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The effect of soil strength on the growth of pigeonpea radicles and seedlings

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Abstract

The effect of soil strength on the growth of pigeonpea radicles and seedlings was investigated in cores of three clay soils prepared at different water contents and bulk densities in the laboratory.

Radicle elongation directly into soil cores was reduced from 50–70 mm d^{-1} at strengths less than 0.5 MPa to 0 mm d^{-1} at 3.5–3.7 MPa. The response to soil strength was affected by the water content of the soil, presumably as a result of reduced oxygen availability in wetter soil. This effect was apparent in soils wet to air-filled porosities less than 0.15 $m^3 m^{-3}$.

Radicles were more sensitive to high soil strength (>1.5 MPa) than were seedling roots which encountered the same conditions at 60 mm in the profile. Radicle growth ceased at 3.5 MPa which reduced seedling root growth by only 60%.

Despite a 60% reduction in root length in the high strength zone, seedling roots compensated in zones of loose soil above and below the compacted layer, and total root length and shoot growth were unaffected. There was no evidence of a 'root signal' response which results in reduced shoot growth in some species in response to high soil strength.

The proliferation of roots in surface layers and the delayed penetration of the root system to depth in compacted soil are likely to expose seedlings to a greater risk of water-deficit in the field, particularly under dryland conditions where plants rely on stored subsoil water for growth.

Introduction

Pigeonpea (*Cajanus cajan*) is a perennial food legume which has demonstrated considerable potential as a new field crop in Australian agriculture (Meekin et al., 1987). During the early 1980s, poor establishment and reduced early growth of pigeonpea was observed at several sites on clay soils in south-east Queensland, despite favourable growing conditions are careful agronomic management. In most cases where plant emergence was patchy and shoot growth restricted, compaction layers were detected by increased resistance to the penetration of a metal probe, and observations of malformed taproot growth.

Soil compaction in south-east Queensland has also been associated with restricted growth of sunflowers (Kirchhof et al., 1986), wheat (Ralph, 1984), guar (Keating, 1984) and cotton (So and Cull, 1985). However the extent of the problem remains unclear (Leslie and McCown, 1988) and the exact mechanism of plant response has not been established. Restricted root growth due to increased soil strength was implicated as an important mechanism in most of the above reports and is considered to be the most serious and widespread consequence of compaction in agriculture (Boone et al., 1978; Taylor et al., 1966; Voorhees, 1977).

The effect of soil strength on the growth of roots has often been studied using the growth of radicles or young seedlings into prepacked cores (Asady et al., 1985; Eavis, 1972; Masle and Passioura, 1987). Russell (1977) criticised the use of small cores for predicting root response in the field since no allowance is made for structural variations (cracks, root channels) which exist in the field. However Bridge (1985) pointed out that restricted root growth is often associated with compacted soil in which structure has been destroyed, and soil strengths found to be critical in core experiments are also associated with seriously restricted root growth in the field. Asady et al. (1985) used small-core experiments on bean seedlings to predict growth responses to compaction in field grown plants.

A series of experiments was conducted to investigate the effect of compaction on the growth of pigeonpea on clay soils. This paper reports the results of laboratory experiments to determine the effects of soil strength on radicle elongation and early seedling growth.

Table 1. Characteristics of experimental soils (0–15 cm)

	Soil 1 Oxisol Kraznosem Gn 3.11	**Soil 2** Oxisol Kraznosem Uf 6.31	**Soil 3** Vertisol Black earth Ug 5.16
Site	Redland Bay (Virgin forest)	Redland Bay (Cultivated)	Dalby (Cultivated)
Clay (%)	33	52	56
Silt (%)	19	15	16
Sand (%)	44	33	28
pH (1:5) H_2O	5.9	6.5	7.4
EC (1:5) H_2O (mS cm^{-1})	0.03	0.06	0.15
Organic C(%)	4.0	3.0	na
Soil water ($g\,g^{-1}$)			
−0.01 MPa	0.31	0.33	0.37
−1.5 MPa	0.18	0.23	0.23

Materials and methods

Soil characteristics and core preparation

Soil samples were collected from the surface horizons (0–150 mm) of three clay soils (two oxisols and one vertisol) from south-east Queensland. Relevant properties of these soils are shown in Table 1. The samples were air dried and passed through a 2 mm sieve after collection.

Soil cores were prepared at varying water contents and bulk densities to produce a range of soil strengths. Batches of soil were wet up to the required water contents using a fine spray in a rotating concrete mixer, and were stored in large plastic bags to equilibrate for one week prior to the preparation of cores. Brass cores, 72.5 mm in diameter and 60 mm deep, were used in all experiments. Cores of low soil strength were prepared by adding soil in stages and tamping on a hard surface. Cores at higher strengths were prepared using a hydraulically-driven double ram packer with variable pressures. By this procedure, soil was compressed from both ends into a brass sleeve containing two end-sections (72.5 mm in length) and the central core (60 mm). After packing at the desired pressure, the highly compressed end sections were cut away and the central section trimmed to provide a uniformly compacted core. At each pressure, replicate cores were produced in which bulk densities varied by ±0.01 Mg m^{-3}.

Experiment 1 – Effect of matric potential on radicle growth

Water content may affect radicle growth independent of its effect on soil strength. An experiment was conducted using the three soils to determine the effect of matric potential on radicle growth. Batches of soils 1, 2 and 3 (Table 1) were prepared at five to seven water contents in the ranges 0.11–0.38, 0.17–0.45 and 0.17–0.28 g g^{-1} respectively, which represented matric potentials of −0.001 to −10 MPa. Three replicate cores of each soil at each water content were hand-packed to 0.95-1.00 Mg m^{-3} bulk density and negligible soil strength. Five pregerminated (24 h) seeds of pigeonpea (cv. Quantum), chosen for uniformity of size and with radicles 1–2 mm in length, were placed on the surface of each core. They were covered with 25 mm of loose soil, at the same water content as the core, contained in a smaller ring taped to the top of the core. This soil was pressed down firmly and the whole unit sealed in a plastic bag and incubated at 30°C for 48 h. After 48 h the seedlings were removed and the lengths of the radicles measured.

Experiment 2 – Effect of soil strength on radicle growth

Temporal growth pattern

The temporal growth pattern of pigeonpea radicles was investigated to determine appropriate harvest times which avoid both the early lag phase in radicle growth, and the radicles reaching the bottom of the cores prior to harvest. A batch of soil 1 was prepared at $0.28\,g\,g^{-1}$ water content and 27 replicate cores were hand-packed to $0.95\,Mg\,m^{-3}$ bulk density. Three pre-germinated seeds were sown in each core as described in Experiment 1, and the cores incubated at 30°C. Three replicates were harvested at 10, 24, 28, 34, 39, 48, 53, 56, and 68 h after sowing and the lengths of the radicles measured. For the final three harvests a second identical core was taped to the bottom to accommodate radicles longer than 60 mm.

Soil strength and radicle elongation

Five replicate soil cores were packed at a range of water contents and bulk densities for each soil (Table 2). Air-filled porosity (AFP) was calculated assuming a particle density of $2.65\,Mg\,m^{-3}$ for each soil. Only one water content ($0.23\,g\,g^{-1}$) could be used for the vertisol (soil 3) as above that level it became too sticky for use in the hydraulic packer. However as that water content was equivalent to the wilting point, radicle growth was likely to have been limited by water supply. Soil strength was measured at four randomly-selected locations on both top and bottom surfaces of each core using a pocket penetrometer (Geotester) after a three-day equilibration period. The blunt 6.2 mm diameter tip was pushed 5.0 mm into the soil surface and the maximum penetration resistance was calculated by dividing the maximum force recorded on the gauge (kg) by the cross-sectional area of the probe (Table 2). The strengths measured with this penetrometer correlated well with those measured using a balance penetrometer (Eavis, 1972) with a 1.6 mm diameter probe and a semi-angle of 30°. The equation relating penetration resistance measured using these two penetrometers is given by:

$Y = mX + c$ where

$m = 0.76 \pm 0.02$ Y = Pocket penetrometer (MPa)

$c = 0.15 \pm 0.04$ X = Balance penetrometer (MPa)

$r^2 = 0.95$

The pocket penetrometer was preferred so that the response could be compared with that of plants in subsequent field trials.

Three pre-germinated seeds of pigeonpea were sown into each core and all cores were placed in a growth cabinet at 30°C as described in Experiment 1. Two of the five replicates were harvested 36 h after sowing and the remaining three replicates 12 h later. The radicles were removed at each harvest, their lengths recorded and the radicle elongation rate (RER) calculated for each of the three cores harvested at 48 h as:

$$\text{RER}\,(\text{mm d}^{-1}) = \frac{(\text{Length at 48 h}) - (\text{Av. Length at 36 h})}{0.5}$$

Measurements at harvest indicated that the strength and water content of the soil had not changed significantly during the experiment.

Experiment 3 – The effect of soil strength on seedling growth

A batch of soil 1 was prepared at $0.19\,g\,g^{-1}$ water content, and eight replicate cores were packed at each of four bulk densities (Table 3). Each treatment core was positioned between top and bottom cores of the same dimensions containing the same soil loosely packed to $0.95\,Mg\,m^{-3}$, and the three cores sealed together with plastic tape. Four pre-germinated seeds of pigeonpea were inoculated and sown into the top of each core assembly as described in Experiment 1, and all were placed in a growth cabinet

Table 2. Soil physical conditions in soil cores for each soil in Experiment one

Soil	Water Content ($g\ g^{-1}$)	Matric potential (MPa)	Bulk density ($Mg\ m^{-3}$)	Soil strength (MPa)	AFP ($m^3\ m^{-3}$)
1	0.190	−0.56	0.97	0.32 (0.06)[a]	0.472
			1.10	0.84 (0.02)	0.375
			1.19	1.29 (0.03)	0.324
			1.27	1.78 (0.04)	0.278
			1.32	2.20 (0.08)	0.250
			1.35	2.68 (0.06)	0.234
			1.40	3.05 (0.04)	0.204
			1.45	3.44 (0.04)	0.176
	0.225	−0.19	0.86	0.19 (0.02)	0.482
			1.00	0.60 (0.02)	0.397
			1.13	1.03 (0.03)	0.319
			1.42	1.90 (0.03)	0.145
			1.53	2.49 (0.02)	0.078
	0.235	−0.10	0.89	0.26 (0.02)	0.460
			1.22	1.11 (0.03)	0.259
			1.34	1.55 (0.02)	0.186
			1.42	1.74 (0.05)	0.138
			1.45	1.89 (0.02)	0.123
			1.51	2.19 (0.02)	0.083
2	0.265	−0.39	0.90	0.41 (0.06)	0.421
			1.00	0.94 (0.07)	0.356
			1.10	1.38 (0.06)	0.292
			1.20	2.71 (0.12)	0.228
			1.30	3.21 (0.08)	0.163
			1.40	3.75 (0.00)	0.098
	0.280	−0.03	0.90	0.56 (0.07)	0.408
			1.00	0.71 (0.04)	0.342
			1.10	1.08 (0.02)	0.277
			1.20	1.61 (0.06)	0.211
			1.30	2.21 (0.07)	0.145
			1.40	2.33 (0.10)	0.079
	0.300	−0.02	0.90	0.36 (0.02)	0.390
			1.00	0.69 (0.03)	0.322
			1.10	0.84 (0.04)	0.255
			1.20	1.08 (0.09)	0.187
			1.30	1.15 (0.09)	0.119
			1.40	1.62 (0.09)	0.051
	0.330	−0.01	0.90	0.21 (0.04)	0.363
			1.00	0.31 (0.03)	0.292
			1.10	0.43 (0.02)	0.222
			1.20	0.55 (0.04)	0.151
			1.30	0.81 (0.04)	0.080
			1.40	1.09 (0.05)	0.009
3	0.230	−1.26	0.71	0.22 (0.08)	0.568
			0.98	1.07 (0.05)	0.404
			1.13	1.51 (0.10)	0.318
			1.30	2.84 (0.06)	0.149

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[a] Numbers in parenthesis are the standard error of means.

Table 3. Soil physical conditions of the central core for each treatment in Experiment 2

Treatment	Water content ($g\,g^{-1}$)	Bulk density ($Mg\,m^{-3}$)	Soil strength (MPa)	AFP ($m^3\,m^{-3}$)
T1	0.19	0.95	0.51 (0.03)[a]	0.46
T2	0.19	1.23	1.53 (0.02)	0.30
T3	0.19	1.30	2.19 (0.02)	0.26
T4	0.19	1.46	3.47 (0.04)	0.17

[a] Numbers in parenthesis are the standard error of means.

at 30°C. Two replicates were harvested at 50 h and three replicates at 74 h to determine the rate of radicle growth through the central core. The remaining three replicates were removed from the plastic bags, thinned to two plants per core, and grown for 14 days at 30/25°C, 75% relative humidity and 12 h photoperiod in a growth cabinet. Cores were watered daily with dilute nutrient solution (1% Aquasol) to maintain the original water content. Plant height was measured daily and after 14 days, shoots were cut at ground level for dry weight and leaf area determination. The core assembly was then separated into the three sections and the root length, dry weight and nodule numbers in each section were determined. The roots were washed free of the soil in centrifugal root washing cylinders, and root length was estimated using computer-assisted image analysis.

Results and discussion

Experiment 1 – Effect of matric potential on root growth

Figure 1 shows the effect of matric potential on radicle growth for the three soils. These data suggest that the critical matric potential under these conditions is very close to the wilting point (−1.5 MPa) for all soils. These results are consistent with those reported by So (1987) who reviewed the results of several experiments and concluded that the roots of several species, except maize, were relatively insensitive to changes in water potential at least down to −1.5 MPa. Mirreh and Ketcheson (1973) found maize root growth was reduced by 50% as matric potential decreased from −0.1 to −0.8 MPa in soil having negligible strength. The model of root growth described by Dexter (1987) proposes a constant linear decline in root elongation as water potential is reduced from 0 MPa to −1.6 MPa based on these results for maize, and those of Greacen and Oh (1972) for peas. The present results indicate a zone of optimum growth between −0.01 and −0.5 MPa, and a critical matric potential for radicle growth close to −1.0 MPa. It is clear that species differ in their response to decreasing matric potential, in addition to the critical matric potential below which growth ceases. The apparent reduction in growth at potentials near −0.001 MPa may be associated with decreased oxygen availability as suggested by Eavis (1972) who made similar observations on low density soils.

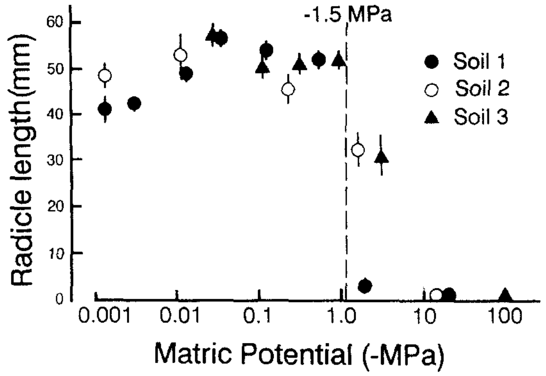

Fig. 1. The effect of matric potential on the length of pigeonpea radicles 48 hours after sowing into loosely packed cores of three soil types. (Vertical *bars* show s.e.m.).

Experiment 2 – Effect of soil strength on radicle growth

Temporal growth pattern

Radicle growth was characterised by a lag phase of approximately 36 h followed by a period of near linear growth (Fig. 2). The harvest times

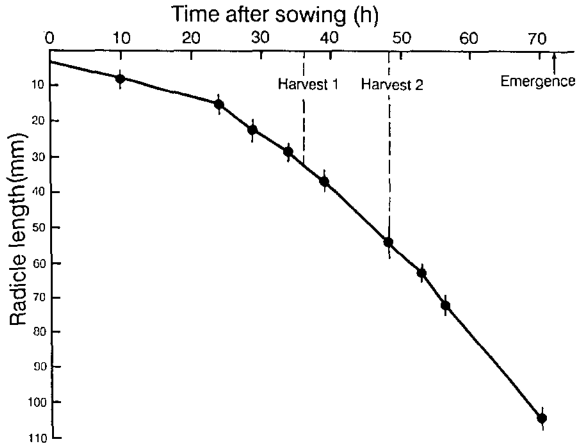

Fig. 2. The temporal pattern of pigeonpea radicle growth in loosely packed soil. The times selected for harvest in Experiment 2 are shown. (Vertical *bars* show s.e.m.).

selected for the strength experiments were 36 and 48 h and it is interesting to note that the radicles had reached a depth of 100 mm prior to emergence of the shoots at around 72 h.

Soil strength and radicle growth

The effect of soil strength on radicle elongation in each soil is shown in Figure 3. The general response of pigeonpea to increasing soil strength follows the typical inverse linear and curvilinear responses first reported by Taylor and Gardner (1963), and since supported by later studies for several soils and crop species (Cornish and Fettell, 1977; Gerard et al., 1972; Gooderham 1977).

Maximum RER at low soil strengths differed between soils. The low maximum RER in soil 3 was likely to have been caused by decreased water availability as the water content of this soil was close to the wilting point. The higher maximum elongation rates on soil 2 may have arisen from improved water availability due to the generally higher matric potentials (Table 2), and improved soil contact at low bulk density due to the finer texture of this soil. At low soil strengths the radicles may be sensitive to textural differences which are not measured by penetrometers. The improved nutrient status of soil 2 due to fertilizer application is unlikely to have influenced radicle growth as the seed reserves of pigeonpea are relatively large.

The critical soil strength which prevented radicle elongation was 3.5–3.7 MPa for soils 1 and 2 and 3.0 MPa for soil 3. Most critical soil strength values reported for the radicles of a variety of species fall in the range of 2.0–3.0 MPa (Cockroft et al., 1969; Gerard et al., 1972; Greacen and Oh, 1972; Taylor and Gardner, 1963).

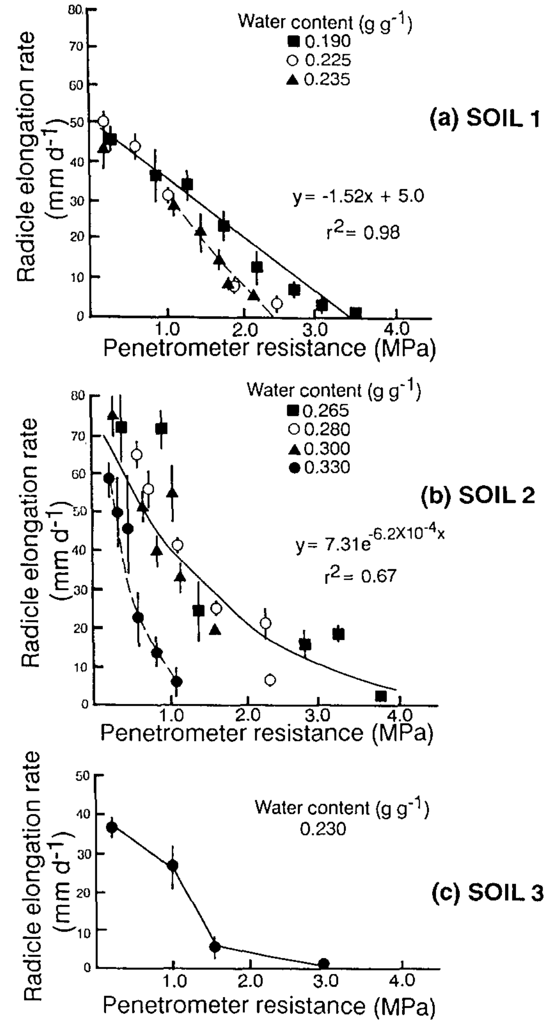

Fig. 3. The effect of soil strength on radicle elongation of pigeonpea in three soils prepared at a range of water contents and bulk densities. The regression equations shown are for (■) only in soil 1 and for (■, ○ and ▲) in soil 2. Dotted lines indicate the response at the highest water content for soil 1 (▲) and soil 2 (●). (Vertical *bars* show s.e.m.).

In addition to the effect of soil strength, a second factor, presumably decreased oxygen availability decreased radicle growth in soils 1 and 2 as they became wetter, as indicated by the dotted lines in Figure 3. These curves indicate that the effect of decreased oxygen supply associated with decreased AFP (Table 2) was gradual rather than an abrupt decrease at some critical level. Eavis (1972) found similar aeration effects in a sandy soil having less than 0.30, 0.22 and 0.11 $m^3 m^{-3}$ AFP at low (1.1 Mg m^{-3}), medium (1.4 Mg m^{-3}) and high (1.6 Mg m^{-3}) bulk densities and suggested that the area of gas/liquid interface influences the diffusive resistance of oxygen. At large bulk densities the effect of small increases in water content on decreasing soil strength may be offset by the decreased availability of oxygen to the radicle. Indeed, greater than additive decreases in root growth have been recorded when increasing soil strength and low oxygen availability occur together (Boone et al., 1984; Hopkins and Patrick, 1969) which may also explain the sensitivity of radicle growth to small increases in water content at high bulk density. The sensitivity of pigeonpea radicles to decreases in air-filled porosity is consistent with the well-known sensitivity of field grown crops to waterlogging (Meekin et al., 1987).

Experiment 3 – Effect of soil strength on seedling growth

The treatments had no effect on shoot height at any time (data not shown) or on shoot growth measured at harvest. The mean height, dry weight and leaf area per plant for all treatments at 14 days were 18.9 ± 0.4 cm, 0.41 ± 0.01 g and 7580 ± 2.10 mm^2 respectively. However root growth and distribution in the cores were influenced by soil strength in the central core (Table 4). Root length, root weight and nodule numbers in the central core were decreased and roots became thickened and distorted (Plate 1) as the strength of the central core increased. Despite reduced root proliferation in the compacted core, the main root had penetrated to the bottom core in all treatments and at the end of the experiment the root length in this core was similar for all treatments. The trend toward higher root growth in the surface as soil strength increased in the central core is likely to be due to the proliferation of lateral roots in the top core

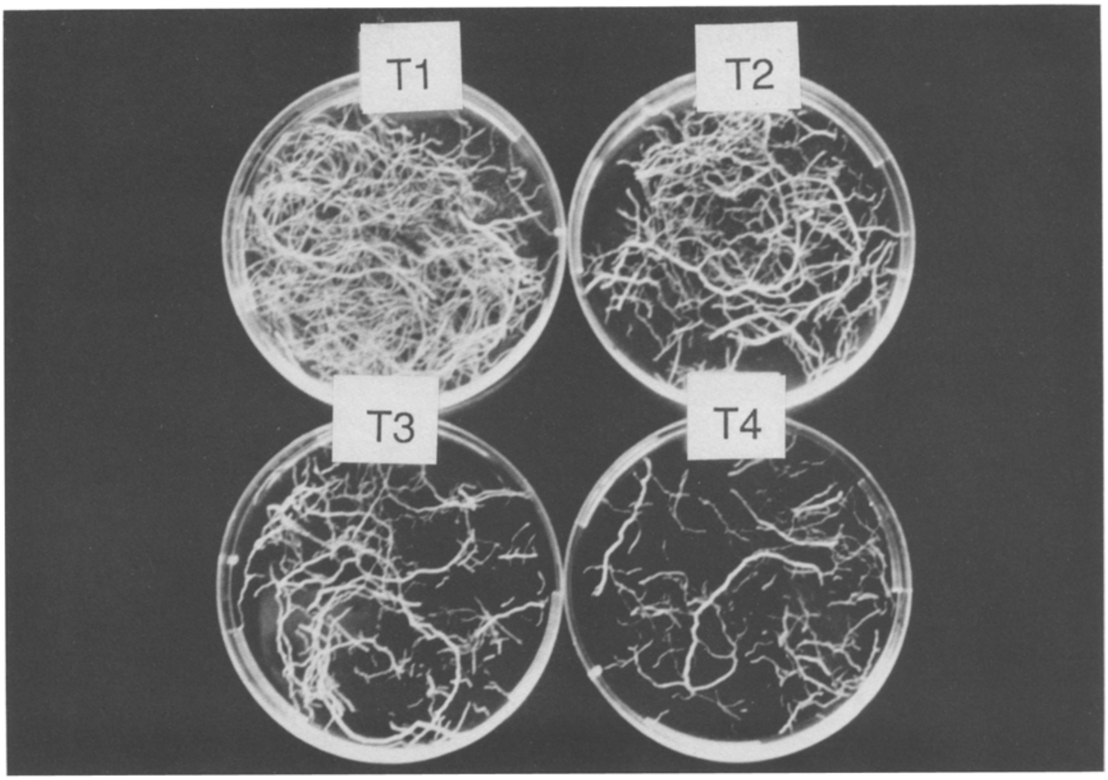

Plate 1. Effect of soil strength on the root growth of pigeonpea seedlings. Each dish contains the total roots washed from the central core in each of the four treatments.

Table 4. The effect of a layer of increasing soil strength on the distribution of roots and nodules of pigeonpea at 14 days

Core section (mm)	Total root length (m)				Relative root length (%)				Nodule number			
	T1	T2	T3	T4	T1	T2	T2	T4	T1	T2	T3	T4
0–60	2.66^{a}	3.62^{a}	3.29^{a}	4.46^{a}	23	40	33	42	17^{a}	27^{a}	23^{a}	12^{a}
60–120	3.90^{a}	2.35^{b}	2.15^{b}	1.59^{c}	34	26	22	15	12^{a}	5^{b}	0^{c}	2^{c}
120–180	4.88^{a}	3.21^{a}	4.50^{a}	4.47^{a}	42	34	45	43	1^{a}	0^{a}	0^{a}	0^{a}
Total	11.44^{a}	9.18^{a}	9.94^{a}	10.52^{a}	100	100	100	100	30^{a}	32^{a}	23^{a}	14^{b}

[a] Numbers in each row with the same letter are not significantly different (LSD $p = 0.05$).

during the slower growth of the main root through the central core. As a result, total root length per plant was not affected.

A comparison of the relative effects of increasing soil strength on direct radicle growth (Experiment 2), radicle growth through the central core and subsequent seedling root growth (Experiment 3) is shown in Figure 4. Despite a similar response at strengths less than 1.5 MPa, radicles were more sensitive to higher soil strengths than seedling roots. Radicles were unable to grow at strengths greater than 3.5 MPa while seedling roots maintained 40% of maximum growth at this strength. This is possibly due to the root system in the top core providing an anchor against which the extending root could push. Some seedling roots also grew down the sides of the cores although the percentage of these was small and roots had grown throughout the soil matrix in all treatments. Another possibility is that the seedlings had available a greater supply of assimilate over a longer time period to facilitate root growth into the hard soil. The results suggest that limiting soil strengths estimated using radicle elongation, usually between 2.0 and 3.0 MPa may underestimate those for the roots of actively growing plants, which is consistent with the generally higher critical values reported for plant roots in the literature. Ehlers et al. (1983) and Boone et al. (1984) reported critical values in excess of 5.0 MPa for the roots of field grown plants. These higher values may have arisen from root systems exploiting the heterogenous structure of soil in the field, and may not represent the critical strength of the soil matrix. In addition variation in penetrometer size, shape, and penetration rate contribute to variation in reported critical values.

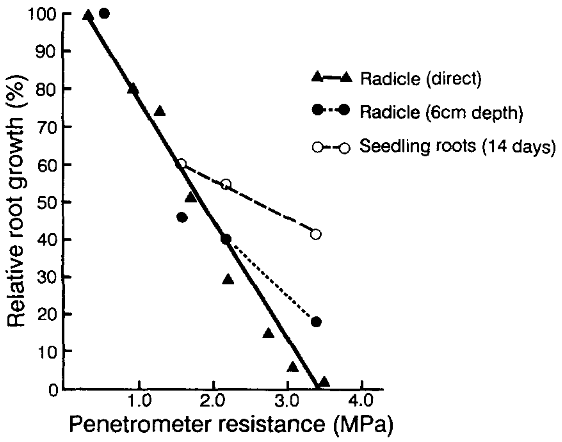

Fig. 4. Effect of soil strength on the relative growth of radicles and seedling roots of pigeonpea. (Calculated as a percentage of maximum treatment).

The decrease in nodule numbers in the central core as soil strength increased was associated with reductions in both root length and nodule number per unit of root length. Both a reduction in infection sites and a physical restriction of nodule formation and growth may have occurred.

The lack of response in shoot growth to the layer of high soil strength may not be surprising since the total root lengths were similar in all treatments (Table 4), and the pots were watered daily with nutrient solution. Cannell (1977) stated that even when severe restriction to root development occurs, plant growth may be little affected if there are sufficient nutrients and water in the zone where roots are present. This view has been challenged by Masle and Passioura (1987) who showed that the shoot growth of wheat seedlings may be reduced by high soil strength independently of soil phosphorus, leaf water potential or seed carbon reserves. They suggested that the growth of the shoot is primarily reduced in response to some chemical 'signal' induced in the roots when they encounter high soil strengths. The results presented here do not support this view, except to raise the question of whether species differ in their signalling ability in response to high soil strength. If pigeonpea roots did produce a signal in response to high soil strength, the favourable signals arising from the roots in loose soil closest to the shoot may have dominated the shoot response in this experiment.

The ability of the root system to compensate above and below a compacted zone under the favourable conditions in this experiment suggests that compaction may not be a serious problem when soil conditions are favourable during early growth, despite significant reductions in root growth within the compacted zone. However under dryland conditions, proliferation of roots in the surface above a compacted layer, and slower penetration of the main root system into the subsoil may result in the root system becoming stranded in rapidly drying soil, which reduces nutrient and water uptake and increases the risk of severe water-deficit in the growing seedling.

Conclusions

The optimum range of matric potential for radicle elongation of pigeonpea was found to be -0.01 to -1.0 MPa with a rapid decline in growth at matric potentials lower than -1.0 MPa.

Radicle elongation into soil cores ceased at a soil strength of approximately 3.5 MPa. The exact response to soil strength was affected by the water content of the soil presumably as a result of reduced oxygen availability in wetter soil. This effect was observed in soils wet to air-filled porosities below $0.15\ \mathrm{m}^3\ \mathrm{m}^{-3}$.

The response of radicles growing directly into soil of increasing strength did not adequately reflect the response of seedling roots which encountered the same soil strengths at a depth of 60 mm in the profile. Seedling roots were able to grow to 40% of maximum length in soil which totally prevented radicle elongation (3.5 MPa).

Restrictions to seedling root growth in the compacted zone were compensated in zones of favourable soil above and below the compacted zone, and shoot growth was unaffected under conditions of adequate water and nutrient supply. However the proliferation of roots in surface layers above, and the delay in penetration of the root system through compacted soil are likely to expose seedlings to a greater risk of water-deficit under less favourable field conditions where evaporation rates are high and extended periods without rain occur.

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