; Griffin and Habetz 1989; Stapleton and Whitwell 1989). Soybean injury by chlorimuron and imadazolinone herbicides typically results in decreased plant height and biomass, and can result in reduced yield (Newsom and Shaw 1992; Newsom and Shaw 1995; Griffin and Habetz 1989; Stapleton and Whitwell 1989).

Plants may exhibit different susceptibility to herbicide damage when under moisture or other stresses than when they are not stressed (Gerber, Hyffeler, and Green 1983; Reynolds et al. 1988; O'Barr). Multiple stressors affecting plant growth and metabolism have the potential to result in increased (or decreased) plant response. Limited information exists on the response of soybeans to a combination of salinity and herbicide treatment. Maftoun et al. (1982) reported no significant interaction of salinity and trifluralin treatment on soybean root or shoot dry weight or root nodulation. O'Barr observed decreases in yield when imadazolinone and sulfonyl urea herbicides were applied to soybeans grown in soils with EC $> 1\ \mathrm{dS\ m^{-1}}$.

These experiments examined the impact of sulfate-dominated salinization and herbicide (imazethapyr and chlorimuron) application on the growth and yield of two soybean cultivars. Experiments were conducted in the greenhouse, in outdoor sand cultures, and in drip-irrigated field plots. Previous experiments conducted under similar salinization conditions suggested that weed control by these herbicides was consistent with the herbicide labels (Papiernik et al. 2003). A large proportion of agricultural land is affected by

sulfate salinity, and the results of these experiments may help determine soybean response and herbicide injury in these systems.

MATERIALS AND METHODS

Seeds

Soybean seeds were provided by the Maryland Agricultural Experiment Station. Cultivars "Manokin" and "Essex" were used in these experiments. "Essex" has been classified as a Cl accumulator (Yang and Blanchar 1993), while "Manokin" has salt tolerance similar to "Lee" (Kenworthy et al. 1996), a chloride excluder (Maftoun et al. 1982). Previous research has indicated that "Essex" metabolizes chlorimuron rapidly and is relatively tolerant to chlorimuron (Moseley, Hatzios, and Hagood 1993).

Greenhouse Experiments

Seeds were planted in potting soil in 2-inch plastic pots. Pots were seated in a sand bed in tanks with 51–54 pots per tank. The experiment was conducted August 26 through October 10, 2000. During the experiment, the mean daytime temperature ranged from 16–35°C with a mean of 26°C. Nighttime temperatures ranged from 16–31°C with a mean of 22°C. Relative humidity ranged from 40–49% during the day and 42–49% during the night, with a mean of 45% both day and night.

Pots were irrigated with nutrient solution (non-saline treatment, EC $\sim 2\,\mathrm{dS\,m^{-1}}$) or Hoagland's nutrient solution plus (in meq $\mathrm{L^{-1}}$) $\mathrm{MgSO_4 \cdot 7\,H_2O}$, 6.6; $\mathrm{Na_2SO_4}$, 23.3; $\mathrm{CaCl_2}$, 7.6; NaCl, 6.1; and $\mathrm{KNO_3}$, 4.0 (salinized treatment, EC $\sim 7\,\mathrm{dS\,m^{-1}}$). This solution was designed to simulate saline drainage water commonly present in the San Joaquin Valley of California. Irrigation water was contained in 60-L reservoirs and two sand tanks were placed on top of each reservoir. Irrigation was accomplished by bubbling air into delivery tubes inside the reservoir to drive water up to the surface and into the sand tank. Each sand tank had a small drainage hole in the bottom so leachate drained back into the reservoirs. The maximum water level was maintained by a second drain several mm above the rim of the pots. Each irrigation event was 30 minutes, allowing for re-equilibration between the soil water and irrigation water so that the salinity in the pots was relatively constant. Soybeans were germinated using non-saline water. Half of the plants (one of two sand tanks) for each variety were irrigated with saline water beginning at the time of herbicide application. Tanks were irrigated as necessary to keep the soil moist, generally twice per week during germination and early growth, and daily later in the experiment.

The salinity of the irrigation water was maintained throughout the experiment by addition of tap water and the pH was maintained at ~7 by addition of sulfuric acid.

Formulated herbicide was donated by the manufacturers. Chlorimuron (Classic)[1] and the ammonium salt of imazethapyr (Pursuit) are labeled for postemergence weed control in soybeans. Chlorimuron was applied at 8.8 g ai ha^{-1} and imazethapyr was applied at 70 g ai ha^{-1}. Formulated herbicides were applied with 2.8 kg ha^{-1} ammonium sulfate and 2.3 L ha^{-1} nonionic surfactant (Spray-Grip, Proguard, Inc., Suisun, CA) according to the label instructions. A low-volume sprayer was used to apply 470 L ha^{-1} herbicide solution uniformly to the treated area, with much of the solution intercepted by the leaf surfaces. Controls consisted of a solution of 2.8 kg ha^{-1} ammonium sulfate and 2.3 L ha^{-1} nonionic surfactant (tank mix without the herbicide) applied at 470 L ha^{-1}. For herbicide application, individual pots were removed, treated, labeled, and replaced in the sand tank so that all herbicide treatments of one variety–salinity combination were included in a single tank. Plants were randomly positioned in each tank, so that 17 or 18 replicates for each herbicide treatment were within each tank (total of 51–54 plants per tank). The plant growth stages at the time of herbicide application are given in Table 1. Plants were irrigated ~4 hours before herbicide application, and were not irrigated again until >24 hours after herbicide application. Application of saline irrigation water began with the first irrigation cycle following herbicide treatment, so that the time of herbicide application coincided with the time of initiation of salinization.

Plant growth variables were measured 30 days after herbicide treatment. Plant height was measured from the soil surface to the main shoot apex. The number of nodes on the main stem was counted, including the cotyledonary node. Some plants exhibited significant growth from shoots emerging from the cotyledons, so the number of nodes on the cotyledonary shoots was also measured. The stem diameter at the cotyledon was measured using a calipers. Using a Li-Cor 3100 area meter (Li-Cor, Inc., Lincoln, NE), leaf area was measured separately for leaves on the primary shoot and leaves on the cotyledonary shoots. Leaves were analyzed for chloride content. Leaves were grouped so that three individual plants from the same salinity–herbicide treatment made up one sample for chloride analysis. Leaf samples were weighed, washed in deionized water, dried in a forced-air oven at 70–75°C for 96 h, reweighed, and ground. Chloride was determined on nitric–acetic acid extracts by coulometric–amperometric titration.

[1]Use of a company product name is for the convenience of the reader and does not imply endorsement of the product by the USDA to the exclusion of others that may also be suitable.

Table 1. Soybean growth stage at time of herbicide application

	Essex		Manokin	
	Non-saline	Salinized	Non-saline	Salinized
Greenhouse Experiment				
Nodes	2	2	3	3
Main stem height (cm)	8.6 ± 0.8	8.3 ± 0.5	4.5 ± 0.3	4.4 ± 0.3
Sand Tank Experiment				
Nodes	2	2	2	2
Main stem height (cm)	5.8 ± 0.9	5.8 ± 0.9	4.6 ± 0.6	4.6 ± 0.6
Stem diameter (mm)	2.2 ± 0.3	2.2 ± 0.3	2.0 ± 0.3	2.0 ± 0.3
Field Experiment				
Nodes	2–4	2–4	2–4	2–4
Main stem height (cm)	~5.5	~5.5	~5.5	~5.5

Sand Tank Experiments

Soybean seeds were germinated in sand in germinating trays. Plants were irrigated with tap water daily. Approximately 5 days after germination (May 17, 2001), chlorimuron, imazethapyr, and control solution were applied broadcast to germination trays using a low volume sprayer. Soybean development stages at the time of herbicide application are given in Table 1. The herbicide formulation, tank mix, and application rate was the same as in the greenhouse experiment. Soybean seedlings were transplanted to large outdoor sand tanks ~24 hours after herbicide application. The sand culture tanks (3 m × 1.5 m × 2 m deep) were filled with washed river sand to a bulk density of 1.7 Mg m^{-3}. Soybeans were planted in 40-cm (15-in.) rows with 21 cm (8 in.) between individual plants. Plants were randomly positioned in each tank; for each cultivar, there were 16 replicate plants that received each herbicide treatment per salinity level. Each tank was irrigated with water from a dedicated reservoir (volume ~4000 L). Irrigation solutions were pumped from the reservoirs to the tanks and a drainage system at the bottom of each sand tank returned the drainage to the appropriate reservoir. In this case, soybeans of one variety were transplanted to two separate tanks; one tank was irrigated with nutrient solution (as described by Grieve et al. (2001)). and the other with nutrient solution prepared to simulate San Joaquin drainage water, the salt composition being the same as in the greenhouse study. Soybean plants in the sand tanks were irrigated <1 hour after transplanting. Salinization began at this first irrigation following transplanting. Irrigation cycles were 20 minutes long. Tanks were irrigated once daily for the duration of the experiment. Insects were controlled by foliar applications of acetamiprid and imadacloprid.

The number of nodes, height, and diameter of the main stem and the number of nodes on the cotyledonary shoots were measured 30 days after herbicide application. Plants were harvested after complete senescence by cutting the stem at the soil surface. Pods were removed from the stems and dried at 50°C in a forced-air oven for 1 week. Seeds were removed from the pods and weighed to determine yield (g per plant).

Field Experiment

The field plot was located at the University of California, Riverside Agricultural Experiment Station. The soil is classified as an Arlington sandy loam (coarse-loamy, mixed, thermic, Haplic Durixeralf). The field plot (24 m × 37 m) was tilled and treated with 10-10-10 fertilizer to prepare for planting. Soybean seeds were inoculated with *Bradyrhizobium japonicum* (USDA RhizoStick, Urbana Labs, St. Joseph, MI). Seeds were planted in 76-cm (30-in.) rows with a 10-cm (4-in.) spacing between plants. The same variety was planted in two sets of nine adjacent rows. The plot was irrigated by surface drip with city of Riverside, CA tap water until 21 days after planting, when herbicide applications were made. Herbicide solution (imazethapyr, chlorimuron, and control) was applied using the same formulation, tank mix, and application rate as in the greenhouse and sand tank experiments. An approximation of the plant development stage at the time of herbicide application is given in Table 1. One-third of each row was treated with each herbicide solution. Beginning with the first irrigation following herbicide application (two days after treatment), surface drip irrigation was used to deliver tap water (non-saline treatment) or salinized water. Salinized irrigation water contained the same concentration of salinizing salts ($MgSO_4$, Na_2SO_4, $CaCl_2$, NaCl, and KNO_3, EC $\sim$7 dS m^{-1}) as in the greenhouse and sand tank experiments, with no addition of nutrient solution.

In the first two months following herbicide application, the plot was hand-weeded as necessary. Insects (particularly glassy-winged sharpshooters, *Homalodisca coagulata*) were controlled by one foliar application of aldicarb and one application of imadacloprid via drip chemigation. At maturity (approximately 2–3 weeks before senescence), leaf area of five plants was measured using a Li-Cor 3100 area meter. Leaves from the primary shoot were separated from leaves on cotyledonary shoots for leaf area measurements.

At senescence, soil samples were collected from the field to determine resident soil electrical conductivity. Samples were collected immediately adjacent to the stem of a soybean plant, so that the center of the soil core was approximately 4 cm from the drip line. Soil samples were obtained using a 5-cm-diameter soil auger in 10-cm depth increments from 0–100 cm below the soil surface. Deionized water (30 mL) was added to

75 g of homogenized fresh soil, stirred until well-mixed, allowed to stand overnight, then filtered, and the electrical conductivity of the solution measured. Soil moisture was determined and the electrical conductivity of the pore water was calculated based on the EC of the measured solution representing diluted pore water (assuming all salt in the extract was contained in the soil water).

When plants had completely matured, the length of continuous stand in each row was measured. Plants for each herbicide treatment were cut at the base and grouped by row. Harvested plants were allowed to dry before they were threshed. Seeds were then dried in a forced-air oven at 50°C for 1 week, and cleaned by sieving followed by passing the seeds in front of a blower to remove chaff. Seed mass from each row was determined, and the seed mass per plant was calculated based on the nominal plant spacing (10 cm).

Statistical Analysis

The experiment was set up as a split-plot design with the salt levels and soybean varieties serving as the main plot effects, and the herbicide treatments representing the sub-plot effect. Two salinity levels (2.5 dS/m and 7.0 dS/m) and two soybean varieties ("Manokin" and "Essex") were assigned to the main plot units. Three herbicide treatments (chlorimuron, imazethapyr, and no herbicide) were randomly assigned to the three sub-plot units. The design was replicated across locations (blocks). For plant growth variables, blocks were the greenhouse experiment and the sand tank experiment. For yield response, blocks were the sand tank experiment and the field experiment. In this design, the location represents a random block effect while the nested/crossed location (salt × variety) effect represents the appropriate main plot error term.

The following plant growth measurements were recorded on each sub-plot experimental unit: 1) the average plant height, 2) the average number of nodes per plant, 3) the average stem diameter, and 4) the average number of nodes on the cotyledonary shoots. All measurements were taken 30 days following herbicide application. Yield response (average seed weight per plant) was determined at maturity. All measurements resulted in a total of 24 (2 salt × 2 variety × 3 herbicide × 2 location) observations for each response variable.

All data sets were analyzed using the following split-plot model:

$$y_{ijkm} = \mu + B_i + S_j + V_k + SV_{jk} + B(SV)_{ijk} + H_m + SH_{jm} + VH_{km} + SVH_{jkm} + \varepsilon_{ijkm} \quad (1)$$

where B represents the random location effect ($i = 1, 2$), S represents the fixed main plot salt effect ($j = 1, 2$), V represents the fixed main plot variety effect ($k = 1, 2$), and H represents the fixed sub-plot herbicide effect ($m = 1, 2, 3$). In Equation (1), μ represents the overall mean response level, the B(SV) effect

represents the main plot error term for testing the salt and variety effects, and ε represents the sub-plot error term for testing the herbicide effects (Montgomery 1997). This model was estimated using the MIXED and GLM procedures in SAS (Statistical Analysis Systems) following the methodology of Littell et al. (1996). The MIXED procedure was used to generate all of the F-test statistics, least-square estimates, and contrasts of interest. The GLM procedure was used to generate some basic model summary statistics (R^2 and %CV) and also to facilitate the analysis of the model residuals. The residuals associated with all three split-plot models successfully passed a standard series of residual diagnostic checks. No outliers were present in any data set and the residuals appeared to be normally distributed. Hence, the ANOVA (analysis of variance) modeling assumptions were deemed appropriate.

RESULTS AND DISCUSSION

Morphological Changes Resulting from Herbicide Application

No leaf necrosis was evident for any salinity–herbicide treatment in any experiment. Morphological changes were observed in herbicide-treated soybeans. For example, some "Essex" plants treated with imazethapyr demonstrated narrow elongated leaves uncharacteristic of soybeans (Figure 1). These effects were observed in both the greenhouse study and in the field study, and in both salinized and non-salinized treatments. These elongated leaves developed after herbicide application, and these leaves were not yet formed when the herbicides were foliar-applied. On these plants, while the

Figure 1. Alteration in soybean leaf shape observed in Essex soybeans treated with imazethapyr (A) compared with control (B). These effects were noted in both the greenhouse and the field experiments.

leaves formed prior to herbicide application were normal, nearly all leaves formed after herbicide application exhibited elongation.

After herbicide application, a large percentage of soybeans developed secondary shoots that emerged from the cotyledonary node. In many cases, particularly in "Essex" treated with chlorimuron, the meristem died following herbicide application, but cotyledonary shoots emerged and continued to grow. In most cases where the meristem survived, the cotyledonary shoots grew at approximately the same rate as the meristem. Thus, plants exhibiting branching at the cotyledonary node had a large fraction of their plant mass comprised of cotyledonary shoots.

Leaf area measurements (greenhouse and field studies) further indicated the morphological changes observed in herbicide-treated plants. A large fraction of the total leaf area was contained on the cotyledonary shoots, the fraction increasing with time. "Essex" plants not treated with herbicide generally had lower percentages of leaf area comprised by cotyledonary shoots than imazethapyr-treated or chlorimuron-treated plants in both the field and greenhouse experiments. At 30 d after herbicide application in the greenhouse experiment, mean leaf area on the cotyledonary shoots represented 2% of the total mean leaf area for the control "Essex," 22% of the total for chlorimuron-treated "Essex," and 48% of the total for imazethapyr-treated "Essex"; for "Manokin," cotyledonary shoot leaf area represented $<0.5\%$ of the total for all herbicide treatments. At plant maturity in the field experiment, mean leaf area on the cotyledonary shoots represented 20% of the total mean leaf area for the control "Essex," 83% of the total for chlorimuron-treated "Essex," and 44% of the total for imazethapyr-treated "Essex"; "Manokin" had about 40% of the leaf area contained on the cotyledonary shoots for all herbicide treatments. In the field experiment, there were a large number of "Essex" plants treated with chlorimuron for which the cotyledonary shoots comprised all of the leaf area, and mature chlorimuron-treated "Essex" generally had higher leaf area on the cotyledonary shoots than imazethapyr-treated or control plants. For some "Essex" plants treated with chlorimuron in the field experiment, after the meristem died, plants developed large cotyledonary shoots that could not be supported by the main stem, and the cotyledonary shoots separated from the stem, leaving no living plant mass for further development.

Effect of Salinity and Herbicide Application on Plant Growth and Yield Variables

Leaf chloride concentrations measured in the greenhouse experiment verified that "Manokin" is a chloride excluder and "Essex" a chloride accumulator. The chloride concentration in herbicide-treated "Manokin" leaves increased from 10 to 20 $\mathrm{mmol\,kg^{-1}}$ in soybeans irrigated with fresh water

(EC $\sim 2\,\mathrm{dS\,m^{-1}}$) to $\sim 70\,\mathrm{mmol\,kg^{-1}}$ in soybeans irrigated with saline water ($7\,\mathrm{dS\,m^{-1}}$). For "Essex," leaf chloride concentrations increased from $\sim 70 - \sim 500\,\mathrm{mmol\,kg^{-1}}$ as salinity increased from $2-7\,\mathrm{dSm^{-1}}$. Soil sampling to determine soil salinity indicated high pore-water salinity in the root zone in salinized plots (Figure 2). Soil planted to "Manokin" had higher maximum pore water salinity at harvest, but integrating the soil salinity values over the entire measurement depth (100 cm) indicated similar salt mass in the soil profile in "Manokin" and "Essex" plots (Figure 2). All herbicide-treatment plots showed the same soil pore-water electrical conductivity profiles.

Plant Height

The split-plot model produced an R^2 value of 0.978 and a CV of 12.62% (when estimated using the GLM procedure). Neither of the main plot effects (salinity or cultivar) were statistically significant, although plants irrigated with non-saline water were consistently taller (10–90%) than those irrigated with saline water across all herbicide treatments.

Herbicide treatment significantly reduced the height of the main stem of both cultivars (Table 2). This reduction was not influenced by changes across the main plot levels (sub-plot interaction effects were not significant), suggesting that the plant height measurements were statistically equivalent

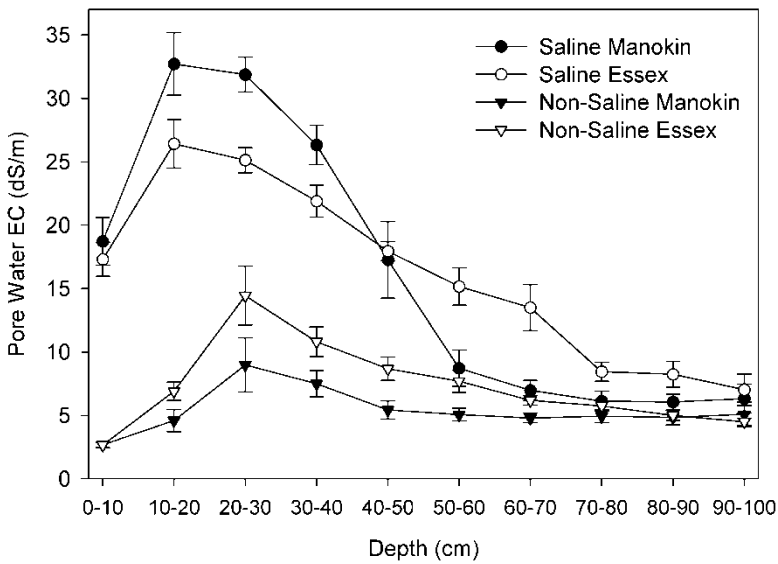

Figure 2. Soil pore-water electrical conductivity determined at soybean harvest. Data points are means of six cores (two for each herbicide treatment, no difference between herbicide treatments) and error bars indicate standard error of the mean.

Table 2. Plant growth variables measured 30 days after herbicide treatment. No significant ($\alpha = 0.05$) differences due to cultivar or salinity were observed; values are the mean across cultivars and salinities. Values within each variable that are followed by the same letter were not significantly different

Variable	Control	Chlorimuron Ethyl	Imazethapyr
Main stem height (cm)	22.3 a	18.8 b	18.5 b
Nodes on main stem	8.0 a	6.3 b	6.9 b
Nodes on cotyledonary shoot	0.9 b	2.5 a	2.2 a
Stem diameter (mm)	3.7 a	3.1 b	3.0 b

across the two cultivars and not impacted by salinity, but were reduced by herbicide treatment ($F = 5.51$, $p = 0.0312$). Soybeans not treated with herbicide (controls) were 3.6 cm (~20%) taller than plants treated with either chlorimuron or imazethapyr at 30 days after application, and the two herbicides reduced main stem height in a statistically equivalent manner (Table 2).

Main-Stem Nodes

The split-plot model produced an R^2 value of 0.931 and a CV of 12.81% (when estimated using the GLM procedure). The cultivar main plot effect was not statistically significant. Thus, the number of nodes on the main stem was the same for both "Essex" and "Manokin." The salinity main plot effect was nearly significant at the 0.05 level ($F = 8.99$, $p = 0.058$). Non-salinized soybeans had 1.6 (~25%) more nodes on the main stem than did salinized soybean across all herbicide treatments.

Herbicide treatment significantly ($F = 7.71$, $p = 0.0136$) reduced the number of nodes on the main stem, and the reduction was apparently not influenced by changes across the main plot levels (no significant sub-plot interaction effects). Plants of both cultivars not treated with herbicides (control) had significantly more nodes on the main stem than did plants treated with either herbicide. Treatment with chlorimuron or imazethapyr resulted in a similar reduction in the number of nodes, with the controls having 1.4 (20%) more nodes on the main stem than herbicide-treated plants (Table 2). Both herbicide treatments resulted in a similar reduction in nodes at 30 days after treatment (Table 2). Other studies have indicated no reduction in number of nodes per plant with chlorimuron application (Newsom and Shaw 1992).

Cotyledonary Nodes

The split-plot model produced an R^2 value of 0.816 and a CV of 51.46% (when estimated using the GLM procedure). Neither of the main plot

effects (salinity or cultivar) were statistically significant, suggesting that the observed number of nodes on the cotyledonary shoots were equivalent across the two cultivars and were not significantly impacted by salinity.

Herbicide treatment significantly ($F = 6.33$, $p = 0.0225$) increased the number of nodes on the cotyledonary shoots, and the increase was apparently not influenced by changes across the main plot levels (no significant sub-plot interaction effects). Control plants of both cultivars had significantly fewer nodes on the cotyledonary shoots at 30 days after treatment than did plants treated with either chlorimuron or imazethapyr. Treatment with chlorimuron or imazethapyr resulted in a similar increase in the number of nodes on the cotyledonary shoots, having more than 1.4 (260%) more nodes on the cotyledonary shoot than control plants (Table 2). Both herbicide treatments resulted in a similar increase in cotyledonary nodes (Table 2).

Stem Diameter

The split-plot model produced an R^2 value of 0.802 and a CV of 12.36% (when estimated using the GLM procedure). Neither of the main plot effects (salinity or cultivar) were statistically significant, suggesting that the observed stem diameters were equivalent across the two cultivars and were not significantly impacted by salinity.

Herbicide treatment significantly ($F = 6.43$, $p = 0.0216$) reduced the stem diameter measured at the cotyledon, and the increase was apparently not influenced by changes across the main plot levels (no significant sub-plot interaction effects). Control plants of both cultivars had significantly larger stem diameters at 30 days after treatment than did plants treated with either chlorimuron or imazethapyr. Treatment with chlorimuron or imazethapyr resulted in a similar decrease in the stem diameter, with the controls having a significantly larger stem diameter [0.6 mm (20%) increase] than herbicide-treated plants (Table 2).

Yield

Plants with <50 pods in the sand tank experiment (10 plants) were damaged prior to pod setting and were excluded from analysis. The split-plot model produced an R^2 value of 0.915 and a CV of 15.31% (when estimated using the GLM procedure). None of the sub-plot effects (including herbicide) significantly impacted yield. The main plot salinity–cultivar interaction effect was highly significant ($F = 52.74$, $p = 0.0054$), and the main plot salinity effect appears to be marginally significant ($F = 6.62$, $p = 0.0822$). Thus, yield for the two cultivars was affected by salinity in dissimilar ways. For "Essex," yield sharply declined with increasing salinity, representing a 40% reduction in yield when irrigation water salinity increased from $2–7\,dS^{-1}$ (Figure 3). In contrast, the yield for "Manokin" increased by $>30\%$ with

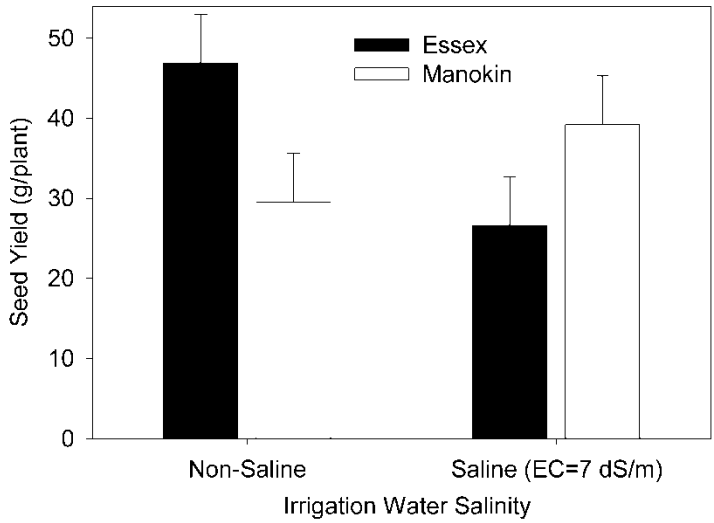

Figure 3. Seed weight (g) per plant measured for Essex and Manokin soybeans. Values indicate the mean yield for each cultivar–salinity combination across blocks (sand tank and field experiments). Error bars indicate the estimated standard error.

the same increase in irrigation water salinity (Figure 3). For plants irrigated with non-saline water, yields for "Essex" were significantly greater than those for "Manokin," representing an increase in yield of 17 g per plant ($\sim$60%) (Figure 3). However, at higher irrigation water salinity of 7 dS^{-1}, "Manokin" yields were significantly greater than those for "Essex", representing an increase in yield of 13 g per plant (50%) (Figure 3).

From the growth and yield results of these experiments, "Manokin" appears to be more a salt-tolerant soybean cultivar than "Essex." Irrigation with saline water significantly decreased yield variables for the Cl-accumulating cultivar, Essex. In contrast, for the Cl-excluding cultivar, Manokin, yield variables were significantly larger in salinized treatments. Similar effects of (chloride) salinity on yield depletion for Cl-accumulating soybean cultivars have been observed in previous studies, but these studies have not reported a yield enhancement in Cl-excluding cultivars (Parker, Gaines, and Gascho 1986; Yang and Blanchar 1993). We are unaware of any previous reports on the response of soybean seed yield to sulfate-dominated salinity. Yield enhancement with salinization has been reported for cotton, where an increase in the number of bolls was observed, although the total biomass per plant was reduced in plants irrigated with brackish water (Pasternak, Twersky, and De Malach 1979). Non-saline treatments in both the sand tank and field experiments resulted in "Manokin" yields that were $\sim$60% of those for "Essex." In contrast, for saline-irrigated plants, "Essex" yield was

only ~70% that for "Manokin" (Figure 3). These results underscore the importance of cultivar choice in optimizing yield: salt-tolerant cultivars may not only outperform salt-sensitive cultivars, but may actually provide increased yields when grown under saline conditions.

Herbicide treatment had no significant impact on yield. Thus, although herbicide treatment significantly impacted several growth variables (Table 2), there was no observable reduction in the yield of surviving plants. Although a large number of plants of both cultivars exhibited morphological effects in which the main stem comprised only a small portion of the total plant biomass, yield was generally not impacted by these morphological changes. In the sand tank and field experiments, a large number of "Essex" plants treated with herbicides developed large cotyledonary shoots on a small main stem (which died or grew slowly after herbicide application), but herbicide-treated "Essex" yields were not significantly different from the control.

Other researchers have also reported no loss in yield with chlorimuron or imazethapyr application (Krausz, Kapusta, and Knake 1992; Newsom and Shaw 1992), while others have reported yield reductions under certain conditions (Newsom and Shaw 1992; Griffin and Habetz 1989; Stapleton and Whitwell 1989). In this study, yield was determined only on plants that survived to harvest, and salinity or herbicide effects that resulted in plant death were not accounted for in yield measurements. In all experiments, herbicide and salinity effects were sub-lethal, with the exception of some "Essex" treated with chlorimuron, as described earlier. These results are important for developing management practices for soybeans in irrigated or salt-affected soils, and indicate that the herbicides imazethapyr and chlorimuron may be used without an expected loss in yield.

ACKNOWLEDGMENTS

The authors are grateful to Dr. William Kenworthy and the Maryland Agricultural Experiment Station for providing the soybean seeds for these experiments. We acknowledge the assistance of Dr. Fred Ernst in designing and implementing the greenhouse and field plot irrigation systems and for his agronomic expertise. Dr. Harold Steppuhn, Dr. Steve Grattan, and several anonymous reviewers provided helpful comments.

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