Management of compaction during harvest of *Pinus* plantations in Queensland: III. Preliminary investigation of the potential for selected soil parameters to predict rut compaction

A. Costantini and D. Doley

C/- The Manager, Forest Development Branch, DPI Forestry, MS 483,
Gympie. Queensland 4570, Australia

Revised manuscript received 20 July 2001

Summary

An assessment has been made of the potential of three soil parameters to predict compaction risk in the coastal lowlands of south-eastern Queensland. The experimental strategy involved: (i) operating a ground-based harvesting/extraction system in low-soil-strength conditions to achieve a range of rutting depths; (ii) assessing pre- and post-compaction soil moisture, cone penetration resistance and shear vane resistance; and (iii) investigating the relationships between both pre- and post-compaction characteristics of these soil parameters and observed rut compaction.

The magnitude of rut compaction was positively correlated with pre-compaction soil moisture content and negatively correlated with pre-compaction penetrometer resistance and pre-compaction shear vane resistance. Soil moisture appeared to be the most sensitive of the three soil parameters tested in discriminating between rut compaction depths, and cone penetrometer resistance the least - though differences between the three were modest. The ability of the three soil parameters tested to discriminate between different levels of rut compaction decreased greatly as average rut depths increased above 5 cm. Rut compaction prediction models based on these soil parameters would therefore provide a much higher degree of confidence in predicting rut depths ≤5 cm than in predicting ruts depths ≥10 cm – the level used for controlling field operations in Queensland.

Development and calibration of rut compaction prediction models for use in the coase-textured soils of the coastal lowlands in south-eastern Queensland are discussed.

Keywords: soil compaction, logging machines, logging effects, site, soil types, mathematical models, *Pinus*, Queensland, Australia

Introduction

Alternative approaches to controlling soil compaction during forest harvesting in periods of low-soil-strength were presented in Paper I of this series (Costantini and Doley 2001). For *Pinus* plantations established on the coastal lowlands of south-eastern Queensland, year-round harvesting operations are permitted providing excessive compaction does not occur. Two systems for objectively assessing excessive soil compaction were canvassed, viz: (i) predictive models; and (ii) reactive approaches. In the former, predicted compaction, and in the latter, observed compaction (rut depth), are compared with a criterion of ‘acceptable’ compaction in order to determine when machinery operations should be suspended and/or re-scheduled to compartments where compaction damage is not expected.

Variables used in prediction models for compaction can be measured or modelled, and include soil parameters that influence the extent of compaction such as soil moisture content and strength, landscape position, and climatic factors affecting soil moisture content such as rainfall and evapo-transpiration. To be useful for operational field managers, model variables should be easily, reliably and economically measured – and be strongly correlated with compaction risk. In this paper, three commonly measured soil physical parameters – soil penetration resistance, shear vane resistance and soil moisture content – are assessed for their utility in predicting risk of soil compaction.

In order to assist harvesting planning, prediction models for compaction would either: (i) replace or supplement presently-used guidelines for identifying when compaction risks are ‘unacceptable’; or (ii) specify maximum ground pressures, defined as types of machinery x passes, that a specific soil can withstand under a range of strength (Wronski *et al*. 1990) or soil moisture (Wronski 1985; Gupta and Allmaras 1987) conditions. This paper is not concerned with the more complex empirical (Froehlich 1980) and process-based (Gupta and Allmaras 1987; Raghavan *et al*. 1990; Wronski *et al*. 1990) models that can be used to assist harvesting planning at a macro-level, for example, to: (i) determine the appropriate size of mill-yard log inventories relevant to a particular harvesting/extraction system, (ii) determine the likely number of days that harvesting/extraction will not be permitted for a range of alternative systems; and/or (iii) delineate compartments least susceptible to excessive compaction, so that they can be divided between various purchasers.

Methodology

The experimental strategy involved: (i) operating a ground-based harvesting system under low soil strength conditions to achieve a range of rutting depths; (ii) assessing pre- and post-compaction soil moisture, cone penetration resistance and shear vane resistance; and (iii) investigating the relationships between both pre- and post-compaction characteristics of these soil parameters and observed rut compaction. The definition of ‘acceptable’ compaction used in this investigation is the same as that presented in Paper I: namely, rutting depth should not exceed 10 cm over an accumulative distance of 10 m in every 100 m of rut.

The study area was located in a 24-year-old *Pinus elliottii* plantation located at Toolara (152°50'E; 26°00'S) on the coastal lowlands of south-eastern Queensland. A Semiaquic Podosol soil type (after Isbell 1996; Uc2.35 after Northcote 1979 - Table 1) was selected because of its tendency to experience short-term saturation in the upper 'B' and lower 'A' horizons, ranging from several days to several weeks. In this soil type, saturation occurs as a consequence of layers of low permeability within the 'B' horizon, impeding substrate layers and/or periodic intrusion of seasonal ground watertables (see also Isbell 1996), and can be aggravated by interflow from upslope areas. When either saturation or near-saturation occur, soil strength decreases and the risk of unacceptable compaction damage during harvesting increases.

Table 1. Classification and physical characteristics of the study soil[1]

Horizon	Depth (cm)	Texture	Structure	Organic carbon (%)	Particle size analyses (%)			
					Clay	Silt	Fine sand	Coarse sand
A11	0 - 35	SL	Massive	1.79	5	10	52	33
A12	35 - 50	LS	Massive	0.38	4	12	58	26
A21	50 - 65	LS	Massive	0.24	25	14	38	23
A22	65 - 80	LFS	Massive	#				
B21	80	*	Massive	*				

1. Notes: + SL = sandy loam; LS = loamy sandy; LFS = loamy fine sand; # weak to moderately cemented pan; * moderately cemented coffee rock pan.
This profile overlaid a mottled, sandy clay loam, in what appeared to be a distinct soil type.

At the time of the study, the plantation was due to be thinned using a system which removed every fifth row of trees, an outrow, together with selected trees from the remaining rows, in order to achieve a stocking reduction from 1100 to 750 trees ha^{-1}. The thinning system was based upon a mechanized harvester (Valmet 901 Feller buncher; 14 tonne tare; 4 tyres 23.1 - 26; all with 0.21 MPa pressure) and a forwarder (Kockums 83 - 35 Forwarder; 20.2 tonne tare, with a 20 tonne load; front two tyres 30.5 - 32; rear four tyres 20.5 - 28; all tyres with 0.22 MPa pressure). Both machines passed down the outrow.

The area was deliberately harvested under conditions of low soil strength in order to achieve a range of average rutting depths. Six sites were selected to sample average rutting depths of 3, 5, 10, 15, 20 and 25 cm. Harvesting/extraction operations at each site involved a single pass of the harvester and a round pass (down empty, up full) of the forwarder. Profile volumetric moisture contents at the time of the study for the six sites are shown in Figure 1. Two additional sites, which experienced average rutting depths of 10 and 15 cm, were also selected, and exposed to a second-round pass of the forwarder.

Rut depth was measured as average depression of the mineral soil below the original ground level along a 3 - 5 m length of rut, and for the deeper ruts, involved measuring through free water (soil/water solution) until reasonable resistance to the ruler was felt. Note that due to the need for a 'point estimate' of rut depth, this definition differs slightly from that detailed above for 'acceptable rut compaction'. At each of the eight sites, six pre- and post-compaction measures of cone penetrometer resistance and shear vane resistance were made immediately following passage of the forwarder. Estimates of pre-compaction characteristics were made by sampling 1.5 m to the side of the rut, while post-compaction characteristics were measured in the rut. The penetrometer used was a 0 - 5 MPa, Rimik CP20 Cone Penetrometer which had a 30°, 12.5 mm diameter cone at the base, and was operated with the insertion speed alarm set at 2.0 m minute^{-1}. The shear vane instrument used was a 0 - 100 kPa, Geonor H-60, hand-held Vane Tester with a 10 mm diameter, 0.5 m extension rod; and a 20 x 40 mm vane. Six measurements at 10, 20, 30, 40 and 50 cm depth were made at each site. When either instrument struck a root, that reading was discarded and another taken.

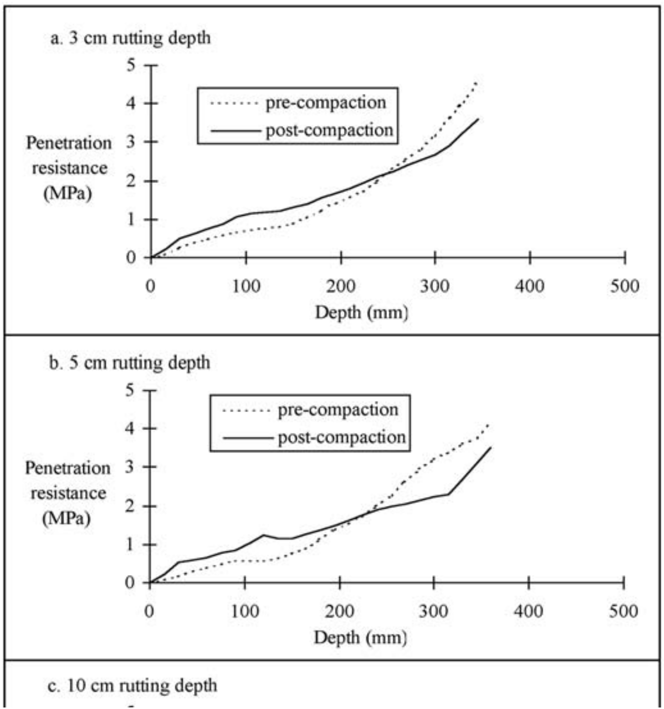

Figure 1. Profile volumetric moisture contents of the six study sites which experienced rut compaction to different depths (n = 6)

Results

Surface soil characteristics of the six sites following a single pass of the harvester and a round pass of the forwarder are shown in Table 2. The forwarder was primarily responsible for observed compaction at all sites: Even at sites where 25 cm ruts were formed, the harvester was not observed to break the soil surface.

Table 2. Surface condition immediately following vehicular passage for various rut depths

Rut depth (cm)	Surface condition following vehicular passage
3	Depression only; surface litter cover of *Pinus* needles intact
5	As for 3 cm ruts
10	Ruts occasionally 'cut' the surface soil; needle cover largely intact
15	Some evidence of mass failure; some mixing of wet soil and needles in the rut base; some displacement of soil from the rut
20	Mass failure; mixing of soil, water and needles in rut; some 5 cm of this mix in the rut base; noticeable displacement of soil from the rut
25	Mass failure; mixing of soil, water and needles in rut; some 15 cm of this mix in the rut base; significant soil displacement from the rut

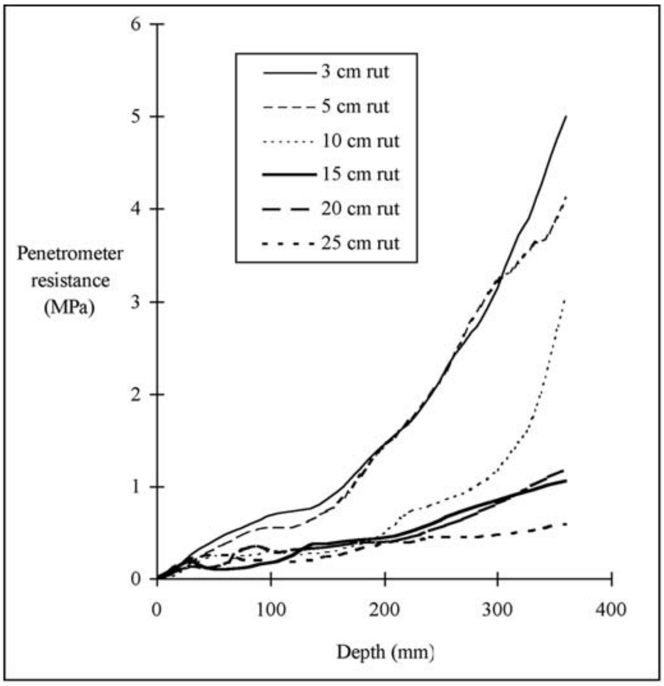

Figure 2. Changes in profile cone penetrometer resistance characteristics following a round forwarder trip which resulted in rut compaction to different depths (n = 6)

Pre-and post-compaction penetrometer resistance profiles (average of six recordings) are shown for the 3, 5, 10, 15, 20 and 25 cm ruts caused by a single round pass of the forwarder in Figure 2. For the 3 and 5 cm ruts, harvesting/extraction have compacted the surface 250 mm of the soil profile, resulting in increased post-compaction cone penetrometer resistance. Where rut depths were ≥10 cm, post-compaction cone penetrometer resistance in the surface horizons was equivalent to, or less than, pre-compaction levels. Note that post-compaction penetrometer readings commenced at the base of the rut, and an adjustment for rut depth should therefore be made if pre- and post-compaction data are compared at the same depth relative to the pre-compaction ground-level. This explains the apparent

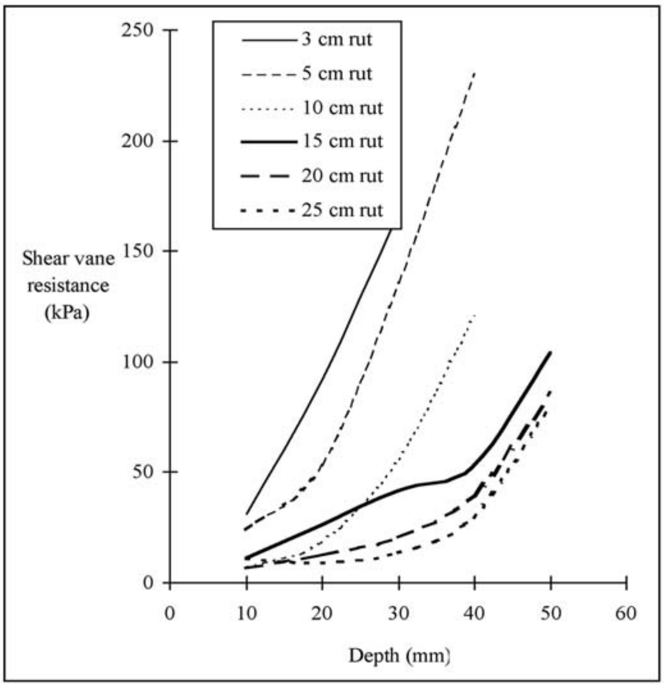

Figure 3. Profile cone penetrometer resistance characteristics of the six study sites which experienced rut compaction to different depths (n = 6)

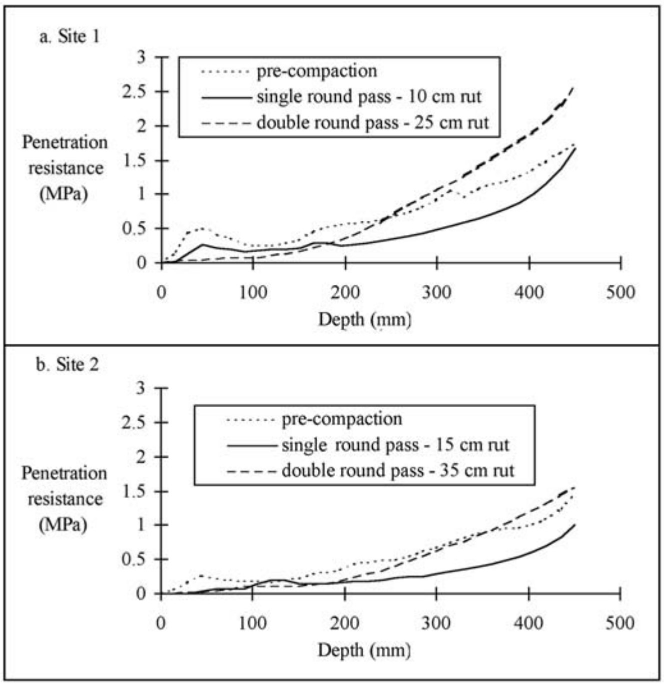

Figure 4. Profile shear vane resistance characteristics of six study sites which expeienced rut compaction to different depths (n = 6)

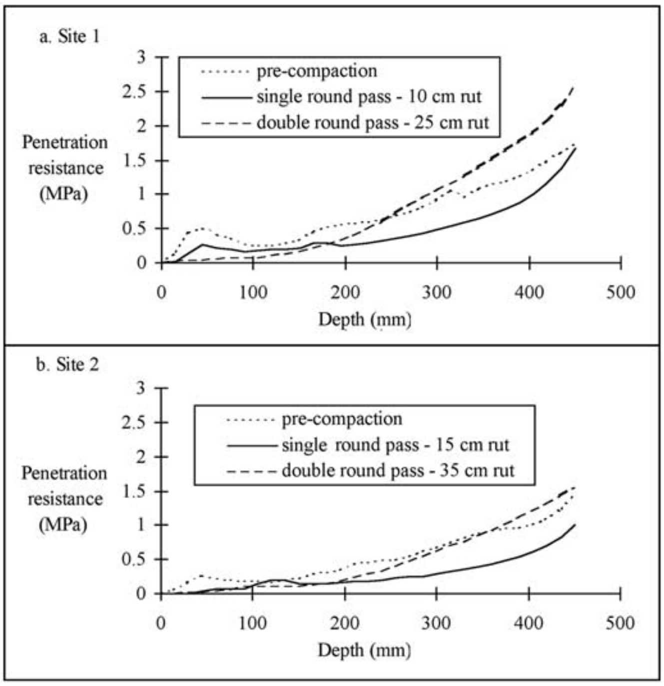

Figure 4. Profile shear vane resistance characteristics of six study sites which expeienced rut compaction to different depths (n = 6)

Figure 5. The effects of multiple forwarder passage during low-soil-strength conditions on profile cone penetrometer resistance (n = 6)

reduction in post-compaction cone penetration resistance at depths of 250 - 350 mm in both the 3 and 5 cm ruts (Fig. 2).

Pre-compaction cone penetrometer resistance and shear vane resistance characteristics (average of six recordings) for the six study sites that received a single-round forwarder pass are shown in Figures 3 and 4 respectively. For both parameters, there is a strong inverse correlation between eventual rut compaction depth and pre-compaction strengths. A comparison of Figures 3 and 4 suggests that shear vane resistance may be a more sensitive parameter for predicting eventual rut compaction than cone penetrometer resistance.

At the two sites that received a second-round forwarder pass, rutting depths increased from an average 10 cm to 25 cm and 15 cm to 35 cm respectively. The pre-, post-one-pass and post-two-pass penetrometer resistance characteristics of these sites are shown in Figure 5. Both sites experienced significant mass failure following the second forwarder passage.

Measurement of rutting depth was complicated by considerable variation over short distances, particularly in the deeper ruts. For example, at the site where rutting depths averaged 25 cm, depths varied from 10 - 35 cm over short distances. Major factors observed to affect variability along a rut included:

- Ground vibrations produced by the harvester varied as the machine progressed down an outrow. Compactive forces appeared greatest when the harvester was stationary (but vibrating) for the purposes of cutting and lifting trees, particularly when the boom was extended.

- Compactive forces produced by the forwarder are also not uniform along an outrow: Ground vibrations appeared greatest when the forwarder was stopped and collecting logs. Interestingly, even though there was a notional single-round pass of the forwarder, the machine actually moved back and forward over short distances in order to attain an position from which logs could be efficiently collected, thus effectively resulting in double passes over short distances.

- The *Pinus* root system, which is an important component of resistance to rutting in low-soil-strength soils, was not uniform along an outrow. Root characteristics such as diameter distribution, frequency and depth (which affect the ability of lateral roots to resist compaction), and the density and spatial arrangement of fine/lateral roots (which affect the ability of surface root mats to resist compaction), showed considerable spatial variation (see also the data presented for root distributions in Study 1 of Paper I).

- The density and distribution of both branches left on the forest floor following de-limbing by the harvester, and natural needle and branch litter, varied along outrows. The former, in particular, can be a significant component of soil profile strength, resisting compaction forces from a single forwarder passage (Wronski *et al*. 1990).

Other factors which may have contributed to heterogeneity along ruts include: (i) variations in soil moisture content, and hence soil strength, as a result of variations in soil profile wetting characteristics, surface hydraulic conductivities (Costantini *et al*. 1995), soil drying processes and depths to transient watertables and impermeable layers; and (ii) variations in soil factors affecting compressibility (Greacen and Sands 1980; Larson *et al*. 1980).

Discussion

The observations that soil moisture content systematically increased (Fig. 1), pre-compaction penetrometer resistance systematically decreased (Fig. 3) and pre-compaction shear vane resistance systematically decreased (Fig. 4) as the magnitude of rut compaction increased are consistent with theory (for the coastal lowlands soil types see Costantini 1996). For each of these soil parameters, it is relatively easy to separate pre-compaction conditions that led to rut depths of 3 and 5 cm from those that led to rut depths ≥10 cm (Figs 1, 3 and 4). On the basis of data presented here, it would appear possible to develop a model for predicting when 'average rutting depths will exceed 5 cm' based upon one, or a combination of, these parameters. However, such a model is likely to be specific to the harvesting system described, and soil type tested.

A comparison of Figures 1, 3 and 4 suggests that soil moisture content was best able to separate sites which experienced ≤5 cm rut depths from those that experienced ≥10 cm rut depths. Of the three soil parameters tested, however, techniques for rapid *in situ* measurement of soil moisture are the least well developed. Various probes are available, but these may require calibration, can be expensive and can be fragile. Moreover, it is likely that any compaction risk model using soil moisture as a variable would need to be calibrated for various soil types. This likelihood is reinforced by the fact that relationships between soil strength and soil moisture content in the coastal lowlands are dependent on soil type (Costantini 1996). Of the two strength parameters tested here, cone penetrometer resistance and shear vane resistance, the latter is better able to separate sites which experienced ruts ≤5 cm deep from those that experienced ruts ≥10 cm deep. Compared to vane testers, however, commercially available, electronic penetrometers are easier to use, particularly where a number of replications are required.

None of the soil parameters tested was unequivocally able to separate sites that experienced ruts ≤10 cm deep from those that experienced ruts ≥15 cm deep (Figs 1, 3 and 4). It would seem therefore that compaction prediction models based on these soil parameters would provide a much higher degree of confidence in predicting rut depths ≤5 cm than ≥10 cm.

For the study soil, overt evidence of mass failure was observed in the ≥15 cm ruts, and increased with increasing rut depth (Table 2). Where 10 cm ruts were formed, there was occasional 'cutting' of the soil surface, though the ground cover of *Pinus* needles and branches was typically left intact. Indeed, the data presented in Figure 2 suggest that mass failure and severe compaction damage can occur in ruts even where overt evidence of mass failure such as cutting of the surface and soil displacement/puddling, is absent. For the 3 and 5 cm ruts, compaction has increased cone penetrometer resistance in the surface 250 mm, consistent with an increase in bulk density in the absence of structural degradation. In the ≥10 cm ruts, post-compaction penetrometer resistance is either equal to, or less than, the pre-compaction penetrometer resistance, notwithstanding an obvious increase in bulk density as evidenced by the rut itself (for a discussion on how increasing compaction can decrease aggregate strength, see Gupta and Allmaras 1987).

These findings support the guideline for acceptable rut depth used in Queensland *Pinus* plantation management, namely 'rut depth should not exceed 10 cm for any accumulative distance exceeding 10 m in every 100 m of rut'. The measure of rut depth used in this study, namely 'average depth over 3 – 5 m', is not strictly comparable to the guideline measure of acceptable rut depth. In reality, the guideline acceptable rut depth will be intermediate between the 'average 5 cm' and 'average 10 cm' rut depths described in this study.

From the evidence presented here, prediction models for compaction are likely to be harvesting system and soil type dependent. For example, ground-snigging extraction systems, involving more frequent passes with lighter total loads, will have compaction effects which differ to those of forwarder-based systems. It is also evident from Figure 5 that different prediction models would be required for the same harvesting system if different intensities of operations were contemplated (see also MacDonald *et al*. 1993). To have practical relevance, a compaction prediction model would need to be developed for a particular harvesting system and include a parameter such as 'length of outrow' as a surrogate for expected number of passes. Given the range of harvesting systems used and the number of major soil types encountered in the coastal lowlands of south-eastern Queensland, either a number of narrowly-focussed models, or fewer larger integrated models, would need to be developed.

Predictive models will clearly require more research data for development and verification than is required to develop a reactive approach to controlling excessive compaction. Because of the need for rapid development of guidelines in the early 1990s and the lack of time available to collect data for development and calibration of predictive models, the 'reactive' approach was selected for use in Queensland *Pinus* plantations (Paper I).

Preliminary findings from this study suggest that prediction models of compaction could be developed for use in the coastal lowlands using either soil moisture content, penetration resistance or shear vane resistance as variables. However, there is a risk that modelling error, resulting either from errors in the measurement/estimation of input variables and/or errors in model formulation, may be too large to fully replace reactive systems for avoiding excessive compaction. For example, the accuracy of any predictive function used in model development may be such that some high-compaction-risk areas may fail to be identified, and thus be seriously degraded by harvesting during low-soil-strength conditions (see also Butt and Rollerston 1988).

Conclusions

It may be possible to develop models that predict soil compaction which can be used in planning harvesting of *Pinus* plantations, using soil parameters such as soil moisture content, penetration resistance and shear vane resistance as variables. Any predictive functions used in these models, however, are likely to be dependent on the harvesting system, harvesting intensity and soil type – thus requiring a considerable data base for both model development and calibration.

In the short to medium term, it is likely that predictive models, if developed, will be used only to supplement, not replace, the 'reactive approach' developed for use in Queensland, namely: *'Machinery operations are permitted in* Pinus *plantations until depths along an accumulative 10 m of ruts in any 100 m length of hillslope exceed 10 cm – at which time, further operations are prohibited until soil strength increases sufficiently to avoid this level of rutting'*.

References

Butt, G. and Rollerston, T. (1988) Prediction of forest soil compaction. British Columbia Ministry of Forests, Land Management Report 56. pp. 153-166.

Costantini, A. (1996) 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-eastern Queensland. *New Zealand Journal of Forestry Research* **26,** 395-412.

Costantini, A. and Doley, D. (2001) Management of compaction during harvest of *Pinus* plantations in Queensland: I. Policy considerations for controlling machine activity. *Australian Forestry* 64, 181-185.

Costantini, A., Loch, R.J., Glanville, S.F. and Orange, D.N. (1995) Evaluation of potential to dispose of sewage sludge in forest plantations on the coastal lowlands of south-eastern Queensland: I. Soil hydraulic properties and overland flow. *Australian Journal of Soil Research* **33,** 1041-1052.

Froehlich, H.A. (1980) Predicting soil compaction on forested land. USDA-Forest Service Equipment Development Centre Report. 7100-Engineering. 120 pp.

Greacen, E.L. and Sands, R. (1980) Compaction of forest soils: A review. *Australian Journal of Soil Research* **18,** 163-189.

Gupta, S.C. and Allmaras, R.R. (1987) Models to assess the susceptibility of soils to excessive compaction. In: Stewart, B.A. (ed.) *Advances in Soil Science. Volume 6.* Springer-Verlag, New York. Pp. 65-98.

Isbell, R.F. (1996) *The Australian Soil Classification*. CSIRO Publishing, Victoria. 143 pp.

Larson, W.E., Gupta, S.C. and Useche, R.A. (1980) Compression of agricultural soils and eight soil Orders. *Soil Science Society of America Journal* **44,** 450-457.

MacDonald, T.P., Stokes, B.J. and Aust, W.M. (1993) Soil physical property changes after skidder traffic. American Society of Agricultural Engineers Pububublication No. 93-7508. 15 pp.

Northcote, K.H. (1979) *A Factual Key for the Recognition of Australian Soils*. Rellim Technical Publications, Adelaide, South Australia. 124 pp.

Raghavan, G.S.V., Alvo, P. and McKyes, E. (1990) Soil compaction in agriculture: a view toward managing the problem. *Advances in Soil Science* **1,** 1-36.

Wronski, E.B. (1985) Prediction of soil trafficability in a karri forest, Western Australia. *Australian Forest Research* **15,** 367-380.

Wronski, E.B., Stodart, D.M. and Humphreys, N. (1990) Trafficability assessment as an aid to planning logging operations. *Appita* **43,** 18-22.