Physical Effects of Soil Compaction and Initial Growth of *Acacia pycnantha* (Leguminosae) in a Clay-loam Soil

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Abstract

An ornamental plant, Golden Wattle (*Acacia pycnantha*) was grown in a clay loam subsoil supplemented with adequate amounts of inorganic fertilizer and then compacted by four methods, namely, light finger pressure, rubber hammer, steel bar and machine pressure. Dry matter accumulation and rooting behaviour after four months growth in pots under glasshouse conditions were studied in relation to the degree of soil compaction. Influences of compaction on such physical properties as dry bulk density, penetration resistance, total porosity, oxygen diffusion rate and moisture content were also investigated. Plant growth and soil penetration resistance were significantly related to the level of compaction. Amelioration by addition of a medium-size grade of sand on a 50% volume basis before applying compaction reduced the soil strength substantially and allowed the plant to grow normally.

Introduction

Soil compaction is a problem confronting urban horticulture in the Republic of Singapore. Construction involving standard engineering procedures for building roads and buildings, reclamation from the sea using clayey subsoils that lack organic matter and the effects of recreational activities on school fields and in parks, often lead to excessive soil compaction. In line with the Singapore Government's 'greening' policy, the Parks & Recreation Department is required to establish vegetation in planting holes frequently impounded by compact subsoil, typified by a myriad of adverse physical conditions such as impeded drainage and high soil strength. Consequently, root-bound vegetation is susceptible to root-rot during the wet seasons (Raghavan *et al.*, 1982 and Vigier *et al.*, 1983).

The adverse effects of compaction on soil physical properties have been extensively reviewed (Barley & Greacen, 1967; Cannell, 1977; Drew & Goss, 1973; Greacen & Sands, 1980; Lal & Greenland, 1970 and Ruark *et al.*, 1982).

The subject of this trial, *Acacia pycnantha* Benth., is much valued as an ornamental plant in New Zealand. In addition, its bark is a source of tannins and gum. This plant is deep-rooting and hardy, and can thrive under severe natural conditions (Audus, 1934). The objectives of this glasshouse trial were to study the rooting configuration of Golden Wattle under various levels of soil compaction, to determine the growth limiting levels of soil compaction and to evaluate the ameliorative effects of different levels of two anti-compaction materials, i.e. sand and sewage sludge, incorporated in the potting medium prior to artificial compaction. If the findings prove significant and beneficial, then they could be adapted for practice in Singapore.

Table 1

Summary of treatments.

*Treatment	Soil medium	Mode of compaction
1	Clay loam	Light finger pressure (uncompacted control)
2	Clay loam	Tapping with a rubber hammer
3	Clay loam	Hitting with a steel bar
4	Clay loam	Mechanical pressure of 5 tonnes applied intermittently with a MTS stiff loading frame
5	Pure sand	Hitting with a steel bar
6	Clay loam + sand (80:20 v/v)	Hitting with a steel bar
7	Clay loam + sand (50:50 v/v)	Hitting with a steel bar
8	Clay loam + sludge (80:20 v/v)	Hitting with a steel bar
9	Silty pan material	No treatment — Natural reconstitution back into a hard pan

* There were 6 replicates in each treatment except for treatment 9 which was replicated twice.

Table 2

Effects of compaction on dry bulk density, total porosity, soil strength and plant dry matter.

Treatment	1 (Control)	2	3	4	5	6	7	8
Parameters								
+ Dry bulk density (g cm^{-3})	1.07	1.13	1.29	1.32	1.22	1.31	1.22	1.29
+ Total porosity (%V)	60.7	58.6	52.6	51.4	54.0	51.5	54.8	51.3
Shoot dry weight (g $plant^{-1}$)	1.46a	0.65bc	0.72b	0.07**c	0*	0.38bc	1.44a	0*
+ Root dry weight (g $plant^{-1}$)	0.54	0.27	0.24	0.03	0*	0.15	0.37	0*
Penetration resistance (bar)								
At 0-1 cm	2.46e	21.14d	39.20b	54.80a	—	34.69bc	5.41e	29.76c
At 1-2 cm	3.69e	31.61d	52.52b	>100.00a	—	40.02c	6.74e	32.02d
At approximately 10 cm	5.75g	24.63e	75.54b	>100.00a	—	51.79c	15.48f	47.62d

Treatment 1-8 have reference in Table 1.
+ Average of two measurements.
* Complete mortality.
– Very low, not measured
**Low value due to mortality of 3 plant replicates.
Values in each row if not followed by the same letter are significantly different as judged by the DMR test at $P < 0.05$.

Materials and Methods

The soil compacted in this trial was taken from a buried reddish clay-loam layer at a depth of 5 to 6 m from the surface of Paremata clay. It was collected from a recently excavated area of quarry used for brick and pipe manufacture (Grid. Ref. NZMS1 N160 473462). The undisturbed material had a dry bulk density of 1.44 g cm^{-3}, particle density of 2.72 g cm^{-3}, native moisture content of 23.7% and a natural penetration resistance of 86 bar measured with a Chatillon Guage-R penetrometer. On mechanical analysis, it was found to contain 52% clay, 45% silt and 3% sand-size particles. Its pH was 5.6 and liming was not necessary. For this study, a pan material was also collected from the natural B horizon and this had an innate mechanical impedance of greater than 100 bar, particle density of 2.66 g cm^{-3} and a native moisture content of 12.8%. Mechanical analysis revealed a composition of 9% sand, 53% silt and 38% clay. This material reconstituted rapidly into a pan after initial disintegration for potting.

For anti-compaction purposes, a medium-size grade of sand, containing 3% silt-size and 2% clay-size particles, was collected from the C horizon of a coastal aeolian dune system at Waikanae. It had a natural moisture content of 4.4% and particle density of 2.64 g cm^{-3}. Digested and dried sewage sludge was collected from a nearby treatment plant and pulverized before mixing with the trial material.

The containers used were sections of PVC drain pipes of dimensions 150 × 300 mm (diameter × height) with one end closed by a black perforated planting bag. The composition of potting media and methods of compaction are summarized in table 1. Each medium, in its naturally moist state, was packed layer by layer by one of 4 methods (table 1).

Seeds of *A. pycnantha* were germinated on moistened filter paper. When 5 mm of root had developed, uniform seedlings were selected and implanted into a 1 cm^3 scarified zone in the middle of each pot. The replicates were arranged in randomized blocks. The plants were watered by spraying twice daily according to their growth requirements, and harvested after 4 months.

For treatments 1 to 8 (table 1), in two of the replicate pots an oxygen platinum electrode was inserted to a depth of 3 cm to determine the oxygen diffusion rate (Gradwell, 1972) and for measurements of penetration resistance using a probe of 5 mm in diameter. A second lot of two pots from each set were cored with the core sampler to a depth of 1 to 4 cm in order to determine the amounts of water held at a range of moisture tensions. Equilibrium times for these cores on the tension plates varied as follows: 10 cm for 1 day; 25, 50 and 75 cm for 2 days and 100 cm for 3 days. Dry bulk densities and porosities were determined from the same cores according to Gradwell (1972). The particle densities were determined separately. The remaining two pots per treatment were washed free of soil on a sieve to retain roots. Plant tops were harvested from all replicates of each treatment. Both the root and the shoot were subjected to dry matter determination after 4 months.

Results and Discussions

Results are presented in table 2, plates 1–4 and figures 1 and 2. Where possible, data were analysed with the Duncan Multiple Range Test for significance.

The highest dry bulk density attained by using machine pressure on the clay-loam soil was 1.32 g cm^{-3} (table 2). This value was less than the native value of 1.44 g cm^{-3} measured of the material in situ. A still higher value of 1.60 g cm^{-3} had been recorded for the B horizon of Paremata clay developed naturally over many wet and dry seasons (New Zealand Soil Bureau, 1968). Repeated attempts to establish *A. pycnantha* on a scarified zone on this pan material supplemented with inorganic fertilizer were in vain (plate 1). The inability of the seedling to root in this pan material guided the limits required for maximum dry bulk density in the pot trial.

The soil strength was directly and significantly proportional to the degree of compaction at the 3 depths concerned (table 2). Such a relationship has been confirmed by other researchers (Cannell, 1977 & 1982; Drew & Goss, 1973 & 1974; Eavis, 1972 a&b; Heilman, 1981; Russell & Goss, 1974; Sands & Bowen, 1978 and Zisa *et al.*, 1980) It was noted that the penetration resistance generally increased with depth (table 2). A soil strength of 25–55 bar in the rooting zone (0–10 cm) resulted in a 50% reduction in shoot and/or root growth (table 2). Compaction with the rubber hammer produced values of soil strength similar to those that were measured in the field, 18–19 bar, on one occasion (New Zealand Soil Bureau, 1968). Data on dry bulk density and total porosity were not statistically analysed. However, as expected, dry bulk density increased and total porosity decreased with increasing rate of compaction (table 2). This is in accordance with Baligar *et al.*, (1981) and Boone *et al.*, (1978).

Amount of shoot dry matter from compacted pots differed significantly from those of the control and an inverse relationship occurred between plant growth and the level of compaction (*cf* Mitchell *et al.*, 1981). There was a 10-fold range in the growth at extreme degrees of soil compaction. However, no difference in shoot dry matter was found between the intermediate rates of compaction (table 2). Top growth is shown in Plate 3: A-E. Dry root matter was not statistically analysed but a downward trend with increasing rate of compaction was apparent. Typical development of the root system in straight, compacted and uncompacted clay loam is depicted in Plate 2: a, b, c & f. Plate 2g represents the root system of an *A. pycnantha* developed in an uncompacted garden loam supplemented with inorganic fertilizer. This was kept solely for observation. Plate 2 shows that the root system became less fibrous and ramified with increasing level of compaction, and in the case of machine compaction (plate 2a), root development was highly incompatible with normal plant growth.

Addition of a medium-size grade of sand on a 20%V basis had no mitigating effect on the mechanical impedance of clay loam compacted with the steel bar. The presence of a small amount of coarse material could have actually promoted the compactibility of the fine clay loam. Consequently, plant growth in treatment 6 did not differ from that in straight clay loam soil compacted similarly (table 2 — treatment 3). The ameliorative effects of sand were prominent on a 50%V basis (table 2).

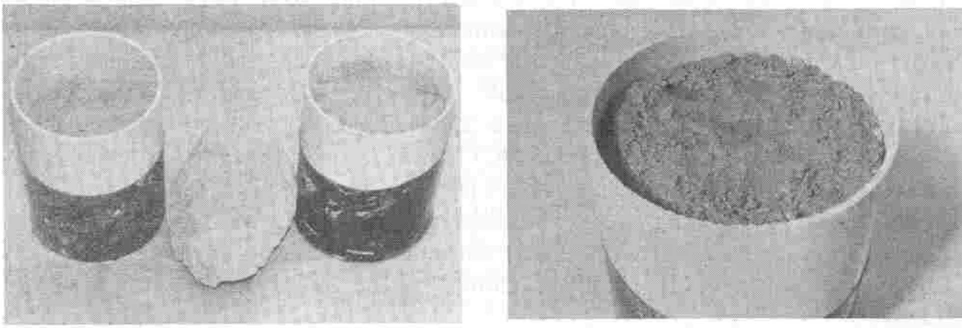

Plate 1. Natural and remoulded pan material.
A, *left*, pots of remoulded and natural pan material (*middle*) from the B horizon of Paremata clay; *B*, *right*, close-up of remoulded material.

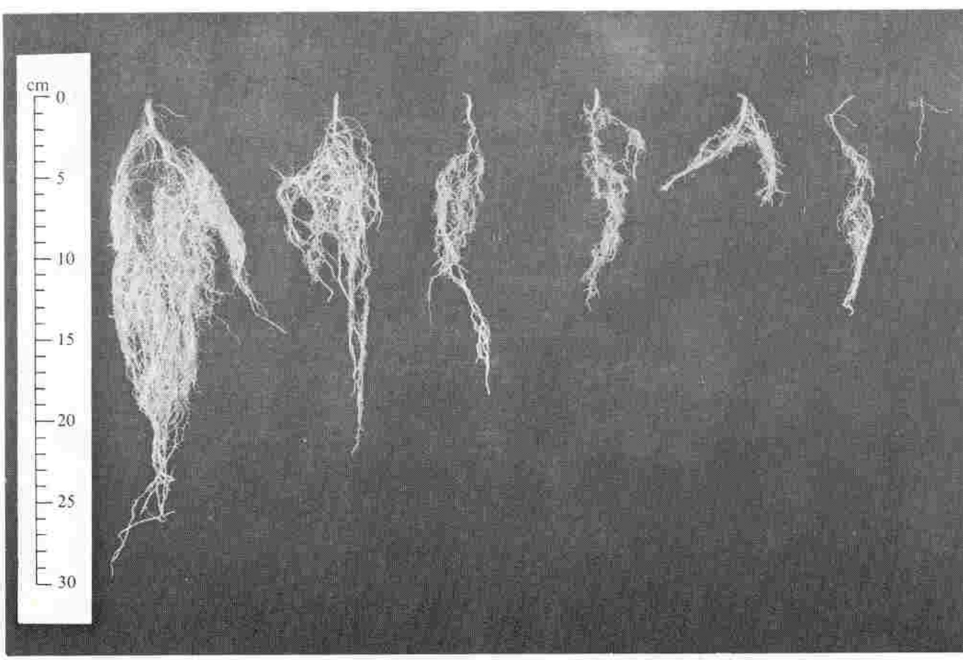

Plate 2. Development of root systems in straight and amended clay loam under different levels of compaction.
Right to left, *a*, treatment 4; *b*, treatment 2; *c*, treatment 3; *d*, treatment 6; *e*, treatment 7; *f*, treatment 1 (uncompacted soil); *g*, root system developed in an uncompacted garden loam.

The penetration resistance was reduced to a level similar to that of treatment 1 and was significantly lower than that of treatment 3 (table 2). On adding 50%V sand, the dry bulk density decreased while the total porosity increased as compared with those in treatment 3 (table 2). As a result, plant growth in treatment 7 was of the same order as in treatment 1 (table 2; plates 2, e&f, 3A & 4B). All seedlings established in pure sand died after 4 months (plate 4C). It was thought that the particular grain size of sand used might have given rise to a transient high water table after irrigation, thereby damaging the root system. The cause of total seedling mortality in clay loam amended with digested sludge (plate 4D) was tentatively attributed to a partial/total reduced state in the rooting zone generated by the initial decomposition of the sludge.

The value obtained from the oxygen microelectrode inserted to depths of 3 to 4 cm below the surface were all greater than 2.5×10^{-7} g cm^{-2} min^{-1}. A value of

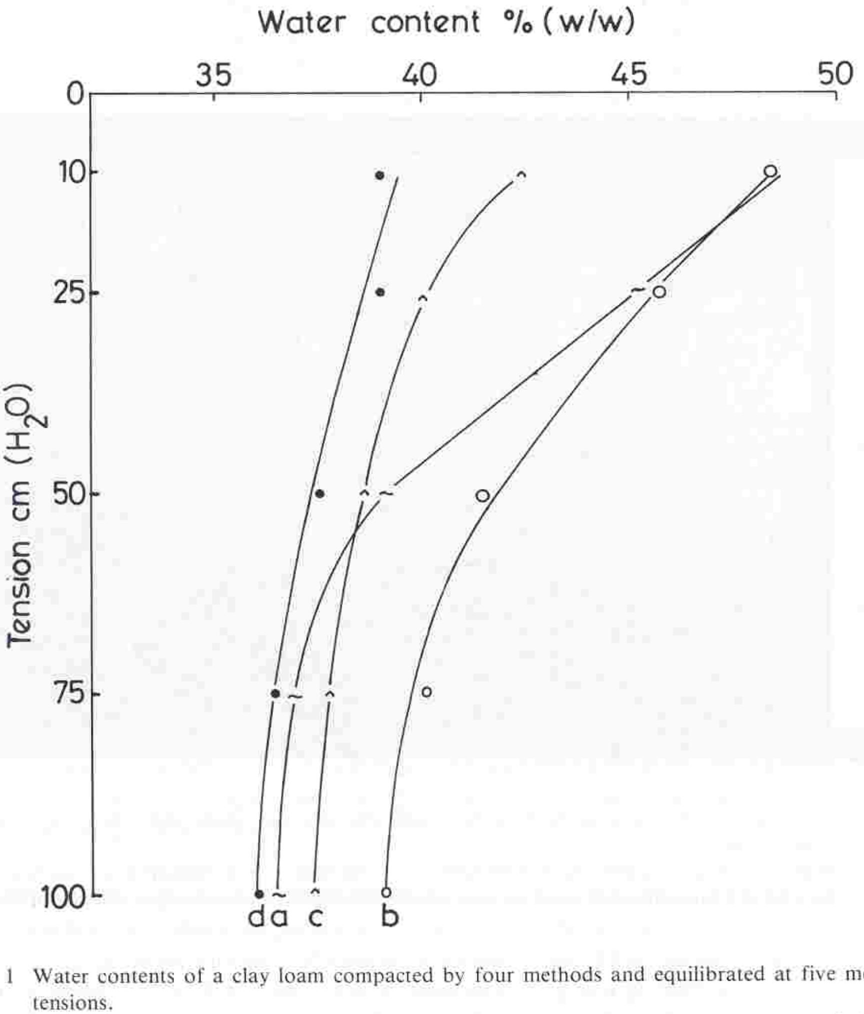

Fig. 1 Water contents of a clay loam compacted by four methods and equilibrated at five moisture tensions.
Soil compacted by: *a*, light finger pressure; *b*, rubber hammer; *c*, steel bar; *d*, mechanical press.

Note. Each point on the graphs is an average of 2 measurements.

1×10^{-7} g cm^{-2} min^{-1} is generally considered adequate for plant growth (Gradwell, 1972). The purely inorganic soil matrix supplemented with inorganic fertilizer had the advantage of not inducing the type of reducing conditions as might be encountered when digested sludge was incorporated in clay soils.

Figure 1 presents pF plots of the average water contents of cores from the compacted clay loam soil after equilibration at five values of moisture tension. Under the weak compaction exerted by finger pressure or rubber hammer, the soil had about 10% more water available at tensions of 10 and 25 cm than in soils compacted by steel bar or by machine compression. At high moisture tensions, above 75 cm, the water contents of the cores were similar for all methods of compaction. Mixing sand with the clay loam had marked influence on the water content of the cores after equilibration at different moisture tensions. Figure 2 shows pF curves of water content against moisture tension for mixtures of clay loam and sand, and clay loam and sludge, when all were compacted with the steel bar. The water contents were all very similar at low moisture tensions. At high moisture tensions, the water contents varied inversely according to the amount of sand that had been added. In other words, addition of sand made water more easily available.

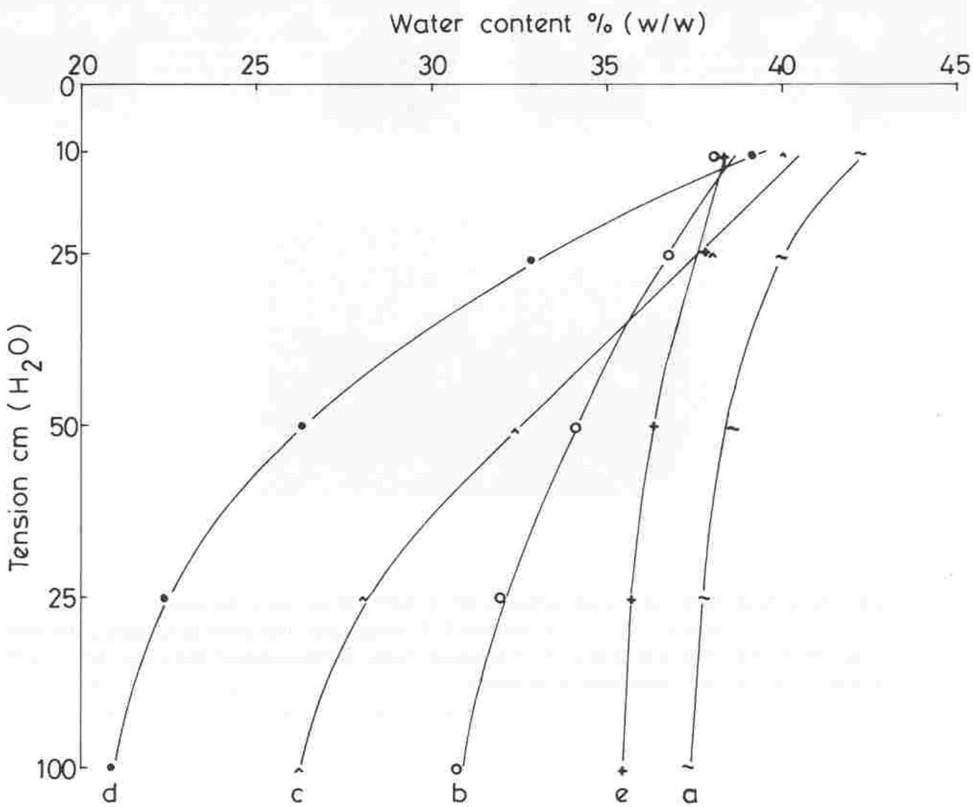

Fig. 2 Water contents of a clay loam ameliorated by sand or sludge and compacted with a steel bar. Composition: *a*, clay loam: *b*, 80% clay loam + 20% medium sand; *c*, 50% clay loam + 50% medium sand; *d*, medium sand; *e*, 80% clay loam + 20% sludge.

Note. Each point on the graphs is an average of 2 measurements.

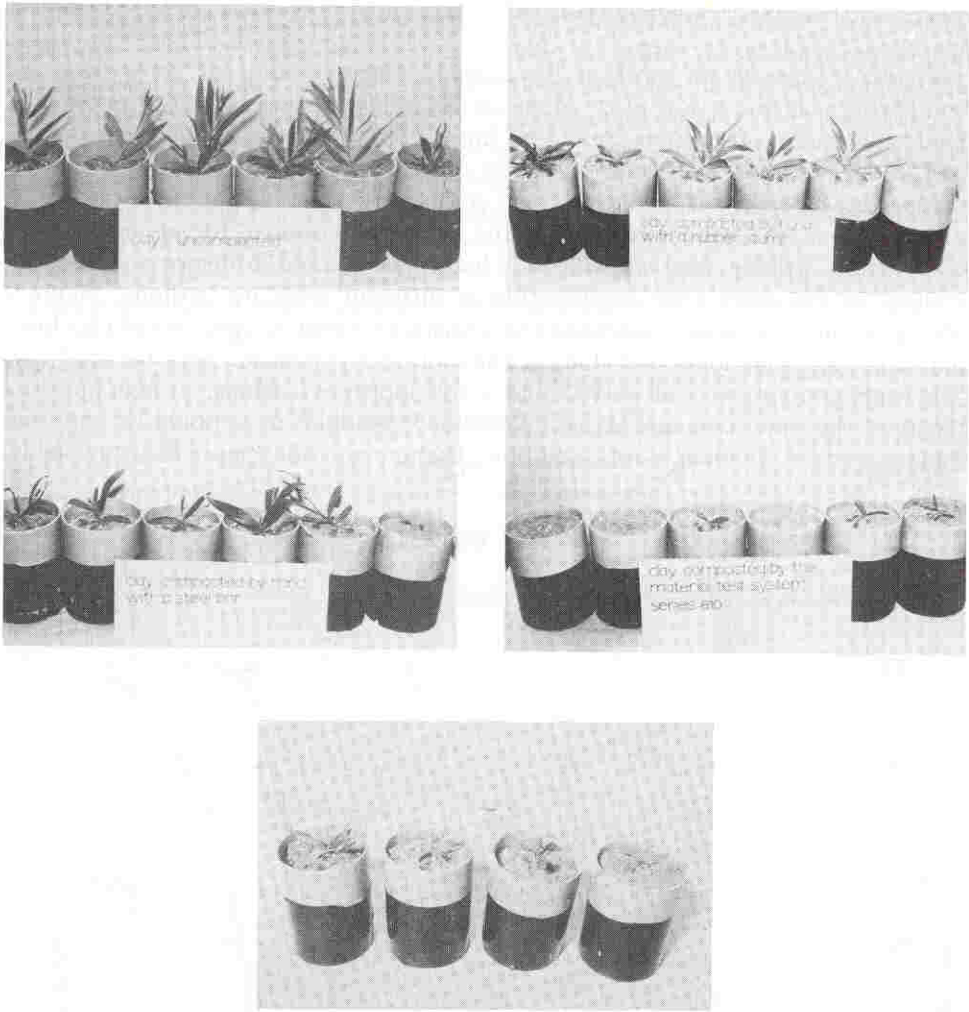

Plate 3. Development of plant top on clay loam under different levels of compaction.
A, *above left*, treatment 1; *B*, *right*, treatment 2; *C*, *middle left*, treatment 3; *D*, *right*, treatment 4; *E*, *below*, comparison of 4 rates of compaction on the development of plant top; *left to right*, treatment 1 (control), treatments 2, 3 and 4.

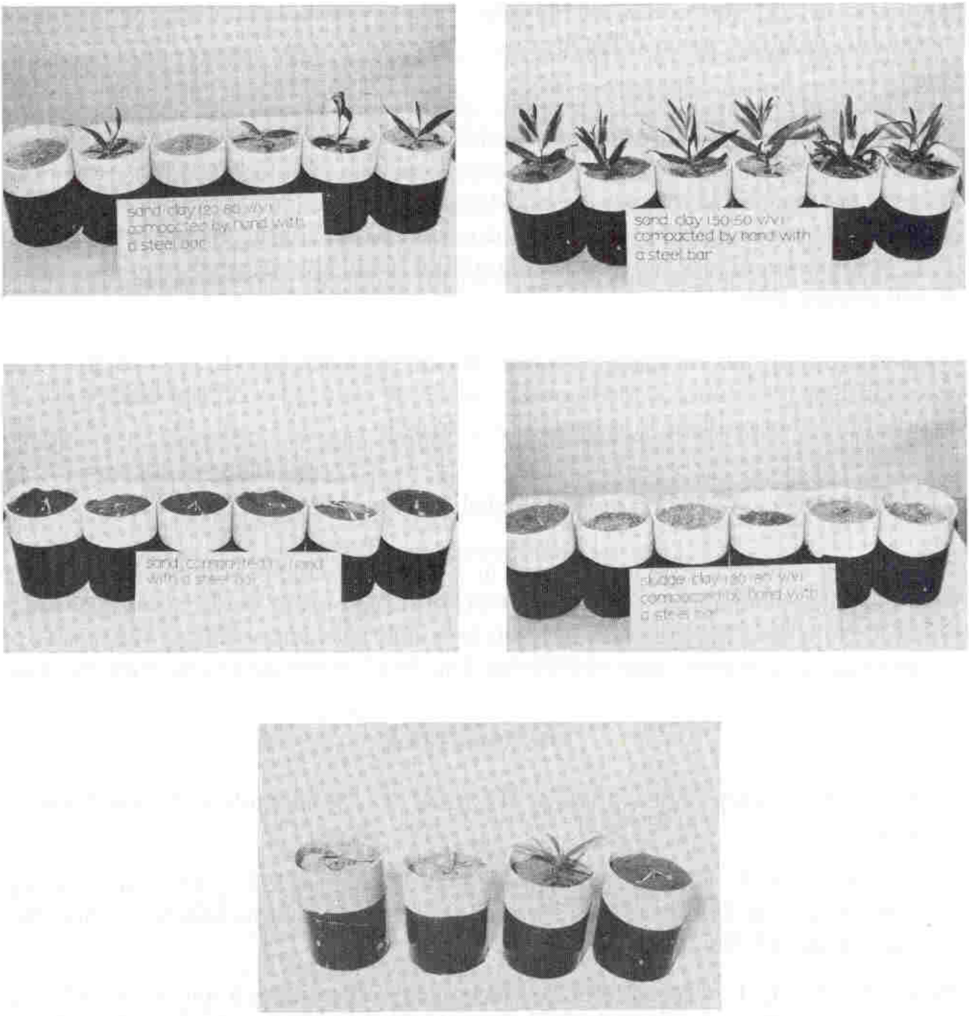

Plate 4. Development of plant top on clay loam amended with 2 rates of sand, pure sand and clay amended with sludge, all compacted with steel bar.
A, above left, treatment 6; *B, right*, treatment 7; *C, middle left*, treatment 5; *D, right*, treatment 8; *E, below*, comparison of the ameliorative effects of 2 rates of sand on the development of plant top; *left to right*, treatment 1 (control), treatments 6, 7, and 5.

Conclusions

A. pycnantha seedlings were unable to establish roots on a scarified surface of a pan material from the subsoil of Paremata clay or on the remoulded pan material containing adequate mineral fertilizer.

It was evident that upon compaction, soil strength became the severely limiting physical attribute that controlled the establishment and early growth of *A. pycnantha* in the Paremata clay-loam subsoil. A direct relationship was found between this property and the degree of compaction. Mechanical impedance, derived from machine compaction, represented a limit to penetration by roots. Hence, the growth of *A. pycnantha*, a very hardy plant, could be inimically affected by high degrees of soil compaction.

Alleviation of the dramatic changes in soil strength due to compaction was accomplished by adding a medium-size grade of sand on a 50%V basis prior to compaction; this resulted in normal plant growth.

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