Management of compaction during harvest of *Pinus* plantations in Queensland: I. Policy considerations for controlling machine activity.[1]

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Summary

The approach used to control compaction damage during forest harvesting in *Pinus* plantations established on coarse-textured soil types in Queensland is to allow year-round harvesting/extraction operations, and prescribe compaction mitigation measures that, *inter alia*, prohibit machine operations when compaction risks are determined to be excessive.

In this paper, alternative approaches to controlling harvesting-induced compaction are examined. This is followed by a discussion of two techniques for determining when compaction risk is excessive for ground-based harvesting: (i) predictive models; and (ii) reactive approaches. With the first, predicted compaction damage is compared to a criterion of 'acceptable' compaction in order to determine when machinery operations should be suspended and/or to schedule harvesting in compartments where compaction damage is not expected. The 'reactive' approach is based upon allowing harvesting/extraction operations to occur until an 'unacceptable' compaction condition results, at which time further operations are prohibited until soil strength increases.

Because of pressure for rapid development of guidelines in the early 1990s, the 'reactive' approach has been used in Queensland. Rut depth and shearing were selected as easily and reliably measured indices of compaction damage. In addition to describing these developments, the notion of 'acceptable' compaction is discussed, and justification given for the 'level of acceptable compaction' incorporated into the guidelines.

Keywords: soil compaction, logging machines, logging effects, forestry practices, *Pinus*, Queensland, Australia

Introduction

The Queensland Department of Primary Industries Forestry (QDPI-Forestry) has established some 110 000 ha of *Pinus* plantations, mainly on coarse-textured soil types in the State's sub-tropical coastal lowlands. Large-scale clearfell harvesting of this resource commenced in the late 1980s, and was accompanied by increased mid-rotation thinning activity as markets for small piece-sizes were developed. At the time, there was an urgent need to develop strategies and techniques for managing compaction during harvesting operations. The three papers in this series detail both the system for managing compaction in Queensland *Pinus* plantations, and its rationale.

Management systems for controlling harvesting (including extraction) induced soil compaction are often referred to as 'wet-weather harvesting systems'. The 'wet-weather' descriptor needs to be broadly defined to include 'wet-soil', or low soil strength, conditions. In reality, compaction is readily avoided during periods of wet weather, typically by precluding machine operation both when heavy rain is falling, and for brief periods following actual rainfall, for example when runoff is flowing in road table drains. The more difficult challenge for forest managers is to avoid compaction during periods of high soil moisture (low soil strength), which persist after rainfall for a length of time dependant upon soil type, landscape position, antecedent moisture conditions and rainfall characteristics.

The primary function of wet-weather harvesting systems is to prescribe when and how harvesting operations can occur. There are a number of possible approaches to designing these systems (Fig. 1), each of which affects three of the major forest industry stakeholders - forest growers, harvesting operators and wood-using industries - in different ways. From the growers' perspective, the major approaches to compaction management (Fig. 1 - Row 2) involve: (i) suspending operations during wet seasons when risks of compaction damage are high; (ii) permitting operations year-round on the basis that any compaction degradation be remediated following harvesting/extraction; or (iii) permitting operations year-round on the basis that the wet-weather harvesting system can control compaction damage and prescribe specific periods when operations are to be precluded. The second approach is difficult to reconcile with the goals of sustainable forest management (Commonwealth of Australia 1992), which are based on protection of ecological systems and avoidance of degradation, rather than allowing degradation and requiring remediation. Moreover, standard techniques for remediating compaction are not universally successful in the coarse-textured soils used for *Pinus* plantations in Queensland (Costantini and Doley 2001a).

There are two distinct, but possibly compatible, strategies for implementing each of the second and third approaches (Fig. 1 - Row 3). From the harvesting and wood-using sectors' perspectives, economic considerations will influence choices in both the short and long term. Strategies 1 and 2 in Figure 1 are practical only if the 'wet' season, or the period of high compaction risk, is well defined. Strategy 1 requires that both sectors carry overhead capital costs during unproductive stand-

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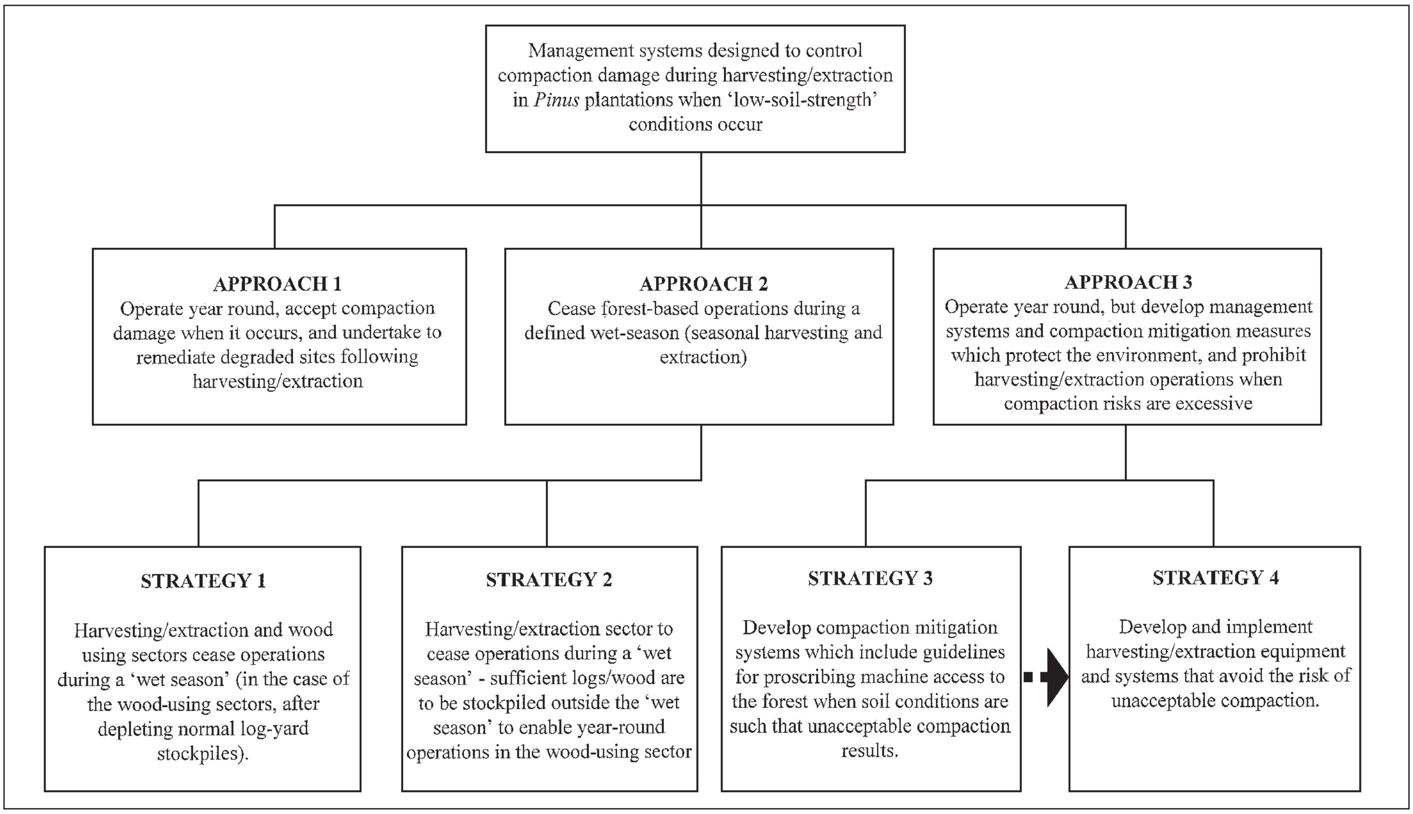

Figure 1. Conceptual model of alternative approaches to controlling compaction damage that can result from forest harvesting conducted during periods of low-soil-strength

down periods, thereby considerably reducing the efficiency of modern, large-throughput, low-profit-margin enterprises such as those based on the Queensland *Pinus* resource. Strategy 2 requires that logs (or partially-processed product, such as chips) be stockpiled and stored, either in the mill-yard or, where the risk of degradation is high, in specialized storage facilities. The latter is the more expensive, though both involve: (i) increased stand-down costs and, if more logs need to be harvested in less time, higher operational costs for the harvesting sector; (ii) double handling of some logs and possible degrade of timber (Wronski *et al*. 1990); and (iii) increased inventory and storage costs for the wood-using sector. Strategy 3 tends to be the preferred short- to medium-term option for the harvesting and wood-using sectors in Queensland. It optimises log flow, use of harvesting equipment and use of capital invested in the wood-using sector. From the forest grower's perspective the strategy is acceptable providing compaction mitigation strategies are effective.

Strategy 4 in Figure 1 is a medium- to longer-term option requiring enhancement of presently used harvesting systems; and development of low-compaction-risk technology, such as aerial, cable, excavator-based, and improved ground-based extraction systems. The dashed arrow in Figure 1 indicates that Strategies 3 and 4 should be viewed as a continuum: developments in harvesting systems should be in the direction of Strategy 4. While the ideal outcome of development efforts would be harvesting systems that avoid unacceptable compaction, a more realistic outcome would be for new systems to reduce compaction risks, but still require use of a Strategy 3 management approach.

Indeed, the cost of implementing 'low-soil-strength harvesting systems' and of using Strategy 3 (Fig. 1) compaction mitigation measures, will influence industry investment in the development of new harvesting technology. Forest growers will weaken these economic incentives if they are lax in applying compaction mitigation measures. For example, a forest grower who allows repeated access to forests and incurs unacceptable compaction because mill-yard log stocks in the wood-using sector are depleted, would: (i) reduce market incentive to invest in new systems; and (ii) subsidise the wood-using sector by internalising the externality costs of compaction-related decline in productivity and sustainability.

Compaction mitigation measures (Strategy 3, Fig. 1) used in Queensland *Pinus* plantations include: scheduling of 'dry-weather' compartments for access during wet periods; minimizing unnecessary machine passes; maintaining surface organic matter cover; configuring machinery so that compactive forces are minimized; and on low-strength soils, prohibiting access where these measures are not sufficient to avoid unacceptable levels of compaction. In addition to the above measures, harvesting systems that stockpile logs at roadside can assist in maintaining log supply to industry users when plantations cannot be accessed. However, if more than one to two days of log supply is accumulated, the risks of wood decay and roads becoming impassable, increase. The challenge in designing and developing mitigation measures is to ensure that unacceptable compaction is avoided, and that log supplies to the harvesting and wood-using sectors remain adequate.

The earlier system used by QDPI-Forestry for managing compaction during forest harvesting required that machinery 'be excluded during heavy rainfall events when runoff water flowed in road table drains, or when the local forest manager considered compaction to be excessive'. The subjective nature of this second criterion meant that machinery exclusion measures were potentially inconsistent in their application and difficult to audit. This lack of objectivity made the forest manager's task of balancing compaction mitigation against demands by the harvesting and wood-using sectors for logs more difficult. There was a risk of favouring one of these at the expense of the other. Furthermore, the subjective nature of decision-making risked damaging relations between forest growers and the harvesting and wood-using sectors. User-friendly and soundly-formulated objective guidelines for determining excessive compaction risk were desired by Queensland plantation managers in order to ensure consistency and accountability when interpreting harvesting rules.

Systems for identifying when harvesting-induced compaction risks are excessive can be based upon: (i) predictive models; and/or (ii) a reactive approach. The former can be either subjective or objective, and is based upon predictions of likely compaction damage using a particular harvesting system. In reality, the pre-1990s 'low-soil-strength harvesting system' described above required that forest managers use a subjective predictive system to determine when compaction risk was excessive. A widely used technique was to push a stainless steel rod into soil suspected to be at risk, and on the basis of both individual and local knowledge, assess whether 'wetness' on the extracted rod was excessive. An objective system for predicting compaction risk will enable a prediction of either likely compaction damage or of a soil characteristic that is highly correlated with compaction risk – for example, soil moisture content, cone penetrometer resistance or shear vane resistance – to be compared with a benchmark 'acceptable risk' standard. A preliminary investigation of the potential for using these soil parameters to predict compaction risk in *Pinus* plantations in Queensland is reported in Costantini and Doley (2001b). A number of weather-related parameters, such as 'days since last significant rain' may also be suited for use in predictive models.

A 'reactive' approach to identifying periods of excessive compaction risk can be used as an alternative to the predictive approach. Essentially it involves allowing harvesting operations to occur until an 'unacceptable' compaction result is observed, at which time further operations are prohibited until soil strength increases. A qualitative evaluation of the strengths and weaknesses of the two approaches is presented in Table 1. Note however that a system for management of compaction in forest harvesting might include elements of both.

Predictive models require more research data for development and verification than do reactive approaches - though the latter do have to be based on a sound understanding of compaction effects and costs. Moreover separate predictive models, or larger integrated models, are required for different harvesting systems, different intensities of operations and possibly for different major soil types. 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 developed for use in Queensland *Pinus* plantations. Two appealing features of the 'reactive' approach reinforced this decision:

- It satisfied the need for guidelines that could be applied consistently and uniformly, and hence applied equitably to a wide range of harvesting systems;

- It encouraged and rewarded operators who used 'compaction-friendly' harvesting systems.

Table 1. A qualitative comparison of predictive and reactive systems for defining excessive soil compaction risk

System	Strengths	Weaknesses
Objective predictive model	1. Does not require that actual compaction damage occur in the field. 2. Can be used by both forest grower and harvesting/extraction sectors to assist planning. 3. Can be used by harvesting/extraction operators to assess compaction risks in a number of plantation areas, and avoid excessive and expensive movement of machinery to high risk areas. 4. May ultimately be modelled.	1. Needs to be developed for each harvesting system, and each harvesting technique (for example, 1, 2 or more passages with a particular machine). 2. Confidence limits on predictions of compaction risk may be large. 3. Depending upon parameters used, models may need to be developed for a range of soil types. 4. Model development and calibration both have a high demand for research data.
Reactive approach	1. Simple and easy to use. 2. Can be used with all harvesting systems in all soil types. 3. Based upon real effects, and therefore is more readily accepted by industry. 4. Not harvesting system specific, and actually 'rewards' operators who use 'compaction-friendly' harvesting systems.	1. Some limited damage may occur in the field before machinery exclusion provisions are activated. 2. Does not provide harvesting/extraction operators with a system for evaluating compaction risk in a wide range of plantation areas - and thus increases the risk that moving equipment from a compartment where compaction has been excessive to a 'dry weather' compartment may still result in unacceptable compaction.

The notion of acceptable compaction

Both the objective predictive and the reactive approaches to identifying excessive compaction risk require that either 'excessive compaction' or its antonym, 'acceptable compaction', be quantified. There is no general agreement, however, about what constitutes acceptable compaction. Moreover, because compaction affects a number of soil parameters that influence physical soil fertility, any definition of acceptable compaction needs ideally to be expressed in terms of multiple soil properties (Lerink 1990). Notwithstanding these deficiencies, a definition of acceptable compaction, even if interim, is needed to underpin any functional compaction management system. Further, for the sake of operational efficiency, the definition will ideally be based upon easily measured and understood soil properties.

There are situations, for example in very low-bulk-density soils or soils with poor moisture holding capacity, where modest compaction may improve a crop's growing environment. These are rare in forestry, however, and do not occur in QDPI-Forestry *Pinus* plantations subsequent to seedling establishment. Indeed, even modest compaction of the coarse-textured soil types throughout the Queensland *Pinus* estate will adversely affect crop growth (Costantini 1995; Costantini *et al*.1996; Costantini and Doley 2001a; and see also Sands and Bowen, 1978; Sands *et al*. 1979 and Sands 1983 for *P. radiata* plantations established on coarse-textured, low-organic-matter soils similar to those experienced in Queensland). Ideally, therefore, the acceptable level of compaction should be zero. However, zero compaction is probably impossible to achieve in the short- to medium-term.

Efficient wood production requires mechanisation, and virtually any level of mechanical activity will result in some compaction. The challenge then is to: (i) minimize compaction; (ii) ensure that developments in harvesting technologies are 'compaction-friendly'; (iii) define a level of compaction that adequately protects both soil ecological processes and plantation productivity; and (iv) ensure that this acceptable level of compaction is not exceeded.

A prescribed level of acceptable compaction should be based upon a sound understanding of compaction effects on key ecological processes and *Pinus* productivity. However, our understanding of these effects is likely to be incomplete at least in the short to medium term, and it is important therefore that management systems which prescribe an acceptable level of compaction be supported by active research (Costantini and Gilmour 1993). Consequently, short-term definitions of acceptable compaction should be viewed as transitional planning entities that will be regularly reviewed.

Importantly, guidelines for acceptable compaction should be user-friendly: any necessary measurement and data interpretation will ideally be reliable and easy to use by field staff. For example, a guideline such as 'compaction is acceptable if less than a 10% weighted increase in bulk density occurs on areas other than dumps and roads' is not user-friendly. This example has been chosen because the 10% value has recently been suggested for use in California (United States Department of Agriculture Forest Service 1993), though it is expressed in terms of soil porosity reduction. Limitations of such a guideline include:

- The depth of compaction effect and the area of compartment to be assessed are not defined.
- Assessment is not easily undertaken by forest managers, and results are likely to be available only after a number of days. They cannot therefore be used to assist in daily forest planning.

This guideline would be relevant only to research projects, where the effects of operational practices in representative areas are being evaluated (in this context, see Australian and New Zealand Environment and Conservation Council 1995).

A compaction management system for Queensland based upon a reactive approach to identifying excessive compaction

In order to avoid the problems highlighted by the guideline example discussed in the preceding section, rut depth and shearing were selected as indices of excessive compaction for the purposes of controlling harvesting in Queensland *Pinus* plantations (see also Wronski *et al*. 1990). These indices apply to the general forest area, and are not intended for use on roads and tracks that are subject to other guidelines governing use during high compaction risk conditions. Rutting is defined to have occurred when the soil has been clearly compacted due to machine pressure, and does not require that the mineral soil be bared. Shearing is defined to have occurred when machine pressure results in a definite break of the soil, and fresh soil is exposed. With modest training, each of the indices can be assessed and interpreted in the field. Compaction is deemed to be unacceptable when: (i) machine pressure causes rutting to a depth exceeding 10 cm for an accumulative distance exceeding 10 m in every 100 m of rut; and (ii) shearing occurs.

These notions of unacceptable compaction are based upon the following research observations in Queensland *Pinus* plantations:

- In a thinning study, rut compaction exceeding 10 cm depth reduced post-thinning productivity, while adverse compaction effects on productivity were not detected for rut depths less than 10 cm (Costantini and Doley 2001a).
- In another thinning study, rut depths greater than 10 cm were associated with structural degradation that was not observed with rut depths of 3 cm or 5 cm (Costantini and Doley 2001b).
- Compaction associated with ruts 15, 25 and 35 cm deep adversely affected physical soil fertility, and the magnitude of damage increased with rut depth (Costantini 1995).
- For most soil types in the coastal lowlands of south-eastern Queensland, soil strength will be limiting to penetration of *Pinus* roots, and any compaction which further increases soil strength is likely to further limit root penetration capacity (Costantini *et al*.1995; Costantini *et al*.1996).

These observations are clearly soil-type specific - and hence the resultant specification of unacceptable compaction may not be relevant to all forest types. For example, all the observations were derived from trials established in either non-mounded plantations, or plantations where small mounds with cross-sectional area of 0.2 m^2 were formed. They may not be relevant to plantations established on the large mounds with cross-sectional area of 0.8 m^2 described by Foster and Costantini (1991), where harvesting equipment passes down the mound furrows. These furrows are typically located in soil horizons of higher bulk density, and are often compacted during silvicultural operations (Costantini 1995). If rut depth is to be used as an index of compaction in the furrows of high-mounded areas, then an 'acceptable' depth may in fact be less than 10 cm.

In the Queensland compaction management system, the definition of acceptable compaction is amended where there is a significant risk of erosion. Costantini (1995) observed that rut compaction indirectly degraded physical soil fertility by decreasing soil infiltration, and thereby increasing runoff and increasing the risk of rill and gully erosion. The compaction management system presently used in Queensland *Pinus* plantations recognizes the potential for erosion where the fall along ruts exceeds 5%, and responds by adjusting the permissible rut depth.

The compaction management system described here is intended for use in harvesting operations. Either the same or a similar system could also be used to guide silvicultural and other operations when the risk of compaction is high.

Conclusions

Because compaction may be persistent and difficult to ameliorate in the coarse-textured soil types used for *Pinus* plantations in Queensland, compaction management will ideally be based upon avoidance rather than rehabilitation. Such a policy of avoiding 'excessive' compaction is consistent with an interpretation of the principles of sustainable forest management which requires that degradation of ecological systems be avoided, rather than be allowed even if remediation is attempted.

In Queensland, a ‘reactive’ approach to identifying excessive compaction risk was developed, based upon objective field parameters that are easily and reliably measured. Harvesting operations are allowed to occur until an unacceptable compaction condition results, at which time further operations are prohibited until soil strength increases. The criteria used to define unacceptable compaction are defined in terms of both rutting depth and shearing.

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