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Soybean Growth and Yield as Affected by Surface and Subsoil Compaction

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ABSTRACT

Axle loads from wheel traffic on farmland ranges from less than 4.5 Mg axle^{-1} to over 20 Mg axle^{-1}. Loads of <4.5 Mg axle^{-1} generally cause compaction only in the upper 0.3 m of the soil (surface compaction), while higher loads have caused soil compaction below this surface layer (subsoil compaction). A replicated field study was conducted on a Webster clay loam (fine-loamy, mixed, mesic Typic Haplaquoll) in southern Minnesota and on two Ves clay loams (fine-loamy, mixed, mesic Udic Haplustoll) in southwestern Minnesota to assess the effect of surface and subsoil compaction on the growth and yield of soybean (*Glycine max* L. Merr.). Surface compaction treatments consisted of no interrow traffic on either side of the row at any time during the experiment and annually applied interrow wheel traffic on both sides of the row from an axle load <4.5 Mg. Subsoil compaction treatments consisted of control (no subsoil compaction), 9 and 18 Mg axle^{-1} loads applied once at the beginning of the experiment. Surface compaction, when averaged over years on both Ves sites, decreased yield by 15% overall and up to 27% in a single year. Yield response to surface compaction on the Webster site was climate dependent, in general, decreasing yield during a wet year but increasing yield during a dry year. Subsoil compaction from the 18 Mg axle^{-1} treatment reduced plant height and integrated leaf area index on the Webster site each year of the experiment, and tended to decrease yield. The response to the 18 Mg axle^{-1} load on the Ves was inconsistent. Yield was increased significantly in 5 out of 14 location-years by the 9 Mg axle^{-1} treatment when compared with the control treatment. Soybean growth parameters and yield were affected more by annual surface compaction than by a one-time application of subsoil compaction. A decrease in vegetative growth did not necessarily result in a comparable decrease in seed yield.

THE CAPACITY and weight of farm machinery has increased over the past few decades as a result of an increase in farm size and the need to improve operator efficiency. Consequently, soil compaction from the wheel traffic of heavy farm equipment has also increased. Soil compaction has contributed to the gradual deterioration of the physical condition of agricultural land and has subsequently decreased potential yields (Soane, 1985).

With the exception of harvest and transport equipment, most agricultural machinery has axle loads less than 5 to 6 Mg. Repeated wheel traffic with axle loads of about 4.5 Mg significantly increased bulk density and penetrometer resistance in the surface 0.3 m of a clay loam soil (Voorhees et al., 1978). Soybean response to such changes in soil physical properties has varied. In a pot experiment, an increase in bulk density of both a sandy loam and a silty loam from 1.1 to 1.6 Mg m^{-3} decreased soybean height, shoot weight and number of trifoliate leaves (Singh et al., 1971). In a 3-yr field study on a sandy loam, yield response to interrow surface compaction was inconclusive due in part to inadequate control of wheel traffic; however, there was a trend for wheel traffic to decrease soybean yield (Nelson et al., 1975). Lindemann et al. (1982) reported a significant increase in bulk density of the surface 0.25 m of a clay loam soil after repeated passes of wheel traffic with a 2.3 Mg axle^{-1} load. Subsequent soybean yield responses were not significant, but showed a tendency to decrease when precipitation was above normal and increase when precipitation was below normal. Fausey and Dylla (1984) reported no significant soybean yield response to interrow wheel traffic from a 3.5 Mg axle^{-1} load on a silty clay loam soil when bulk density in the surface 0.3 m was significantly increased from 1.3 to 1.5 Mg m^{-3}.

Increased machinery weight has also increased the depth of compaction. An increase in vertical strain was measured at depths >0.5 m under axle loads >8 Mg, an effect still measurable 2 yr later (Danfors, 1974). Annual freeze-thaw cycles may not effectively ameliorate wheel traffic-induced subsoil compaction. Blake et al. (1976) found that bulk density and penetrometer resistance of a Nicollet clay loam (Udic Haplustoll) with an artificial plow pan at a depth of 0.3 to 0.5 m was still higher than in the noncompacted control 9 yr after applying the compaction. This soil was annually cropped to corn (*Zea mays* L.) and alfalfa (*Medicago sativa*), and annually froze to a depth >0.3 m. On a Webster clay loam, penetrometer resistance was higher in the compacted subsoil than in the noncompacted subsoil 4 yr after initial trafficking with an 18 Mg axle^{-1} load (Voorhees et al., 1986). Research on a sandy soil with fine-textured inclusions (albic Luvisol) indicated that several freeze-thaw cycles did not loosen the soil structure (Dannowski, 1987).

Significant plant response to subsoil compaction from high axle loads has been documented for several crops. In an international study of soils subjected to annual freezing and thawing over a range of clay contents and climatic conditions, crop yield response to subsoil compaction was reported to be a function of axle load applied, number of passes of the heavy axle load, and time lapsed since initial high axle loading (Hakansson et al., 1987). Most of the crops in this study were cereals and maize (*Zea mays* L.). (Maize growth and yield response in Minnesota were previously reported by Voorhees et al., 1989.) Of the 26 experimental sites in this international study, soybeans were grown only in Minnesota.

The research reported here is part of the above international effort to determine the effect of high axle loads on the extent and persistence of subsoil compaction and subsequent crop yields over a range of soil and climatic conditions. Specifically, the objective of this paper is to describe the effects of surface and subsoil compaction on the growth and yield of soybeans on two soils in Minnesota over a 5-yr period.

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METHODS

Detailed description of the compaction treatments were previously reported (Voorhees et al., 1986). Briefly, three experiment sites were established—one on a Ves clay loam (formerly Nicollet clay loam) in the fall of 1981 when the soil was relatively dry (160 g H_2O kg^{-1} soil, which corresponds to approximately 60% of field capacity, hereafter referred to as *Ves-dry*), and one on a Ves soil in the fall of 1982 when the subsoil was relatively wet (230 g H_2O kg^{-1} soil, which corresponds to approximately 90% of field capacity, hereafter referred to as *Ves-wet*). Both of these sites are located at the University of Minnesota Southwest Experiment Station, Lamberton, MN. The third site was established in the fall of 1981 on a Webster clay loam under relatively wet conditions (230 g H_2O kg^{-1} soil, which corresponds to 90 to 100% of field capacity). This site is located at the University of Minnesota Southern Experiment Station, Waseca, MN. The Ves soil is a deep, well-drained, moderately permeable soil formed in calcareous loamy glacial till. The Webster soil is classified as a deep, poorly drained, moderately permeable soil formed in glacial till. All three sites are nearly level and are tile-drained.

A strip plot design was used on the Ves sites and a split plot design used on the Webster site, with each main and secondary treatment replicated four times. The split plot design uses one error term to test both the secondary treatment and the interaction, whereas the strip plot design has a separate error term for each secondary treatment and the interaction, thus decreasing the degrees of freedom (Gomez and Gomez, 1984).

Each of the main treatment plots were 9.1 m (12 rows) wide by 16.8 m long. The main treatments were stripped or split to include secondary treatments that were 2.3 m (three rows) wide by 16.8 m long. The remaining area was used as border between treatments. The main compaction treatments were axle loads of 9 and 18 Mg, applied only at the beginning of the experiment, wheel track-by-wheel track, covering 100% of the plot surface a total of four times. A control treatment received no axle loads in excess of 4.5 Mg at any time during the experiment. The secondary treatment of annual surface compaction was accomplished by confining all wheel traffic from annual field operations, and an additional set of wheel traffic shifted laterally by one row, to the same interrow areas within and across seasons (after the initial application of high axle load wheel traffic). This annual wheel traffic carried less than 4.5 Mg $axle^{-1}$. Thus, there were three subsoil compaction treatments: (i) control (no subsoil compaction), (ii) 9 Mg $axle^{-1}$, and (iii) 18 Mg $axle^{-1}$ loads; and two surface compaction treatments: (i) no wheel traffic on either side of the row (NWT, no surface compaction), and (ii) annual interrow wheel traffic of less than 4.5 Mg $axle^{-1}$ on both sides of the row (WT, surface compaction in the 0- to 0.3-m depth).

Soybeans and corn were grown in rotation in 0.76-m spaced rows using six row equipment with both crops being planted each year. Only the soybean data are reported here. Soil tests indicated 32 and 85 kg ha^{-1} P (Bray P1 extractant) and 223 and 239 kg ha^{-1} K (ammonium acetate extractant) on the Webster and Ves site, respectively. Additional P and K fertilizer was not recommended as these levels are considered high for the Webster and Ves soils. Fall tillage was not performed after the initial moldboard plowing. Annual spring tillage consisted of tandem disking prior to planting. Planting dates ranged from 3 May to 20 May, depending on field and climatic conditions. Indeterminate soybean cultivars were used at all sites, Corsoy on the Ves sites and Hardin on the Webster. Chemical weed control on the Webster included 3.4 kg ha^{-1} (a.i.) of Chloramben (3-Amino-2,5-dichlorobenzoic acid) and 4.5 kg ha^{-1} (a.i.) Alachlor [2-chloro-2'-6'-diethyl-*N*-(methoxy-methyl)-acetanilide]. In 1982 only, 0.21 kg ha^{-1} (a.i.) of Sethoxydem with oil {2-[1-(ethoxyimino)butyl]-5-[2-ethylthio-propyl]-3-hydroxy-2-cyclohexen-1-one} was applied on the Webster in addition to Alachlor. On the Ves, 2.8 kg ha^{-1} (a.i.) Alachlor and 1.7 kg ha^{-1} (a.i.) of Linuron [3-(3,4-dichlorophenyl)-1-methoxy-1-methylurea] was applied annually. There was also shallow mechanical cultivation (<50 mm) as needed on the Ves sites. The weed control was satisfactory throughout the experiment at all sites.

Plant emergence counts were made in two rows of each treatment in all four replications. Daily emergence counts were made on two 1.5 m long randomly selected sections within each row until the population became constant. Population was determined from the final emergence count.

Whole plant samples were collected periodically during the growing season to determine leaf area index, dry matter accumulation and nutrient uptake. In 1982 samples were collected weekly, beginning 26 d after planting. The initial sample size was 0.76 m of row per treatment per replication but was gradually decreased to 0.25 m of row by 110 d after planting. The sampling procedure was modified in 1983 and 1984 to include only four sampling dates, each consisting of two pooled 0.76-m subsamples per treatment and replication. The sample size was again modified in 1985 and 1986 to three pooled 0.51-m subsamples. The modifications were designed to acquire a more representative sample. In 1983 to 1986, four samples were collected at growth stages V4–V5, V11–R2, R4–R5 and R6 (Fehr et al., 1971). The plants were clipped off at ground level, placed in plastic bags and refrigerated until leaf area was measured. In 1982 the entire sample from each sampling date was processed, but in subsequent years only the first sample was processed in its entirety, after which a randomly selected subsample of 10 plants was used for leaf area measurements. The entire sample was used to determine dry matter accumulation. The number of plants in the sample was determined before the entire sample was dried at 68 °C.

Soybeans were harvested with a small plot combine at growth stage R8 (Fehr et al., 1971). Two 16.8-m rows were harvested on the Webster site and two 12.2-m rows on the Ves sites. Field weight and percent moisture were determined to calculate grain yield based on 130 g H_2O kg^{-1} plant material.

Bulk density and penetrometer resistance were measured before and immediately after the heavy loading, to assess the extent of subsoil compaction. Within 7 d after the 9 and 18 Mg axle loads were applied, all plots were disked to 0.1 m and then moldboard plowed to approximately 0.2 to 0.3 m, essentially alleviating the bulk soil compaction in the surface till layer caused by the heavy axle loads (Voorhees et al., 1986). Annual penetrometer resistance was also measured immediately after spring planting to assess the extent of surface compaction. These measurements were taken at regularly spaced intervals to a maximum depth of 0.5 m in each treatment. Measurements were made with a hand-held penetrometer with a 30° conical probe, 19 mm in diameter, interfaced to a data storage unit (Wagner et al., 1989). Two subsamples were taken in each replication of all treatments for a total of eight data points per depth per treatment. Soil water content was determined gravimetrically at the same time and at corresponding depth intervals.

The analysis of variance (ANOVA) appropriate for each design was used to indicate significantly different treatment means and interactions. The least significant difference (LSD) comparison was used only when the *F* test of the ANOVA for the treatment was significant at the 5% level.

RESULTS

Changes in soil physical properties in response to the heavy axle load wheel traffic were previously discussed in detail by Voorhees et al. (1986), and are briefly summarized here as a prelude to the detailed plant growth response discussion. The 18 Mg axle^{-1} subsoil treatment significantly (P = 0.10) increased bulk density by 0.1 to 0.2 Mg m^{-3} to a depth of 0.5 to 0.6 m on the Ves-wet and Webster sites. The Ves-dry site showed no measurable response below 0.3 m to the high axle loads. Penetrometer resistance data was similar to bulk density data in that the magnitude of the response to high axle loads was less in the wet soils, but the responses were measured to a deeper depth than in the dry soil.

The following spring, bulk density below 0.3 m on the 18 Mg axle^{-1} subsoil treatment was still significantly higher than the control on both the Ves-wet and Webster sites even though the soil had frozen to a depth of 0.7 m. On the Webster site, penetrometer resistance was still higher for both subsoil compaction treatments 4 yr after compaction. These bulk density and penetrometer measurements are evidence that subsoil compaction can persist for more than 1 yr in spite of annual freezing and thawing.

The annually applied interrow wheel traffic of spring tillage and planting operations (<4.5 Mg axle^{-1}) significantly increased penetrometer resistance in the surface 0.1 m every year at all sites. In 11 and 7 of the 14 location years, penetrometer resistance was significantly increased in the 0.1 to 0.2- and 0.2 to 0.3-m layers, respectively. Penetrometer resistance never exceeded 2.25 MPa in the surface 0.3 m after the initial moldboard plowing. The maximum value varied depending on the soil water content at the time of trafficking and measuring.

Yield, Emergence and Population

Soybean yield as affected by surface and subsoil compaction is summarized in Table 1. On the Webster site in 1982 and 1983, interrow surface compaction (WT) significantly increased yield above no interrow surface compaction (NWT) by about 10%. In 1984 and 1986, WT significantly decreased yield by 6 to 14%. There was no effect of surface compaction on yield in 1985. The yield difference between NWT and WT treatments was significant in 6 out of the 9 Ves location-years, with the soybeans on the WT treatment having an average 17% lower yield (2.9 vs. 2.4 Mg ha^{-1}).

Subsoil compaction effects on the Webster site were inconsistent (Table 1). The 18 Mg axle^{-1} treatment resulted in a 9% increase in soybean seed yield over the control in 1985. Compared with the control, the 9 Mg axle^{-1} treatment yielded significantly higher in 1985 and 1986. Yields from the 9 Mg axle^{-1} treatment were significantly higher than the 18 Mg axle^{-1} treatment only in 1986.

The 9 location-year average on the Ves sites was 2.6, 2.8, and 2.7 Mg ha^{-1} for the control, 9, and 18 Mg axle^{-1} treatments, respectively. On the Ves-dry site, soybean yield on the 9 Mg axle^{-1} treatment was significantly higher than the control by an average of 13% 3 out of 5 yr, and significantly higher than the 18 Mg axle^{-1} treatment by an average of 10% 3 out of 5 yr. There were no significant yield responses to subsoil

Table 1. Soybean seed yield as affected by surface and subsoil compaction on Webster and Ves clay loam soils, 1982 to 1986.

Surface compaction	Soybean seed yield 1982	1983	1984	1985	1986
			Mg ha^{-1}		
			Webster		
NWT†	2.82b‡	2.90b	2.58a	3.28	3.26a
WT	3.10a	3.16a	2.43b	3.30	2.81b
CV (%)	4.5	4.5	5.2	5.0	3.7
			Ves-dry		
NWT	3.23a	2.79	2.80	2.62a	2.84a
WT	2.52b	2.58	2.70	2.07b	2.35b
CV (%)	6.4	10.9	4.4	13.2	8.4
			Ves-wet		
NWT	–	2.58	3.61a	2.34a	3.08a
WT	–	2.48	3.12b	2.00b	2.23b
CV (%)		4.8	4.1	4.7	18.4
Subsoil compaction mg axle^{-1}					
			Webster		
Control	2.99	3.19	2.83	3.08b	2.97b
9	2.96	3.18	2.51	3.42a	3.28a
18	2.94	2.73	2.18	3.36a	2.86b
CV (%)	10.9	14.2	17.5	4.5	4.6
			Ves-dry		
Control	2.63b	2.63	2.64b	2.29	2.56b
9	3.15a	2.74	2.93a	2.38	2.79a
18	2.84b	2.68	2.67b	2.36	2.45b
CV (%)	6.8	2.9	5.4	7.9	6.1
			Ves-wet		
Control	–	2.43	3.35	2.11	2.63
9	–	2.64	3.53	2.12	2.83
18	–	2.25	3.22	2.28	2.66
CV (%)		5.8	8.6	13.6	8.3

† No wheel traffic on either side of the row at any time (NWT). Annual wheel traffic (<4.5 Mg axle^{-1}) on both sides of the row (WT).
‡ Yields within a year and site followed by a different letter are significantly different as indicated by ANOVA and $LSD_{\alpha = 0.05}$.

compaction on the Ves-wet site. There were no significant yield interactions between surface and subsoil compaction at any of the three sites.

Of the 14 location-years among the three sites, there were only occasional effects of either surface or subsoil compaction on plant emergence, and these differences were not related to final seed yield (data not shown). Plant populations calculated from the final emergence counts (data not shown) were generally not significantly different and were not related to yield. The Webster site had populations of approximately 500 000 plants ha^{-1} and the Ves sites had approximately 300 000 plants ha^{-1}.

Plant Height

Plant heights were measured at the end of the growing season only on the Webster site. In 1983 the plants on the WT treatment were significantly taller and in 1986 significantly shorter than those in the NWT treatment; there were no differences in 1982 or 1984 (Fig. 1, 1985 data unavailable). The 18 Mg axle^{-1} treatment was significantly shorter (0.15–0.2 m) than either the control or the 9 Mg axle^{-1} treatment in 1982 to 1986. Internodal length and node numbers were not measured, therefore it is not known which contributed to

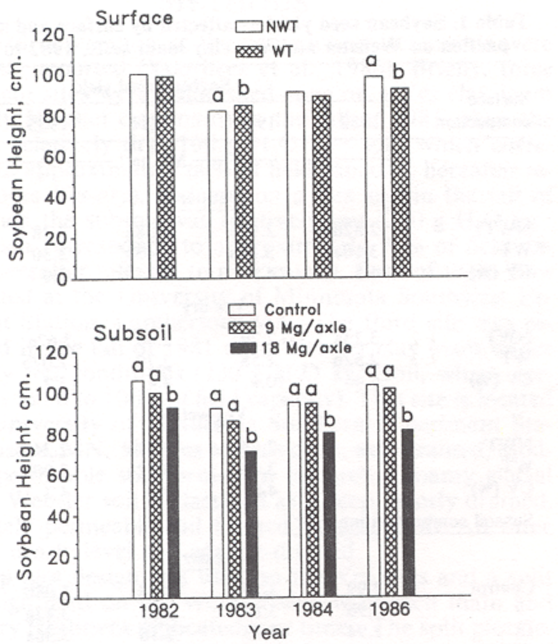

Fig. 1. Soybean final plant height as affected by surface and subsoil compaction on Webster clay loam, (1982–1986). Bars with different letters within a year are significantly different as indicated by ANOVA and $LSD_{\alpha = 0.05}$.

the height differences. In 1986 on the Webster, the ANOVA indicated a significant interaction between surface and subsoil compaction (Fig. 2). The plant heights from the 18 Mg axle^{-1} WT treatment were significantly shorter than all other treatments. The plants on the 18 Mg axle^{-1}-NWT treatment were taller than the 18 Mg axle^{-1}-WT treatment plants but shorter than those on the remaining treatments.

Leaf Area

Leaf area index (m^2 leaf m^{-2} soil, LAI) was measured as an indicator of photosynthetic potential. Maximum LAI ranged from two to five during the 5 yr of the experiment on all sites (data not shown). The NWT treatment plants tended to have a higher maximum LAI than the WT treatment plants at the Webster site each year. In 1982 the LAI of the NWT treatment at R4 to 5 was significantly higher (17%) than the WT treatment, and in 1984 the NWT treatment had a significantly higher LAI than the WT treatment throughout the growing season. The higher maximum LAI did not necessarily indicate a higher yield; in 1983 the NWT treatment had a higher maximum LAI but the WT treatment had significantly higher yield. On the Ves sites, differences in maximum LAI between surface compaction treatments were not well correlated with yield differences. For example, in 1982 on the Ves-dry the WT treatment had a higher maximum LAI at R3 but yielded significantly less.

On the Webster sites, in 4 out of 5 yr, the attainment of maximum LAI was delayed on the 18 Mg axle^{-1} treatment compared to the control and 9 Mg axle^{-1} treatments. The 18 Mg axle^{-1} treatment also had the lowest maximum LAI each year of the experiment on the Webster site, and also had the lowest overall average yield. There was no corresponding delay on the

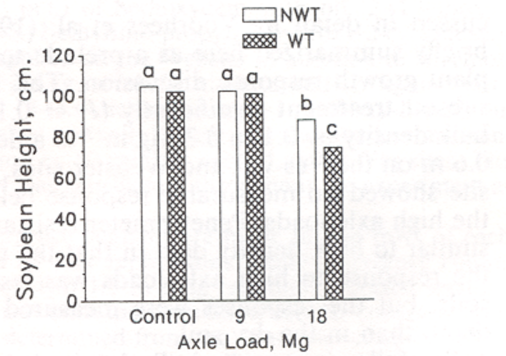

Fig. 2. Soybean plant height as affected by the interaction between surface and subsoil compaction on Webster clay loam, 1986. Bars with different letters are significantly different as indicated by ANOVA and $LSD_{\alpha = 0.05}$.

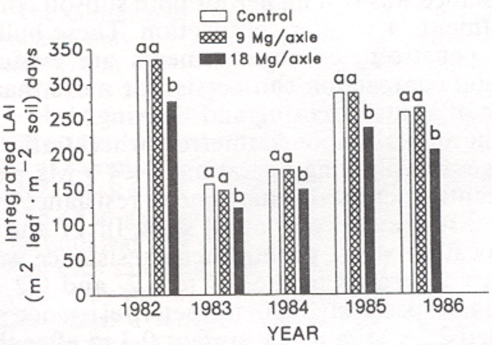

Fig. 3. Soybean integrated LAI as affected by subsoil compaction on Webster clay loam, (1982–1986). Bars with a different letter within a year are significantly different as indicated by ANOVA and $LSD_{\alpha = 0.05}$.

Ves sites in the value or timing of the maximum LAI between subsoil treatments.

An integrated LAI parameter was determined by integrating the area under the curve of LAI vs. time, described by the individual samples through the season, assuming a LAI value of zero at planting and harvest. The NWT treatment had significantly higher integrated LAI than the WT on the Webster soil from 1982 to 1984. The only significant difference between the soybeans on the NWT and WT treatments at the Ves sites was on the Ves-wet in 1983, when the integrated LAI for the NWT treatment was higher than the WT treatment (data not shown).

On the Webster site, the 18 Mg axle^{-1} treatments always had significantly less integrated LAI than either the control or the 9 Mg axle^{-1} treatments (Fig. 3). This was the same pattern that was observed for the plant heights on the Webster. There were no apparent patterns in the integrated LAI on the Ves sites when comparing the high axle load treatments (data not shown). There were no significant interactions between surface and subsoil compaction.

Dry Matter

Dry matter (DM) accumulation was measured as an indicator of overall plant growth (Table 2). There was a significant decrease in DM on the WT treatments on the Webster site in 1984 and at the Ves-wet, 1983

Table 2. Soybean dry matter at growth stage R6, as affected by surface and subsoil compaction on Webster and Ves clay loam soils, 1982 to 1986.

Surface compaction	Soybean dry matter 1982	1983	1984	1985	1986
	Mg ha^{-1}				
	Webster				
NWT†	8.85	4.10	5.91a‡	5.72	5.53
WT	7.95	3.79	4.95b	5.62	5.63
CV (%)	22.8	9.0	12.8	6.0	8.8
	Ves-dry				
NWT	8.09	4.74	5.35	4.94	7.09
WT	7.96	4.53	5.87	4.80	6.63
CV (%)	29.4	20.6	32.6	10.0	11.2
	Ves-wet				
NWT	–	5.29a	6.65	5.57a	6.35
WT	–	4.44b	6.37	4.66b	6.56
CV (%)		8.2	31.2	9.0	31.3
Subsoil compaction Mg axle^{-1}					
	Webster				
Control	8.96	4.29	5.15	5.94	5.44b
9	9.17	4.09	5.96	5.67	6.25a
18	7.07	3.45	5.18	5.40	5.05b
CV (%)	31.0	14.0	16.6	14.3	11.7
	Ves-dry				
Control	7.70	4.38	5.67	4.81	6.69
9	7.81	4.98	5.35	5.15	7.38
18	8.57	4.55	5.81	4.65	6.52
CV (%)	52.3	12.8	10.9	14.8	11.9
	Ves-Wet				
Control	–	4.78	6.08	5.04	6.34
9	–	5.07	5.91	5.24	6.60
18	–	4.75	6.04	5.06	6.42
CV (%)		13.9	8.60	10.6	17.3

† No wheel traffic at any time on either side of row (NWT). Annual wheel traffic (<4.5 mg axle^{-1}) on both sides of row (WT).
‡ Values within a year and site followed by a different letter are significantly different as indicated by ANOVA and $LSD_{\alpha = 0.05}$.

and 1985. In general during these specific location years the WT also had significantly less DM ha^{-1} throughout the growing season. Differences in DM between the NWT and WT treatments were in general similar to the grain yield response.

Even though there was only 1 location-year when subsoil compaction had any significant effect on DM production at R6 (Table 2), there were significant differences between subsoil compaction treatments on at least one sampling date during the season 10 of 14 location-years (data not shown). In general, on the Webster site the 18 Mg axle^{-1} treatment averaged less DM than the control and the 9 Mg axle^{-1} treatments on most sampling dates throughout the experiment. This is consistent with the plant height and accumulative leaf area results on the Webster. There were no such patterns on the Ves sites. The interaction between surface and subsoil compaction was not significant.

DISCUSSION

It was hypothesized that soybeans may respond to surface and subsoil compaction, and any response to subsoil compaction may persist for a number of years. Other researchers have observed that soybean response to surface compaction is related to climatic conditions (Lindemann et al., 1982). Voorhees (1987) reported that, under southwest Minnesota climatic conditions, surface compaction can reduce soybean yields 20% when May to August precipitation exceeded approximately 360 mm; however, below this threshold precipitation surface compaction could cause a similar yield increase. Rainfall exceeded 360 mm every year on the Ves sites except 1983 when May to August precipitation was 355 mm (Table 3). Surface compaction significantly decreased yield every year on the Ves sites when precipitation exceeded 360 mm, except Ves-dry, 1984. These results are in agreement with the model proposed by Voorhees (1987).

Table 3. Accumulative May through August precipitation in the test area, 1982 to 1986.

Year	Rain mm	Open pan evaporation, mm
	Webster	
1982	363	767
1983	491	766
1984	329	804
1985	307	878
1986	456	717
Normal†	413	787
	Ves	
1982	424	1017
1983	355	1068
1984	405	1041
1985	435	1046
1986	422	1035
Normal	337	856

† Thirty-year average 1951 to 1980.

The Webster site has a higher normal (normal is defined as the 30-yr average from 1951 to 1980) May to August precipitation and lower normal pan evaporation than the Ves sites. In general, when May to August precipitation was below the normal, WT treatment increased yield at the Webster site. Even though the 1983 May to August precipitation was 490 mm (almost 20% above normal), 120 mm of that rain occurred during the last 10 d of August, with only 27.7 mm of rain in the previous 41 d. Therefore, the 1983 growing season can be considered a relatively dry year. In the 3 of the 4 yr that can be considered as relatively dry (1982, 1983, and 1985), the WT treatment yield was either greater than or equal to that of NWT treatment. The WT treatment might have been expected to yield higher than the NWT treatment in 1985, considering the May to August precipitation (307 mm). However, the rainfall distribution that year was such that there was adequate moisture during reproductive growth, eliminating the surface compaction treatment effects. The yields of both treatments in 1985 were high, suggesting no yield-limiting water stress. Yield was decreased 14% by the WT treatment in 1986 when May to August precipitation was 43 mm above the normal.

Voorhees (1989) reported that when comparing no wheel traffic to wheel traffic on both sides of the row, soybean root length was decreased under the interrow but increased under the row. Voorhees et al. (1976) reported similar effects of wheel traffic on quantity and spatial distribution of nodules on soybean roots. Specific nodule mass (mg nodule^{-1}) was increased, but the total nodule mass was decreased in the trafficked interrow compared to the nontrafficked. The effects of compaction on root growth and nodulation may be directly related to physical resistance or indirectly to changes in O (oxygen), nonmobile nutrient availability and soil water status. All of these factors may dynamically interact to cause the above observed differences in plant growth and seed yield.

Soybeans were more responsive to the annual surface compaction than to the one-time applied subsoil compaction treatments. Surface and subsoil compactive forces may alter physical parameters similarly; however, the biological response to those changes may be different. The rooting pattern and physiological function of roots vary spatially and temporally. Most of the nutrient uptake, particularly of nonmobile nutrients, and N fixation generally occurs within the surface rooting zone. As the surface dries and the growing season progresses, more water and nutrients will come from below the surface zone. The plant encounters different physical stresses during the growing season as the roots grow through the soil profile (Marschner, 1986). The plant will be at different physiological stages when first encountering surface compaction compared with subsoil compaction zones. Therefore, the physiological plant response to the different compaction treatments should not be the same.

The 18 Mg axle^{-1} treatment had more detrimental effects at the Webster site than at the Ves sites. The integrated LAI and final plant heights were consistently reduced by the 18 Mg axle^{-1} subsoil compaction, but this did not necessarily translate into significantly reduced dry matter or seed yield. Although the dry matter and seed yield tended to be reduced by the 18 Mg axle^{-1} treatment on the Webster site 3 out of 5 yr, dry matter and seed yield responses were not well correlated with each other. For example, in 1985 the control treatment had the greatest amount of dry matter at growth stage R6, but had the lowest final seed yield. Also in 1984 the 18 Mg axle^{-1} subsoil treatment had very similar dry matter at growth stage R6 compared with the control, but had significantly less seed yield.

There are several possible reasons why the Webster and the Ves sites responded differently to subsoil compaction. The bulk density differences between the control and 18 Mg axle^{-1} treatment were not significant at the Ves-dry site. Changes in bulk density on the Ves-wet and the Webster were similar but plant response to the high axle loads were very different. Vegetative soybean growth on the Webster was consistently reduced by the 18 Mg axle^{-1} subsoil treatment, but not on the Ves-wet. The Webster soil has a hydraulic conductivity of approximately 1 to 2 cm h^{-1} compared with approximately 10 to 20 cm h^{-1} on the Ves sites (Voorhees et al., 1986). Infiltration rates decrease logarithmical with increasing load (Akram and Kemper, 1979). Further reduction in water movement in the slow draining soil of the Webster site would be expected to have more effects on plant growth than similar changes on the more permeable Ves soil. Different cultivars were grown at the Webster site compared with the Ves sites. Tu and Tan (1988) reported that different varieties of field beans (*Phaseolus vulgaris* L.) varied in the magnitude of response to compaction. The Webster site also has higher growing season rainfall and lower pan evaporation (Table 3). The effects of surface and subsoil compaction are related to soil water status, which in turn is directly related to climate.

Soybeans responded differently to the high axle load treatment than did corn. Corn showed the greatest response to subsoil compaction the 1st yr after the application of the high axle loads, and the response slowly dissipated over time (Voorhees et al., 1989). The 18 Mg axle^{-1} subsoil treatment caused up to 0.5-m reduction in corn height the 1st yr after applying the compaction on the Webster site. By the 5th yr after applying the compaction there were no differences in the extended corn height between treatments throughout the growing season. However, relative reduction in soybean plant height and integrated LAI caused by the 18 Mg axle^{-1} subsoil treatment were consistent over time. The relative reduction was the same in 1986, 5 yr after the application of the compaction, as it had been in 1982, the 1st yr on the Webster site. Corn plant height differences were more closely correlated with the yield differences; soybean plant heights, however, were not. The mechanisms involved that interact among soil characteristics altered by high axle loads, seasonal growth and final yield are apparently different for corn and soybean.

Corn also exhibited dramatic differences in soil water extraction between the control and 18 Mg axle^{-1} treatment, particularly in the first 2 yr of the experiment. The control lost more water than the 18 Mg axle^{-1} treatment from 63 to 91 d after planting (Voorhees et al., 1989). There were no obvious differences in soybean water extraction caused by subsoil compaction (data not shown).

CONCLUSIONS

Soybean yield generally responded favorably to surface compaction in a relatively dry year, but negatively in a wet year. These data fit an empirical model proposed earlier by Voorhees (1987). The response of soybean to subsoil compaction was related to the axle loads, moisture content at the time of compaction, and seasonal growing conditions. On the Webster site, integrated LAI and plant height were more sensitive than seed yield to the 18 Mg axle^{-1} load treatment. The 9 Mg axle^{-1} load treatment was frequently beneficial. Plants do not respond to compaction per se, but rather to the alteration in the physical environment. A more deterministic approach to the problem will be required to understand the cause-and-effect relationships between compaction and plant growth.

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