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Effects of soil air-filled porosity, soil matric potential and soil strength on primary root growth of radiata pine seedlings

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Abstract

The effects of soil air-filled porosity, soil matric potential and soil strength on primary root growth of radiata pine (*Pinus radiata* D. Don) seedlings were examined in four soil textures ranging from coarse to fine.

At low penetrometer resistance (< 0.5 MPa) and high soil matric potential (≥ -0.01 MPa), root elongation rate was close to zero when air-filled porosity was < 0.05 m^3 m^{-3}, and it increased sharply to 90% of its maximum value at 0.15 m^{3}m^{-3}. This relationship was independent of soil texture. The diameter of the root tip increased as air-filled porosity decreased, particularly below 0.10 m^3 m^{-3}.

Root elongation rate decreased linearly with decreasing soil matric potential over the range -0.01 to -0.35 MPa at both 0.5 MPa and 1.5 MPa soil strength. This relationship was independent of soil texture. The rate of root elongation at 0.5 MPa was about twice that at 1.5 MPa and the rate of decrease in root elongation with decreasing soil matric potential was 1.35 times greater at the lower (0.5 MPa) than the higher (1.5 MPa) soil strength. The effect of water potential (over the range -0.01 to -1.5 MPa) on root elongation at zero soil strength was simulated using PEG 4000 solutions as rooting media. Root elongation declined exponentially over the range of water potentials established in the rooting medium.

Root elongation rate decreased exponentially with increasing soil strength when soil matric potential was constant and air-filled porosity was > 0.20 m^3 m^{-3}. This relationship was independent of soil texture. Root elongation rate was half its maximum at a penetrometer resistance of 1.3 MPa. Increasing bulk density has a greater effect of increasing soil strength in coarse soil than in fine soil but decreasing soil water content has a greater effect on increasing soil strength in fine soil than in coarse soil.

Introduction

It is generally accepted that if air-filled porosity in soil is 0.10 m^3 m^{-3} or less, plant growth will be significantly limited (Baver and Farnsworth, 1940; Wesseling and Van Wijk, 1957). For some time, this limiting value of air-filled porosity has been assumed in various investigations on the root growth of radiata pine (Sands and Bowen, 1978; Sands et al., 1979; Theodorou et al., 1991). However, a critical point value has not yet been demonstrated for root growth of radiata pine, nor for any other species for that matter. Grable and Siemer (1968) reported that a range of 0.12 – 0.15 m^3 m^{-3} would be a more appropriate limit of air-filled porosity for growth of plants, and Costantini et al. (1996) suggested there is no critical level of aeration, above which radicle elongation of *Pinus caribaea* var. *hondurensis* would be unaffected by air-filled porosity. The concept of a critical point value of aeration independent of species, root type and

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soil characteristics seems unlikely and this is one of the aspects examined in this study.

Determining the effect of soil matric potential on root growth is not simple because a reduction in matric potential concurrently increases soil strength and air-filled porosity, both of which also affect root growth directly. In order to exclude or separate the effect of soil strength from that of matric potential, experiments have been carried out in loose soil or soil at an arbitrarily chosen value of low soil strength (e.g. Eavis, 1972). In such experiments, the effect of soil strength is assumed to be negligible and any effect on root growth due to changes in matric potential is attributed to soil matric potential and air-filled porosity. The observed profile is typically a bell-shaped curve which represents optimal root growth over a certain range of matric potentials, with poor aeration reducing root growth above this range and low soil matric potential reducing growth below this range (Costantini et al., 1996; Eavis, 1972). However, soil strength cannot be ignored because root growth is restricted by soil strength even in loose soils with very low values of soil strength (Greacen and Sands, 1980). The interacting effects of soil strength and soil matric potential are examined in this study. A range of soil matric potentials was established in soils of four different textures and at two soil strengths all at values of soil air-filled porosity known to negligibly, if at all, limit root growth. Zero soil strength was simulated by growing roots in Polyethylene Gycol 4000 (PEG 4000) solutions over a range of water potentials.

There is extensive published information on the relationship of root growth to soil strength for annual agricultural plants, but such information is scarce for woody perennials (Misra and Gibbons, 1996). Greacen and Sands (1980) showed that root density decreased with increasing soil strength and Dexter (1986) showed that the proportion of roots penetrating dense, strong untilled soil decreased exponentially with increasing subsoil strength. However, the direct effect of increasing soil strength on the elongation rate of radiata pine roots is to date not known because the effects of soil water and air-filled porosity have not been separated (Box and Taylor, 1962; Yapa et al., 1988). Sands et al. (1979) showed that root growth of radiata pine growing in well-aerated sandy soil was restricted at high soil strength, and later proposed a process-based model for root growth in soil (Sands, 1983) as follows:

$$\Delta R = \Phi(P_t - Y - P_s) \qquad \text{for } Pt > (Y + P_s) \quad (1)$$

where ΔR is root elongation rate, Φ is cell-wall-yielding coefficient, P_t is the turgor pressure of the root cell in the elongation zone, Y is the turgor pressure at yield and P_s is the mechanical impedance of the soil to root penetration. Recently, P_t and Y were reported to be only slightly affected by soil strength (Zou, 1999), implying a relationship between root elongation rate and P_s should be linear (Greacen, 1986), if Φ is independent of P_s. However, it is unlikely that Φ is independent of P_s, and P_s is very difficult to measure in practice. The effort to determine a quantitative relationship between penetrometer soil strength and P_s has been inconclusive (Bengough and Mullins, 1991). In this study, a root growth model using penetrometer soil strength as a surrogate for P_s is developed.

It is possible that differences between contrasting soil textures on root growth can be explained in terms of their effects on soil water, soil strength and soil air. This is examined in this study.

Materials and methods

Soils and seedling establishment

Four soil types of contrasting textures and origins were collected from radiata pine plantations belonging to Rayonier NZ. The top 20 cm of the soil profile was collected and was passed through a 2 mm sieve and stored in plastic bins for further use. The particle size distribution and particle density were determined by the methods described by McIntyre and Loveday (1974); the organic matter content was determined using the Walkley-Black procedure (Nelson and Sommers, 1982); and soil total N, Bray P, Bray K, Bray Ca and Bray mg were measured using standard techniques.

Radiata pine seeds (GF-17, Proseed New Zealand) of uniform weight (0.004 g ± 0.0005 g) were treated with fungicide (Thiram, Arthur Yates & Co. Ltd, New Zealand) and immersed in distilled water overnight. Seeds were then germinated on water-saturated filter papers in a petri dish. Germinated seeds with 2 mm radicles were selected for planting. All seedlings in this study were grown in a growth cabinet with a controlled environment of 12 h light (20 °C, 80% relative humidity, 700 μmol $m^{-2}s^{-1}$ photosynthetic photon flux density) and 12 h dark (17 °C, 80% relative humidity).

Soil moisture and soil strength characteristic curves

The soil was repacked into stainless steel rings of 48 mm internal diameter and 15 mm height. The rings were packed from both ends in order to achieve a homogeneous bulk density with depth (Misra and Li, 1996). Penetrometer resistance was measured with a laboratory cone penetrometer (cone base diameter 2 mm, tip semi-angle 30°) which penetrated the soil sample at a constant speed of 3 mm min^{-1}. The force was measured by an electronic balance every 10 s (each 0.5 mm depth). The penetrometer resistance is used as a surrogate for soil strength in this study. The soil moisture characteristic curves and soil strength characteristic curves (quantitative relationship between soil strength and volumetric water content) were established at low, medium and high bulk density (ρ_b) levels for pumice (ρ_b = 0.70, 0.80 and 0.85 Mg m^{-3}), argillite (ρ_b = 0.90, 1.0 and 1.1 Mg m^{-3}), ash (ρ_b = 0.70, 0.80 and 0.85 Mg m^{-3}) and loess (ρ_b = 0.85, 0.95 and 1.05 Mg m^{-3}) in a pressure plate apparatus. The bulk densities of these soils are lower than global averages because of low particle densities (Zou et al., 2000).

Air-filled porosity and root growth

Three soils (argillite, ash and loess) were packed into stainless steel tubes of 48 mm internal diameter and variable heights. Pumice was not used in this experiment because the air-filled porosities were > 0.32 m^3 m^{-3} at -0.01 MPa even at the highest bulk density of 0.85 Mg m^{-3}. There were four replicates of six air-filled porosities at three bulk densities for each of three soil types (ash, argillite and loess). The four highest air-filled porosity levels (0.14, 0.17, 0.21 and 0.25 m^3 m^{-3}) were produced by maintaining free-draining tubes of different heights. The two lowest levels of soil air-filled porosity (< 0.14 m^3 m^{-3}) were produced by maintaining two tubes of different heights (100 mm and 200 mm) in water-baths. The matric potential of the soil in all tubes was ≥ -0.01MPa and samples with penetrometer resistance > 0.5 MPa were discarded. Water lost through evaporation was replaced daily to maintain the original free draining situation. Pregerminated radiata pine seeds were grown in the tubes for 12 days.

Soil matric potential and root growth

The soil moisture and soil strength characteristic curves were used to determine the combination of bulk density and water potential that would give a soil strength close to target levels of 0.5 and 1.5 MPa (Table 1).

Table 1. Soil strength and air-filled porosities at given soil matric potentials calculated from soil moisture characteristic curves and soil strength characteristic curves. ρ_b = bulk density (Mg m^{-3}), Ψ_m = soil matric potential (MPa), ϵ_a = air-filled porosity (m^3 m^{-3}) and Q = soil strength (MPa)

Q (MPa)	Soil Types	ρ_b	Ψ_m	ϵ_a	Q
Target 0.5	Argillite	0.90	-0.01	0.29	0.60
	Ash	0.80	-0.03	0.41	0.45
	Loess	0.85	-0.07	0.36	0.53
	Ash	0.70	-0.1	0.53	0.65
	Pumice	0.70	-0.20	0.57	0.57
Target 1.5	Argillite	1.10	-0.01	0.14	1.50
	Argillite	1.0	-0.03	0.26	1.44
	Loess	1.05	-0.07	0.20	1.55
	Pumice	0.80	-0.10	0.48	1.55
	Ash	0.80	-0.20	0.48	1.54

Soils were packed uniformly to the required bulk density in stainless steel tubes (48 mm internal diameter, 100 mm height). The packed soil was saturated and then equilibrated to the desired matric potential in pressure plate apparatus. The volumetric water content was measured at equilibrium and air-filled porosity was calculated. The strength of the equilibrated soil was measured again to check that it lay within the range of the target levels ± 10%. Soil samples with soil strength values outside of this range was discarded. There were three replicates for each of the five matric potentials at each of the two target strength levels (Table 1).

Pregerminated seeds were then planted into the soil in the steel tubes. The soil surface was divided into four quadrants (Figure 1). The penetrometer resistance was measured at position D. Pre-germinated seeds were planted at positions A, B and C. In order to minimise water loss, the pregerminated seeds were covered with a 6 mm layer of wet soil of the same texture and bulk density in a stainless steel ring (48 mm internal diameter, 15 mm height) taped to the top of the tube. The bottom of the tube was sealed with airtight plastic film. The pregerminated seeds were grown for seven days.

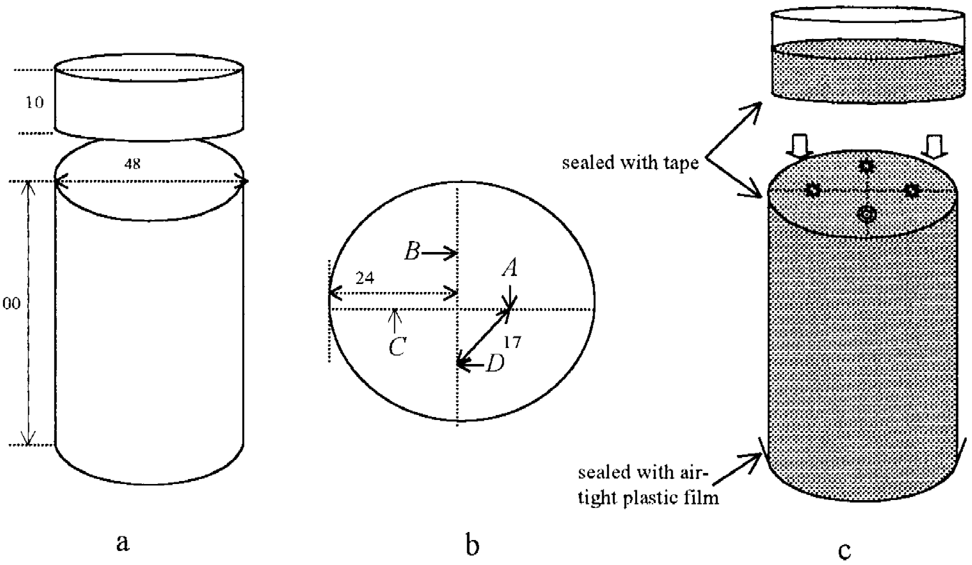

Figure 1. Design of stainless steel tube and seedling planting. The stainless steel tube was 48 mm in internal diameter and 100 mm in height (Figure 1a). The soil surface was divided into four quadrants (Figure 1b). Positions A, B and C were used to plant seedlings and position D was used to determine the soil strength. A stainless steel ring of 48 mm in internal diameter and 15 mm in height packed with soil of the same texture and bulk density to a depth of 6 mm was attached to the top of the tube (Figure 1c).

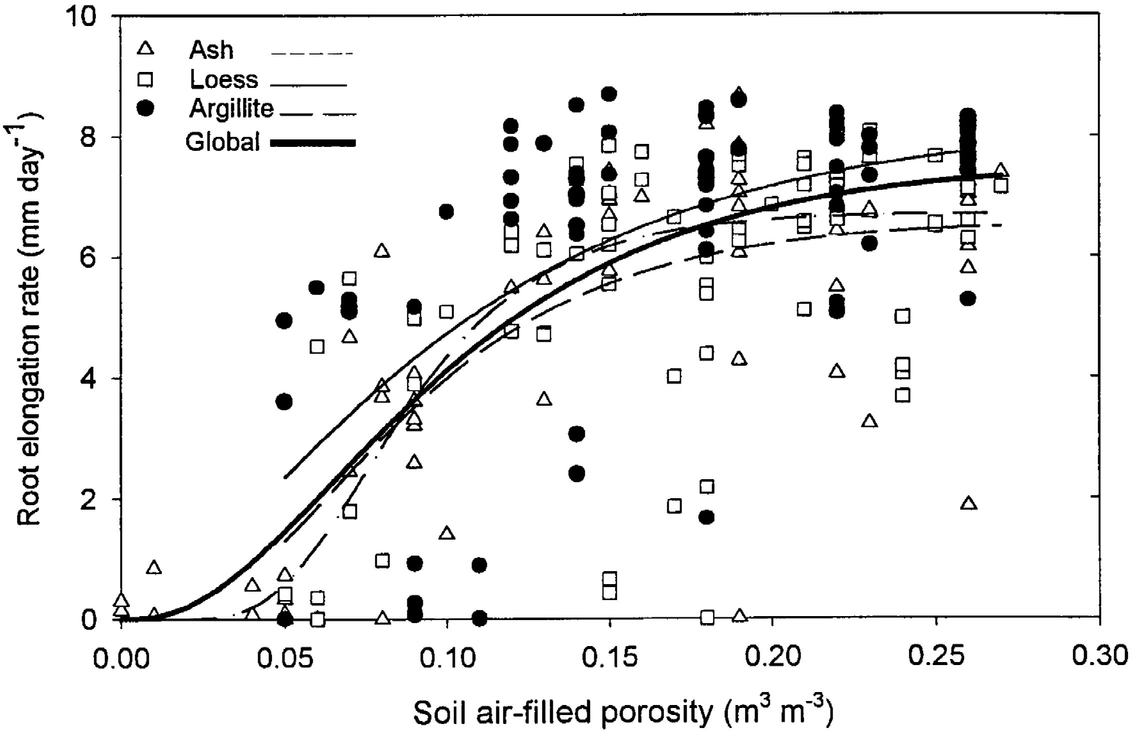

Figure 2. Relationship between air-filled porosity and root elongation rate of radiata pine in soils of different textures. Matric potential was ≥ -0.01 MPa and soil strength was < 0.5 MPa.

Root growth in PEG 4000 solutions

Radiata pine seeds were germinated on saturated filter paper until the radicle was 2 mm long after which they were transplanted into sand and, after the radicle was approximately 20 mm long, 200 of these were grown in complete nutrient solution known to be suitable for the growth of radiata pine seedlings (Sun and Payn, 1999). This solution had a water potential of −0.01 MPa. They were grown in this solution for three or four days until the needles of the seedlings were fully opened and 144 seedlings with radicle length from 25 to 40 mm were selected and transferred into 500 ml plastic pots containing the same nutrient solution at a range of water potentials (−0.01, −0.03, −0.07, −0.1, −0.2, −0.5, −1.0, −1.5 MPa). The range of water potentials was achieved by adding Polyethylene Glycol 4000 (PEG 4000) to the base nutrient solution. The required amount of PEG 4000 was calculated from the calibration of PEG 4000 concentration in nutrient solution against its water potential as measured by psychrometer (TruPsi Water Potential Meter, Decagon Devices Inc., Pullman, WA). The lid of each pot had three seedlings inserted through holes and anchored with Blue Tak (a reusable adhesive manufactured by Bostik (New Zealand) Pty Ltd). All pots were kept in the growth cabinet for seven days. Aeration was provided by a pumping system.

Soil strength and root growth

The soils were packed into stainless steel tubes (48 mm internal diameter, 100 mm height) to the same low, medium and high bulk density levels used in determining the soil moisture and soil strength characteristic curves. There were at least six replicates for each of the three bulk densities for each of the four soils. All soils were saturated in a water bath overnight and then equilibrated over a pressure plate at −0.1 MPa soil matric potential. The soil strength of the equilibrated soil samples was measured as before, and three pregerminated seeds were planted in each tube (Figure 1) and grown in the growth cabinet for seven days.

Growth measurement

At harvest (after seven days) the volumetric water content of the soil was determined by weighing the soil samples and the matric potential and soil strength were calculated for each sample from the moisture and strength characteristic curves. The corresponding air-filled porosities were calculated by subtracting the volumetric water content from total porosity. Seedlings were carefully removed from the tubes and washed clean of soil. The total length, root length and shoot length of the seedlings were measured with a scale. Root diameters were measured with a calliper in the middle of the shoot and root segments. Root tip diameter was measured 200 – 450 μm from the root tip using a microscope with a graduated eyepiece. This is the zone of most rapid elongation in radiata pine roots (Youngman, 1998). After these measurements, the roots were separated from the shoots at the root collar and were oven-dried at 70 °C for 72 h to determine dry mass.

Results

Some physical and chemical properties of the soils are given in Table 2.

Air-filled porosity and root growth

The relationship between root elongation rate (ΔR, mm d^{-1}) and air-filled porosity (ϵ_a, $m^3\ m^{-3}$) was similar between soil textures (Figure 2). The relationship modelled by SigmaPlot 4.01 was sigmoidal and best fitted a Chapman-Richards curve.

$$\Delta \mathrm{R} = \alpha(1 - e^{-\beta\epsilon_a})^{\gamma} \quad (2)$$

where α = 7.57 (0.55), β = 16.55 (4.95), γ = 2.87 (1.18) (R^2 = 0.53, $p < 0.0001$). Standard errors are shown in parentheses.

Root elongation rate was low at $\epsilon_a = 0.05$ m^3 m^{-3}air-filled porosity but increased rapidly over the range $0.05 < \epsilon_a < 0.15$ $m^3\ m^{-3}$ and then less rapidly at $\epsilon_a > 0.15$ $m^3\ m^{-3}$ (Figure 2).

The diameter of the root tip increased as air-filled porosity decreased, particularly at $\epsilon_a < 0.10$ $m^3\ m^{-3}$ (Figure 3a). Root biomass increased rapidly over the range $0.05 < \epsilon_a < 0.20$ $m^3\ m^{-3}$and then less rapidly at $\epsilon_a > 0.\ 20$ $m^3\ m^{-3}$ (Figure 3b).

Matric potential and root growth

The elongation rates of radiata pine roots decreased linearly with decreasing soil matric potential at the two levels of soil strength (Figure 4). A comparison of the slopes of the regression lines showed that the rate of decrease in root elongation rate at 0.5 MPa soil

Table 2. Physical and chemical properties of the four experimental soils (ρ_s: particle density, OM: organic matter content), ± SE

Soil types	Pumice	Argillite	Ash	Loess
Soil texture	loamy sand	loam	sandy clay loam	silty clay
ρ_s (Mg m^{-3})	2.44 ± 0.014	2.55 ± 0.003	2.41 ± 0.008	2.53 ± 0.014
OM (mg g^{-1})	20.6 ± 1.2	58.8 ± 1.6	79.5 ± 2.99	37.1 ±1.4
pH	6.07	5.83	5.32	5.26
Total N (mg g^{-1})	1.04	2.89	5.08	0.84
Bray P (μg g^{-1})	12.17	6.99	22.59	1.74
Bray K (mmol kg^{-1})	1.1	5.4	3.9	0.09
Bray Ca (mmol kg^{-1})	9.5	39.6	75.9	8.4
Bray Mg (mmol kg^{-1})	0.8	16.0	10.6	15.9

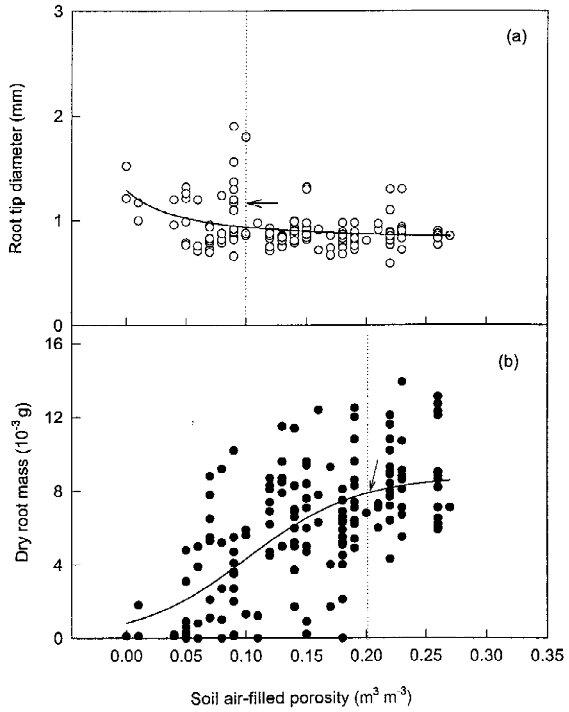

Figure 3. Relationship between air-filled porosity and root tip diameter and root dry weight of radiata pine. Matric potential was ≥ -0.01 MPa and soil strength was < 0.5 MPa. The dotted vertical lines represent suggested critical values (see text).

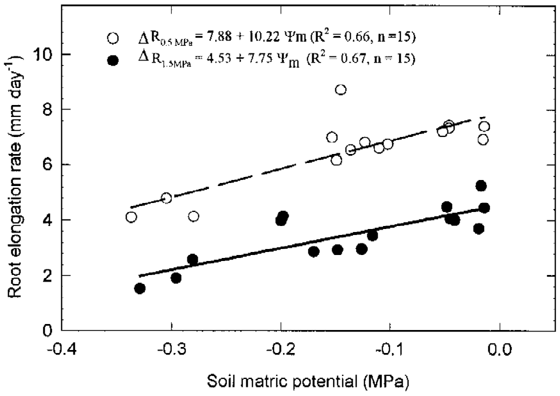

Figure 4. Relationship between root elongation rate of radiata pine seedlings and soil matric potential at target soil strengths of 0.5 MPa (○) and 1.5 MPa (●).

strength was greater than at 1.5 MPa soil strength (Figure 4). Root elongation rate was significantly greater ($p < 0.0001$) at 0.5 MPa than at 1.5 MPa soil strength, for all levels of soil matric potential.

The range in soil matric potential was kept small to maintain low soil strength. A greater range in water potential was obtained at zero soil strength by growing seedlings in PEG 4000 solutions. As the water potential of the rooting medium decreased, the rate of root elongation decreased exponentially from a maximum of 3.80 mm d^{-1} at zero water potential to 0.19 mm d^{-1}

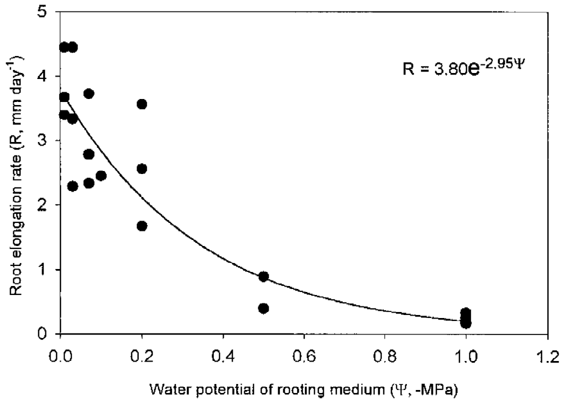

Figure 5. Relationship between root elongation rate of radiata pine seedlings and soil water potential of the PEG 4000 rooting medium.

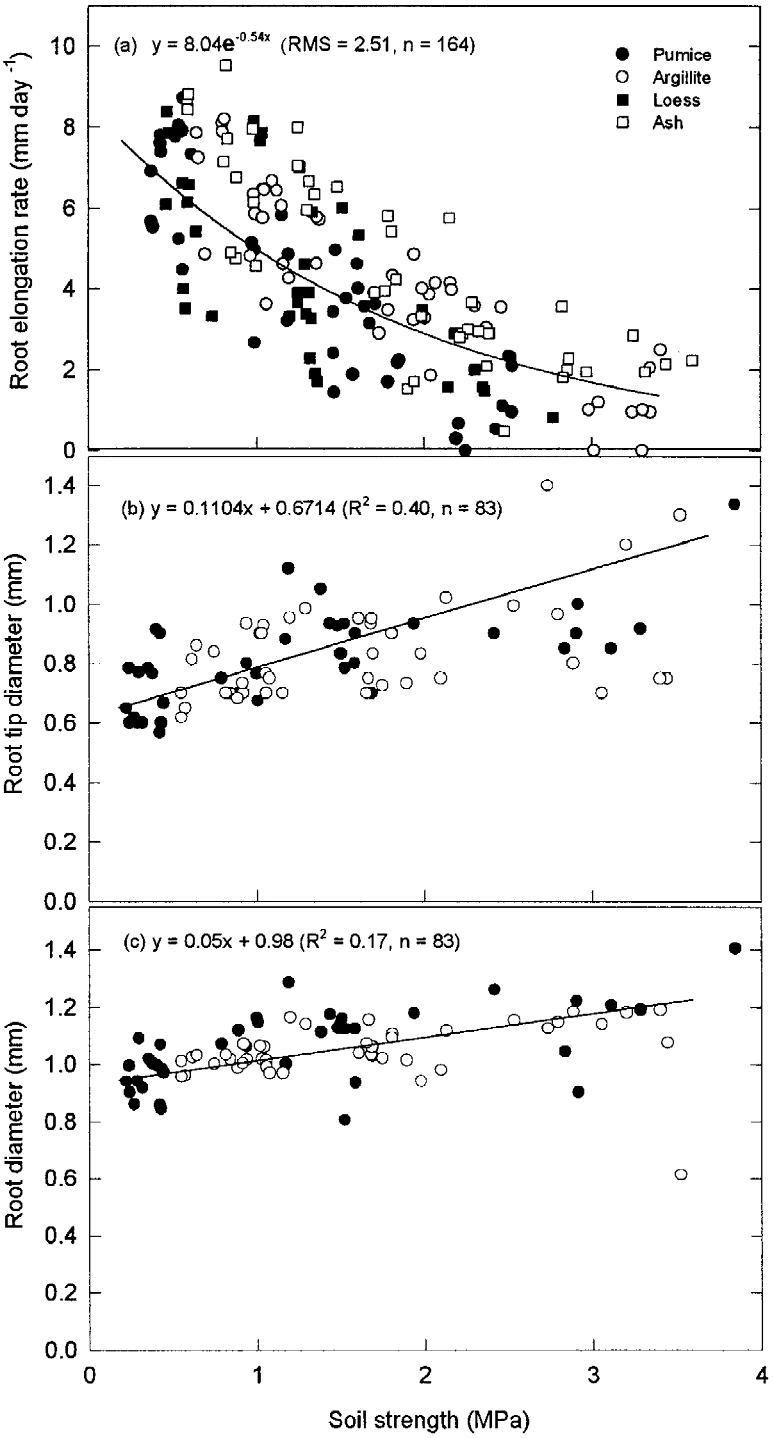

Figure 6. The effect of soil strength on (a) the elongation rate, (b) root tip diameter and (c) root diameter at the midpoint of the root segment of radiata pine seedlings at constant soil matric potential (−0.1 MPa) in soils of different texture.

at -1.0 MPa water potential of the rooting medium (Figure 5).

Soil strength and root growth

The relationship between root elongation rate and soil strength is shown in Figure 6a for soils of various textures at a matric potential of -0.10 MPa and an ideal air-filled porosity of > 0.20 m^3 m^{-3}. SAS GLM procedure (SAS System for Windows v 6.12) was used to model the log value of root elongation rate with soil texture and soil strength. The effect of soil texture ($p = 0.37$) and the interaction of soil texture with soil strength ($p = 0.38$) on root elongation rate was not significant. Root elongation rate was mainly determined by soil strength ($p = 0.0004$). Therefore, the effect of soil strength on root elongation rate could be tested without any contributing effects of air-filled porosity or soil matric potential. This relationship is shown in Figure 6a.

Root elongation rate decreased exponentially with an increase in soil strength (Figure 6a). The relationship can be described as:

$$\Delta \mathrm{R} = \alpha \mathrm{e}^{-\beta Q} \tag{3}$$

where ΔR = root elongation rate (mm d^{-1}), Q = soil strength (MPa), α = 8.04 (0.36), β = 0.54 (0.047). Standard errors are shown in parentheses and RMS (residual mean square from SAS NLIN) = 2.51. Both the diameter of the root tip and the diameter of the root at its midpoint increased linearly with increasing soil strength (Figure 6b,c). The rate of increase in root diameter was greater at the tip than at the mid-point. Root weight decreased linearly with increasing soil strength and there was no significant effect of soil strength on shoot biomass or stem diameter (data not shown).

Discussion

Preliminary unpublished experiments showed that there was no significant difference in radicle growth with variation in soil texture over 12 days when air-filled porosity was > 0.25 m^3 m^{-3}, soil water content was near field capacity and soil strength was ≈ 0.50 MPa. There was also no apparent effect of added nutrients on the pine roots for the soils of different texture over 12 days. These results suggest that the nutrient reserves in the pine seeds and in the soil were adequate to meet the nutrient demand by the seedlings in the short-term experiments described in this study. Consequently, there were no complicating effects of differences in nutrition between soil textures in this study. Therefore, the root growth in soils of contrasting textures in this study could be largely attributed to the single or joint effects of soil air, soil water or soil strength.

Due to good control of humidity in the growth cabinet and use of the taped ring technique, there was very little loss of water over time in the matric potential and soil strength experiments. The average water loss by volume over the experimental period (seven days) ranged from 0.0046 m^3 m^{-3} to a maximum of 0.0304 m^3 m^{-3} with an average of 0.016 m^3 m^{-3}, ie a decrease of 4.69% from the initial water content. The corresponding increase in air-filled porosity ranged from about 2% to about 14% with an average of 7.7% of the air-filled porosity at time zero. This water loss represented an average (over time and soil depth) increase of about 10% in soil strength and a decrease of about 50% in matric potential. The average matric potential of soils initially at -0.01 MPa fell to about -0.015 MPa and those initially at -0.2 MPa fell to about -0.3 MPa. Water loss was confined almost entirely to the top 25 mm. Therefore, the initial (at planting) values were used for soil strength and the mean values (between planting and harvest) were used for matric potential.

Soil air

The relationship between root growth and air-filled porosity (Figure 2) was not greatly complicated by soil strength because only those points where soil strength was less than 0.50 MPa were included. The results (Figure 2) show that there was no sudden critical limit of 0.10 m^3 m^{-3} air-filled porosity for radiata pine above which growth was unaffected and below which it became suddenly inhibited. However there was a narrow range from about 0.05 m^3 m^{-3}to 0.15 m^3 m^{-3} air-filled porosity over which root growth changed from seriously inhibited to largely unaffected (Figure 2) and this was independent of soil texture. Therefore the use of a critical limit of 0.10 m^3 m^{-3} for radiata pine, such as has been used in the literature in the past, is not seriously in error and still may be appropriate as a rough and simple guide. It follows that in the experiments looking at the interaction between matric potential and soil strength, soil air was not a complicating factor because air-filled porosity was always $>$ 0.20 m^3 m^{-3}, except for argillite which had a value of 0.14 m^3 m^{-3} at the highest bulk density (Table 2).

Matric potential

The effect of soil matric potential on root growth depended on soil strength. The slope of the linear regression line declined from 10.22 mm d^{-1} MPa^{-1} soil matric potential at low soil strength (0.50 MPa target soil strength level) to 7.75 mm d^{-1} MPa^{-1} soil matric potential at high soil strength (1.50 MPa target soil strength level). This indicated that a change in soil matric potential has a greater effect on root growth in non-compacted than in compacted soil. One possible explanation is that the root growth in high soil strength may be seriously restricted by soil strength and the influence of soil water potential becomes minor.

The effect of a greater range of water potentials, and at zero soil strength, was examined in the experiments using PEG 4000 solutions. The rate of root elongation decreased exponentially with decreasing water potential of the rooting medium (Figure 5). The rate of decrease in root elongation became progressively less as the water potential of the rooting medium decreased. This suggests that some physiological processes were induced to compensate for the reduced root growth under water stress. These physiological processes might include changes in root cells in the elongation zone of osmotic potential, yield turgor and wall yielding coefficient, singly or in combination (Zou, 1999).

Root elongation rates in PEG 4000 solutions were less than in soil at the same water potential (Figures 4 and 5). The maximum growth rate in the solution experiment was 3.8 mm d^{-1} but it was 7.9 mm d^{-1} in soil at 0.50 MPa soil strength and 4.5 mm d^{-1} in soil at 1.50 MPa soil strength. One possible reason is the differences in the physiological age of the seedlings between the two experiments. Even though in both experiments the elongation rate was made on newly elongating roots, the age of the seedlings in the PEG 4000 experiment was about two weeks, while that in soil was about one week. There is also some evidence in the literature which indicates that PEG might be toxic to root (Lawlor, 1970; Lesham,1966) or even restrict oxygen availability to roots (Mexal et al., 1975).

Soil strength

The rate of root elongation decreased exponentially with increasing soil strength and this was independent of soil texture (Figure 6). Sands et al. (1979) and Mason et al. (1988) reported that root growth of radiata pine growing in a well-aerated sandy soil was severely restricted above a soil strength around 3.0 MPa. However, 3.0 MPa seems quite arbitrary and corresponds to a root elongation rate of 1.6 mm d^{-1}, less than 20% of the maximum root growth rate, in this study. Forest managers have sometimes interpreted 3.0 MPa as being a critical limit above which root growth is severely restricted but below which root growth is largely unaffected. This is incorrect. Soil strength reduced root growth over the whole range tested in this study including low levels of soil strength. Indeed, the rate of reduction in root elongation decreased exponentially with increasing soil strength. It is therefore inappropriate to assume that soil strength affects root growth only in compacted soils. Extrapolating the data in Figure 6a suggests that the root elongation rate at zero soil strength would be 8.04 mm d^{-1}.

In order to compare the growth response of primary roots of radiata pine to soil strength with other plants, the soil strength at which root growth rate is reduced to 50% ($P_{1/2}$) was used (Dexter, 1987; Misra and Gibbons, 1996). A large value of $P_{1/2}$ indicates the root can tolerate high soil strength. The $P_{1/2}$ calculated for radiata pine from Equation (3) was 1.3 MPa, which is significantly lower than 2.54 MPa for eucalypts reported by Misra and Gibbons (1996), but was at the middle range of 0.72 – 2.03 MPa for annual plants reported by Dexter (1987). Therefore, the primary root growth of radiata pine is more likely to be restricted by high soil strength than the root growth of eucalypts.

Table 3. Interaction of soil strength and soil water content in soils of contrasting textures. ρ_b = bulk density (Mg m^{-3}), Q_{fc} = soil strength at field capacity (MPa), Q_{wp} = soil strength at wilting point (MPa)

Soil type (textures)	ρ_b	Q_{fc}	Q_{wp}
Pumice (loamy sand)	0.7	0.48	0.98
	0.8	0.89	2.44
	0.85	1.65	3.66
Loess (silty clay)	0.85	0.35	1.16
	0.95	0.46	2.08
	1.05	0.78	5.14

Soil texture

The effects of soil texture on root growth could be mainly explained in terms of differences in soil air, soil water and soil strength between textures. The soil strengths at nominal field capacity (−0.01 MPa, Q_{fc}) and nominal wilting point (−1.5 MPa, Q_{wp}) are compared between the two extremes of texture (pumice and loess) in Table 3.

When soil bulk density of pumice increased from low to medium (from 0.7 to 0.8), both Q_{fc} and Q_{wp} increased about 2 to 2.5 times (from 0.48 to 0.89 MPa and 0.98 to 2.4 MPa, respectively). However, when bulk density increased from low to medium (from 0.85 to 0.95) in loess, $Q_{\mathrm{fc}}$and Q_{wp} increased only from 0.35 to 0.46 and 1.16 to 2.08 MPa, respectively. Compaction had a greater effect of increasing soil strength than did decreasing soil water content in the coarse soil (pumice), but decreasing soil water content had a greater effect on increasing soil strength than did compaction in the fine soil (loess). At both low and high bulk densities, the finer loess had lower soil strength than the coarser pumice at field capacity, but higher soil strength at wilting point. In addition, drying soil will cause greater increases in soil strength in an already high strength soil (high bulk density) than in a lower strength soil (lower bulk density) particularly in finer soils. Conversely, watering a dry compact soil will cause a greater reduction in soil strength than watering a relatively non-compact soil, and particularly a fine soil.

The practical implications are that traffic will compact coarse soil to values of soil strength that do not differ greatly with soil water content. Adding water to a dry coarse soil will do little to reduce soil strength. The reduction of soil strength in coarse compacted soils can be achieved best by reducing soil bulk density by mechanical means. In fine textured clay soil, traffic ideally should be confined to dry soils where the soil strength is already high and, therefore, will resist compaction. The high soil strength will be reduced when the soil is wet.

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