RELATIONSHIPS BETWEEN CONE PENETRATION RESISTANCE, BULK DENSITY, AND MOISTURE CONTENT IN UNCULTIVATED, REPACKED, AND CULTIVATED HARDSETTING AND NON-HARDSETTING SOILS FROM THE COASTAL LOWLANDS OF SOUTH-EAST QUEENSLAND

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(Received for publication 14 September 1995; revision 10 March 1997)

ABSTRACT

Relationships between cone penetration resistance (PR), soil moisture (SM), and bulk density (BD) were derived for: (i) cultivated (ripped) and uncultivated, hardsetting and non-hardsetting, field soils; and (ii) repacked cores of the uncultivated soils. Each of the soils supports commercial *Pinus* plantations in the coastal lowlands of south-east Queensland, Australia.

Penetration resistance was positively correlated with bulk density and negatively correlated with soil moisture for all soils. In the uncultivated soils, penetration resistance was less sensitive to bulk density than typically reported in the literature, or than observed in the cultivated soils where a wider range of bulk density values was studied. In both the cultivated and the repacked soils, penetration resistance was more sensitive to soil moisture at higher bulk density, and more sensitive to bulk density at lower soil moisture.

It was not possible to fit the same models to uncultivated, repacked, and cultivated soils, and therefore not possible to compare relationships for each statistically. Relationships between penetration resistance, bulk density, and soil moisture were best described by additive models in the uncultivated soils and multiplicative models in the cultivated soils. For the repacked soils, models had to be developed relating penetration resistance to bulk density for each soil moisture class separately.

The study demonstrated that: (i) relationships between penetration resistance, bulk density, and soil moisture were insufficiently sensitive to predict responses in the penetration resistance of field soils to changes in soil moisture, as might occur temporally, or bulk density, as might occur with compaction or reconsolidation after cultivation; and (ii) repacked soils could not be used to simulate the relationships between penetration resistance, bulk density, and soil moisture for cultivated field soils. Therefore, penetration resistances measured at different times in studies in which either bulk density or soil moisture are expected to change cannot be easily compared. In these situations, which include compaction and consolidation studies, both penetration resistance and bulk density, or bulk density alone, should be used to monitor change.

New Zealand Journal of Forestry Science 26(3): 395–412 (1996)

Relationships between penetration resistance, soil moisture, and bulk density, together with moisture characteristic drying curves for individual soils, were used to define relationships between penetration resistance and matric suction. These relationships define a soil characteristic that may be useful for: (i) explaining varying responses of different soils to drying; (ii) explaining various *Pinus* seedling growth responses to cultivation and compaction; and (iii) delineating soils which are functionally hardsetting upon drying.

Keywords: resistance to penetration; soil moisture; bulk density; hardsetting soils; cultivation; ripping.

INTRODUCTION

High strength soils can physically impede root elongation (Barley & Greacen 1967; Taylor 1971), and thereby restrict oxygen, water, and nutrient uptake by plants, and reduce above-ground biomass production (Burdett *et al.* 1983). In forest plantations, restricted root system development may also directly decrease wind stability, and indirectly increase weed control costs as reduced growth rates lengthen the period between planting and canopy closure when weed competition is greatest.

While high strength soils occur naturally in Australia (Northcote 1979), compaction resulting from machine activity during establishment, management, and harvesting of forests can result in strength increases detrimental to growth (Sands *et al.* 1979; Costantini 1995a). Shear strength is the soil characteristic that resists deformation from an applied force. The techniques for its assessment (*see* Hillel 1980) do not, however, lend themselves to rapid and repeated field use and, as a result, cone penetration resistance (PR), a closely related but more easily measured strength parameter, is widely used in trafficability, tillage, and compaction studies (O'Sullivan *et al.* 1987; Campbell & O'Sullivan 1991). Like shear strength, penetration resistance is typically strongly correlated with root growth (Sands *et al.* 1979; Greacen & Sands 1980; Bengough 1991; Costantini *et al.* 1996).

Penetration resistance is a measure of soil resistance to penetration by a cone, and has two components: (i) resistance to deformation forces ahead of the advancing cone; and (ii) friction between soil moving into the cavity behind the cone and the penetrometer shaft (Greacen *et al.* 1968; Koolen & Kuipers 1983). Penetration resistance is therefore a function of soil factors affecting resistance, and of penetrometer design and use, including cone angle, shaft diameter, penetration rate, and cone roughness (Campbell & O'Sullivan 1991). Standard penetrometer designs and operating instructions provide a common basis for determining and interpreting penetration resistance.

The major soil factors affecting penetration resistance (PR) are soil moisture (SM), bulk density (BD), soil type, and soil structure (Koolen & Kuipers 1983; Campbell & O'Sullivan 1991). Important components of soil type affecting penetration resistance include texture, mineralogy, chemical properties, and organic matter. Both soil structure and type are difficult to measure for predictive purposes. If, however, only one soil type is considered and soil structure does not vary, the major factors affecting penetration resistance will be soil moisture and bulk density.

Campbell & O'Sullivan (1991) reported that relationships between penetration resistance, bulk density, and soil moisture can often be described either by additive models of the form:

$$PR = a + b \times SM + c \times BD + d \times BD \times SM \qquad [1]$$

or, where relationships are derived from a wider range of bulk density and soil moisture values, by multiplicative models of the form:

$$PR = a \times SM^{b}\,(BD)^{c} \qquad [2]$$

where a, b, and c are empirical constants.

Relationships between penetration resistance, soil moisture, and bulk density will differ for hardsetting and non-hardsetting soils. McDonald *et al.* (1990) defined hardsetting as the "compact, hard, apparently apedal condition [which] forms on drying but softens on wetting". When dry, hardsetting soils "cannot be disturbed or indented by pressure of [the] forefinger". Many soils in Australia's summer-rainfall-dominated tropical and sub-tropical zones, including some of those used for *Pinus* afforestation, exhibit hardsetting characteristics upon drying (Northcote 1979).

The two studies reported here were designed to investigate relationships between penetration resistance, bulk density, and soil moisture for four soils from the *Pinus* plantation estate of the Queensland Department of Primary Industries, Forest Service, in south-east Queensland. The intention was to develop models which could be used to predict responses in penetration resistance to management-induced changes in soil moisture and/or bulk density. A second objective was to determine if repacked soils could be used to simulate cultivated soils for the purposes of defining relationships between penetration resistance, bulk density, and soil moisture.

Two uncultivated field soils, one hardsetting and the other non-hardsetting, and repacked cores of these were tested in Study 1, while two cultivated field soils were tested in Study 2.

METHODS

Study sites were located in *Pinus* plantations at Toolara (152°50'E; 26°00'S), 150 km north of Brisbane in the coastal lowlands of south-east Queensland. Coaldrake (1961) has described the sub-tropical nature of the climate and the soils of the area. Soils are mostly derived from Mesozoic and early Cainozoic sediments, and are acidic, coarse textured, and deficient in nutrients. In the studies reported here, soil descriptions and terminology follow the system of McDonald *et al.* (1990), and soils are classified according to the Australian Northcote (1979) and Isbell (1993) systems.

All of the soils studied belong to the Alfisol Soil Taxonomy Order (Soil Survey Staff 1975, correlation from Moore *et al.* 1983). Soil moisture characteristic drying curves were determined for intact cores of the field soils and for repacked soil cores using pressure and suction plate apparatus (after Reeve & Carter 1991).

Study 1

A very strong-consistence hardsetting red dermosol and a weak-consistence non-hardsetting brown sodosol were studied (Tables 1 and 2). Organic carbon contents of six bulked samples from the surface 0–5 cm for each soil type were 2.8% and 1.2% respectively. Both soil types carried improved pastures (predominantly *Setaria sphacelata* var. *sericea* and *Trifolium repens*) and were previously grazed with cattle. Neither had been previously cultivated.

TABLE 1–A description of soils used in Studies 1 and 2.

Surface condition	Soil type–Classification of:		Soil description			
	Isbell (1993)	Northcote (1979)	Horizon	Depth (cm)	Texture*	Structure†
Study 1						
Hardsetting	Red dermosol	Gn 3.54	A1	0–20	CL	Strong
			A2	20–45	L	Strong
			B21	45–60	CL	Weak
			B22	60–100	CL	Strong
Non-hardsetting	Brown sodosol	Dy 5.41	A1	0–20	SL	Massive
			A2	20–40	LS	Massive
			B2	40–80	SC	Strong
			C	80–100	SC	Strong
Study 2						
Hardsetting	Red dermosol	Gn 3.11	A1	0–20	CL+	Strong
			B1	20–40	LC	Strong
			B21	40–80	LMC	Massive
			B22	80–110	LMC	Strong
			B23	110–150	LMC	Moderate
Non-hardsetting	Red kandasol	Um 4.41	A1	0–20	SCL	Massive
			A2	20–30	SCL	Massive
			B2	30–85	SCLFS	Weak
			B22	85–100	SCLFS	Moderate

* CL = clay loam; L = loam; SL = sandy loam; LS = loamy sand; SC = sandy clay; LC = light clay; LMC = light medium clay; SCL = sandy clay loam; SCLFS = sandy clay loam fine sandy.

† Moist soil condition.

TABLE 2–Particle size characteristics of soils studied.

Study	Surface condition & soil type	Depth (cm)	Particle size characteristics					
			Sand (%)		Silt (%)		Clay (%)	
			mean	s.d.	mean	s.d.	mean	s.d.
Study 1	Hardsetting red dermosol	10	73	7.4	34	6.3	22	7.1
Study 1	Non-hardsetting brown sodosol	10	73	3.3	17	3.4	10	2.0
Study 2	Hardsetting red dermosol*	10	41	6.9	37	4.4	22	6.1
		20	37	5.6	33	3.9	30	4.6
Study 2	Non-hardsetting red kandasol*	10	55	11.4	30	8.7	15	3.8
		20	53	11.7	28	7.7	19	4.9

* Pre-cultivation

Undisturbed, uncultivated, field soils

Penetration resistance, bulk density, and soil moisture measurements were made at 36 randomly selected locations throughout a 100-m^2 area for each soil type. Penetration resistance at 10 cm depth was measured using a chart recording Eijkelkamp Stiboka penetrograph with a 1-cm^2 cone ('Cone 1' 60° top angle, and 8-mm-diameter shaft) used in accordance with the manufacturer's recommendations. The penetrometer was inserted to 30 cm. While the designed operating limit for the penetrometer is 5 MPa, it was difficult to achieve uniform penetration into the soil when the initial resistance exceeded 4.5 MPa. Where root or rock impediments were encountered during penetrometer insertion, the reading was discarded and another taken.

After each penetrometer assessment, a trench profile approximately 50 cm long and 25 cm deep was excavated 15 cm away from the penetrometer entry point, beyond the influence zone of the penetrometer cone. Samples for bulk density and soil moisture (gravimetric moisture content, the preferred soil moisture measure in this type of study—*see* Koolen & Kuipers 1983) determination were then collected using the core sampling technique described by Costantini (1995b) and a 6-cm-diameter × 10-cm-long sampler which was driven horizontally into the carefully prepared profile at 10 cm depth. Twelve penetration resistance, bulk density, and soil moisture determinations were made on three occasions for the red dermosol and on four occasions for the brown sodosol in order to measure a range of soil moisture conditions.

Repacked soils

Soil was collected from the 5–15 cm horizons of both Study 1 soils (Tables 1 and 2), transported to the laboratory, air dried on plastic sheets, and sieved to remove the >2-mm fraction. Twenty-kilogram lots of sieved soil were then placed in a cement mixer, wetted by adding distilled water as an atomised spray, thoroughly mixed, sealed in plastic bags, and allowed to equilibrate for 3 days with twice daily inversion. Moisture contents achieved were 11.4%, 13.8%, 17.0%, and 19.2% for the red dermosol and 3.7%, 6.9%, 9.5%, 11.9%, and 14.1% for the brown sodosol.

Samples were loaded into three 6.0-cm-long × 7.25-cm-diameter brass rings, enclosed inside a brass sleeve, and compacted in a uni-axial compression chamber designed to provide equal compaction at both ends and a uniform compaction in the centre ring. A range of compaction forces was used to produce a range of bulk density values. The minimum compaction pressure that could be achieved with the compression apparatus was 0.7 MPa, and as a result, a hand compaction (loose fill) treatment was also prepared. Three replicates were prepared for each compaction pressure in each soil moisture class.

Penetration resistance was determined with a Geotester penetrometer. A 6.5-mm-diameter blunt tip was used for all levels of compaction except the hand compaction treatments which required a 2.0-cm-diameter blunt tip. Assessments were made at the surface and base of each soil ring.

Study 2

A very strong-consistence hardsetting red dermosol and a very weak-consistence non-hardsetting red kandasol were studied (Tables 1 and 2). Organic carbon contents of six bulked samples from the surface 0–5 cm for each soil type averaged 1.6% and 1.4% respectively. Both sites carried improved pastures and were previously grazed. The soils were cultivated in March 1988 with a 1.5-m-wide bulldozer-drawn wing ripper (blade cultivator) to a depth of 20 cm. Particle size characteristics of soils after ripping are given in Table 3.

TABLE 3–Post-cultivation particle size range of soils sampled in Study 2.

Soil	Depth (cm)	Particle size details								
		Sand (%)			Silt (%)			Clay (%)		
		range	mean	s.d.	range	mean	s.d.	range	mean	s.d.
Red dermosol	10	34–71	49.5	12.1	18–42	31.5	8.0	11–29	19.1	5.4
	20	31–71	45.5	13.2	14–39	29.7	6.9	12–36	24.7	7.3
	10 & 20	31–71	47.4	12.8	14–42	30.6	7.5	11–36	21.9	7.0
Red kandasol	10	31–72	44.9	11.8	17–46	36.4	7.5	9–32	18.7	6.1
	20	26–66	42.9	11.6	23–45	33.5	5.9	11–43	23.7	7.7
	10 & 20	26–72	44.0	11.7	17–46	35.0	6.9	9–43	21.1	7.3

On each of five occasions over the next 2 years, nine penetration resistance, bulk density, and soil moisture determinations were made as per Study 1 for both soil types, in both cultivated and uncultivated zones, at depths of 10 and 20 cm. Samples collected for soil moisture determination were also used for particle size analysis using the hydrometer technique (Loveland & Whalley 1991). The ranges of soil moisture and bulk density studied were 8.9–35.1% and 0.8–1.55 g/cm^3 respectively for the red dermosol and 13.8–34.5% and 0.9–1.65 g/cm^3 for the red kandasol.

Analyses

At seven of the 36 assessment sites used in the uncultivated field soils study (Study 1), penetration resistance exceeded 5 MPa, the design working limit of the penetrometer. Rather than exclude these data sets, penetration resistances were censored to 5 MPa for analyses. The multi-linear and non-linear curve fitting routines available in Genstat 5 (Genstat 1987) were used to define relationships between penetration resistance, soil moisture, and bulk density. For all relationships, the square roots of the residual mean square are reported as a measure of the distribution of individual data points around the response surface.

Relationships between penetration resistance, soil moisture, and bulk density were then combined with the relevant drying curves for individual soils, in order to investigate the nature of relationships between penetration resistance and matric suction (at mean bulk density).

RESULTS

The two clay loam red dermosol field soils maintained higher water contents at all matric suctions than the sandy loam brown sodosol or the sandy clay loam red kandasol. Repacked soils in Study 1 maintained higher water contents below 0.03 MPa and above 1.0 MPa than the same soils in an undisturbed condition. In the range 0.03–1.0 MPa, undisturbed field soils maintained higher water contents than repacked cores of the same soils.

Study 1

Undisturbed, uncultivated field soils

For both uncultivated soils, relationships between penetration resistance, soil moisture, and bulk density at 10 cm depth were best described by additive models of the form presented in Equation 1 (Fig. 1, Table 4). In the red dermosol, penetration resistance increased marginally with increasing bulk density, and soil moisture had a greater impact on penetration resistance than bulk density (Fig. 1). By contrast, penetration resistance of the brown sodosol was more sensitive to bulk density, particularly at high soil moisture.

For the red dermosol, penetration resistance exceeded 5 MPa for all data sets in which soil moisture was less than 15%, and in each of these penetration resistance was censored to 5 MPa. The models presented in Fig. 1 therefore under-predict penetration resistance of the high strength red dermosols. Nonetheless, penetration resistance of the hardsetting red

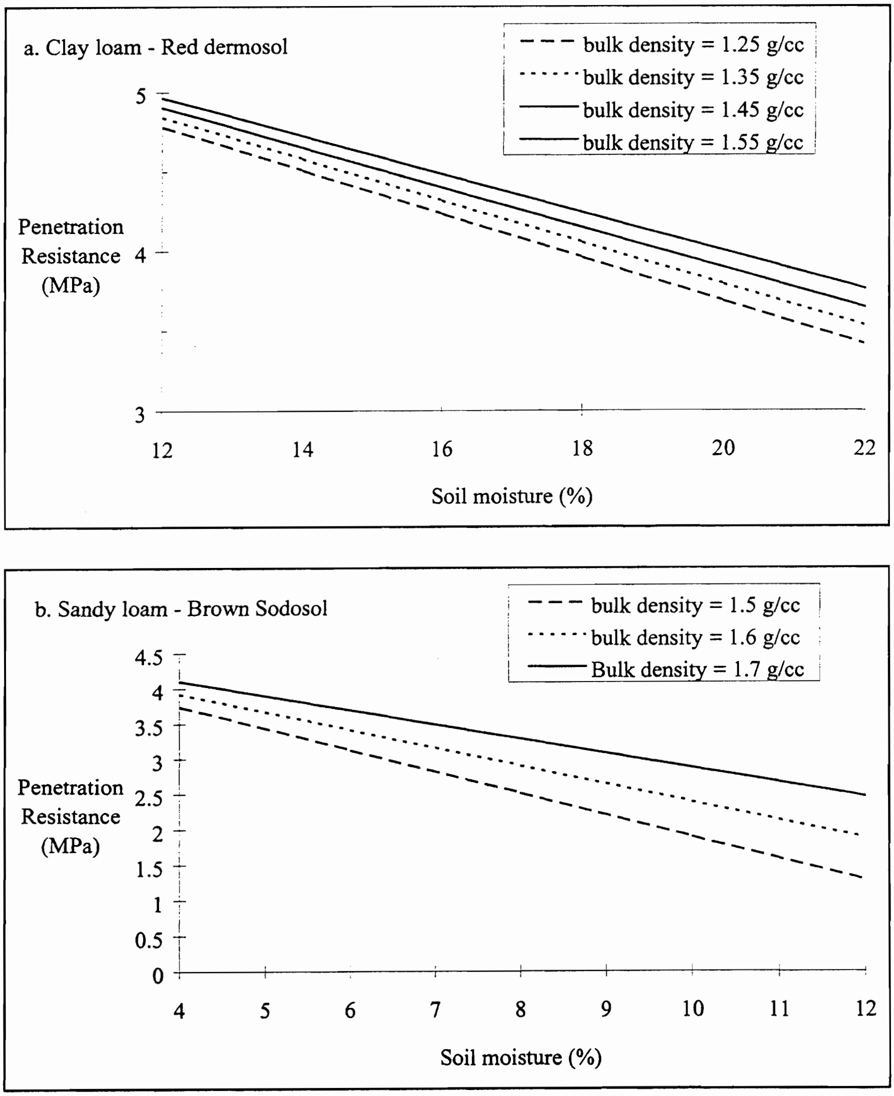

FIG. 1–Fitted relationships between penetration resistance, bulk density, and soil moisture at 10 cm depth for the uncultivated red dermosol and brown sodosol from Study 1.

TABLE 4–Results of the multi-linear regression estimation of coefficients and fit parameters for the relationship between penetration resistance (PR), soil moisture (SM), and bulk density (BD) in two uncultivated soils at 10 cm depth: $PR = a + b \times SM + c \times BD + d \times BD \times SM$.

Soil type	Coefficients				r^2 (%)	√ (residual mean square)
	a	b	c	d		
Red dermosol	6.47	–0.207	–0.0612	0.0556	63.0	0.47
Brown sodosol	5.33	–1.08	–0.238	0.515	59.3	0.58

dermosol is greater than the penetration resistance of the non-hardsetting brown sodosol at equivalent matric suctions (Fig. 2).

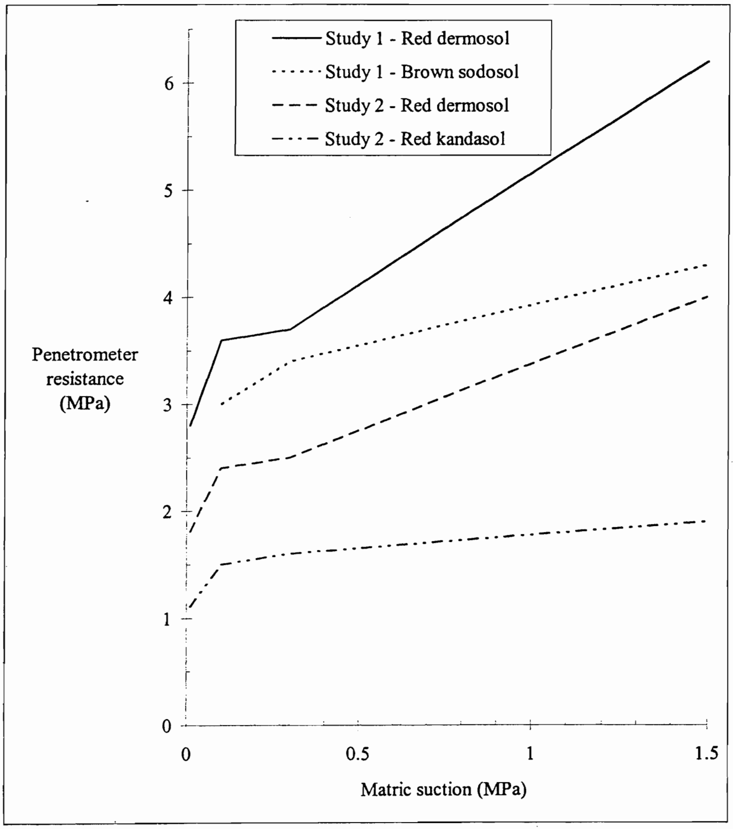

FIG. 2–Relationships between penetration resistance and matric suction for both Study 1 and 2 soils at mean bulk density.

Repacked soils

Neither the Equation 1 additive model nor the Equation 2 multiplicative model provided a satisfactory fit to the PR-SM-BD data for repacked soils. Indeed, it was not possible to find a model which simultaneously fitted all soil moisture classes. By considering each soil moisture class separately, however, relationships could be described by power models of the form:

$$PR = a \times (BD + k)^c \quad [3]$$

where a, k, and c are coefficients (Fig. 3, Table 5). Values of k were negative for the red dermosol, and not significantly different from zero for the brown sodosol. For both soils, the rate of change in penetration resistance with soil moisture was greater at higher bulk density, and the rate of change in penetration resistance with bulk density was greater at lower soil moisture (Fig. 3).

For the red dermosol, a coefficient values decreased with increasing soil moisture, k coefficient values reached a minimum at 17.0% SM, and c coefficient values were unrelated to soil moisture. For the brown sodosol, a coefficient values peaked at 6.9%, and

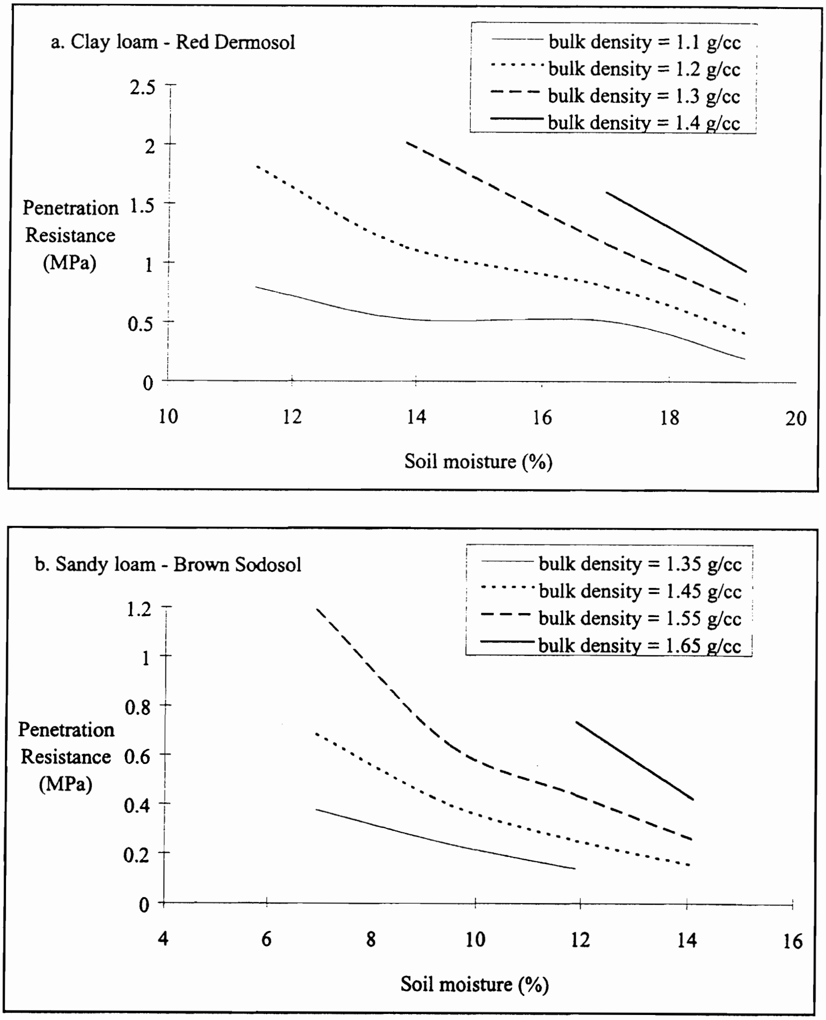

FIG. 3—Fitted relationships between penetration resistance, bulk density, and soil moisture for the repacked red dermosol and brown sodosol from Study 1.

TABLE 5–Results of the nonlinear regression estimation of coefficients and fit parameters for the relationship between penetration resistance (PR), soil moisture (SM), and bulk density (BD) in two repacked soils: $PR = a \times (BD + K)^c$.

Soil type and moisture content (%)	Coefficients a	k	c	r^2 (%)	√ (residual mean square)
Red dermosol					
11.4	21.3	–0.896	2.07	98.9	0.114
13.8	12.5	–0.840	2.35	98.5	0.139
17.0	3.01	–0.645	2.25	99.5	0.057
19.2	2.91	–0.944	1.44	99.2	0.051
Brown sodosol					
3.7	0.00804	*	11.6	98.3	0.069
6.9	0.0312	*	8.31	97.5	0.100
9.5	0.0275	*	7.18	97.7	0.049
11.9	0.0115	*	8.30	99.1	0.023
14.1	0.00800	*	7.92	97.9	0.024

* For the brown sodosol, model fit was not improved by giving “k” a non-zero value.

c coefficient values were unrelated to soil moisture (Table 5). The models provided good fits to the data, with r^2 values ranging from 97.5% to 99.5%, and average square root residual mean square values being 0.09 and 0.05 for the red dermosol and brown sodosol respectively.

Study 2

For both cultivated soils, relationships between penetration resistance and soil moisture and bulk density were best described by models of the Equation 2 multiplicative form (Fig. 4, Table 6). Plots of residuals against sand, silt, and clay content suggested no functional relationships between these texture parameters and penetration resistance. Increases in penetration resistance associated with soil drying were greater for the hardsetting red dermosol than for the non-hardsetting red kandasol (Fig. 2). Across the soil moisture range sampled, penetration resistance of the red dermosol (at mean bulk density) exceeded that of the red kandasol (at mean bulk density) by 0.5 MPa at high soil moisture, increasing to 2.0 MPa at low soil moisture.

TABLE 6–Results of the nonlinear regression estimation of coefficients and fit parameters for the relationship between penetration resistance (PR), soil moisture (SM), and bulk density (BD) in two blade-cultivated soils at 10 cm, 20 cm, and both depths combined: $PR = a \times SM^b (BD)^c$.

Soil type and depth (cm)	Coefficients a	b	c	r^2 (%)	√ (residual mean square)
Red kandasol					
10	2.49	–0.362	1.28	15.2	0.92
20	3.03	–0.655	2.86	38.5	0.87
10 & 20	2.95	–0.539	2.74	25.9	0.90
Red dermosol					
10	17.4	–0.781	1.09	24.8	0.91
20	12.8	–0.752	2.01	34.7	0.95
10 & 20	15.3	–0.772	1.52	29.2	0.93

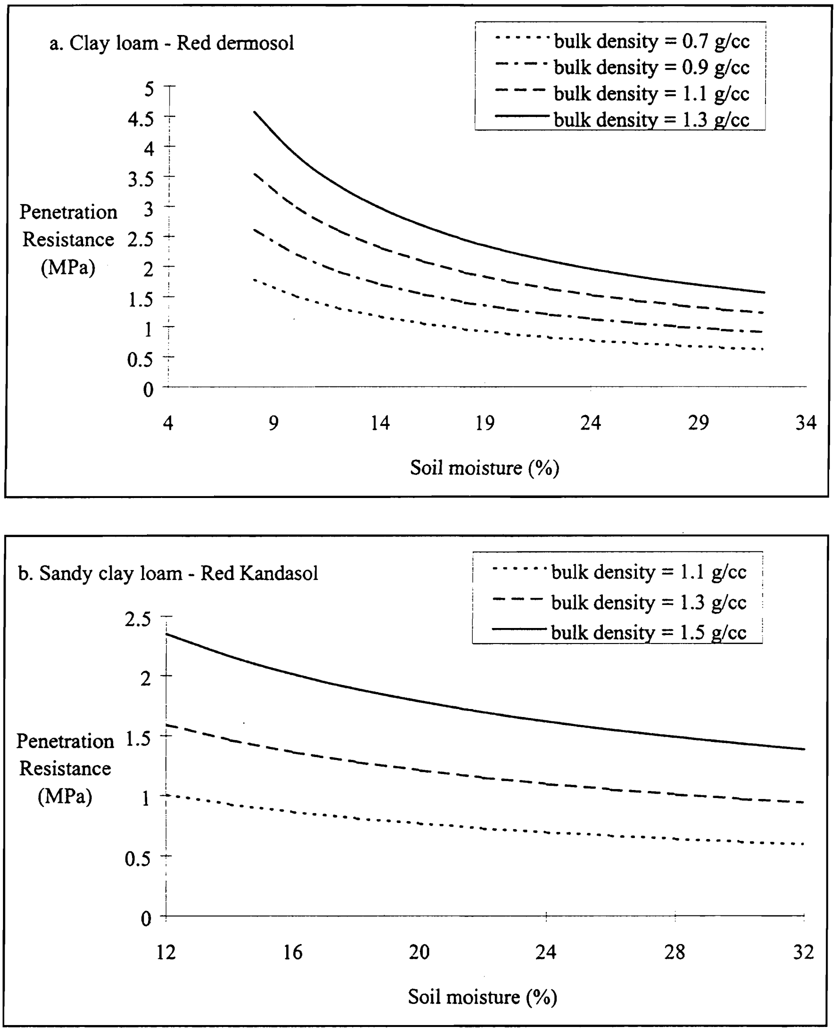

FIG. 4—Fitted relationships between penetration resistance, soil moisture, and bulk density for the blade-cultivated red dermosol and red kandasol from Study 2 (data for 10-cm and 20-cm depths combined).

DISCUSSION

Relationships between Penetration Resistance, Bulk Density, and Soil Moisture

A major objective of the study was to develop relationships between penetration resistance, soil moisture, and bulk density that would enable responses in the penetration resistance of field soils to be predicted from either changes in soil moisture as might occur temporally, or bulk density as might occur with compaction or reconsolidation after cultivation. Although it is possible to obtain point estimates of penetration resistance throughout a soil profile by excavation and use of needle or hand-held penetrometers (for example, Cockroft *et al.* 1969; Sands *et al.* 1979; Campbell & O'Sullivan 1991), the intention here was to model the penetration resistance measured by routinely-used field penetrometers (Campbell & O'Sullivan 1991), and so standard field measurement techniques and equipment were used to measure penetration resistance, bulk density, and soil moisture. It was hoped that relationships would provide a robust and practical means of modelling field soil penetration resistance where none previously existed, though it was recognised that this approach increased errors in the following ways: (i) penetration resistance, unlike soil moisture and bulk density which were volumetric estimates, was a point-like estimate (for a description of cone penetration into soil, *see* Farrell & Greacen 1966; Greacen *et al.* 1968; Koolen & Kuipers 1983); (ii) samples for soil moisture and bulk density assessment were collected 15 cm to the side of the cavity formed by the penetrometer shaft to ensure that the penetrometer did not influence bulk density; and (iii) penetration resistance estimates >5 MPa could not be achieved (where penetration resistance exceeded 5 MPa, data were subsequently censored to 5 MPa).

For the uncultivated red dermosol, penetration resistance increased marginally with increasing bulk density, while soil moisture had a relatively greater impact on penetration resistance than bulk density (Fig. 1a). A similar trend was observed for the uncultivated brown sodosol (Fig. 1b), though penetration resistance was more sensitive to bulk density at high soil moisture. Penetration resistance of both the red dermosol and the brown sodosol was less sensitive to bulk density than that typically reported for field soils (Sands *et al.* 1979) due, in part, to the sampling approach used. The inclusion of censored penetration resistance data in the model depicted in Fig. 1a has resulted in penetration resistance being biased downward, particularly at high bulk density and low soil moisture.

For both cultivated soils, the rate of change in penetration resistance with soil moisture was greater at higher bulk density, and the rate of change in penetration resistance with bulk density was greater at lower soil moisture (Fig. 4). Both of these trends appeared more pronounced in the red kandasol which, at bulk density of 0.9 g/cm^3 for example, had a low penetration resistance throughout the entire soil moisture range sampled (Fig. 4b), and contrasted with the red dermosol which, at the same bulk density, had a relatively high penetration resistance at low soil moisture (Fig. 4a). Relationships between penetration resistance, soil moisture, and bulk density for the cultivated soils were similar to those reported by Ehlers *et al.* (1983), Koolen & Kuipers (1983), and Campbell & O'Sullivan (1991).

Correlations between penetration resistance, bulk density, and soil moisture were stronger in the uncultivated soils than the cultivated soils (Tables 4 and 6), due in part to increased heterogeneity of cultivated soils. The blade cultivation used in the present study had the effect of fracturing soil, forming both large clods and large inter-clod fissures (Costantini *et al.* 1995a).

The penetration resistance range of most interest to forest managers is 0–5 MPa. Within this range, root growth will be severely restricted or inhibited (Sands *et al.* 1979; Costantini *et al.* 1996), and soil shear strength will provide sufficient resistance to compaction from commonly-used mechanical equipment (Wronski *et al.* 1990). It follows, therefore, that if responses in field soil penetration resistance to changes in bulk density and soil moisture are to be usefully predicted, narrow confidence limits of prediction (possibly less than ±0.25 MPa) will be required. Though predicted penetration resistance was more responsive to bulk density and soil moisture in the cultivated soils than in the uncultivated soils, models developed for cultivated soils had relatively low coefficients of determination (15–35%) and relatively high square root residual mean squares (0.87–0.95 MPa). While coefficients of determination (59–63%) were higher and square root residual mean squares (0.47–0.58 MPa) were lower in models for uncultivated soils, penetration resistance was only weakly responsive to bulk density and soil moisture. None of the models depicted in Fig. 1 and 4 can be used to predict penetration resistance with the desired certainty.

The implication of not being able to predict responses in penetration resistance to bulk density and soil moisture with sufficient certainty is that penetration resistance cannot be used effectively in longitudinal studies in which either bulk density or soil moisture are expected to change. In these situations, which include compaction and consolidation studies, both penetration resistance and bulk density, or bulk density alone, should be used.

In the repacked soils, there were strong positive correlations between penetration resistance and bulk density, and strong negative correlations between penetration resistance and soil moisture (Fig. 3). These relationships are consistent with those reported from other studies (Koolen & Kuipers 1983; Campbell & O'Sullivan 1991), but should not be used to extrapolate beyond the data range. The negative k coefficients reported for the red dermosol imply that penetration resistance will be zero when $BD = -k$, and that penetration resistance increases as bulk density decreases further.

Correlations between penetration resistance, bulk density, and soil moisture differed between undisturbed soils and repacked cores (compare Fig. 1 and 3) and were much stronger in the repacked soils (compare Tables 4 and 5) due to differences in structure and spatial variability (Koolen & Kuipers 1983; Campbell & O'Sullivan 1991). Likewise, correlations between penetration resistance, bulk density, and soil moisture differed between the cultivated and repacked red dermosol (compare Fig. 3a and 4a) and were much stronger in the repacked soil (compare Tables 5 and 6). It is clearly not possible to use the relationship between penetration resistance, bulk density, and soil moisture for the repacked red dermosol, which was relatively easy to define, for the purposes of simulating penetration resistance responses to soil moisture or bulk density changes in the cultivated red dermosol.

Hardsetting Characteristic upon Drying

Forest managers working in the coastal lowlands of south-east Queensland have developed an operational distinction between hardsetting and non-hardsetting soils. The former develop a sufficiently hard (high strength) condition upon drying, which can be referred to as a "hardsetting characteristic upon drying", to make efficient cultivation difficult. McDonald *et al.* (1990) described a "finger indenting test" which can be used to identify the hardsetting characteristic in dry soils.

Northcote (1979) noted that (i) the majority of soils in Australia's climatic zones which experience distinct wet/dry periods are hardsetting, and (ii) that non-hardsetting soils tend to be pedal in the moist and dry condition, or single-grained sands. This implies that some soils may display modest pedality when dry, yet still be hardsetting for operational purposes, especially if they dry quickly. On this basis, some non-self-mulching clays, such as the red dermosols studied here, could be classified as "operationally" hardsetting.

However, more recent technical definitions of hardsetting exclude these soils. Mullins *et al.* (1992) and Mullins & Ley (1994) defined the major hardsetting features as (i) structural breakdown upon wetting, followed by (ii) hardening without structural redevelopment upon drying. Using this definition, it is possible for clay soils to have a hardsetting characteristic upon drying, yet not be classified as hardsetting (Mullins & Ley 1994).

Even though the red dermosol soils studied here are more pedal moist than dry, they do not satisfy the technical criteria of Mullins & Ley (1994) for classification as hardsetting. However, both soils dry relatively quickly after rains, are operationally-defined by forest managers as hardsetting, and need to be delineated from non-hardsetting soils for the purpose of cultivation during dry periods. Clearly, a disparity has emerged between the operational definition of hardsetting and the technical definition. The operational hardsetting classification is important for forest managers, and at least for dry soils, is easily assessed in field surveys. The remainder of this section focuses on the operationally-defined "hardsetting characteristic upon drying".

Harper & Gilkes (1994) suggested that it would be desirable to define objective boundaries for discrete hardsetting classes, particularly if the hardsetting characteristic is to be used in soil classification. There is, however, no generally accepted strength specification for defining the hardsetting characteristic. Northcote (1979) originally suggested 0.5 MPa when measured with a 6.35-mm-diameter blunt-tip penetrometer, though this criterion was not incorporated into the field handbook for Australian soil survey (McDonald *et al.* 1990). On the basis of a 0.5 MPa criterion, however, even the red kandasol in Study 2 would be classed as hardsetting, despite it being manifestly non-hardsetting.

It is suggested that the relationships in Fig. 2 provide a more useful model for conceptualising the "hardsetting characteristic upon drying" than an arbitrary strength specification (*see also* Mullins *et al.* 1987). For the red dermosol in Study 1, penetration resistance increased markedly as matric suction increased, indicating a strong hardsetting characteristic upon drying. If the assumption is made that the red dermosol soils in both studies are similar, a reasonable assumption based upon Table 2 and similarities in observed drying characteristics, then the results in Fig. 2 imply that the cultivated red dermosol retains its hardsetting characteristic upon drying, though at each level of suction the cultivated soil is weaker than the uncultivated soil. In contrast to the red dermosols, the red kandasol from Study 2 did not have a hardsetting characteristic, and penetration resistance was relatively insensitive to soil drying. The brown sodosol showed a hardsetting characteristic upon drying, intermediate between the red dermosol and red kandasol but closer to the latter (Fig. 2). Consistent with its single-grained texture, massive structure, and weak consistence (Table 1), the brown sodosol was classified as being non-hardsetting in field surveys because the dry surface could be indented by finger pressure.

Understanding Cultivation Effects

Large-scale and long-term field cultivation trials are expensive to establish and manage. Their results are often temporally and spatially specific, being affected by soil type and soil moisture. Knowledge of the Fig. 2 relationships may assist in (i) interpretation of findings from field trials, and explanation of how these are affected by soil type and growing conditions, and (ii) conceptualising the nature of root growth responses to cultivation.

In order to elongate, roots must either extend through pores/fissures larger than the root diameter, or physically displace the soil (Cannell 1977). Because of the need for roots to overcome penetration resistance in order to physically displace soil during elongation, *Pinus* root development is inversely related to penetration resistance, and is severely restricted at penetration resistance exceeding 3.0 MPa (Sands *et al.* 1979; Costantini *et al.* 1996). For matric suctions above 0.02 MPa, penetration resistance of the uncultivated red dermosol exceeded 3.0 MPa (Fig. 2). Using the criterion of Sands *et al.* (1979), this soil can be expected to severely impede root development for most soil moisture conditions (*see also* Costantini *et al.* 1995b).

At each level of suction, the cultivated red dermosol was at least 1 MPa weaker than the uncultivated soil, with the magnitude of difference increasing as the soil dried. Penetration resistance was less than 3.0 MPa at suctions below 0.7 MPa (23% SM) and, as a result, the cultivated red dermosol will be considerably more favourable to root elongation than the uncultivated soil, because of both the relative increase in fissures and the reduced resistance to penetration. Assuming that penetration resistance reductions persist for a number of years, cultivation of the red dermosol can be expected to result in an on-going improvement in the soil physical growing environment. In any one year, the magnitude of any growth response to cultivation will be dependent on soil moisture, with the more significant gains occurring in moister years. For example, at matric suctions between 0.1 and 0.7 MPa, penetration resistance of the cultivated and uncultivated red dermosol will be 2.4–3.0 MPa and 3.6–4.6 MPa respectively: *Pinus* roots will be capable of elongating by physically displacing the cultivated red dermosol, but not the uncultivated red dermosol. Cultivation of this soil does in fact benefit *Pinus* growth (Fig. 2) (Costantini *et al.* 1995b).

Throughout the matric suction range of agronomic interest, penetration resistance of the red kandasol was relatively independent of matric suction, and did not exceed 2.0 MPa (Fig. 2). *Pinus* root growth in this soil type can be expected to be far less sensitive to soil moisture than in the red dermosol.

In the uncultivated brown sodosol, penetration resistance exceeded 3.0 MPa when matric suction exceeded 0.1 MPa, or 8% SM (Fig. 2). If cultivation resulted in a persistent penetration resistance reduction, positive root growth responses would be expected.

Understanding Compaction Susceptibility and Effects

Being closely related to shear strength, penetration resistance values can provide a measure of soil ability to resist compaction. Clearly, the uncultivated brown sodosol will provide less resistance to compaction deformation than the uncultivated red dermosol at equivalent matric suctions (Fig. 2). Likewise, the cultivated red kandasol provides less resistance to compaction deformation than the cultivated red dermosol at equivalent matric suctions. The positive relationships between penetration resistance and matric suction depicted in Fig. 2 can be used to conceptualise how resistance to compaction is affected by matric suction. For example, a dry cultivated red dermosol will have a much greater ability to resist compaction than a dry cultivated red kandasol.

The relationships between penetration resistance and bulk density depicted in Fig. 1 and 4 can be used to assess the magnitude of increases in mechanical impedance which will be experienced by roots after compaction (or consolidation). If relationships between penetration resistance and root elongation are known, the models depicted in Fig. 1 and 4 may be used to predict the loss in root growth potential associated with compaction.

CONCLUSIONS

In the uncultivated field soils there was a positive correlation between penetration resistance and bulk density, though the correlation was less sensitive than typically reported for field soils, and a stronger negative correlation between penetration resistance and soil moisture. In the cultivated field soils, where a wider range of bulk density values was studied, similar correlations were observed but penetration resistance was more sensitive to changes in bulk density and soil moisture. Moreover, the rate of change in penetration resistance with soil moisture was greater at higher bulk density, and the rate of change in penetration resistance with bulk density was greater at lower soil moisture. Relationships between penetration resistance, bulk density, and soil moisture were insufficiently sensitive to predict responses in the penetration resistance of field soils to changes in soil moisture as might occur temporally, or bulk density as might occur with compaction or reconsolidation after cultivation. The implication of this conclusion is that penetration resistance cannot be used effectively in longitudinal studies in which either bulk density or soil moisture are expected to change. In these situations, which include compaction and consolidation studies, both penetration resistance and bulk density, or bulk density alone, should be used.

It was not possible to develop models relating penetration resistance to bulk density and soil moisture for the repacked soils. While general power models relating penetration resistance to bulk density for each soil moisture class were able to be developed, it was concluded that repacked soils could not be used to simulate PR-BD-SM relationships of cultivated field soils.

Relationships between penetration resistance, soil moisture, and bulk density differ between soils that are hardsetting for operational management purposes and those that are not. Over the soil moisture range of agronomic interest, penetration resistance of soils with the "hardsetting characteristic upon drying" increases strongly as matric suction increases.

Knowledge of the relationships between penetration resistance, soil moisture, and bulk density for cultivated and uncultivated soils can assist understanding of root growth responses to cultivation and compaction, and the ability of soil to resist compaction deformation.

ACKNOWLEDGMENTS

The work reported in this paper forms part of the Queensland Forest Research Institute hydrology research programme. The critical comments of Greg Dunn and John Comrie Greig are gratefully acknowledged. Bing So is thanked for his advice and for access to the University of Queensland, uni-axial, compression chamber used in Study 1.

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