Root distribution of lychee trees growing in acid soils of subtropical Queensland

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Summary. A core sampling technique was used to investigate the vertical root distribution of 8–10-year-old lychee trees (*Litchi chinensis* cv. Tai So) growing on 5 acid soils in subtropical Queensland (lat. 27°S.). At each site, soil and roots were sampled at 10 cm depth intervals to 100 cm, the root density determined and a range of soil chemical and physical properties measured.

Eighty percent of the feeder roots were located within the top 0–20 cm (1 site), 0–40 cm (2 sites) or 0–60 cm (2 sites). The depth of rooting was greatest in the fine textured soils, while the greatest total root density was recorded in the coarse textured soils. The data suggest that the placement of tensiometers for water scheduling needs to take into account the effective rooting depth of lychee because it may vary with soil type.

At all sites, pH values were acidic (pH<6.0) and subsoil pH values were below 5.5, and exchangeable Ca decreased and exchangeable Al increased with depth. Four of the 5 sites had subsoil with >30% Al saturation of the cation exchange capacity.

Although root density (all sites) was correlated with a number of soil chemical properties, stepwise multiple linear regression showed that 62% of the variation in root density could be explained by a curvilinear function of depth. The intercorrelations between soil properties and the correlation of depth with some properties demonstrate the difficulties in separating the effects of depth *per se* from those of soil properties in reducing root growth.

Introduction

Lychees from southern China are grown on a range of soils along the eastern coast of Australia from Cairns and the Atherton Tableland in northern Queensland to Coffs Harbour in northern New South Wales (Menzel *et al.* 1988). The Chinese recognized the importance of soil conditions on root growth and productivity in lychee (Anon. 1978) and considered lychees to generally have a poor root system because trees propagated by air-layers did not have a tap root. This poorly developed root system is possibly responsible for the sensitivity of some lychee cultivars to lodging, especially those cultivars with a dense canopy (Menzel *et al.* 1988). Lychees are also susceptible to water stress under high evaporative demand, even with plentiful soil moisture, because of limited root distribution in the soil profile at depth (Menzel and Simpson 1986).

Howard (1925) showed that although some lychee roots (cultivar not specified) were found at 3.75 m depth in a deep calcareous sandy loam in India, most roots were located in the top 45 cm. He reported that the deep root system was capable of absorbing enough water during the dry season to support a large crop. Nel (1983) reported that Tai So lychee had an extensive network of roots that extended to a depth of 100 cm in a sandy soil in the subtropical areas of South Africa. In contrast, C. M. Menzel and A. G. Banks (unpublished data) noted that most of the roots of an 8-year-old Tai So tree growing in a sandy clay loam overlying a light clay in subtropical Queensland were in the top 0–40 cm. Roy *et al.* (1987) found that most of the roots of 25-year-old lychee trees (cv. Bombai) in 6 different orchards in India were in the top 30 cm of the soil profile. High yielding trees usually had a greater feeder root density than low yielding trees.

The study of root systems of tropical and subtropical fruit trees has been largely neglected by horticulturists, and little information is available on the role of soil properties in root distribution. This paper describes the effective rooting depth of lychee in 5 orchards with variable soil types in subtropical Queensland (lat. 27°S.). Measurement of the effective rooting depth (depth in which 80% of the feeder roots are located) is very important for water and nutrition management for a crop, and indicates the appropriate locations for the monitoring of soil moisture and fertility.

Many lychee growing soils in subtropical Queensland are acid or strongly acid (Menzel *et al.* 1991), and Ca deficiency or Al toxicity have often been implicated when growth is poor (Soileau *et al.* 1969; Bruce *et al.* 1988).

Table 1. Total root density (0–100 cm depth) and feeder root distribution in the five lychee orchards
Means followed by different letters are significantly different (P=0.05)

Site, soil type and classification[A]	Texture class (0–20 cm)[B]	Tree age (years)	Tree height (m)	Crown diameter (m)	Root density (g/core)	Location of feeder roots (cm)[C]
1. Prairie soil (Dy 5.11)	Loamy coarse sand	10	3.0	3.5	25.8b	0–20
2. Prairie soil (Gn 3.44)	Clay loam	10	4.0	4.0	22.0b	0–40
3. Red earth (Um 5.52)	Sandy clay loam	10	3.5	4.0	16.9ab	0–40
4. Krasnozem (Gn 3.11)	Clay loam–light clay	10	3.0	3.5	9.4a	0–60
5. Red podsolic soil (Dr 3.21)	Clay loam–light clay	8	2.5	3.0	7.4a	0–50

[A] Northcote (1979). [B] Stace et al. (1968).
[C] Depth of soil profile where 80% of feeder roots are located (calculated on fresh weight basis for roots <5 mm in diameter).

Consequently, the second objective of this survey was to relate root distribution patterns to soil physical and chemical properties, especially profile acidity, and Ca and Al concentrations. This approach has not been attempted previously with lychee or any tropical fruit tree.

Materials and methods

Site description

Root and soil samples were taken from 5 lychee (cv. Tai So) orchards near Nambour in subtropical Queensland, Australia (lat. 27°S.) in January–February 1986. Trees were 8–10 years old and were grown from air-layers at 6–8 m intervals in rows 8 m apart (equivalent to a density of 160–200 trees/ha). Sites and soil texture classes are described in Table 1. Trees were managed as commercial crops with respect to water, nutrition, pest and weed control (Menzel *et al.* 1988). The inter-rows of all orchards were under grass.

The climate at Nambour, which is close to all sites, is subtropical with no arid months. Average annual rainfall is 1779 mm with 42% falling in summer. Temperatures range from an average daily minimum of 6.9°C in July to an average daily maximum of 28.7°C in December. Temperatures above 35°C are occasionally experienced in spring, usually accompanied by dry westerly winds.

Soil and root sampling

Soil samples were taken at 10 cm intervals to a depth of 100 cm from under each of 4 trees at each orchard. After removal of surface litter, 4 cores (10 cm diameter) per tree were taken halfway between the trunk and the dripline in a north, south, east and west orientation (Menzel *et al.* 1991). Previous experiments showed that lychee roots were concentrated in this zone and that there was no interaction between soil depth and distance from the trunk on root weight, at least to a depth of 80 cm (C. M. Menzel and A. G. Banks, unpublished data). Each soil core was sieved, and the roots removed after washing. The percentage of roots with different diameters (<1 mm, 1–2 mm, 2–3 mm, 3–4 mm, 4–5 mm and >5 mm) was recorded. In addition, root fresh weight and root projected area (Li-Cor area meter) were recorded for each core. Root density was expressed as either fresh weight (g) or root area (cm^2) per core volume (approximately 7850 cm^3).

Soil from each tree was bulked for each site for chemical analysis. Soil preparation and analytical methods were those described by Bruce and Rayment (1982). Soils were air-dried (40°C) and ground to <2 mm prior to analysis. Soil pH, EC and Cl concentration were measured in a 1:5 suspension in water. Exchange acidity (H^+ and Al^{3+}) was displaced with 1 mol/L KCl (1:10 soil solution) and the acidity (H^+ plus Al^{3+}) and Al concentration determined separately by auto-titration. The effective cation exchange capacity (ECEC) was calculated as the sum of exchangeable acidity and basic cations (Ca, Mg, K and Na) displaced with 1 mol/L NH_4Cl.

Single soil samples (725 cm^3) were taken at 10 cm increments to a depth of 100 cm from under each tree at each orchard and sealed in plastic bags for determination of bulk density.

Statistical analysis

Root density (fresh weight or area) and root size distribution were analysed using 2-way ANOVA (site x depth). Data were square root transformed before analysis. In order to ascertain if one or more soil properties were governing root density across all sites, the relationships between root density and soil chemical and physical properties were determined by regression analysis.

Results

Root distribution with depth

Root area is not presented because its variation with depth and site was similar to that of root fresh weight. There was also no significant effect (P>0.05) of orientation (N, S, E, W) on root distribution and data for 4 soil cores per tree were pooled.

The greatest root density (root fresh weight/core) was recorded in the coarse texture soil (site 1), with the lowest root densities occurring in the fine textured soils (sites 4 and 5) (Table 1). The clay loam soils (sites 2 and 3) contained root densities that were intermediate

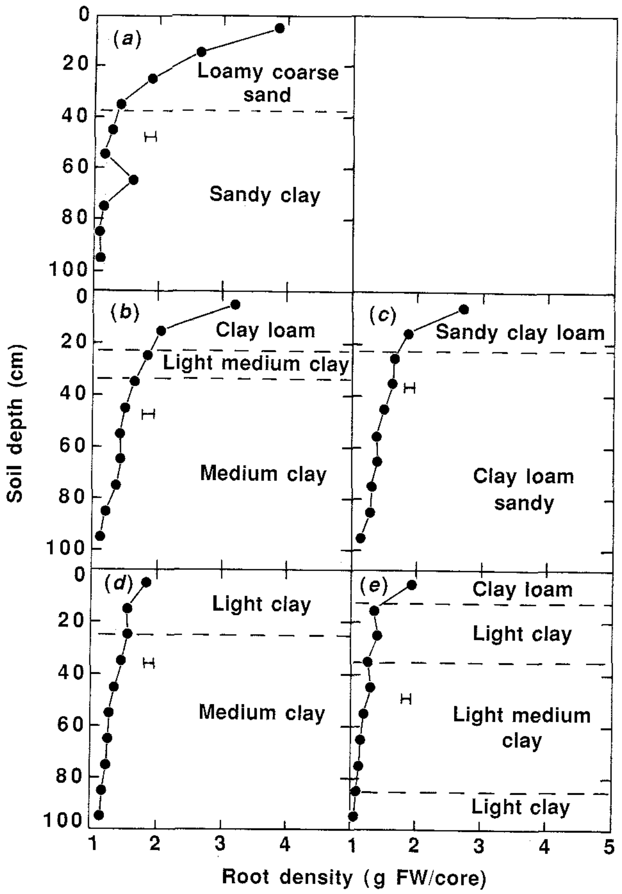

Fig. 1. Distribution of root density (root fresh weight/soil core volume of 7850 cm^3) in 5 lychee orchards (*a–e*), sites 1–5. Data are the means of 16 samples over 4 trees and have been square root transformed. Horizontal bars indicate l.s.d. at $P = 0.05$. Boundaries between texture classes are indicated by the dashed lines.

between those in the coarse-textured (site 1) and finer textured soils (sites 4 and 5).

Eighty percent of the roots were located within the top 0–20 cm (site 1), 0–40 cm (sites 2 and 3), 0–50 cm (site 5) or 0–60 cm (site 4) of the soil profile (Fig. 1). Although some roots were found at the lowest depth sampled (90–100 cm), their contribution to the feeder root system was less than 3%. The sites had different root density distributions with soil depth (Fig. 1). The coarse-textured soil (site 1) had more roots than the fine-textured soils (sites 4 and 5) in the 0–60 cm soil layer, but the effect diminished with depth. However, when root density in a given depth interval was expressed as a percentage of the total density (0–100 cm), all sites tended to follow the same pattern (data not presented).

Root size distribution

The percentage of roots in each size category was: <1 mm, 75.6%; 1–2 mm, 16.3%; 2–3 mm, 5.5%;

Table 2. Soil pH, effective cation exchange capacity (ECEC), exchangeable cations Ca and Al and bulk density (BD) at 10 cm intervals at the 5 lychee sites

Data are the means of 16 cores

Soil depth (cm)	pH	ECEC	Exc. Ca	Exc. Al	BD (g/cm^3)
		(cmol(+)/kg)			
1. Prairie soil, loamy coarse sand					
0–10	5.9	6.2	4.60	0.01	1.42
10–20	6.0	4.4	3.20	0.02	1.60
20–30	5.6	3.2	2.10	0.05	1.62
30–40	5.5	2.5	1.40	0.25	1.53
40–50	5.4	2.4	1.10	0.30	1.55
50–60	5.2	3.1	1.10	1.07	1.52
60–70	5.1	3.7	1.70	0.88	1.61
70–80	5.0	4.6	1.70	1.80	1.65
80–90	5.0	4.6	1.50	3.40	—
90–100	4.8	6.7	1.50	3.77	—
2. Prairie soil, clay loam					
0–10	5.1	15.0	8.20	1.64	1.17
10–20	4.9	11.0	3.60	3.84	1.07
20–30	5.0	8.8	2.70	3.24	1.03
30–40	4.9	9.2	2.30	4.08	1.17
40–50	4.8	8.8	2.10	4.22	1.38
50–60	4.8	9.8	2.10	4.98	1.55
60–70	4.8	10.0	1.70	5.69	1.60
70–80	4.7	11.0	1.70	6.49	1.61
80–90	4.7	12.0	1.30	7.56	1.53
90–100	4.6	14.0	1.40	8.62	1.60
3. Red earth, sandy clay loam					
0–10	5.4	10.0	8.10	0.02	1.39
10–20	5.6	5.1	3.70	0.10	1.40
20–30	5.1	4.7	3.10	0.32	1.39
30–40	5.0	4.0	2.30	0.42	1.37
40–50	4.9	3.5	1.70	0.48	1.33
50–60	4.8	3.3	1.30	0.65	1.38
60–70	4.9	3.8	1.70	0.42	1.39
70–80	5.0	3.3	1.30	0.29	1.49
80–90	4.9	3.6	1.20	0.35	1.55
90–100	5.0	3.0	0.94	0.23	—
4. Krasnozem, clay loam–light clay					
0–10	5.5	5.8	3.70	0.06	1.01
10–20	5.4	4.9	3.20	0.22	1.07
20–30	5.2	3.7	1.70	0.42	0.97
30–40	5.1	3.3	1.30	0.45	1.01
40–50	5.1	3.2	1.10	0.48	1.12
50–60	5.1	4.0	1.30	0.63	1.11
60–70	5.1	5.5	1.40	0.99	1.12
70–80	5.0	5.9	1.20	2.56	1.18
80–90	5.0	7.1	0.93	3.47	1.23
90–100	4.9	8.1	0.79	3.92	1.21
5. Red podsolic soil, clay loam–light clay					
0–10	5.2	14.0	7.50	0.31	1.22
10–20	5.1	10.0	4.60	1.57	1.41
20–30	4.9	11.0	3.60	3.29	1.35
30–40	4.8	12.0	2.90	5.59	1.37
40–50	4.8	14.0	2.40	6.97	1.40
50–60	4.8	16.0	2.00	7.91	1.40
60–70	4.8	17.0	1.60	8.46	1.50
70–80	4.8	19.0	1.30	9.66	1.53
80–90	4.9	20.0	0.78	11.33	1.60
90–100	4.9	20.0	0.60	10.71	1.65

Table 3. Correlation coefficients for the relationships between depth, several soil properties and root density for all sites

	Depth	pH	ECEC	Exch. Ca	Ca%	Exch. Al	Al%	Bulk density
Root density	–0.61***	0.61***	0.0	0.68***	0.59***	–0.31	–0.45***	0.14
Bulk density	–0.11	0.09	0.24	0.02	0.01	0.21	–0.02	
Al%	0.64***	–0.75***	0.57***	–0.43	–0.87***	0.85***		
Exch. Al	0.50***	–0.62***	0.86***	–0.29	–0.81***			
Ca%	–0.76***	0.81***	–0.55***	0.58***				
Exch. Ca	–0.75***	0.37	0.20					
ECEC	0.13	–0.43						
pH	–0.63***							

*** $P < 0.001$.

3–4 mm, 0.8%; 4–5 mm, 0.5% and >5 mm, 1.3%. Site and profile depth had no significant effect on root size distribution ($P>0.05$).

Soil properties

Selected soil properties for the various depth intervals at each site are presented in Table 2. Soil pH and exchangeable Ca generally decreased with soil depth, whereas exchangeable Al generally increased. At all sites, pH values were <6.0 and subsoil pH values were <5.5. Electrical conductivity was low at all sites and declined with soil depth, i.e. 0.08–0.22 mS/cm at 0–10 cm to 0.05–0.11 mS/cm at 90–100 cm (data not presented).

Exchangeable Ca levels declined with soil depth and ranged from 3.7–8.2 cmol(+)/kg at 0–10 cm to 0.6–1.5 cmol(+)/kg at 90–100 cm. Values were lower at depth at sites 3, 4 and 5 (0.6–1.0 cmol(+)/kg) and higher at sites 1 and 2 (1.4–1.5 cmol(+)/kg). Calcium saturation was high (54–81%) in the top 10 cm, and declined with soil depth. At a depth of 90–100 cm, it was below 12% at sites 2, 4 and 5. Levels of exchangeable Al at 0–10 cm were low at all sites (0.01–0.31 cmol(+)/kg) and Al saturation was <3%. The only exception was at site 2 where exchangeable Al was 1.64 cmol(+)/kg and Al saturation was 10.9%. In contrast, at 90–100 cm levels of exchangeable Al were low at site 3, intermediate at sites 1 and 4 (3.7–3.9 cmol(+)/kg) and high at sites 2 and 5 (8.6–10.7 cmol(+)/kg). With the exception of site 3, Al saturation in the lower part of the profile (50–100 cm) was high (>20%).

Bulk density ranged from 0.97 to 1.65 g/cm^3 and, generally increased with depth (Table 2).

Relationship between root density and soil properties

There was considerable intercorrelation between soil properties, and a number of soil properties were correlated with soil depth and root density (Table 3). The relationship between root density (RD) and depth (D) was curvilinear and could best be represented by the relationship:

$$RD = 0.653 - 0.008D + 31.335D^{-1} \quad (R^2 = 0.62, P<0.001)$$

Although root density was significantly ($P<0.001$) correlated with depth, pH, exchangeable Ca, Ca and Al saturation (Table 3), a step up multiple linear regression indicated that only depth and 1/depth terms significantly ($P<0.01$) affected root distribution. There was also no relationship between root density and bulk density.

Discussion

Root distribution

Our results indicate that lychees are shallow rooted in acid soils of subtropical Queensland, and that the depth of rooting is greater in fine textured soils than coarse textured soils. Most roots were located within the top 0–20 cm or 0–60 cm of the profile. Although some roots were found at greater depths, their contribution to the feeder root system was less than 3%. Many papers that have investigated the effects of soil type on tree root growth (e.g. Atkinson 1980) and depth of rooting have shown that the total amount of roots is generally greater in fine-textured soils. However, there are many examples where rooting was better in coarse-textured soils (e.g. Salazar-Garcia and Cortes Flores 1986 in avocado). In our study, there was no relationship between changes in root density and soil texture. For example, at sites 1, 2 and 3 there was a reduction in root density with depth even though texture remained unchanged. This is confirmed by the lack of any significant relationship between root density and soil bulk density across all sites.

Menzel *et al.* (1988) recommended that irrigation scheduling in lychee should be controlled by the use of 2 tensiometers, 1 installed in the middle of the root zone and the other below the root zone. The top tensiometer indicates when irrigation should be commenced, while the lower tensiometer is used to indicate when there is adequate reserves of soil moisture at depth. Similarly, nutrition management should be supported by soil analysis every 1–2 years (Menzel *et al.* 1991). Our data indicate that the location of tensiometers needs to take in account the effective rooting depth of the orchard and its variation with soil type. However, the current practice of taking soil samples for nutrient analysis from the 0–15 cm depth under fruit trees in Queensland

(Anon. 1984) would appear reasonable for lychee. This is because a large proportion of the root system (40–80%) was located in the top 0–20 cm of the profile.

Several tree crops, including apple and pear (Atkinson 1980), avocado (Salazar-Garcia and Cortes-Flores 1986) and citrus (Avilan *et al.* 1986) appear to have rooting patterns similar to lychee. The vertical spread of roots ranged from 1–9 m, commonly 1–2 m, and the zone containing most roots was 0–50 cm and in many cases, 0–30 cm depth. Assuming a mean root diameter of 1.0 mm, root density for lychee orchards ranged from 11.3 to 28.1 cm/cm^2 soil surface (0–100 cm profile). In *Gramineae*, reported values are in the range 100–4000, and in herbs, 52–310 cm/cm^2 (Newman 1969). Values for fruit trees and forests are considerably lower, ranging from 0.8 to 126 cm/cm^2, with 2–6 cm/cm^2 commonly reported for apples (Atkinson 1980).

Various methods have been used to study root systems in tree crops: excavation, profile wall, core sampling, radioactive tracers, rhizotrons (Atkinson 1980; Purohit 1983; Taylor 1986). Core sampling has been used frequently in studies of fruit and other trees because it allows relatively rapid comparisons of the effects of cultural treatments on rooting density at different depths, without disturbances caused by total excavation, and it gives acceptable recovery of fine roots. The distribution of feeder roots obtained by core sampling agreed with estimates of rooting depth from studies of ^{32}P uptake in many tree crops (e.g. Purohit and Mukherjee 1974 in guava).

The variations amongst cores in our survey were not too large to override site or soil depth effects. Coefficients of variation for root weight from 16 samples at site 1 (high root density) ranged from 8.1 to 40.0% at 0–10 and 90–100 cm, respectively. Values at corresponding depths at site 5 (low root density) were 13.2 and 33.3%, respectively. In contrast, Reynolds (1970) and Atkinson (1974) found that variation in root density amongst core samples was sometimes so large that they were unable to detect significant differences among different horizontal zones or depths, possibly because they used smaller cores than used in the present study.

Soil cores need to be taken during periods of root flushing because many roots in perennial crops die within weeks of emergence and are replaced only when favourable conditions return (Richards 1983). Howard (1925) in India and Anon. (1978) in China indicated that lychee roots flushed actively after harvest, before panicle formation and after fruit set, however, until further information is available, we suggest that any period during the main growing season could be suitable for estimation of root distribution in lychee.

Relationships between root density and soil properties

The intercorrelation between soil properties and the correlation of many soil properties with root depth (Table 3) highlight the difficulties in interpreting relationships between profile root data and soil properties. Root growth naturally decreases with soil depth, thus the effects of depth *per se* and adverse soil properties are often difficult to separate.

Soil pH values at all sites were <6.0 and subsoil <5.5. Menzel *et al.* (1991) indicated that soil pH values in Australian lychee orchards seldom reached levels of 6.0–6.5 proposed by Childers (1975) for satisfactory tree growth, despite the application of dolomite. They attributed the low pH to high average rainfall and neutralisation of applied dolomite by acidifying fertilisers. Nanz (9155) surveyed the growth and yield of lychee orchards in Florida and reported better performance was achieved in the pH range of 5.0–5.5; however, trees on soils with pH <5.0 grew poorly. Although most plants will grow satisfactorily in solution culture over the pH range from 4–8, our results show only a weak correlation between root density and soil pH across the sites. Strongly acid soils may limit growth via one or more of Ca deficiency, Al toxicity or Mn toxicity (Adams 1984; Roy *et al.* 1988). Manganese levels were not excessive in the soils studied (Menzel *et al.* 1991).

The decrease in Ca and increase in Al with depth in our soils (Table 2) is typical of acidic tropical and subtropical soils of Queensland (Bruce *et al.* 1989). Several studies have shown that acidic subsoils can restrict root growth because of deficient Ca supply and/or toxic Al (Soileau *et al.* 1969; Bruce *et al.* 1988). However, in our experiment root density was related primarily to soil depth. This is supported by data from site 3, where Ca saturation levels were high (>31%), and Al saturation levels were low (<20%), yet root densities and root distribution at this site (Fig. 1*c*) were similar to site 2 (Fig. 1*b*) which had high Al saturation values and lower Ca saturation. However, pot and field experiments are required to define the role of Ca deficiency and Al toxicity in lychee growth. If subsoil acidity limits growth, ameliorative strategies such as lime, gypsum and phosphogypsum (Sumner and Carter 1988) can then be evaluated.

Soil infertility has been implicated as a causal factor in limiting root growth, since shallow rooting occurs more often on infertile sites (Kimmins and Hawkes 1978). However, there are only a few instances where root densities have been positively correlated with soil N, P or K levels (e.g. Strong and La Roi 1985 in boreal forests). There was no relationship between the rooting depth of lychee and levels of N, P and K in these soils (Menzel *et al.* 1991). Similarly, soil Na, Cl, Cu, Zn and B values were below toxic levels at all sites and would not be considered limiting to root growth.

Bulk density could not explain the variation in root density across different sites. In contrast, Penkov *et al.* (1979) showed that grapevine root growth markedly declined when bulk density exceeded 1.5 g/cm^3, while there was a gradual reduction in rooting depth in tomato as bulk density increased from 1.32 to 1.76 g/cm^3 (Rickman *et al.* 1965). The poor correlation between root density and soil bulk density in our survey can possibly be attributed to the latter being within the acceptable range for lychee root growth. An alternative explanation is that water content and particle size distribution, which vary with soil type, can affect the relationship between root growth and bulk density (or total porosity). A good example of this response is provided by Strong and La Loi (1985) and Kimmins and Hawkes (1978). These authors found that root growth of forest species was generally poorly correlated with bulk density, with soil P and Al levels being more important.

Over 90% of the lychee roots were <2 mm in diameter and less than 2% were >4 mm in diameter. Lyr and Hoffmann (1967) reported that, 86–90% of the total root length was represented by fine roots <1 mm in diameter in 4 tree species. Atkinson (1980) indicated that most roots were involved in water and nutrient uptake, but that the smaller roots were more important because of their greater contribution to the total root surface of the plant.

Conclusion

Lychee trees were found to have a shallow root distribution when grown on a range of acid soils in subtropical Queensland. Although some roots were found down to a depth of 100 cm, most roots were located in the top 0–20 to 0–60 cm of the soil. The depth of rooting was greater in fine textured soils compared with coarse textured soils but the total amount of roots in the profile showed the reverse trend.

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