The effects of soil compaction, soil moisture and soil type on growth and nodulation of soybean and common bean

B. R. Buttery[1], C. S. Tan[1], C. F. Drury[1], S. J. Park[1], R. J. Armstrong[1], and K. Y Park[2]

[1]*Agriculture and Agri-Food Canada, Greenhouse and Processing Crops Research Centre, Harrow, Ontario, Canada N0R 1G0; and* [2]*Upland Crop Division, National Crop Experiment Station, Suwan, 441-100, Korea.*
Received 31 October 1997, accepted 1 June 1998.

Buttery, B. R., Tan, C. S., Drury, C. F., Park, S. J., Armstrong, R. J. and Park, K. Y. 1998. **The effects of soil compaction, soil moisture and soil type on growth and nodulation of soybean and common bean**. Can. J. Plant Sci. **78**: 571–576. In field tests we have observed year-to-year differences in the severity of the effects of soil compaction on nodulation and growth of common bean; these differences appeared to be related to the amount of rainfall during the growing season. We decided to use better controlled conditions in the greenhouse, and extend the scope of the study to another legume crop and a different soil type, in order to investigate the hypothesis that copious water supply alleviates the adverse effects of soil compaction on nodulation and plant growth.

The effects of two levels of soil compaction and of high and low water supply on the growth and nodulation of common bean and soybean were investigated in separate pot tests using a Fox sandy loam and a Brookston clay loam soil.

Root growth of both species was severely restricted by dry compacted conditions. Plant growth as a whole was clearly reduced by both increased compaction and by reduced water supply, presumably mediated by the effects on root growth. The effect of reduced water supply was more severe in the highly compacted pots, and more severe in the clay loam than in the sandy loam.

In the sandy loam, low moisture reduced nodule numbers and weights in both species, while increased bulk density reduced the numbers of nodules but not the dry weights. In the clay loam, nodule weights and numbers were very low, presumably, owing to high levels of nitrate, which may have resulted from mineralization of soil organic matter during storage.

A generous supply of water obviously alleviated some of the adverse effects of soil compaction on plant growth. This is in general agreement with results of earlier field trials, where severity of the effects of soil compaction varied with the quantity of rainfall.

Key words: Soybean, common bean, soil compaction, soil moisture, nodulation, bulk density

Buttery, B. R., Tan, C. S., Drury, C. F., Park, S. J., Armstrong, R. J. et Park, K. Y. 1998. **Effets de la compaction, de la teneur en eau du sol et du type de sol sur la croissance et sur la nodulation chez le soja et le haricot**. Can. J. Plant Sci. **78**: 571–576. Nous avons précédemment observé en essai, en vraie grandeur les différences interannuelles affectant la gravité des effets de la compaction du sol sur la nodulation et sur la croissance chez le haricot. Les différences paraissaient être reliées à la quantité de pluie tombée durant l'année précédente. Afin de vérifier l'hypothèse selon laquelle un apport abondant d'eau atténuerait les effets adverses de la compaction du sol sur la nodulation et sur la croissance, nous avons décidé de répéter l'expérience en serre, dans des conditions mieux maîtrisées en l'étendant cette fois à une autre légumineuse et à un type de sol différent. Nous avons donc examiné les effets de deux niveaux de compaction et de deux niveaux d'approvisionnement hydrique, l'un élevé, l'autre faible, sur la croissance et sur la nodulation chez le haricot et chez le soja. L'expérience était réalisée en essais en pots distincts, à la fois sur loam sableux Fox et sur loam argileux Brookston. Chez les deux espèces, la croissance racinaire était gravement restreinte en conditions sèches et compactées et la croissance générale était nettement réduite à la fois par l'accroissement de la compaction et par la diminution des apports hydriques vraisemblablement par suite des effets de ces facteurs sur la croissance racinaire. Les effets de la diminution de l'approvisionnement en eau étaient plus graves dans les pots soumis à une forte compaction et en loam argileux qu'en loam sableux. Dans ce dernier type de sol, la baisse du niveau hydrique provoquait chez les deux espèces une réduction du nombre et du poids des nodosités, tandis que l'accroissement de la densité apparente ne causait une réduction que du nombre seulement de nodosités. Dans le loam argileux, le poids et le nombre des nodosités étaient très bas, vraisemblablement à cause de la présence d'un niveau élevé de nitrates, lesquels proviendraient de la minéralisation de la matière organique du sol durant l'entreposage. Un approvisionnement hydrique abondant a manifestement atténué certains des effets nocifs de la compaction sur la croissance des plantes, ce qui, grosso modo, concorde avec les essais au champ précédent, dans lesquels les effets de la compaction variaient en gravité selon la pluviométrie.

Mots clés: Soja, haricot, compaction, teneur en eau du sol, nodulation, densité apparente

Many soils used for soybean (*Glycine max* [L.] Merr.) and bean (*Phaseolus vulgaris* L.) production suffer from some degree of compaction. There is much anecdotal evidence that plants grow poorly in compacted soils (having high bulk density), but published information is sparse and somewhat contradictory (Rosenberg 1964; Lindemann et al. 1982).

There were considerable differences between years in the severity of the effects of soil compaction on growth and nodulation of common bean in a field experiment (Buttery et al. 1994). In the third year of testing, the effect of com-

Abbreviations: **ASM**, available soil moisture

Table 1. Mean values of plant dry weight (g plant^{-1}) for A300 common bean and Elgin soybean, 40–50 d after planting, at two levels of bulk density (g cm^{-3}) and two moisture levels. Analysis of variances was performed on log transformed data. Mean values shown are those obtained by back transformation from log values

Bulk density (g cm^{-3})	Moisture	Sandy loam A300	Sandy loam Elgin (g plant^{-1})	Sandy loam Mean	Bulk density (g cm^{-3})	Moisture	Clay loam A300	Clay loam Elgin (g plant^{-1})	Clay loam Mean
1.2	High	6.34	4.28	5.23	1.2	High	9.45	5.81	7.44
1.2	Low	2.45	3.18	2.92	1.2	Low	2.71	1.91	2.23
1.6	High	3.49	2.98	3.22	1.5	High	7.58	3.98	5.53
1.6	Low	0.86	0.86	0.86	1.5	Low	0.50	0.52	0.52
Significant effects in ANOVA of log values									
Source									
Cultivar (cult.)		–	–	NS			–	–	(**)
Bulk density (BD)		*	(**)	(**)			*	**	(**)
Moisture (moist.)		*	(**)	(**)			**	**	(**)
BD × moist.		NS	**	*			NS	NS	*
Cult. × BD		–	–	NS			–	–	NS
Cult. × moist.		–	–	NS			–	–	*

*, **, NS, treatment effects were significant ($P > 0.05$), highly significant ($P > 0.01$) or non significant. Asterisks in parentheses indicate effects of interaction.

paction was much less than in the first year, and this was associated with a much higher rainfall in the third than in the first year. In attempts to study the effects of soil compaction on bean growth in pot tests we found only small effects of soil compaction when the pots were subjected to the normal (fairly generous) watering regime in the greenhouse. Furthermore, even when we attempted to reduce water supply, the effects were small if the pots were near field capacity at the beginning of the test.

In attempting to unravel the interacting effects of moisture stress and soil compaction there are a number of practical problems. In the field, it is difficult to maintain bulk density at a constant level, and it is difficult (under our sub-humid weather conditions) to precisely control moisture supply. On the other hand, in pot experiments it is difficult to reproduce the effects of compaction, partly because the roots tend to grow into the space between the soil-mass and the pot wall thus avoiding some of the effects of compacted soil. In studies of nodulation we also need to take into account the effects of nitrate present in the soil or available from the breakdown of organic matter, since nitrate level has a profound effect on nodulation (e.g. Hansen et al. 1992).

We decided to conduct a test to determine the effects of both soil moisture and soil compaction on legume growth and nodulation, using large pots and a fairly short growing period to minimize pot wall effects. Since different soil types seem to behave somewhat differently to compaction, we used both a clay loam and a coarse sandy loam in separate experiments.

MATERIALS AND METHODS

Soybeans were represented by the cultivar Elgin, a maturity group II, *Phytophthora* tolerant line, recommended in Ontario. Common bean was represented by A300, an indeterminate erect vine tolerant to root-rot, originally from CIAT, Colombia (Tu and Park 1993). Plants were grown in galvanized steel buckets with a total volume of 14.3 L, lined with 4-mm-thick polyethylene film. After checking the soils for low levels of available nitrate and ammonia, the Fox sandy loam was collected from the Research Centre field at Harrow, and the Brookston clay loam was collected from the Eugene F. Whelan Sub-station 40 km away near Woodslee, Ontario. Both sites had soybean crops in the recent past, but only the sandy loam had recently grown a common bean crop. The soils were allowed to partially air-dry (to about 5% moisture), then sieved to remove stones and gross plant residues. The Fox sandy loam contained 76% sand, 19% silt and 5% clay with a field capacity in the top 30 cm of soil of 26.2% on a volume basis, and a permanent wilting point of 5.6%. The Brookston clay loam contained 30% sand, 42% silt and 28% clay with a field capacity in the top 30 cm of 39.4% on a volume basis, and a permanent wilting point of 17.5%.

In all cases, soil was packed into the buckets to the height of a marker 6 cm below the rim. The effective volume was 11.1 L. For the compacted sandy loam soil, 10 g of an appropriate commercial *Rhizobium* inoculum, and 600 mL of a N-free nutrient solution were added to 17.75 kg of soil and mixed in a “cement mixer”. After packing in the buckets the bulk density was 1.6 g cm^{-3}. For the clay loam soil, which proved more difficult to pack; only 16.6 kg was used resulting in a bulk density of 1.5 g cm^{-3}. For the low compacted series, 13.3 kg soil was mixed with 4.4 L of vermiculite and packed to a bulk density of 1.2 g cm^{-3}. The vermiculite was necessary to maintain the bulk density for the duration of the experiment. Three seeds were planted in each pot and a small volume of water was added to encourage germination. After emergence, only one seedling per pot was retained. Two levels of ASM were established (Tan and Fulton 1981) after seedling emergence: 1) low moisture at 30% ASM and 2) high moisture at 75% ASM. Low moisture level is equivalent to 11–13% on a volume basis for sandy loam soil and 23–25% for clay loam soil. High moisture level is equivalent to 20–22% for sandy loam soil and 33–35% for clay loam soil. Soil moisture probes (Trase

Table 2. Mean values of leaf area per plant (cm^2 plant^{-1}) for A300 common bean and Elgin soybean, 40–50 d after planting, at two levels of bulk density (g cm^{-3}) and two moisture levels. Analysis of variances was performed on log transformed data. Mean values shown are those obtained by back transformation from log values

Bulk density (g cm^{-3})	Moisture	Sandy loam A300	Sandy loam Elgin (cm^2 plant^{-1})	Sandy loam Mean	Bulk density (g cm^{-3})	Moisture	Clay loam A300	Clay loam Elgin (cm^2 plant^{-1})	Clay loam Mean
1.2	High	1798	829	1221	1.2	High	2196	1215	1633
1.2	Low	620	578	592	1.2	Low	517	300	378
1.6	High	1004	569	756	1.5	High	1454	792	1073
1.6	Low	182	132	151	1.5	Low	76	73	74
Significant effects in ANOVA of log values									
Source									
Cultivar (cult.)		–	–	**			–	–	**
Bulk density (BD)		**	(**)	(**)			(**)	(**)	(**)
Moisture (moist.)		**	(**)	(**)			(**)	(**)	(**)
BD × moist.		NS	**	**			*	*	*
Cult. × BD		–	–	NS			–	–	NS
Cult. × moist.		–	–	NS			–	–	NS

*, **, NS, treatment effects were significant ($P > 0.05$), highly significant ($P > 0.01$) or non significant. Asterisks in parentheses indicate effects of interaction.

Table 3. Mean values of root dry weight per plant (g plant^{-1}) for A300 common bean and Elgin soybean, 40–50 d after planting, at two levels of bulk density (g cm^{-3}) and two moisture levels. Analysis of variances was performed on log transformed data. Mean values shown are those obtained by back transformation from log values

Bulk density (g cm^{-3})	Moisture	Sandy loam A300	Sandy loam Elgin (g plant^{-1})	Sandy loam Mean	Bulk density (g cm^{-3})	Moisture	Clay loam A300	Clay loam Elgin (g plant^{-1})	Clay loam Mean
1.2	High	1.14	0.63	0.87	1.2	High	1.04	0.79	0.91
1.2	Low	0.49	0.53	0.52	1.2	Low	0.52	0.38	0.44
1.6	High	0.86	0.55	0.70	1.5	High	1.11	0.62	0.85
1.6	Low	0.28	0.26	0.27	1.5	Low	0.14	0.13	0.14
Significant effects in ANOVA of log values									
Source									
Cultivar (cult.)		–	–	(*)			–	–	*
Bulk density (BD)		NS	(**)	**			NS	*	(**)
Moisture (moist.)		*	(**)	(**)			**	**	(**)
BD × moist.		NS	**	NS			NS	NS	*
Cult. × BD		–	–	NS			–	–	NS
Cult. × moist.		–	–	*			–	–	NS

*, **, NS, treatment effects were significant ($P > 0.05$), highly significant ($P > 0.01$) or non significant. Asterisks in parentheses indicate effects of interaction.

moisture system) were installed in the pots as a guide for watering. Water was applied from the soil surface on a volume basis to maintain a given level of soil moisture in the pots. The experiment using sandy loam soil was run from January to March 1996 in a heated greenhouse (20–30°C), while the experiment with clay loam soil was run from April to June 1996 in the same greenhouse compartment. Plants were harvested 40–50 d after planting. Leaf area was measured using a LI-COR leaf area meter (Model LI-3000); nodules were counted; dry weights of leaves, stems, roots and nodules were obtained after drying at 80°C for 24 h. Samples of soil were taken from each pot for determination of residual inorganic nitrogen.

Analysis of variance of the data was carried out using PROC GLM of the SAS system (SAS Institute, Inc., Cary, NC, USA). Values for the dry weights of roots, nodules and whole plant, leaf areas and nodule numbers were transformed to natural logarithms (ln) prior to analysis in order to stabilize the variances.

RESULTS

Plant Dry Weight

Analysis of the log-transformed data showed that for the plant dry weights combined over crops, the dry treatment decreased to a greater extent in the high than in the low bulk density soils resulting in a moisture × bulk density interaction (Table 1). Similarly, the difference between the two levels of bulk density was greater for the dry series (low moisture level) than the wet series (high moisture level). This was true for both the sandy loam and the clay loam soils, and for both crops, although ANOVA for the individual crops showed significant interaction only with Elgin in sand.

For both species combined in the sandy loam soil, with low bulk density, the dry treatment reduced plant dry weight by 44.2% compared with the wet, while at high bulk density, the dry treatment reduced plant dry weight by 73.3% compared with the wet. In clay, the corresponding reduc-

Table 4. Mean values of nodule dry weights per plant (mg plant^{-1}) for A300 common bean and Elgin soybean, 40–50 d after planting, at two levels of bulk density (g cm^{-3}) and two moisture levels. Analysis of variances was performed on log transformed data. Mean values shown are those obtained by back transformation from log values

Bulk density (g cm^{-3})	Moisture	Sandy loam A300	Sandy loam Elgin (mg plant^{-1})	Sandy loam Mean	Bulk density (g cm^{-3})	Moisture	Clay loam A300	Clay loam Elgin (mg plant^{-1})	Clay loam Mean
1.2	High	23.4	37.2	29.5	1.2	High	0.34	10.2	2.9
1.2	Low	2.1	32.2	14.0	1.2	Low	0.60	1.3	1.1
1.6	High	6.0	28.6	13.4	1.5	High	0.34	4.4	1.7
1.6	Low	5.8	10.3	8.1	1.5	Low	0.00	0.2	0.1
Significant effects in ANOVA of log values									
Source									
Cultivar (cult.)		–	–	**			–	–	(**)
Bulk density (BD)		NS	**	NS			NS	**	(**)
Moisture (moist.)		NS	*	*			NS	**	(**)
BD × moist.		NS	NS	NS			NS	NS	NS
Cult. × BD		–	–	NS			–	–	*
Cult. × moist.		–	–	NS			–	–	**

*, **, NS, treatment effects were significant ($P > 0.05$), highly significant ($P > 0.01$) or non significant. Asterisks in parentheses indicate effects of interaction.

Table 5. Mean values of nodule numbers per plant for A300 common bean and Elgin soybean, 40–50 d after planting, at two levels of bulk density (g cm^{-3}) and two moisture levels. Analysis of variances was performed on log transformed data. Mean values shown are those obtained by back transformation from log values

Bulk density (g cm^{-3})	Moisture	Sandy loam A300	Sandy loam Elgin (no. plant^{-1})	Sandy loam Mean	Bulk density (g cm^{-3})	Moisture	Clay loam A300	Clay loam Elgin (no. plant^{-1})	Clay loam Mean
1.2	High	71.1	116.1	90.8	1.2	High	4.1	39.0	13.3
1.2	Low	11.8	42.5	28.0	1.2	Low	2.9	7.6	4.8
1.6	High	37.3	66.5	49.8	1.5	High	5.2	23.9	11.5
1.6	Low	15.4	11.8	13.2	1.5	Low	0.0	0.2	0.1
Significant effects in ANOVA of log values									
Source									
Cultivar (cult.)		–	–	*			–	–	(**)
Bulk density (BD)		NS	**	**			NS	(**)	(**)
Moisture (moist.)		*	**	**			*	(**)	(**)
BD × moist.		NS	NS	NS			NS	**	**
Cult. × BD		–	–	NS			–	–	NS
Cult. × moist.		–	–	NS			–	–	**

*, **, NS, treatment effects were significant ($P > 0.05$), highly significant ($P > 0.01$) or non significant. Asterisks in parentheses indicate effects of interaction.

tions were 70.0% for the low bulk density and 90.6% for the high bulk density. Similarly, in sand, increased compaction reduced plant weight by 38.4% in the wet treatment, but by 70.5% in the dry treatment. In clay, compaction reduced plant weight by 25.7% in the wet treatment, but by 76.6% in the dry. The experiment using clay loam produced heavier plants in the wet series than did the sandy loam soils, but lighter plants in the dry series. This effect is probably the result of soil factors, but since the experiments were conducted at different times of year, other environmental factors may be involved.

Leaf Area

Analysis of the log-transformed data showed that for the plant leaf area (combined over species), the difference between the wet treatment and the dry treatment was greater in the high than in the low bulk density pots (Table 2). Similarly, the difference between the leaf areas observed in the two levels of bulk density was greater for the dry series than the wet. This was true for both the sandy loam and clay loam soils, but with the individual species was significant only for Elgin. The experiment in the clay loam soil produced plants with larger leaf area than those in sandy loam soil, under wet conditions, but clay-grown plants had less leaf area than sand-grown plants in dry conditions.

For both species combined, with low bulk density, in sandy loam, the dry treatment reduced leaf area by 51.5% compared with the wet, whereas at high bulk density the dry treatment reduced leaf area by 80.0% compared with the wet. In clay the corresponding figures were 76.9% for low bulk density and 93.1% for the high bulk density. Similarly, in sand, increased compaction reduced leaf area by 38.1% in the wet treatment but by 74.5% in the dry treatment. In clay loam, compaction reduced leaf area by 34.3% in the wet treatment but by 80.4% in the dry.

Table 6. Mean values of the root to shoot ratio (g g^{-1}) for A300 common bean and Elgin soybean, 40–50 d after planting, at two levels of bulk density (g cm^{-3}) and two moisture levels

Bulk density (g cm^{-3})	Moisture	Sandy loam A300	Sandy loam Elgin (g g^{-1})	Sandy loam Mean	Bulk density (g cm^{-3})	Moisture	Clay loam A300	Clay loam Elgin (g g^{-1})	Clay loam Mean
1.2	High	0.226	0.186	0.206	1.2	High	0.122	0.157	0.140
1.2	Low	0.250	0.217	0.228	1.2	Low	0.235	0.254	0.246
1.6	High	0.318	0.244	0.281	1.5	High	0.172	0.188	0.180
1.6	Low	0.508	0.474	0.489	1.5	Low	0.394	0.347	0.363
Significant effects in ANOVA									
Source									
Cultivar (cult.)		–	–	NS			–	–	NS
Bulk density (BD)		*	(**)	(**)			(**)	**	(**)
Moisture (moist.)		NS	(**)	(**)			(**)	**	(**)
BD × moist.		NS	**	**			**	NS	**
Cult. × BD		–	–	NS			–	–	NS
Cult. × moist.		–	–	NS			–	–	*

*, **, NS, treatment effects were significant ($P > 0.05$), highly significant ($P > 0.01$) or non significant. Asterisks in parentheses indicate effects of interaction.

Root Dry Weight

Root weight was generally reduced by increased bulk density and by reduced water supply, and there was a tendency for these two factors to interact — the effect of dryness being greater in the high than in the low bulk density soils — although this interaction was statistically significant only for Elgin in the sand and for the overall mean in the clay loam (Table 3). There was also a cultivar effect with A300 having a greater root weight than Elgin.

Nodule Dry Weight per Plant

No significant effects of moisture or compaction on nodule weight were observed in A300, but reduced moisture and increased bulk density decreased nodule weight in Elgin (Table 4). In clay, nodulation was generally much less than in sandy loam especially with A300. No nodules were found with A300 in the dry compacted clay loam. In the clay loam soil, both high bulk density and low moisture reduced nodule weight in Elgin but not in A300, and this is reflected in the significant interactions between cultivar × bulk density, and between cultivar × moisture.

Number of Nodules per Plant

In the sandy loam soil, more nodules were formed on Elgin than on A300 (Table 5). Lack of moisture reduced nodule numbers in both species; high bulk density reduced nodule numbers in Elgin, and in the two species combined. There were no significant interactions. In the clay loam soil, there was a significant interaction between bulk density × moisture level, for Elgin on its own and for the two species combined, in which dry conditions reduced nodule numbers more in the compacted than the non-compacted soil. The cultivar × moisture interaction indicated the different responses of the two species to dry conditions with Elgin being more sensitive than A300. The average dry weight per nodule (calculated on an individual pot basis) was not affected by bulk density (data not shown), but in the sand, averaged over the two cultivars and density treatments, the wet treatment produced a lower average weight than the dry (0.38 mg vs. 0.63 mg), and A300 (0.34 mg) had lighter nodules than Elgin (0.63 mg) when averaged over density and moisture treatments. No significant treatment effects on average nodule weight were found in the clay loam where the overall mean was 0.15 mg.

Soil Nitrogen

The nitrogen content of the sandy soil was quite low, more or less what would be expected for a field soil that had not been supplied with fertilizer for many years. However, the mean values for the clay loam soil analysed at the end of the experiment were surprisingly high: 68.3 mg N kg^{-1} nitrate, and negligible ammonium (1.6 mg N kg^{-1})· There were no significant differences due to treatments (data not shown). We had sampled several prospective areas in the field and checked that the nitrogen content was suitably low, before collecting the bulk sample clay loam used for filling the pots. The soil was collected in October but not used until the following May. Possibly, the nitrate was released by mineralization of organic nitrogen during the 7 mo storage.

Root-to-shoot Ratio

In both species and soils, the root-to-shoot ratio was increased by the dry treatment and also by increased compaction (Table 6). The effects of dryness were greater in the compacted pots, resulting in a bulk density × moisture interaction.

DISCUSSION

The range of bulk densities used in these pot experiments was greater than that normally found in local agricultural soils. Values for the compacted pots were fairly similar to those achieved in the compacted plots in the field, but the bulk densities in the non-compacted pots were lower than those found in the deep-tilled, and in the standard tillage plots in the field (Buttery et al. 1994). Also, the bulk densities of the deep-tilled (non-compacted) plots in the field increased during the growing season, while the bulk densities of the vermiculite-amended pots remained essentially constant during the experimental period. Under controlled conditions we were able to examine the influence of density and moisture while keeping other factors constant.

The levels of water supply used in these pot experiments would commonly occur in the field at some times during the growing season. However, it would be rare for either level to remain constant in the field for a prolonged period.

Root growth in our experiments was severely restricted by dry compacted conditions. The poor root growth would exacerbate the water shortage: in these conditions, water (and nutrient) uptake by the plant would be restricted both by the lack of water in the soil and by the inadequate penetration of the soil volume by the roots. The effects of both compaction and moisture supply on plant growth as a whole were presumably mediated by their effects on root growth. Plant growth was clearly reduced by both increased compaction and by reduced water supply. The effect of reduced water supply was more severe in the highly compacted pots, and was more severe in the clay loam than in the sandy loam soil. This is consistent with the results of Taylor and Gardner (1963), and Taylor et al. (1964), who showed that soils gain strength and resist root penetration when they are compacted, and compacted soils gain additional strength as they become drier. Soil strength also increases with clay content (Mathers et al. 1966). Both crop species responded fairly similarly to the experimental treatments, although A300 appeared more responsive than Elgin to increased water supply. A generous supply of water obviously alleviates a fairly large part of the adverse effects of soil compaction on plant growth. In the field, therefore, the effects of compaction would likely be less under conditions of high rainfall. However, compaction also reduces drainage (Rowse and Stone 1980) and, under field conditions, if rainfall were excessive, compacted soils (especially clay) would be more likely to flood with consequent adverse effects (Wolfe et al. 1995).

Nodule weights and numbers were very low in the clay soil. This can be attributed to the inhibiting effect of high nitrate levels: nodulation in A300 seemed more sensitive to nitrate than it was in Elgin. Low moisture and high bulk density reduced nodule weights, and interacted to reduce nodule numbers in Elgin. Even in the sandy loam soil, A300 had lower numbers and weights of nodules than Elgin. In sandy loam soil, low moisture reduced nodule numbers and weights, while increased bulk density reduced the numbers of nodules but not the dry weights. Buttery et al. (1994) showed that under field conditions in sandy loam soil, nodule weights and numbers of common bean were not reduced by soil compaction. In fact, nodule weight as a fraction of total plant weight increased with increasing compaction, as did the root-to-shoot ratio. In our pot tests in common bean, nodules as a fraction of total plant weight was not changed by soil treatments (data not shown) although root-to-shoot ratio tended to increase with increase in bulk density.

These experiments have clearly demonstrated that the effects of soil compaction on plant growth and nodulation are profoundly affected by the level of water supply. We conclude, therefore, that the year-to-year variation in the severity of the effects of compaction found in our earlier field tests can be largely accounted for by the seasonal variation in rainfall.

Buttery, B. R., Tan, C. S. and Park, S. J. 1994. The effects of soil compaction on nodulation and growth of common bean (*Phaseolus vulgaris* L.). Can. J. Plant Sci. **74**: 287–292.

Hansen, A. P., Martin, P., Buttery, B. R. and Park S. J. 1992. Nitrate inhibition of N_2 fixation in *Phaseolus vulgaris* L. cv. OAC Rico and a supernodulating mutant. New Phytol. **122**: 611–615.

Lindemann, W. C., Ham, G. E. and Randall, G. W. 1982. Soil compaction effects on soybean nodulation, N_2 (C_2H_4) fixation and seed yield. Agron. J. **74**: 307–311.

Mathers, A. C., Lotspeich, F. B., Laase, G. R. and Wilson, G. C. 1966. Strength of compacted Amarillo fine sandy loam as influenced by moisture, clay content, and exchangeable cation. Soil Sci. Soc. Am. Proc. **30**: 788–791.

Rosenberg, R. J. 1964. Response of plants to the physical effects of soil compaction. Adv. Agron. **16**: 181–196.

Rowse, H. R. and Stone, D. A. 1980. Deep cultivation of a sandy clay loam. II. Effects on soil hydraulic properties and on root growth , water extraction and water stress in 1977 especially of broad beans. Soil Till. Res. **1**: 173–185.

Tan, C. S. and Fulton, J. M. 1981. Estimating evapotranspiration from irrigated crops in southwestern Ontario. Can. J. Plant Sci. **61**: 425–435.

Taylor, H. M. and Gardner, H. R. 1963. Penetration of cotton seedling taproots as influenced by bulk density, moisture content and strength of soil. Soil Sci. **96**: 153–156.

Taylor, H. M., Mathers, A. C. and Lotspeich, F. B. 1964. Pans in the southern Great Plains soils: I. Why root restricting pans occur. Agron. J. **56**: 328–332.

Tu, J. C. and Park, S. J. 1993. Root-rot resistance in common bean. Can. J. Plant Sci. **73**: 365–367.

Wolfe, D. W., Topoleski, D. T. Gundersheim, N. A. and Ingall, B.A. 1995. Growth and yield sensitivity of four vegetable crops to soil compaction. J. Am. Soc. Hortic. Sci. **120**: 956–963.

This article has been cited by:

1. Tino Colombi, Serge Braun, Thomas Keller, Achim Walter. 2017. Artificial macropores attract crop roots and enhance plant productivity on compacted soils. *Science of The Total Environment* **574**, 1283-1293. [CrossRef]
2. Audrey St-Martin, Riccardo Bommarco. 2016. Soil compaction and insect pollination modify impacts of crop rotation on nitrogen fixation and yield. *Basic and Applied Ecology* **17**:7, 617-626. [CrossRef]
3. Vinay Kumar Gadi, Sanandam Bordoloi, Ankit Garg, Yasufumi Kobayashi, Lingaraj Sahoo. 2016. Improving and correcting unsaturated soil hydraulic properties with plant parameters for agriculture and bioengineered slopes. *Rhizosphere* **1**, 58-78. [CrossRef]
4. Tino Colombi, Achim Walter. 2016. Root responses of triticale and soybean to soil compaction in the field are reproducible under controlled conditions. *Functional Plant Biology* **43**:2, 114. [CrossRef]
5. Márcio Renato Nunes, José Eloir Denardin, Eloy Antônio Pauletto, Antônio Faganello, Luiz Fernando Spinelli Pinto. 2015. Effect of soil chiseling on soil structure and root growth for a clayey soil under no-tillage. *Geoderma* **259-260**, 149-155. [CrossRef]
6. Anna Siczek, Rainer Horn, Jerzy Lipiec, Bogusław Usowicz, Mateusz Łukowski. 2015. Effects of soil deformation and surface mulching on soil physical properties and soybean response related to weather conditions. *Soil and Tillage Research* **153**, 175-184. [CrossRef]
7. Márcio Renato Nunes, José Eloir Denardin, Eloy Antonio Pauletto, Antonio Faganello, Luiz Fernando Spinelli Pinto. 2015. Mitigation of clayey soil compaction managed under no-tillage. *Soil and Tillage Research* **148**, 119-126. [CrossRef]
8. Anna Siczek, Jerzy Lipiec, Jerzy Wielbo, Paweł Szarlip, Dominika Kidaj. 2013. Pea growth and symbiotic activity response to Nod factors (lipo-chitooligosaccharides) and soil compaction. *Applied Soil Ecology* **72**, 181-186. [CrossRef]
9. Anna Siczek, Jerzy Lipiec. 2011. Soybean nodulation and nitrogen fixation in response to soil compaction and surface straw mulching. *Soil and Tillage Research* **114**:1, 50-56. [CrossRef]
10. Juliano C. Calonego, Ciro A. Rosolem. 2010. Soybean root growth and yield in rotation with cover crops under chiseling and no-till. *European Journal of Agronomy* **33**:3, 242-249. [CrossRef]
11. Angie Y. S. Ng, Billy C. H. Hau. 2009. Nodulation of native woody legumes in Hong Kong, China. *Plant and Soil* **316**:1-2, 35-43. [CrossRef]
12. Nyambilila Amuri, Kristofor R. Brye. 2008. RESIDUE MANAGEMENT PRACTICE EFFECTS ON SOIL PENETRATION RESISTANCE IN A WHEAT-SOYBEAN DOUBLE-CROP PRODUCTION SYSTEM. *Soil Science* **173**:11, 779-791. [CrossRef]
13. S.S. Kukal, Yadvinder Singh, Sudhir Yadav, E. Humphreys, Amanpreet Kaur, S. Thaman. 2008. Why grain yield of transplanted rice on permanent raised beds declines with time?. *Soil and Tillage Research* **99**:2, 261-267. [CrossRef]
14. V.M. Blouin, M.G. Schmidt, C.E. Bulmer, M. Krzic. 2008. Effects of compaction and water content on lodgepole pine seedling growth. *Forest Ecology and Management* **255**:7, 2444-2452. [CrossRef]