Review of Factors Affecting Disturbance, Compaction and Trafficability of Soils with Particular Reference to Timber Harvesting in the Forests of South-West Western Australia

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Cover photograph: An uncorded extraction track through jarrah forest in the south-west of WA (Taken by Kim Whitford)

Executive summary

1. Background

The Forest Management Plan (FMP) 2004-2013, which covers the forests of south-west Western Australia (SW WA), introduces several new measures to protect soil during harvesting of native forest. Briefly summarized, these measures introduce regular monitoring and soil disturbance surveys of harvesting areas during periods when soils are moist, place limits on the allowable amount of the various types of soil disturbance, and restrict the use of heavy machinery associated with timber harvesting. The restrictions use the Soil Dryness Index (SDI) as the measure to determine whether the use of heavy machinery may proceed. In the high risk period SDI < 250 in spring or < 100 in autumn, timber harvesting operations using heavy machinery for snigging must cease. This equates to approximately five months over the winter and spring period of the year, depending on the location in south-west Western Australia.

With the aim of further progressing the development of these soil protection measures, and providing additional information to assist with a review at the end of a one-year trial of this new system, CALM has initiated a consultancy to review factors affecting trafficability of soils in the south-west forests (CALM RFQ, 2004).

The overall aim of the review is to consider the system and the mechanisms currently employed to manage soil disturbance associated with timber harvesting, and to make recommendations that will assist in the further development of this management system.

The main focus of the review is on the factors that affect the compactibility and trafficability of soils, particularly soil moisture and soil type, and how knowledge of the effect of these factors on trafficability can be used to improve the current management system.

2. Review findings

Critical soil characteristics (Section 2)

The impact of harvest operations on forest soils can be divided into three major categories: soil profile disturbance, soil compaction and soil puddling and rutting.

Soil profile disturbance is usually defined in terms of mixing and/or removal of litter and soil, which may change the physical, chemical or biological properties of a soil. Soil profile disturbance changes bulk density by exposing subsoil, reduces/redistributes organic matter; changes macroporosity and saturated hydraulic conductivity. The loss of surface soil or damage to the soil structure may consequently reduce tree growth. Soil profile disturbance is considered one of the important factors which determines the extent and degree of erosion. Knowledge about soil disturbance is also important in relation to flora, because soil disturbance may result in the local decline of some species, especially rare species and those that regenerate from underground organs. Conversely soil disturbance may be seen in a positive sense where it facilitates the regeneration of desirable species.

Soil compaction occurs when a soil is subjected to an external pressure that exceeds its strength. The result is compression of the soil due to the rearrangement of soil particles and a decrease in pore volume. The movement of harvesting and snigging machinery and logs over soil can cause severe compaction. Compaction can also occur naturally in soils over longer periods as a result of settlement and slumping. Soil compaction increases bulk density, decreases macroporosity, infiltration and saturated hydraulic conductivity. These soil properties may change to such an extent that the resulting land surface may be more susceptible to soil erosion, impede root growth, impede early tree growth and decrease site productivity.

Soil puddling and rutting can be defined as the destruction and loss of soil structure caused by deformation of the soil. Soil puddling occurs when soil is saturated or nearly saturated. Sometimes compaction and puddling occur at the same time and are very difficult to separate.

Soil damage factors (Sections 2, 3, 4, and 10)

The review of factors affecting the degree and extent of soil profile disturbance and compaction during timber harvesting revealed that the factors which are most relevant for minimising disturbance in SW WA are soil moisture content at the time of logging, machinery type, snig track design, soil factors and cording and matting.

The review of the effect of soil moisture on soil compactibility and trafficability showed that the critical moisture content at which maximum compaction occurs for a forwarder would be higher compared to a skidder due to lower drawbar pull of the harvester compared to that of the skidder. In other words, harvesting during winter using a forwarder can continue for longer periods than harvesting using a skidder.

The podsolic duplex and clay soil is likely to be more severely compacted than the red loam soils, in the karri forest. The upland sands and gravels are likely to be less compacted during timber harvesting.

It was concluded that for SW WA the duplex yellow (eg. Dy 3.41) and duplex grey soils (Dy 2.41 on granitic areas) with bleached underlying horizons, are likely to be particularly susceptible to traffic problems in wet conditions experienced over the winter and spring periods. Other soils (for example the karri red loams) in SW WA are well structured, permeable and therefore well drained and have a higher organic matter content. These soils are likely to be less susceptible to traffic problems in wet conditions. A method for classifying soils of SW WA forest into similar compactibility groups is proposed.

Soil trafficability (Section 5)

Some important factors affecting soil trafficability are soil strength, critical soil layer, soil moisture and gravel content. The critical soil layer is the soil layer that supports the machine traffic.

Based on the types of machinery used for harvesting operations in the forest of SW WA, an average depth of 0 to 150 mm is recommended as the critical soil depth for measuring trafficability in the upland sand and gravels; and 200 to 400 mm in karri loams and shallow duplex and clay soils.

Soil moisture content at field capacity, saturation and plastic limit are the most useful criteria for determining soil trafficability of SW WA forest soils. No information is available on the relationship between these criterion and trafficability of SW WA forest soils. As an interim approach, it is recommended that the upper limit of soil moisture for harvesting in autumn or summer should be 99% of field capacity for upland sands and gravels; 95% of field capacity for karri loams and duplex soils; and 90% of field capacity for clay soils. During spring and winter, it is recommended that 95% of field capacity be used for upland sands and gravels; 90% of field capacity for karri loams and duplex soils; and 85% of field capacity for clay soils. These threshold values need to be refined on the basis of operational outcomes over a representative range of sites, seasons and operating systems.

Gravel content (Section 9)

The gravel content is currently used as a strategy to plan and layout snig tracks in SW WA forests. It is recommended to continue the use of gravel content as an indicator of soil trafficability during harvesting of timber in spring and winter in SW WA forests. There is a lack of information on the threshold values of gravel content at which soil compacts or rut occurs. As an interim approach, a threshold gravel content value of 60% is recommended for snig tracks that can be trafficked throughout the winter period when SDI is low.

Soil Dryness Index model (Sections 6 and 7)

The use of the Soil Dryness Index (SDI) model for predicting soil moisture deficit and threshold values for defining the risk of soil damage from harvesting was reviewed. The strengths of the SDI model are that it is a very simple model and easy to understand; and it requires only two input parameters: daily rainfall and maximum temperature. The major weaknesses of the SDI model are: (i) it is not sensitive at the wet end of the drying cycle; (ii) in estimating SDI a hypothetical value of 200 mm is assumed as a maximum soil moisture deficit of a 1-m profile depth; (iii) it does not take into account of variability of soil types; (iv) it estimates evapotranspiration (ET) based on a pan evaporation approach thereby overestimating ET and consequently SDI value; and (v) it does not take into account variability of tree species in estimating ET.

Weaknesses in the current SDI system for SW WA may be overcome in a number of ways including improving the accuracy of the estimated value of SDI and developing threshold values of SDI based on soil types. The accuracy of the SDI model prediction can be improved by better estimation of ET values and calculating SDI values based on rainfall and temperature at the site rather than interpolating from a regional centre. Threshold values of SDI for various risk classes for four major soil types and recommended harvesting practices in SW WA forests are proposed.

Alternative water balance models for determining soil trafficability of SW WA forests were reviewed. These models are better in term of assumptions and application of general soil physical principles in determining various components of the model. However, they require additional input data, which are not available, for SW WA forests. Use of an improved SDI model is likely to be a better option than using an alternative water balance model.

Field measurement of soil trafficability (Section 8)

Soil moisture in one of the key indicators of soil trafficability. A review of field methods for measuring soil moisture revealed that Aquaflex and EnvrioSCAN units are suitable for permanent in-situ continuous monitoring of soil moisture at a number of depths within the soil profile. The Gopher, Diviner and neutron probe have been designed as portable instruments, which are moved from site to site after the soil moisture profile has been recorded. The time domain reflectometry (TDR) probes can be installed semi-permanently or used for one-off measurements. The determination of soil moisture using the TDR or neutron moister meters are likely to be relatively more accurate than that determined by the Aquaflex and capacitance based sensors. Methods that may be appropriate for measurement of soil moisture in the SW WA forests include: (i) installing neutron probe access tubes or TDR probes at strategic locations where weather stations are installed and monitoring soil moisture as a function of depth and time when required; and (ii) using the TDR with two-wire probes for measuring soil moisture before harvest at various locations within a given harvest cell.

A field method for estimating indices of soil moisture (plastic limit and saturation moisture content) is also proposed so that SDI values at the wet end can be verified and trafficability more directly estimated.

Trafficability periods may also be determined by comparing measured values of shear strength with the threshold values of shear strength. If the measured values of shear strength fall below the threshold value then the day could be assigned as non-trafficable. The review of field methods for measuring trafficability of soils revealed that the cone penetrometer is likely to provide more meaningful results on soil trafficability than the shear vane for karri loams and podsolic soils of jarrah forests in SW WA forests. The cone penetrometer is recommended for determining the trafficability of these soils during timber harvesting.

The shear vane can also be used with limited success for measuring trafficability of gravelly soils in SW WA forests. However, this test should be used with other tests when evaluating the soil shear strength.

When using the both cone penetrometer and shear vane for assessing soil trafficability care needs to be taken to avoid solid objects, and a representative range of samples need to be taken to account for spatial variability. Both penetrometer and shear vane methods are not likely to provide meaningful results for soil with more than 30% gravel content.

3. Soil management system recommendations (Sections 11 and 12)

The current soil management system was reviewed and recommendations for the progressive development of the system were presented.

Primary recommendations include:

- Refine broad soil maps where necessary and examine the potential of alternative soil grouping based on Ag WA soil maps.
- Use an improved SDI model and soil groups for prediction of soil damage risk and subsequent

broad-scale planning.

- Monitor soil conditions at the cell level and use this as a confirmation of predicted conditions as a basis for day to day control of harvest operations.
- Use an adaptive management approach for continuous improvement of guidelines relating to cell design, extraction network design and harvest machine systems to minimize soil damage.
- Review and improve the soil disturbance monitoring system, including the definition of damage and the sampling method, and extend monitoring to all risk periods.
- Record the location of current extraction routes and use them in future operations as far as is possible.
- Provide specialised training and certification to practitioners responsible for field monitoring of soil outcomes to ensure accuracy and consistency.
- Implement a collaborative Research and Development program aimed at continuous improvement in planning, operations and performance improvement systems. Use pilot SFM development cells to trial new and improved systems in each season, including the recommendations outlined in this report.

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1. Introduction

1.1 Terms of reference

The Forest Management Plan (FMP) 2004-2013, which covers the forests of south-west Western Australia (SW WA), introduces several new measures to protect soil during harvesting of native forest. These are covered in Appendix 6 of the FMP, which sets out the key requirements for the soil protection measures established by the FMP (Conservation commission of Western Australia, 2005). Briefly summarized, these measures introduce regular monitoring and soil disturbance surveys of harvesting areas during periods when soils are moist, place limits on the allowable amount of the various types of soil disturbance, and restrict the use of heavy machinery associated with timber harvesting. The restrictions use the Soil Dryness Index (SDI) as the measure to determine whether the use of heavy machinery may proceed. In the high risk period SDI < 250 in spring or < 100 in autumn, timber harvesting operations using heavy machinery for snigging must cease. This equates to approximately five months over the winter and spring period of the year, depending on the location in south-west Western Australia.

Due to the recognized encumbrance this places on the timber industry, the Minister for the Environment approved the implementation of adaptive management trials to investigate methods by which harvesting operations involving the use of heavy machinery for snigging may extend the period of operation into the high risk period. After a one-year trial of this new system, the new soil protection measures introduced by the FMP will be reviewed and the results from the various trials considered. Where appropriate the soil protection measures will be revised to achieve the objective of improving soil conservation whilst seeking to minimize unnecessary impacts on those undertaking timber harvesting.

With the aim of further progressing the development of these soil protection measures, and providing additional information to assist with the review at the end of the one-year trial of this new system, CALM has initiated a consultancy to review factors affecting trafficability of soils in the south-west forests (CALM RFQ, 2004).

1.2 Objectives

The overall aim of this review is to consider the system and the mechanisms currently employed to manage soil disturbance associated with timber harvesting, and to make recommendations that will assist in the further development of this management system.

The main focus of the review is on the factors that affect the compactibility and trafficability of soils, particularly soil moisture and soil type, and how knowledge of the effect of these factors on trafficability can be used to improve the current management system. The specific objectives of this consultancy are to:

(i) review the general factors affecting soil profile disturbance and compaction during timber harvesting;

(ii) review specific factors affecting soil compactibility;

(iii) identify those factors most relevant to management for the purposes of minimising soil disturbance and compaction during timber harvesting in SW WA;

(iv) review factors, criteria and threshold values of soil trafficability with reference to SW WA;

(v) review selected water balance models including the Soil Dryness Index model for determining trafficability periods with reference SW WA forests;

(vi) review operational techniques for measurement of soil moisture, indices of soil moisture and trafficability of soils with reference to SW WA forests;

(vii) classify SW WA forest soils into similar compactibility and trafficability groups;

(viii) advise on potential improvements or changes to management practices and operational systems that could be considered reasonably practical for the purposes of minimising soil disturbance and compaction during timber harvesting in SW WA;

(ix) review the current soil disturbance management system; and

(x) provide a plan for the progression and development of the current soil disturbance management system.

This information will contribute to ongoing development and improvement of management practices to minimise soil disturbance and compaction in the SW WA forest, including refinement of the Soil Dryness Index model for assessing the trafficability of soil.

2. Factors affecting soil profile disturbance and compaction during timber harvesting

In forestry operations, the use of ground-based heavy machinery for harvesting, snigging, sorting and carting of logs to a mill is common practice around the world. The effects of harvesting operations on soils have been studied in Australia (eg. Incerti et al., 1987; Lacey, 1993; Rab, 1990; King, 1993; Rab, 1994; Lacey et al., 1994; Huang et al., 1996; Rab, 1996; Rab, 1998b; Raison and Rab, 2001; Lacey and Ryan, 2002; Whitford, 2001, Lacey et al., 2002, Pennington et al., 2004; Rab, 2004; Whitford et al., 2005), Canada (eg., Krag et al, 1986; Lewis and THS, 1991; Lewis, 1988), Malaysia (Jussof and Majid, 1987), New Zealand (Murphy, 1984; McMahon, 1995), South Africa (Grey and Jacobs, 1987), Sweden (Malmer and Grip, 1990) and United States (eg., Froehlich, 1979b; Froehlich et al., 1985; Froehlich et al., 1986). These studies showed that the major impacts of harvesting operations are soil profile disturbance and soil compaction. The degree and extent of soil profile disturbance and compaction during timber harvesting are influenced by various factors, which are discussed below with reference to the SW WA forests.

2.1 Soil profile disturbance

Soil profile disturbance is usually defined in terms of mixing and/or removal of litter and soil, which may change the physical, chemical or biological properties of a soil (Rab, 1990). Soil profile disturbance can be used as an index of the environmental impacts of logging (Dyrness, 1967; Klock, 1975; Bockheim et al., 1975; Krag et al*.,* 1986; Miller and Sirois, 1986; Rab, 1999). Soil profile disturbance changes bulk density by exposing subsoil (Rab, 1994, Rab, 1996), reduces/redistributes organic matter (Sands et al., 1979; Ole-Meiludie and Njau, 1989; Anderson et al., 1992; Ryan et al., 1992); and changes macroporosity and saturated hydraulic conductivity (Rab, 1994). The loss of surface soil may consequently reduce tree growth (Farrish, 1990).

Soil profile disturbance is one of the important factors determining the extent and degree of erosion. Knowledge about soil profile disturbance is also important in relation to flora, because at the harvesting coupe scale soil profile disturbance may result in the local decline of some species, especially those that regenerate principally from underground organs (Ough and Murphy, 1999; Harris, 2004). Conversely soil profile disturbance may be seen in a positive sense where it may be used to facilitate the seed regeneration of desirable species (Cunningham, 1960; NRE, 1998; Flint and Fagg, 2005). The degree and extent of soil disturbance varies greatly, depending on logging method, machinery type, terrain and soil type, and seasonal effects. Rab and Dignan (2002) investigated the effect of slope class (low (0-9^{o}), moderate (10-18^{o}) and steep (>18^{o})), aspect, (north, east, south and west), logging season (winter, moderately wet, and summer, generally dry), snigging method (wheeled or tracked), coupe area (ha), timber volume harvested (m^3/ha), log processing (wheeled or tracked) and geology (igneous, metamorphic or sedimentary) on various types of soil disturbance in the Victorian Central Highlands forests. They reported that there was no significant influence of logging season, machine configuration and site topography on the proportion of the coupe area affected by each soil profile disturbance. The main factor found to significantly influence the extent of soil profile disturbance was the volume of timber extracted per hectare of coupe area. Overall coupe area was also a significant factor in the proportion of topsoil disturbed, with the proportion increasing with increasing coupe area (see Fig. 2.1). The general trend was an increase in litter disturbance and topsoil disturbance and a decrease in undisturbed area and subsoil disturbance with increasing volume extracted per unit area. The decrease in sub-soil disturbance was counter intuitive and assumed to be associated with an increasing depth to sub-soil as site quality increased (the depth of top soil varied from 300 to 500 mm). It is expected that this would mean that for a given depth of disturbance the frequency of subsoil exposure would be greater on poorer sites (less topsoil depth and less vol/ha).

These factors are further explored over a broader range of studies below.

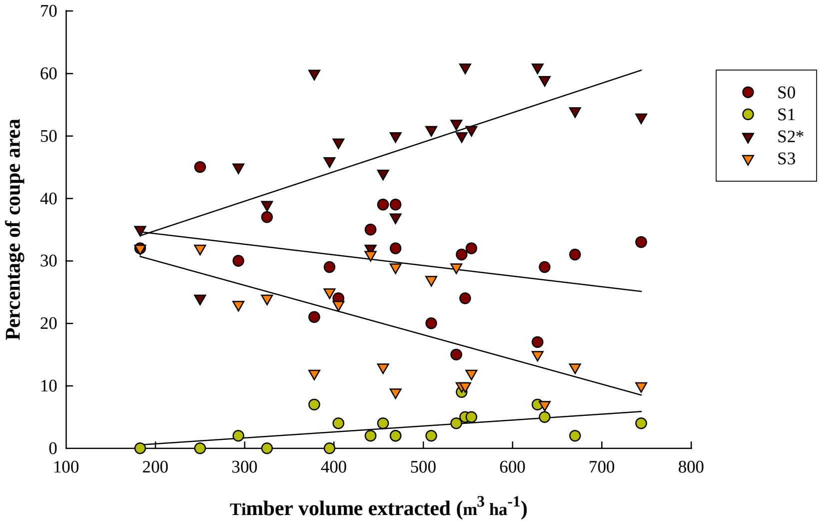


Fig. 2.1 The significant models from logistic regression analysis of the relationship between soil profile disturbance and timber volume extracted, overlaid on the field data. (S0 = undisturbed, S1 = litter disturbed, S2 = topsoil disturbed, and S3 = subsoil disturbed) (Rab and Dignan, 2002).

*** Total coupe area was also a significant factor in the percentage of S2 and was held constant at the mean value of 12.9 ha.**

2.1.1 Logging methods

The effect of logging methods on soil disturbance has been reported from several overseas studies (e.g. Bockheim et al., 1975; Miller and Sirois, 1986), but not specifically from Australian studies. These findings indicate that helicopter or skyline systems produce the least soil disturbance since logs are generally suspended (Table 2.1). Ground-based logging using wheeled and tracked machinery, typical of SW WA harvesting operations, produces more soil disturbance, as snig tracks are required.

Table 2.1 Comparison of mineral soil exposure (% of total coupe area) generated by ground-skidding, cable and helicopter logging systems (Rab, 1992).

Investigator	Ground Skiding	Cable Highlead	Cable Skyline	Helicopter logging
Dyrness (1965, 1967)	35	31	12	nm
Bockheim et al. (1975)	69	29	nm	5
Klock (1975)	74	76	25	12
Smith and Wass (1976)	46	17	8	nm
Krag et al. (1986)	45	31	nm	nm
Miller and Sirois (1986)	31	nm	16	nm
Rab et al. (1992)	63	nm	nm	nm

nm - not measured.

However, to gain this advantage cable systems must be carefully planned and implemented, especially on steep slopes where disturbance can be severe (Krag et al., 1986). Furthermore, studies done by Krag et al. (1986) show that except for snig tracks the source of disturbance was similar for both systems, and cable systems are very expensive. Welburn (1975) estimated total logging costs per unit for rubber-tyred skidders (RTS), steel-tracked skidders (STS), and a variety of alternative cable systems and determined that RTS were least expensive and STS next least expensive. Lack of data on long-term effects of soil disturbance precludes determining whether any increases in site productivity will offset the additional costs of cable logging.

2.1.2 Logging seasons

The seasonal influence on temperature, rainfall, evaporation, daylight hours and other factors such as wood supply pressures can mean that the season of harvest is an important soil disturbance variable, often having a close association with soil moisture conditions. Several workers have reported the effect of season of logging on soil disturbance. Hatchell et al. (1970) studied nine tractor-logged areas on low-lying flatlands with soils of medium-to-fine texture in the USA and reported that wet weather adversely affected both the depth and amount of disturbance as the operator was forced to abandon more areas and cause more damage. Murphy (1982) found three times as much deep disturbance on the wetter of two logging sites in western Oregon that were both stocked with Douglas fir, had the same soil type, and were thinned by the same tractor.

Hammond (1978) (cited by Krag et al., 1986) found that winter logging caused more soil disturbance than summer logging, whereas Smith and Wass (1976) and Krag et al. (1986) observed less disturbance in winter than summer logging. A limited sample size, variability between sample sites, or differences in depth of snow or depth of soil freezing may have confounded the effect of seasonal differences in the Krag et al. (1986) study.

Rab and Dignan (2002) studied the effect of various factors including logging seasons, machinery types and slopes on degree and extent of soil disturbance in the Victorian Central Highlands forests. They reported that about 3% more topsoil disturbance was associated with ‘wet season’ logging.

There are no reported studies of the effect of the logging season on soil profile disturbance in the jarrah and karri forests. However, during winter and spring the risk of soil damage from compaction and rutting is clearly higher than in drier periods of the year (Bradshaw, 1978; Schuster 1979; Wronski, 1984) (see Section 3.1).

2.1.3 Slope

A study by Krag et al. (1986) showed that during timber harvesting slope steepness had a stronger effect than season of logging on soil disturbance. Their data suggested that disturbance increased in both extent and depth with increasing slope. They also reported that snig track related disturbance was greater on slopes >20% than on slopes <20%, and log landing related disturbance was greater on slopes <40% than on slopes >40%. Smith and Wass (1976) also found similar results. They reported that snig track disturbance was twice as high on slopes steeper than 60% than on gentler slopes for winter but not for summer logging.

Garrison and Rummell (1951) (cited in Murphy, 1984) investigated the effects of logging on ponderosa pine forest range lands in Oregon and Washington and found that slope affected deep disturbance for tractor logging. On slopes greater than 40% (22^o) there was 2.8 times the amount of deeply disturbed area as on slopes under 40%, with some gouges up to 1.2 m deep. The greater amount of deep disturbance resulted from more use of fewer extraction tracks. Ninety-eight percent of the forest in SW WA is less than 10^o (17.5%) slope, therefore the effect of slope on soil profile disturbance during timber harvesting in the south-west Western Australia would be minimal compared to that caused by logging seasons, methods and machinery types.

2.1.4 Machine type

The type of machinery used in timber harvesting can be a significant factor in determining the extent of soil disturbance. In the context of this review, which is largely about ground-based systems, steel-tracked skidders (STS) have often been proposed as having a lower impact on soil than rubber-tyred skidders (RTS), due primarily to lower static ground pressures. Some support has been found for this proposition, however it is not unanimous. Murphy (1982) has studied the effect of various types of machinery on severity of soil disturbance. He found that a Clark 66 RTS with its high ground pressure and fast speeds caused more severe soil disturbance than an FMC 100 STS. He also found that the Timbermaster TM70 (RTS) caused less severe disturbance than the Bombardier Muskeg (STS), although the Timbermaster exerted slightly higher ground pressures than the Bombardier Muskeg. This was probably because the Timbermaster had articulated steering while the Bombardier had controlled differential steering (Murphy, 1982).

Rab et al. (1994) reported that the CAT D7G STS (“hard tracked”) crawler tractor caused 6% more topsoil disturbance than the FMC 210 STS (“soft tracked”) and CAT 518 Cable RTS in the Victorian Central Highlands forests. This may be because the CAT D7G is heavier than both the FMC 210 and the CAT 518 Cable. It also appears from this study that FMC 210 and CAT 518 produced a similar amount of topsoil disturbance and subsoil disturbance. McMorland (1980) reported the use of small crawler tractors (e.g. equivalent CAT D4 STS) in place of conventional sized crawler tractors (e.g. D6

STS size) in Nelson Forest Region reduced total soil disturbance by one-third as a result of narrower snig tracks than those created by larger machinery.

A study comparing the effects of shovel logging and RTS on soil attributes (Egan et al., 2002*)* found that shovel logging offered the potential to land felled wood with less impact to forest soils than conventional RTS methods. Shovel logging (7.7%) resulted in significantly less “75% removed litter class” area than RTS (23.5%). Also, about 31% of the RTS treatment area was primary snig track compared to no snig tracks on the shovel logged sites. This can be explained by the shovel “throwing” tree lengths towards treatment edges. Shovel logging relies on a tracked excavator-based grapple to lift and move logs while the machine is stationary. Logs are passed or thrown from stack to stack or in a continuous ribbon across the coupe to the landing (Wilkinson, 2001) for distances of 200-300 m (CSIRO, 1997; Yankee, 2005). The low static ground pressure, due to their large tracks, and moving of logs by lifting or sliding across other logs can result in reduced environmental impacts.

Using Forwarders (eg. 8x8 wheeled/half-tracked) to transport logs can reduce soil disturbance compared to skidders. Their low nominal ground pressure and their mode of transporting logs from the stump to the landing/roadside, means that the ground disruption incidental to dragging logs using skidders is avoided and the drawbar pull reduced. Where there are many smaller pieces (eg. thinnings), the forwarder will require fewer trips as it has a better capacity to be fully loaded than a skidder (Roberts and McCormack, 1991). Also, by having a capacity to extract debarked shortwood to set-out trailers Forwarders can reduce the concentration of extraction tracks close to landings.

2.1.5 Resource removal

There appears to be a difference in the area and severity of disturbance between thinning and clearfelling (Murphy, 1984). Haupt (1960), Froehlich et al. (1981) and Murphy (1982) reported that exposed mineral soil and deep soil disturbance in tractor-thinned stands were considerably lower than those found in tractor-clearfelled areas. These lower values possibly occurred because there was a less choice of extraction routes in thinned stands, a lower volume per hectare was removed and the machine, and load sizes were smaller (Murphy, 1984).

Haupt (1960) (cited by Murphy, 1984) observed that initial stand volume and volume removed were among the factors causing variation in the amount of soil disturbance after partial cutting on gentle slopes in old-growth ponderosa pine. As the removal intensity increased (over a range of 1 to 25 stems/ha), the percentage of area disturbed also increased. On the other hand, a study by Murphy (1982) showed that percentage of area disturbed decreased as removal intensity increased in thinned douglas fir stands in western Oregon. However, there were much greater removal intensities on these logging sites (200 to 550 stems/ha). Once removal intensities were high enough to easily accumulate a reasonable load for the machine, the machine operator pulled the winch-line to the logs rather than driving the machine to them.

2.2 Soil compaction

Soil compaction occurs when a soil is subjected to an external pressure that exceeds its strength. The result is compression of the soil due to the rearrangement of soil particles and a decrease in pore volume (Kirby, 1991). In logging, compaction can occur as a result of the movement of the harvesting and snigging machinery and logs over the soil. Compaction can also occur naturally in soils over longer periods as a result of settlement and slumping (Soane, 1999). Compaction is a process that leads to increased density of soils as a result of the application of stresses, usually of short duration, resulting from passes of vehicle traffic. The degree of soil compaction can be expressed by a number of quantifiable properties including pore space, bulk density and void ratio (Koolen and Kuipers, 1983; Barber et al., 1989; Rab, 1992; Canarache, 1991). However, bulk density is a commonly used measure of soil compaction. Bulk density may be used as an index of relative compaction, but it does not allow an assessment of soil strength, and it is soil strength, which determines resistance to compaction (Greacen and Sands, 1980). Therefore, several authors have used soil strength as a measure of compaction (Paul and de Vries 1979; Bradford and Grosman, 1982; Vepraskas, 1984). Soil strength tends to increase with increasing bulk density, but the relationship is complex (Sands et al*.,* 1979; Gerard et al*.,* 1982).

Soil compaction due to timber harvesting increases bulk density (Gent et al., 1984; Incerti et al., 1987; Jussof and Majid, 1987; Ole-Meiludie and Njau, 1989; Malmer and Grip, 1990; Rab et al., 1992; Aust et al. 1993; Aust et al., 1995; Gent et al., 1983;) (Table 2.2), decreases macroporosity (Gent et al., 1983; Gent et al., 1984; Incerti et al., 1987; Rab et al., 1992), infiltration (Ole-Meiludie and Njau, 1989; Malmer and Grip, 1990) and saturated hydraulic conductivity (Gent et al., 1983; Gent et al., 1984; Incerti et al., 1987; Rab, 1994).

These soil properties may change to such an extent that the resulting land surface may be more susceptible to soil erosion (Johnson and Beschta, 1980; Mackay et al., 1985; Farrish et al., 1993), impede root growth (Heilman, 1981; Mitchell et al., 1982), impede early tree growth (Minko, 1975; Donnelly and Shane, 1986; Farrish, 1990; King et al., 1993a; King et al., 1993b) and decrease site productivity (Perry, 1964; Wert and Thomas, 1981; Lockaby and Vidrine, 1984).

The recovery of compacted forest soils, in the absence of ameliorative treatment, is slow under the influence of climatic processes and the activity of roots and soil fauna. It may take 10-20 or more years for soil to recover after shallow compaction (Dickerson, 1976; Froehlich, 1979; Jakobsen, 1983), while compaction of deeper layers may persist for 50 to 100 years (Greacen and Sands, 1980) depending on soil type, vegetation, moisture conditions, depth of compacted layer and degree of compaction (Greacen and sands, 1980; Rab, 1992; Rab, 1998b, Rab, 2004). The potential negative impacts of soil compaction are summarised in Table 2.3.

During timber harvesting the degree of soil compaction depends on various factors including: the inherent physical properties of the soil, the number of times a vehicle passes over the site, ground pressure of the machinery, and soil moisture at the time of logging (Howard et al., 1981; Butt and Rollerson, 1988; Wronski et al., 1989; Soane, 1990; Rab, 1992; Ghuman and Lal, 1992; Rab, 1998a). These factors are discussed in detail below.

Table 2.2 Comparison of soil bulk densities (Mg/m3) following tractor logging as reported in Australia and overseas (Rab, 1992).

Source	Undisturbed areas	Logging disturbed sites: Harvested areas [A]	Snig tracks	Log landings
		Soil depth: 0-10 cm		
Dickerson (1976)	1.29	1.42	1.55	nm
Froehlich (1979)	0.97	nm	1.14	nm
Jakobsen (1983)	0.90	nm	1.07	nm
Gent et al. (1984)	1.14	1.36	1.52	nm
Incerti et al. (1987)	0.96	0.99	1.22	1.33
Rab et al. (1992)	0.94	1.02	1.12	1.19
Anderson et al. (1992)	0.71	0.86	1.10	1.22
		Soil depth: 20-30 cm		
Jakobsen (1983)	0.98	nm	1.36	nm
Gent et al. (1984)	1.49	1.46	1.61	nm
Rab et al. (1992)	1.08	1.19	1.29	1.48
Anderson et al. (1992)	1.00	1.14	1.32	1.46

[A] Harvested areas: the areas which were not occupied by snig tracks and log landings are defined as harvested areas.

nm - not measured

2.2.1 Machine type

The type of machinery is one of the important factors determining the degree and extent of compaction. Murosky and Hassan (1991) found that a steel-tracked skidder caused a smaller increase in bulk density than did two different rubber-tyred skidders over a range of conditions and at different depths. However, Sheridan (2003) and Burger et al. (1984, 1985) found no significant differences between the soil impact of steel-tracked skidders and rubber-tyred skidders and highlight the dangers in assuming that reduced machine static ground pressures will automatically lead to reduced soil impacts. Other factors such as differences in the operation of skidders are also likely to influence soil impacts. It appears from the study by Rab et al. (1994) that the CAT D7G produced 1.5 times and 1.3 times more snig tracks than the CAT 518 Cable and FMC 210 respectively. This may be because the CAT D7G is wider than both the FMC 210 and the CAT 518 Cable.

Table 2.3 Potential negative effects of severe compaction on root growth of forest trees (DeYoe, 1982).

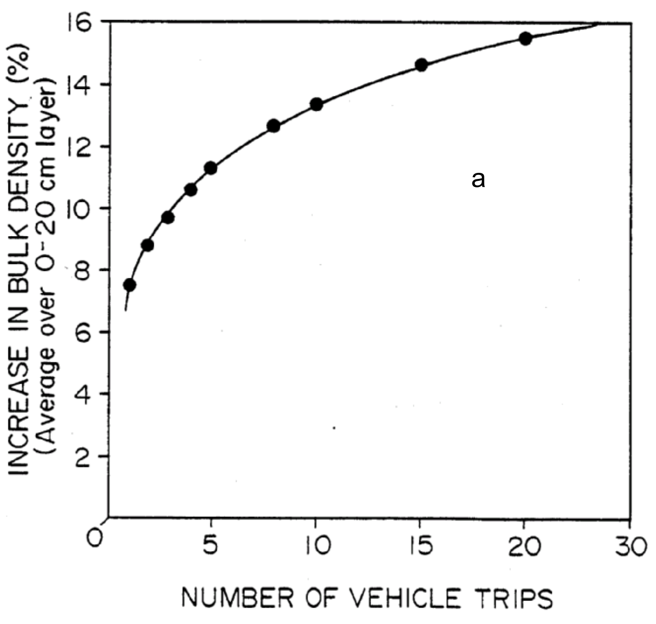
Factor	*Status in compacted soil*	*Potential effects*
Oxygen	Decreased availability	Decrease or cessation of aerobic respiration; anaerobic respiration results in toxin production
Water	Decreased percent water content; availability usually reduced, occasionally enchanted	Mechanism of nutrient acquisition disrupted, reduced cell growth, cell dessication
Nutrients	Increased diffusion rates of most ions; mineralization of nutrients from organic matter decreased	Reduced nutrient availability; reduced efficiency of osmotic; adjustment specific nutrient deficiencies
Temperature	Thermal conductivity and diffusivity increased, leading To greater variations in soil	Growth decreases as temperature declines bellow or increases above optima for cellular reactions
Soil structure	Bulk density and strength increased and porosity decreased	Exerts physical resistance to root penetration; affects oxygen water nutrient availability

A study comparing the effects of shovel logging and RTS on soil attributes (Egan et al., 2002*)* found that while shovel logging offered the potential to land felled wood with less impact to forest soils than conventional RTS methods, compaction impacts, as measured by soil bulk density, were similar on shovel trails and combined RTS primary/secondary snig tracks.

Western Australian experience has indicated that rubber tyred skidders are capable of producing more severe damage than tracked machines due to their ability to continue skidding under more severe conditions of trafficability (Bradshaw, 1978). ‘Soft tracked’ machines such as the FMC skidder were shown to cause less damage than ‘hard tracked’ machines and wheeled skidders but were expensive to maintain. For a given soil type and moisture condition, logging using a skidder is likely to produce more soil disturbance than using a forwarder in the SW WA forests.

2.2.2 Frequency of traffic

Several authors (eg. Froehlich, 1978b; Jakobsen and Moore, 1981; Sidle and Drlica, 1981; Burger et al., 1985; Wronski et al., 1989; Williamson, 1990) have studied the impacts of the frequency of vehicle passes on soil compaction. These studies show that most compaction occurs during the first few passes of a vehicle (Fig. 2.2). Subsequent passes have less effect (Hatchell et al., 1970), but may increase density levels and reduce non-capillary porosity to critical levels for tree growth (Burger et al., 1985). Hatchell et al. (1970) showed that only four passes with a tractor were needed to reach 90% of the maximum obtained density in surface soils in the Atlantic Coastal Plain of USA. Repeated passes with a low-ground pressure skidder on three sites in Oregon, USA, indicated that most of the surface compaction occurred during the first few passes, although density continued to increase in amount and depth with the number of passes (Froehlich, 1978b). Sidle and Drlica (1981) found that increased bulk density of clay loam soil on snig tracks in the Oregon Coast Ranges, USA, was most highly correlated with the number of passes with a low-ground pressure skidder. They also found that the surface 15-cm of soil was compacted more by uphill than downhill skidding.



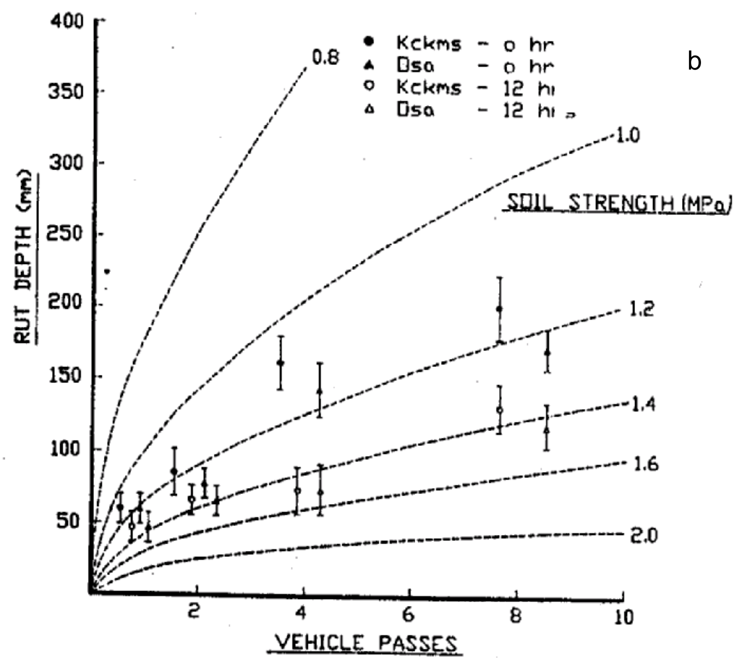


Fig. 2.2 The effect of vehicle passes on (a) soil bulk density (Froehlich et al., 1980) and (b) rut depth (Wronski et al., 1989)

2.2.3 Soil moisture

The potential for soil compaction is greater on wet soils than on dry soils. Moehring and Rawls (1970) found that more severe compaction occurs from traffic on saturated soils than dry soils. Steinbrenner (1955) found that one passage of a tractor over wet soil, which made the soil almost impermeable to water, caused an equivalent reduction in infiltration rate to four passages over dry soil. Sands et al. (1979) reported that sandy soils under *Pinus radiata* plantations in South Australia were considerably more prone to compaction when wet. If the soil is wet enough, puddling can occur. Puddling and compaction can occur simultaneously and their effect can be difficult to separate (Froehlich and

McNabb, 1984).

Burger et al. (1984) investigated the effect of two machine types (RTS - John Deere 540b and crawler tractor (STS)- Komatsu D53A), soil moisture conditions and number of passes on soil bulk density porosity of sandy clay soils in Virginia, USA. They reported that despite the greater contact pressure of the skidder, changes in soil bulk density and porosity caused by the two machines were the same. They also reported that both soil moisture and the number of passes significantly affected these soil properties. Soil bulk density was 56% greater and total porosity was 62% less at 21% compared with 18% soil moisture content.

The logging of both jarrah and karri forest in the SW WA is likely to compact the soil more during winter and spring than during summer.

The effect of soil moisture on compactibiliy of soils is discussed in Section 3.1.

2.2.4 Inherent soil properties

The soil texture, initial bulk density and organic matter content significantly affect the degree of compaction during timber harvesting. Thomas et al. (1969) (cited by Froehlich, 1972; and Murphy, 1984) provided compaction hazard ratings for a large number of soils in the USA. Bockheim et al. (1975) found that in southeastern British Columbia granitic soils were less disturbed by timber harvesting than shales. The effect of soil factors on soil compactibility are discussed in detail in Section 3.2.

2.2.5 Snig track layout

Pre-planning of snig track layout has been evaluated by various authors (Bradshaw, 1979; Froehlich et al., 1981; Murphy, 1982; Olsoon and Seifert, 1984). Froehlich et al. (1981) have demonstrated that snig track related disturbance was reduced by 45-65% from unplanned operations. Murphy (1982) reported that exposed mineral soil and deep soil disturbance as low as 3% and 0% respectively for thinned douglas fir stands with designated snig tracks.

Planning, designing and layout of snig tracks before harvest is likely to reduce the severely compacted area during timber harvesting in SW WA forests. This is further discussed in Section 4.

2.2.6 Cording, matting and brushing

The techniques of cording, matting and brushing refer to the placement of small logs, understorey vegetation, bark and logging slash to create a physical layer over the ground. This layer spreads the ground pressure of the logging machinery and separates the soil surface from their tyres and tracks. These materials can be used either individually or in combination, and have been used very successfully in Victoria and Tasmania to ‘protect’ snig tracks and landings by reducing ground pressure and subsequent rutting. There has been very little reporting of these techniques in the general literature, but some quantitative and qualitative internal reporting by various agencies has occurred. In the highly productive ‘ash’ forests of Victoria, Campbell (2003) found that the use of cording and matting (combined) greatly reduced the area of compacted and sub-soil disturbed coupe. To get an indication of compaction he used a 5 mm diameter wire pig tailed pin (PTP), and compared the relative penetration on snig tracks to other coupe areas. On undisturbed areas he consistently recorded soil penetrations of 25-30 cm for these mountain ash coupes, using the PTP as a cost-effective tool to assess soil structure for root and soil penetration. He found very little severe compaction (<10 cm penetration, see Fig. 2.3). A systematic assessment of 681 m of corded and matted snig track (edge points excluded) indicated that 4 of 53 points (8%) had severe compaction, 34 of 53 (64%) slight compaction (10-19 cm penetration) and 15 of 53 (28%) no compaction (>19 cm penetration). This level of compaction was considered minimal compared to a nearby conventional RTS system. For a comparable section of snig track, 60% of points were severely compacted, 15% slightly compacted and 26% uncompacted (see Fig. 2.4). In a subsequent study (Campbell, 2005), it appeared that where corded and matted snig tracks were side-cut and drainage was poor there was a higher risk of compaction and puddling. These two study sites are characterised by rainfall greater than 1100 mm and deep friable clay loam. In Tasmania, Wilkinson (2000) reported that matting (understorey material and bark), complemented with cording in wet areas, had been adopted extensively by harvesting contractors in the wetter, more productive forests of Tasmania. He also reported that the environmental benefits of cording and matting are profound, with virtually no soil disturbance even on primary snig tracks. He noted that matting/cording can be up to 1 metre thick in places, and for best results any soil disturbance should be avoided prior to laying the matting. In trials of cording and matting conducted in Jarrah and Karri forests of SW WA, Whitford et. al. (2005) reported reductions in snig track compaction. At the jarrah trial sites the reduction in compaction was found to vary on the basis of soil type and the intensity of traffic. Reductions were significant on the lightly trafficked sand and gravel soil site, but not significant on the more heavily trafficked gravelly soil site with shallow sheet rock. In the karri forests, while the reduced compaction in these intensive operations on loamy soils was not large, there was a noticeable improvement in soil outcomes. Compared to previous conventional winter harvesting operations there was an obvious and substantial reduction in rutting and associated soil mixing.

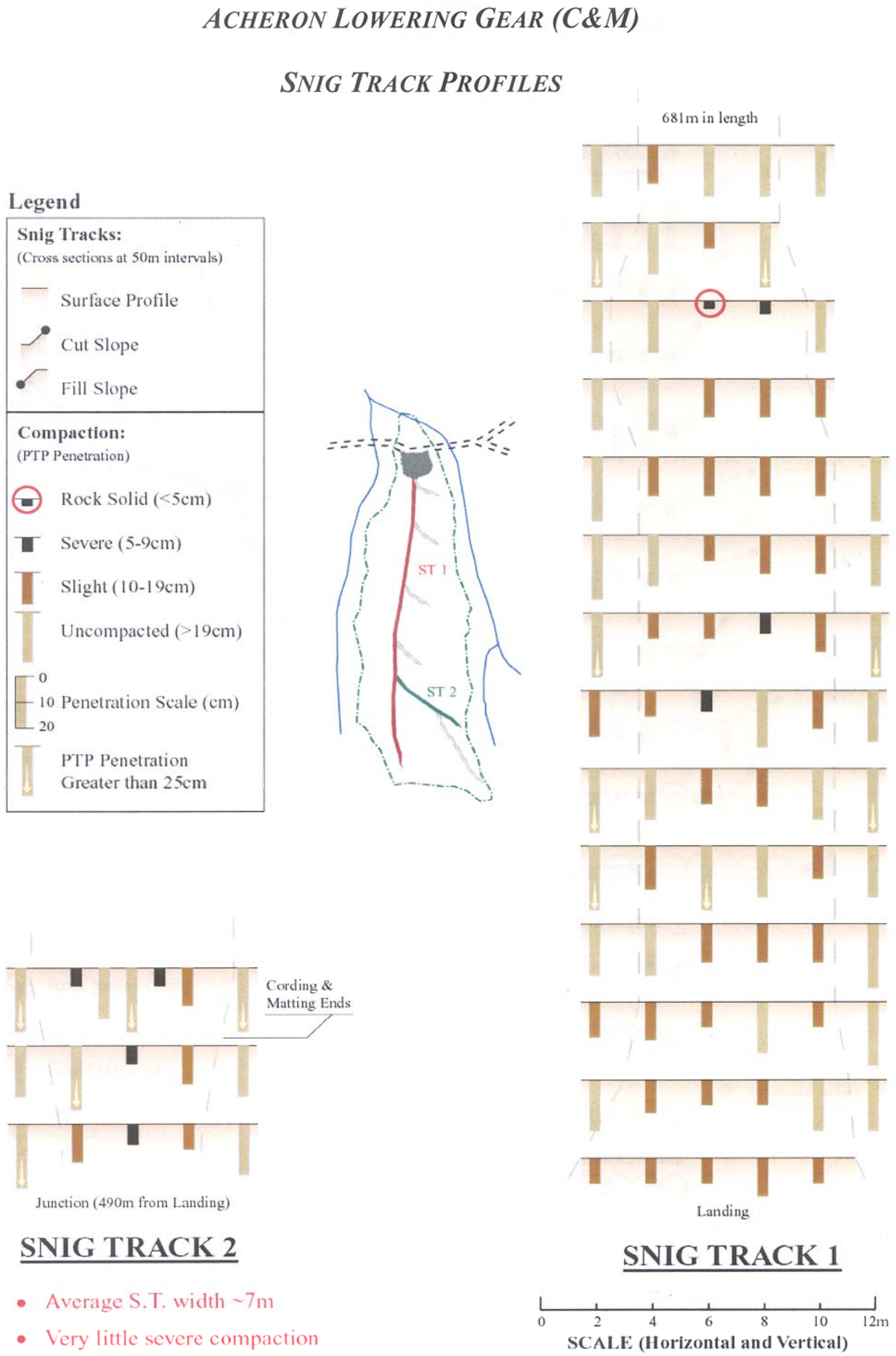


Fig. 2.3 Pig tailed pin penetrations on corded and matted snig tracks, at the 17 ha Acheron Lowering Gear logging coupe, Central Highlands, Victoria (Campbell, 2003).

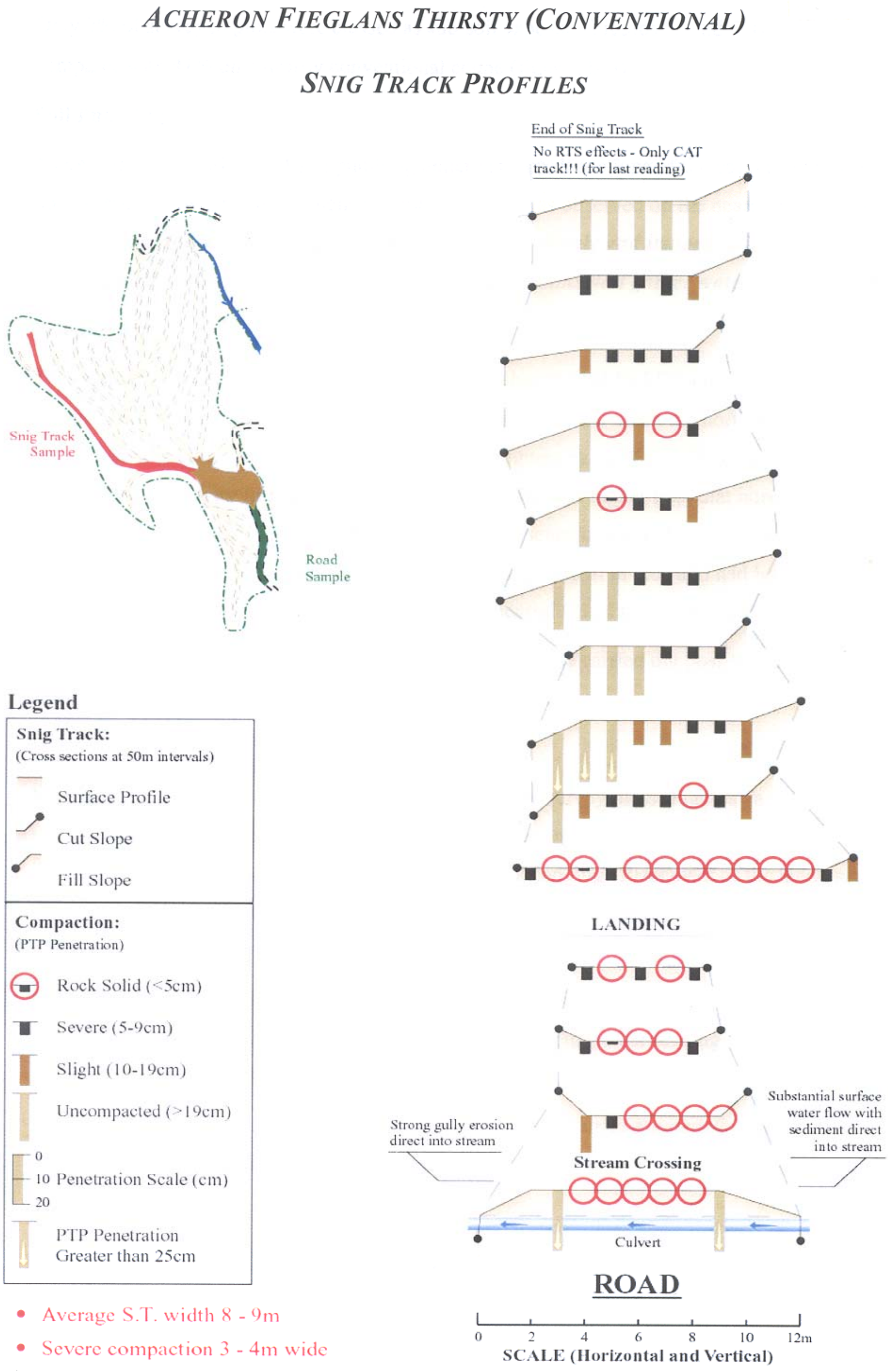


Fig. 2.4 Pig tailed pin penetrations on conventional snig tracks, at the 20 ha Acheron Fieglans Thirsty logging coupe, Central Highlands, Victoria (Campbell, 2003).

2.3 Summary

Important considerations affecting soil disturbance and compaction during timber harvesting can be summarised as follows (see Table 2.4):

Logging systems

- Helicopter and cable harvesting produce minimal soil disturbance where logs are adequately suspended compared to ground-based harvesting methods. The cost-effectiveness of these expensive systems needs to be adequately determined though.

Snig track design

- Planning, designing and layout of snig tracks before harvest is likely to reduce the area of severe compaction and soil mixing during timber harvesting
- Cording and matting of snig tracks and landings has the potential to reduce soil compaction, rutting and soil mixing, particularly when soil moisture levels are high.
- Increasing slope can cause disturbance to increase in both extent and depth. Uphill skidding increases compaction more than downhill skidding.

Harvesting machinery

- Reduced static ground pressures of harvesting machines will not automatically lead to reduced soil impacts. Other factors, such as differences in their operation are also likely to be important.
- Wheeled skidders are likely to cause more soil disturbance and compaction than Forwarders.
- ‘Soft tracked’ machines cause less disturbance than ‘hard tracked’ and wheeled skidders. Shovel logging can result in significantly less surface soil disturbance and can eliminate the need for primary snig tracks.

Soil impacts

- Most compaction occurs during the first machinery passes. Subsequent passes have less effect.
- Soil compaction, due to timber harvesting increases bulk density, decreases macroporosity, infiltration and saturated hydraulic conductivity. The change in soil properties may be sufficient to lead to a decrease in site productivity.
- Recovery of severely compacted forest soils, in the absence of ameliorative treatment is slow.
- Higher soil moisture associated with winter and spring can increase the risk of soil damage from compaction, rutting and soil disturbance compared to drier periods of the year.

Table 2.4 Factors affecting soil disturbance and compaction during timber harvesting with implications for SW WA.

Factors	Comments	Implications for SW WA forests
Logging methods	Helicopter logging causes less disturbance Machine felling and shovelling reduces snig soil damage	Not cost effective, Encourage where possible
Snig track layout	Carefully designed, constructed and maintained snig tracks can reduce soil damage	Wherever practical, design snig tracks to minimize soil damage and optimize harvest efficiency
Snigging machines	Skidder is likely to cause more disturbance and compaction than forwarder	Use forwarder instead of skidder during the high risk periods
Frequency of traffic	Most of the compaction occurs after few passes	Keep snigging machines on designated snig tracks
Logging season and soil moisture	Winter logging causes more severe soil disturbance and soil compaction compared to summer logging	Determine threshold for trafficability Restricts traffic during spring and winter using SDI model and field evaluation
Soil types	Gravely and sandy soil less prone to compaction, clay soils are highly prone to compaction	Harvest forest in sandy soils during winter and shallow duplex and clay soil during summer
Cording, matting and brushing	Reduces soil mixing, removal and compaction in some cases	May be applied on some sites
Resource removal	Top soil disturbance increases with increase in timber volume in the high production forests	Relatively low timber volume removed from SW WA forests Not applicable to SW WA
Slope	Soil disturbance increases with increase in slope.	Slopes in SW WA are relatively gentle Disturbance to due to slope would be minimum compared to other factors eg. soil moisture
Management Systems	Collaborative planning, operations and monitoring improvement systems can greatly reduce damage.	Develop formal practitioner driven processes for continuous improvement based on field outcomes.

3. Effect of soil moisture, soil type and compactive effort on compactibility of soils

Successful planning to minimise soil compaction during logging depends on knowledge of the distribution of soils in the area to be managed, coupled with knowledge of the behaviour of each soil in response to compactive effort. Traditional approaches in assessing the susceptibility of soils to compaction have usually involved the determination of maximum bulk density (MBD) or compression index (C). MBD is a useful physical value as it may be used as a reference point to describe the degree of compactness of a soil and the potential for soils to develop high bulk densities (Smith et al., 1997b). Soils with the highest MBD are judged most susceptible. However, some coarse textured soils (eg. sands) usually have high bulk density compared to medium to fine textured soils. The compaction of the coarse textured soils will result in a higher MBD compared to fine-texture soils. It is the shape of the moisture-density curves which determines the compactibility of soils rather than MBD value itself.

Several factors influence soil compactibility, for example, soil texture, organic matter, inherent bulk density and most importantly soil water content and compactive effort (Thacker et al., 1994). These are discussed below. These factors also influence soil trafficability (see Section 5).

3.1 Effect of soil moisture

Civil engineers for many years have used the Proctor Compaction test (Proctor, 1933) to determine the moisture content at which maximum bulk density (MBD) occurs (Fig. 3.1), known as the optimum moisture content (OMC). In agriculture this is called 'critical moisture content' (CMC) because soil compaction is undesirable (Saini et al., 1984; Stone and Ekwue, 1993). More recently, this test has been used to determine MBD and CMC to study the compaction behaviour of agricultural soils (eg. Soane et. al., 1972; De Kimpe et al., 1982; Felton and Ali, 1992; Thomas et al., 1996, Wagner et al., 1994; Ekwue and Stone, 1995, 1997; Zhang et al., 1997; Mapfumo and Chanasyk, 1998; Aragon et al., 2000; Ball, 2000) and forest soils (Froehlich et al., 1980; Howard et al., 1981; Murphy and Robertson, 1984; Beekman, 1987; Smith et al., 1997a; Smith et al., 1997b).

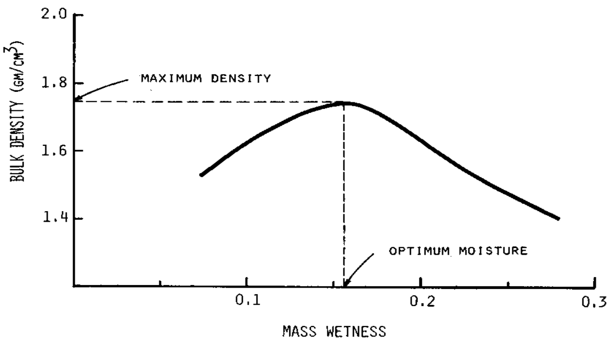


Fig. 3.1 A typical moisture-density curve for a medium textured soils, indicating maximum bulk density with a particular compactive effort (Hillel, 1982).

Compaction curves determined using the Proctor test have been used by some logging managers in North America to help make management decisions about whether machines should be permitted to work at certain critical soil moisture conditions. However, in one American study (Froehlich et al., 1980; cited in Murphy and Robertson, 1984;) where actual compaction by normal ground extraction logging equipment was compared with that achieved by the laboratory Proctor test, it was found that the laboratory test was too severe and that as a result the moisture content at which maximum damage would have occurred was unpredicted (Murphy and Robertson, 1984). A modified version of the test with only 8% of the compactive effort provided a reasonable estimate of actual snig track bulk densities after 20 round-trip passes with logging machines. That the standard compaction test gave erroneous result was not unexpected; the standard test is designed to show what you can do if you really try to compact the soil. Provided a logging manager recognises this difference, the compaction curves are still of considerable use; they give a very strong indication of soils which are particularly sensitive to compaction and will help to identify forest soils that need care at the time of logging (Murphy and Roberston, 1984).

Numerous authors investigated the effect of soil moisture content at various levels of compactive effort on compactibility of both agricultural and forest soils around the world (eg. Saini et al., 1984; Ohu et al., 1987; Stone and Ekwue, 1993; De Kimpe et al., 1982; Felton and Ali, 1992; Wagner et al., 1994; Ekwue and Stone, 1997; Zhang et al., 1997; Mapfumo and Chanasyk, 1998; Aragon et al., 2000; Froehlich et al., 1980; Howard et al., 1981; Murphy and Robertson, 1984; Beekman, 1987; Smith et al., 1997a; Smith et al., 1997b).

Rab (unpublished) studied 60 Victorian forest soils that exhibited a similar behaviour, ie. for a given level of compactive effort, the bulk density increased with increasing soil-water content until it reached a maximum density, after which the density of the soils decreased with further increase in soil-water content (Fig. 3.2). Similar typical behaviour has been observed for other forest soils (Fig. 3.3) (Froehlich et al., 1980; Howard et al., 1981; 1984; Smith et al., 1997a). It is expected that SW WA soil would exhibit similar behaviour when subjected to various levels of moisture content and compactive forces. However, the CMC and MBD will be different depending on soil types. This is discussed further in Section 3.2.1.

The bulk density of soil subjected to compactive effort increases with increasing soil-water content up to a maximum. This occurs because as the soil becomes wetter, water films weaken the interparticle bonds and reduce internal friction by lubricating the particles thus allowing the particles to slide together and compact by squeezing out air. However, the bulk density decreases at higher soil-water contents (after the maximum density is reached) because with further addition of water, soil has greater pore water pressures and the soils became less compactible. At saturation, the non-compressibility of liquids prevents further compaction. As soil nears saturation, there is very little air left to squeeze out, and soil compactibility is limited (Hillel, 1980; Ohu et al., 1989). However, it could be expected that soil puddling will occur and logging machinery may sink and bog at this stage (Murphy and Robertson, 1984).

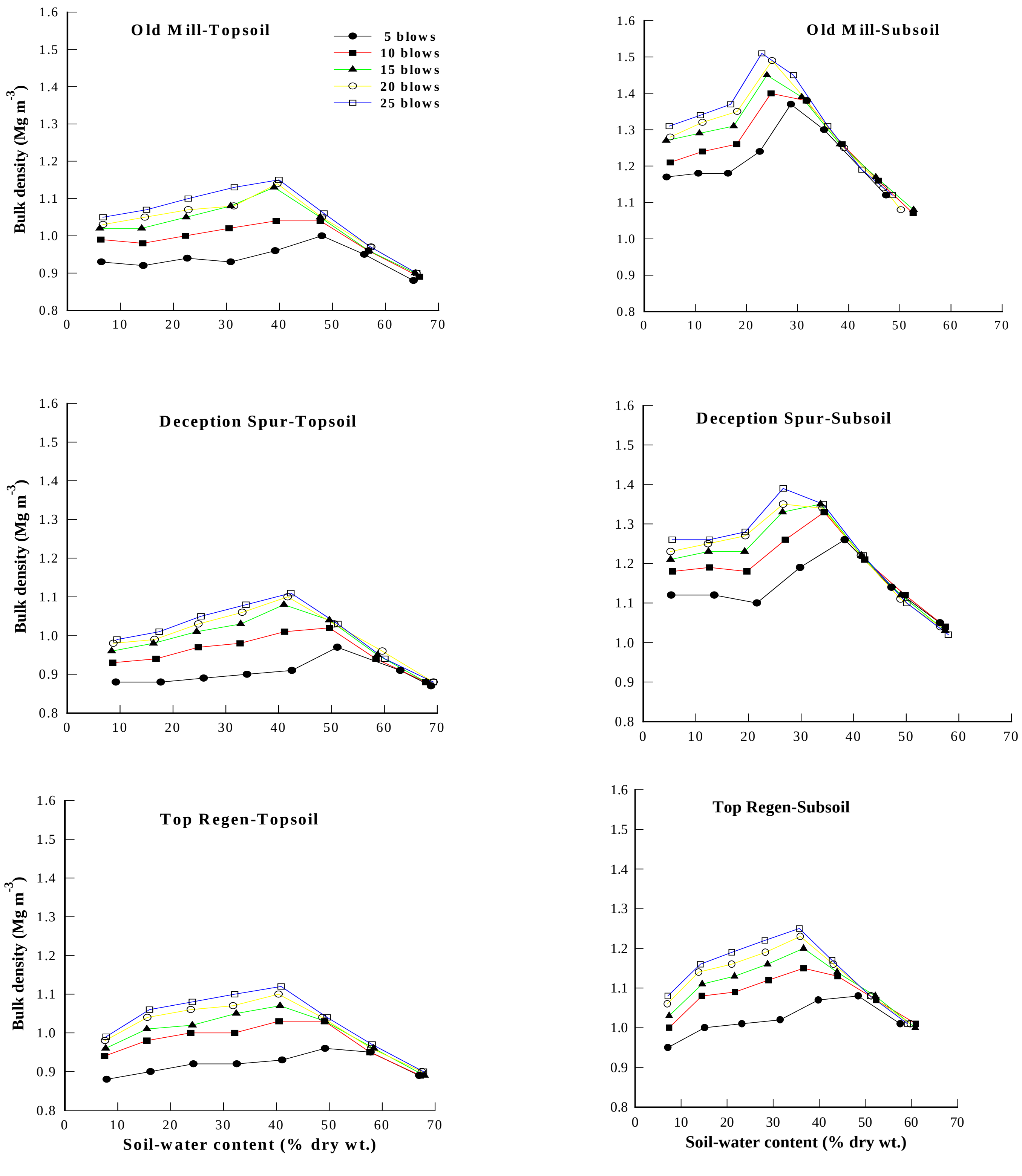


Fig. 3.2 Bulk density versus water content of soils at three forest sites in the Noojee district, Victoria (Rab, 1998a).

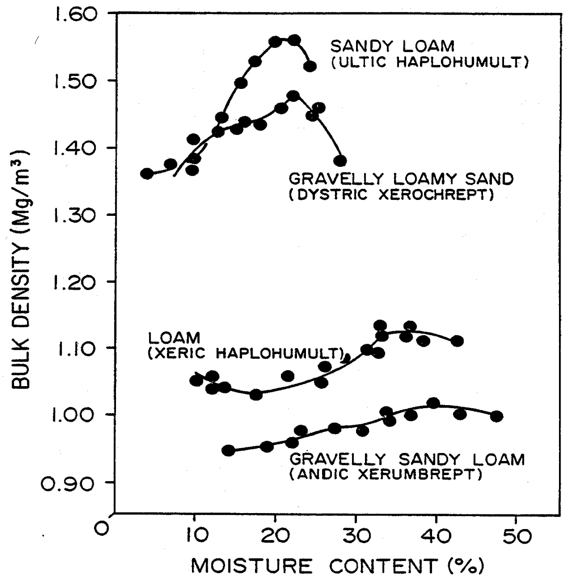


Fig. 3.3. Effect of moisture and soil type on compacted bulk density (standard Proctor compaction test) on four soils from western slopes of the Sierra-Nevada Mountains of northern California (Froehlich et al., 1980).

Examples of the effect of compactive effort on bulk density at various levels of soil-water content for one soil is given in Fig. 3.4 (Rab, 1998a). At soil-water contents below the critical level, the bulk density increased with increase in compactive effort. However, the rate of increase in bulk density decreased with increase in compactive effort and for a compactive effort of 15 blows the increase becomes negligible. This was because with the increase in bulk density the soil became more resistant to compaction. At soil-water contents above the critical level, the compactive effort had little or no effect on bulk density. As discussed earlier, the logging machinery may sink and bog at this stage.

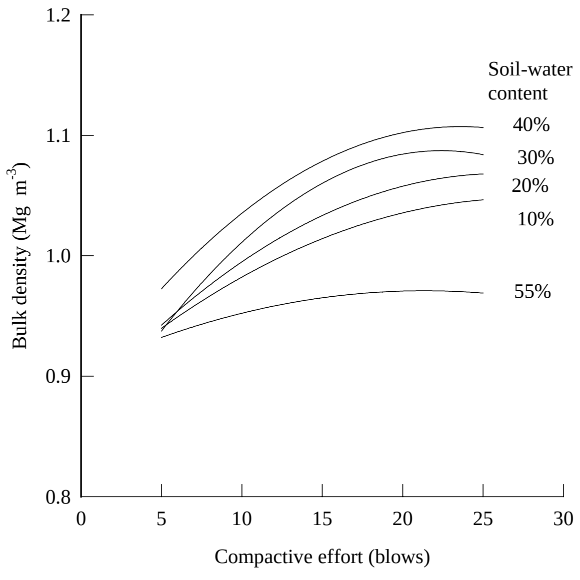


Fig. 3.4 Effect of compactive effort on bulk density at various soil-water contents for one soil (Old Mill- topsoil) (Rab, 1998a).

With increase in compactive effort, the maximum bulk density occurred at a lower critical soil-water content (CMC) (Fig. 3.5). Similar results were found for other soil types (Howard et al., 1981; Ohu et al., 1989). Several authors presented relationships between CMC and soil properties (eg. Ekwue and Stone, 1995). These models are site specific, and therefore, may not be suitable for predicting CMC for different WA soil groups. The values of CMC were also related to soil moisture contents at field capacity and plastic limits (see Section 5.2.3). The threshold value of soil moisture at which severe soil damage may occur is discussed in Section 5.

Skidders usually drag the log along snig tracks while the forwarder carries the log. A skidder is thus likely to produce more drawbar pull compared to that produced by a forwarder. Therefore, critical moisture content for a forwarder would be higher compared to a skidder. In other words, logging during winter using a forwarder can continue for longer periods than logging using a skidder.

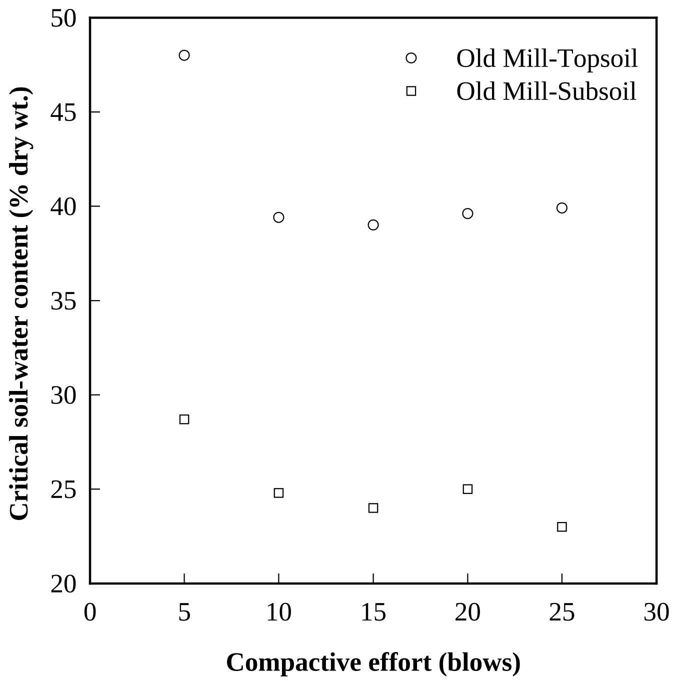


Fig. 3.5 The effect of compactive effort on critical soil-water content at MBD for two soils in the Victorian Central Highlands forests (Rab, 1998a).

3.2 Soil factors influencing compactibility

3.2.1 Soil texture

Texture imparts particular physical qualities to the soil and therefore determines to a large extent the physical and chemical behaviour. Texture is one of the important factors which determines the susceptibility of soil to compaction. Various authors have investigated the effect of texture on soil compactibility (eg. Saini et al., 1984; Ohu et al*.,* 1989; Stone and Ekwue, 1993). Rab (1998a, and unpublished data) investigated the effect of soil type on soil compactibility for 60 Victorian forest soils. Examples of the effect of soil type on compactibility are presented in Fig. 3.6. For the Victorian study, at all sites, the shape of the relationship between bulk density and soil-water content was steeply peaked for subsoils, while for topsoils the shape of the curves was relatively flat. The maximum bulk density for the subsoil occurred at a lower critical soil-water content than that which produced the maximum bulk density for the topsoil. For a given site, the maximum bulk density, penetrometer resistance and shear strength of the subsoil were higher than those of topsoil (Table 3.1). This shows that subsoil is more susceptible to compaction than the topsoil. This will have implications in terms of movement of machinery in the areas of subsoil exposed snig tracks. The higher percentage of clay content may have played a role in increasing the compactibility of the subsoil. Bodman and Constantin (1965) and Saini et al. (1984) also found a positive influence of clay content on compactibility of soils. On the other hand Howard et al. (1981), Ohu et al. (1989) and Stone and Ekwue (1993) found positive relationships between maximum bulk density and sand content.

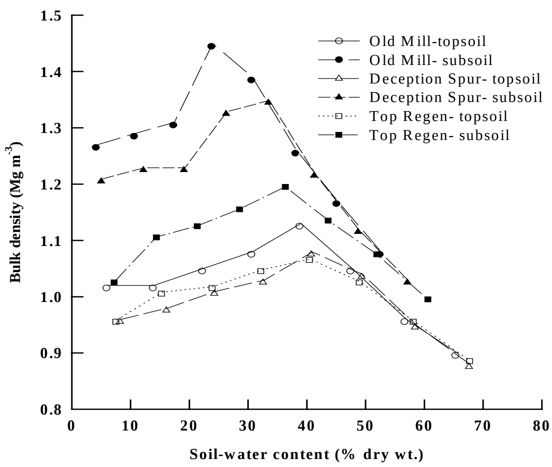


Fig. 3.6 Examples of the effect of soil type on bulk density-soil-water content relationships at 15 blows per layer in the Victorian Central Highlands forests (Rab, 1998a).

Table 3.1 Maximum bulk density (MBD, Mg/m^3), penetrometer resistance (MPR, kPa) and shear strength (MSS, kPa) at three levels of compaction for three uncut forest sites in Noojee district (Rab, 1998a).

		MBD			MPR			MSS		
Sampling site	Horizon	5 blows	15 blows	25 blows	5 blows	15 blows	25 blows	5 blows	15 blows	25 blows
Old Mill	A	1.00	1.13	1.15	3089	3967	4157	39	155	208
	B	1.37	1.45	1.51	4005	4348	4348	126	nd	nd
Deception Spur	A	0.97	1.08	1.11	3128	4081	4234	55	158	nd
	B	1.26	1.35	1.39	4043	4348	4348	128	nd	nd
Top Regen	A	0.96	1.07	1.12	3280	4119	4234	80	165	218
	B	1.08	1.20	1.25	3509	4272	4384	86	231	nd

The variation in MBD has been widely attributed to changes in particle size distribution (Smith et al., 1997a). Bennie and Burger (1988) developed models relating MBD to clay plus silt content. Van Der Watt (1969) concluded that about sixty-six percent of the variation in MBD could be attributed to varying amounts of very coarse sand (1 to 2 mm) and clay plus silt (<0.002 mm) but presented regression equations suggesting that, in the absence of data on very coarse sand, MBD could be equally well predicted by coarse sand (0.5 to 2 mm) and clay plus silt as independent variables.

Fine sand is often mentioned as an important factor influencing compaction of soils (Bennie and Krynauw, 1985) but the literature is conflicting. Milford et al. (1961), Bodmin and Constantin (1985) and Bennie (1972) reported that sandy loams and loamy sands with fine sand fractions were highly susceptible to compaction whereas Moolman and Weber (1978) and Van Huysteen (1989) concluded that sorting of particle sizes was more important than that of fine sand alone.

Hatchell et al*.* (1970) found that bulk densities of compacted forest soils were positively correlated with percent silt, and negatively correlated with percent clay. Froehlich and McNabb (1984) reported that water retention may increase in compacted sandy soils, may decrease in compacted loamy soils, and may either decrease or increase in compacted clay soils.

The podsolic duplex and clay soils in SW WA are likely to be more severely compacted than the red loam soils, in the karri forest. The upland sands and gravels are likely to be less compacted during timber harvesting.

3.2.2 Organic matter

Organic matter also plays an important role in the compaction process as increasing compactibility related to decreasing in organic matter content (Saini, 1966; Adams, 1973; Howard et al, 1981). Soils rich in organic matter are more difficult to compact than soils with low organic matter (Mulqueen 1973; Sands et al. 1979; Greacen and Sands 1980).

De Kimpe et al. (1982) reported that the most important physical properties influencing compaction behaviour were water retention properties at high matric potentials and these were primarily influenced by both clay and organic matter content. However, Van Huysteen (1989) could not establish a relationship between organic matter content and MBD, but this was probably due to the low organic carbon contents of the soils used in that study. Aragon (2000) found that MBD was highly correlated with the organic carbon and silt content.

Smith et al. (1997b) assessed the factors affecting the compaction susceptibility of South African forest soils and concluded that particle size distribution rather than organic carbon content increased in importance at lower clay contents. They reported that clay plus silt, clay, coarse silt, fine silt, medium sand and fine sand were each significantly correlated with MBD.

Rab (1998a) found for Victorian forest soils that, for a given compactive level, the maximum bulk density, penetrometer resistance and shear strength, for the subsoil occurred at lower critical soil-water content than that which produced the maximum bulk density for the topsoil (Table 3.2). This shows that subsoil is more prone to compaction than the topsoil. He attributed this to a lower percentage of organic matter in the subsoil. He also reported that the higher amount of organic matter in the topsoil may have played a beneficial role in reducing the compactibility of this soil. This suggestion is in line with other studies that reported that organic matter reduces the maximum bulk density of soils (Sands et al., 1979; Soane, 1990; Stone and Ekwue, 1993; Ekwue and Stone, 1995).

Table 3.2. Critical soil-water contents (CMC) (% dry weight) for maximum bulk density (MBD), penetrometer resistance (MPR) and shear strength (MSS) at three levels of compaction for four uncut forest sites in Noojee district, Victoria (Rab, 1998a).

Sampling site	Horizon	CMC for MBD			CMC for MPR			CMC for MSS		
		5 blows	15 blows	25 blows	5 blows	15 blows	25 blows	5 blows	15 blows	25 blows
Old Mill	A	48.0	39.0	39.9	22.6	22.4	22.8	22.6	30.8	31.5
	B	28.7	24.0	23.0	16.4	17.5	11.0	22.6	nd	nd
Deception Spur	A	51.1	41.0	42.3	34.0	24.5	25.3	42.5	32.8	nd
	B	38.3	33.7	26.6	21.6	19.3	19.4	29.8	nd	nd
Top Regen	A	49.2	40.7	40.9	32.5	24.1	24.1	41.1	32.4	32.1
	B	48.5	36.6	35.7	31.5	21.6	21.0	31.5	28.8	nd

nd not determined

Murphy and Roberston (1984) found considerable differences in the MBD and CMC for New Zealand forest soils (Fig. 3.7, Table 3.3). They reported that soils at most risk from compaction were clay soils with low organic matter contents, which display steeply peaked curves; with increasing sand and organic matter content, soils become less susceptible to compaction and exhibit flat curves.

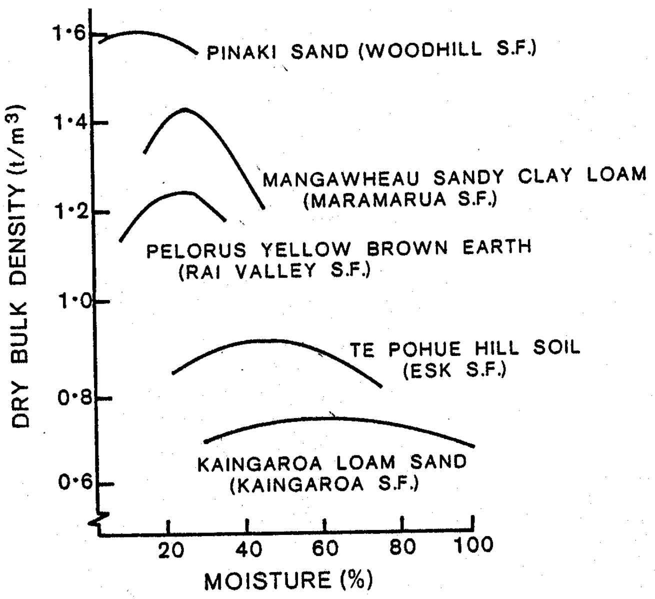


Fig. 3.7 Effect of moisture and soil type on compacted bulk density (standard Proctor compaction test) on five soil types from New Zealand forest (Murphy and Roberston, 1984).

Table 3.3 N.Z. Standard compaction test results for selected soils from 15 forests (Murphy and Robertson, 1984).

Forest	Soil type	Horizon	Texture Class	CMC (% dry wt.)	Compaction index (t/m^3)
Woodhill	Pinaki sand	B	Sand	12	0.02
Kaingaroa	Kaingaroa loam	A	Sand	61	0.07
		B	Sand	25	0.02
Mohaka	Tuai sandy loam	A	Loamy sand	59	0.10
		B	Sand	40	0.10
Esk	Te Pohue hill soil	A	Sand	42	0.07
		B	Sand	41	0.06
Long Mile	Arawa sandy loam	A	Sand	39	0.03
		B	Sand	30	0.16
Lismore	Pohangina steepland soil	A	Sandy loam	30	0.13
		B	Silt loam	18	0.16
Eyrewell	Lismore yellow grey earth	B	Sandy loam	19	0.10
Tairua	Wharekawa soil (podsolised)	A	Loamy sandy	52	0.05
		B	Loamy sand	70	0.01
Mangatu	Wanstead clay loam	A	Sandy loam	37	0.10
		B	Silt loam	24	0.15
Golden Downs	Spooner yellow brown earth	A	Clay loam	24	0.15
		B	Clay loam	24	0.15
Conical Hill	Kaikuku yellow brown earth	A	Clay loam	24	0.18
		B	Silt loam	29	0.12
Ngaumu	Ngaumu fine	A	Clay loam	32	0.16
	Sandy loam	B	Clay	24	0.16
Riverhead	Waikarel silt clay loam	A	Clay loam	26	0.15
		B	Silty clay loam	26	0.13
Rai Valley	Pelorus podsolised Yellow brown earth	B	Clay loam	22	0.09
Maramarua	Mangawheau sandy clay loam hill soil	A	Silty clay loam	22	0.14
		B	Silty clay	29	0.18

Mulqueen (1973) found that the bearing capacity was increased when subsoil was mixed with topsoil. Free et al. (1947) and Bodman and Constantin (1965) found that the addition of organic matter increased the water content at which maximum bulk density was achieved. The role of organic matter in soil compactibility is extensively reviewed by Soane (1990). He reported that compactibility is sensitive to even quite small changes in the amount of organic matter. He also reported that increases in organic matter content may reduce compactibility by increasing resistance to deformation and/or by increasing elasticity (rebound effects). Sands et al. (1979) reported that sandy soils low in organic matter are especially sensitive to compaction.

Duplex yellow (eg. Dy 3.41) and duplex grey soils (Dy 2.41 on granitic areas) with bleached underlying horizons of SW WA are known to be low in organic matter. Therefore, these soils are likely to be particularly susceptible to traffic problems in wet conditions experienced over the winter and spring periods.

On the other hand, red loams soils of karri forests of SW WA are well structured, permeable and therefore well drained and have a higher organic matter content. These soils are likely to be less susceptible to traffic problems in wet conditions.

3.2.3 Initial bulk density

Some forest soils that have low bulk density also have relatively low soil strength, making them susceptible to compaction, displacement, or mixing during timber harvesting operations. Other soils have naturally high bulk densities with relatively high soil strength, at least when dry, but even slight compaction may significantly increase resistance to root penetration (Standish et al., 1988).

A review of literature suggests that initial soil bulk density can be used as an indicator of potential compaction (Butt and Rollerson, 1988). Fig. 3.8 shows that degree of compaction increases with decreasing initial bulk density. As bulk density and bearing capacity are related, this relationship is not surprising. Unfortunately, despite the empirical relationship indicated by Fig. 3.8, initial bulk density by itself cannot be used to predict compaction. Light soils are not necessarily weak soils (discussed in Section 3.2.1) and, moreover, certain light soils may experience increased strength with compaction at the same rate as heavier soils (Froehlich and McNabb, 1984; Butt and Rollerson, 1988). In one particular study, Froehlich et al. (1980) (cited by Butt and Rollerson, 1988) found that initial bulk density added little to the explanation of variability in compacted density.

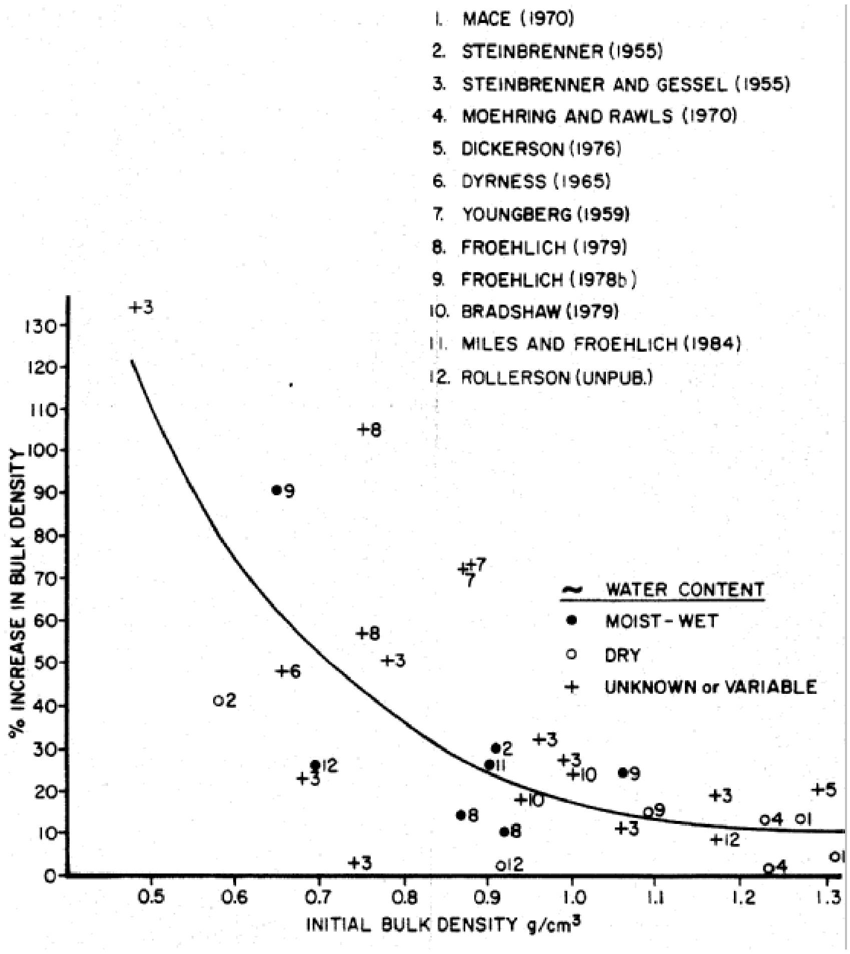


Fig. 3.8 Maximum percentage increase in bulk density recorded versus initial density for surface soils. Note that the depth interval samples are not always comparable among studies nor is the degree of use. (Butt and Rollerson, 1988).

3.3 Relative influence of compactive force and soil moisture

The development and implementation of practical guidelines in order to manage soil compaction for a wide range of machinery types and forest soils depends upon an understanding of the relative importance of applied pressure and water content during the compaction process. It allows the planners to decide whether water sensitivity of a particular soil or overall load is more important in order to minimise soil compaction.

Smith et al. (1997a) evaluated the relative importance of soil moisture content and applied pressure for four different forest soils from South Africa: sandy loam, silty clay, sandy clay loam and clay soils. They found that compaction of sandy loam was almost independent of moisture content. Increases in soil compaction were almost entirely due to increasing ground pressure. As these soils are insensitive to moisture content there is unlikely to be any benefit in restricting harvesting operations to a particular season. The principal factor influencing compaction of silty clay was applied pressure. They found that doubling of the ground pressure from 200 to 400 kPa substantially increased the level of compaction, even when the soil was dry, and had a similar effect to compacting the soil with 200 kPa of ground pressure when the soil was wet.

In managing silty clay soils, there are no environmental benefits in waiting for the soil to dry out before commencing harvesting operations (Smith et al., 1977a). The greatest overall advantage in reducing compaction on this soil would be to reduce overall axle load and minimise vehicle passes regardless of moisture content. Sandy clay loam soils were extremely sensitive to moisture content at the time of compaction. Scheduling harvesting operations on these soils to drier periods will have the greatest benefit in lowering soil compaction, notwithstanding changes in ground pressure (Smith et al., 1997a). The clay soils were sensitive to both moisture content and applied pressure. Smith et al. (1977a) concluded that clay soil should be trafficked during dry periods with low ground pressure.

Soil strength is more important than ground pressure in order to manage wet soils. Kirby and Blunden (1990) studied the relative importance of soil strength and machinery ground pressure on soil compaction in agricultural soils. They found that soil strength varies by a factor of about 100 whereas vehicle ground pressure varies only by about 5.7 times. So it follows that it is more important to operate in dry soil than it is to choose another machine or wide tyres.

In SW WA forests, in terms of managing wet soils, it would be more appropriate to restrict machinery movements during spring and winter than changing or adopting to low ground pressure machinery types (see Section 4).

4. Management options for minimising soil disturbance and compaction in SW WA forests

Management systems can significantly influence the nature and magnitude of soil disturbance and compaction. For example, codes of forest practice can influence the nature of harvesting systems and their method of employment, matching them to the specific soil, slope, seasonal and resource factors associated with the coupe. The level of influence will generally depend on the regulatory framework in which the management systems reside and the level of compliance achieved. In the context of this review, management systems for influencing soil disturbance usually have a wet-weather descriptor, which relates to wet-soil conditions and associated low soil strength. The primary function of wet-weather systems is to prescribe when and how harvesting can occur. Preferably this is based on objective criteria which allow an appropriate balance between the competing demands of soil disturbance mitigation and the harvest and supply of wood. Following on from Sections 2 and 3, this Section explores some of the management options available. From the previous Sections it is apparent that there are various options for minimising soil disturbance and compaction during timber harvesting. These are discussed below under the headings of logging methods, machinery types, soil factors, snig track layout, cording, matting and brushing, and restrictions during wet weather.

4.1 Logging methods

While the use of helicopter and cable harvesting systems instead of conventional ground skidding systems will help minimise soil disturbance and compaction there are issues of cost-effectiveness to consider. To gain the advantages of these systems careful planning and implementation is required. Generally, these systems are only considered where the cost of ground-based systems is very high (eg. steep slopes), or minimising soil disturbance is critical. Studies (eg. Krag et al., 1986; Welburn, 1975) show cable systems are very expensive, much more expensive than ground-based systems, particularly on terrain with low to moderate slopes. A lack of data on long-term effects of site disturbance precludes determining whether any reductions in site productivity will offset the additional costs of cable logging. Also, with the average slope of the majority of areas in SW WA less than 7^{o}, the major advantage of cable systems will be removed. Low slopes will reduce the ability to suspend logs causing increased soil disturbance. Harvested volumes are also critical to a consideration of harvesting system. In SW WA forests, under the FMP (2004-2013) the harvested yield in jarrah forest is likely to be between 20 to 120+ tonnes per hectare, and the karri forest clearfell operations are likely to yield about 250 tonnes per hectare. The karri thinning will yield 70 to 120 tonnes per hectare. These per hectare volumes are considerably lower than those normally cable harvested, so it is unlikely that cable logging systems would be an option for SW WA forests. Given the terrain and harvested volumes of SW WA, ground-based harvesting systems would be expected to be the most cost-effective management option.

4.2 Machine type

Ground-based systems have a broad range of machinery configurations, with Western Australian experience indicating that rubber tyred skidders are capable of producing more severe damage than tracked machines due to their ability to continue skidding under more severe conditions of trafficability (Bradshaw, 1978). Steel-tracked machinery is also generally considered to have a lower impact on soil than rubber-tyred machinery due to lower static ground pressures. However, this is very dependent on the specifics of the machinery and modifications that have been made to it to reduced soil impacts. The modifications to equipment are usually based around reducing ground pressure through the use of wide tyres, wide tracks, or half-track systems (Forest Practices Board, 2000). Also, purpose built “soft-tracked” machinery featuring flexible wide tracks, such as the FMC, can provide improved soil outcomes. This is mainly achieved through their ability to travel over logging slash, but usually comes at a higher purchase and maintenance cost. Lower cost options such as shovel logging, using modified excavators, can often reduce soil disturbance more cost effectively. Matching the harvesting machinery, the operator and the method of its employment to soil type, slope, and seasonal and resource factors such as volume per hectare and piece size will be critical.

However, there is a lack of information on the impacts of machinery on soils of the SW WA forests. Further research is needed to evaluate the type of machinery in the context of its soil impact during timber harvesting. However, it is unlikely that logging contractors are going to purchase new harvesting machinery just to minimise soil disturbance. Rather, machinery that will meet the dual requirements of soil prescriptions and wood production will be selected on the basis of demonstrated performance.

4.3 Soil factors

Successful planning of harvesting operations to minimise soil compaction will depend on knowledge of the distribution of soils in the area to be managed, coupled with knowledge on the response of each soil to compactive effort. There is a clear need to better understand the relationship between the forest soils of SW WA and their susceptibility to soil disturbance from harvesting equipment. Mapping the soils on the basis of a soil compaction hazard rating, and then basing the different management strategies on this rating would help address this issue. The methods for mapping compaction prone soils are described in Section 10.

The importance of organic matter in relation to soil compactibility has been discussed earlier in Section 3 and highlights the need for long-term management to maintain organic matter in soil types that have low organic matter content (eg. fine sands and dispersive clays). The management of soil fauna to promote rapid breakdown and incorporation of litter into the soil mass would be valuable (Greacen and Sands, 1980). The regeneration silviculture adopted following harvesting should attempt to minimise the loss of organic matter (ie. slash burning versus slash retention). This will need to be managed within the requirement of achieving satisfactory regeneration of the full suite of species.

4.4 Snig track layout

During harvesting operations, machine operators are commonly allowed to select travel routes as needed. As a result, the area covered by snig tracks varies considerably. One way of reducing the total area disturbed was found to be planning, designing and marking designated snig tracks (Froehlich et al., 1981; Murphy, 1982; Murphy, 1984). Reducing the area covered by snig tracks reduces compaction regardless of how the tracks are used. Compaction of lightly-used snig tracks is similar to that of heavily-used snig tracks because most compaction occurs in the first few passes of a machine (Sidle and Drlica, 1981; Wronski et al., 1989; Roberts et al., 1989; Rab, 1992). Conversely, increasing the number of passes over a limited number of snig tracks only slightly increases the bulk density of those tracks. Restricting the number of snig tracks can be best accomplished by designing their location before harvest (Bradshaw, 1979). Currently, in SW WA snig tracks are layed out on the basis of gravel content in some cells during winter and spring harvesting periods (see Fig. 4.1). However, to minimise soil compaction, it is recommended that whenever practicable, designing and marking snig tracks should be done in all cells during both summer and winter harvesting periods.

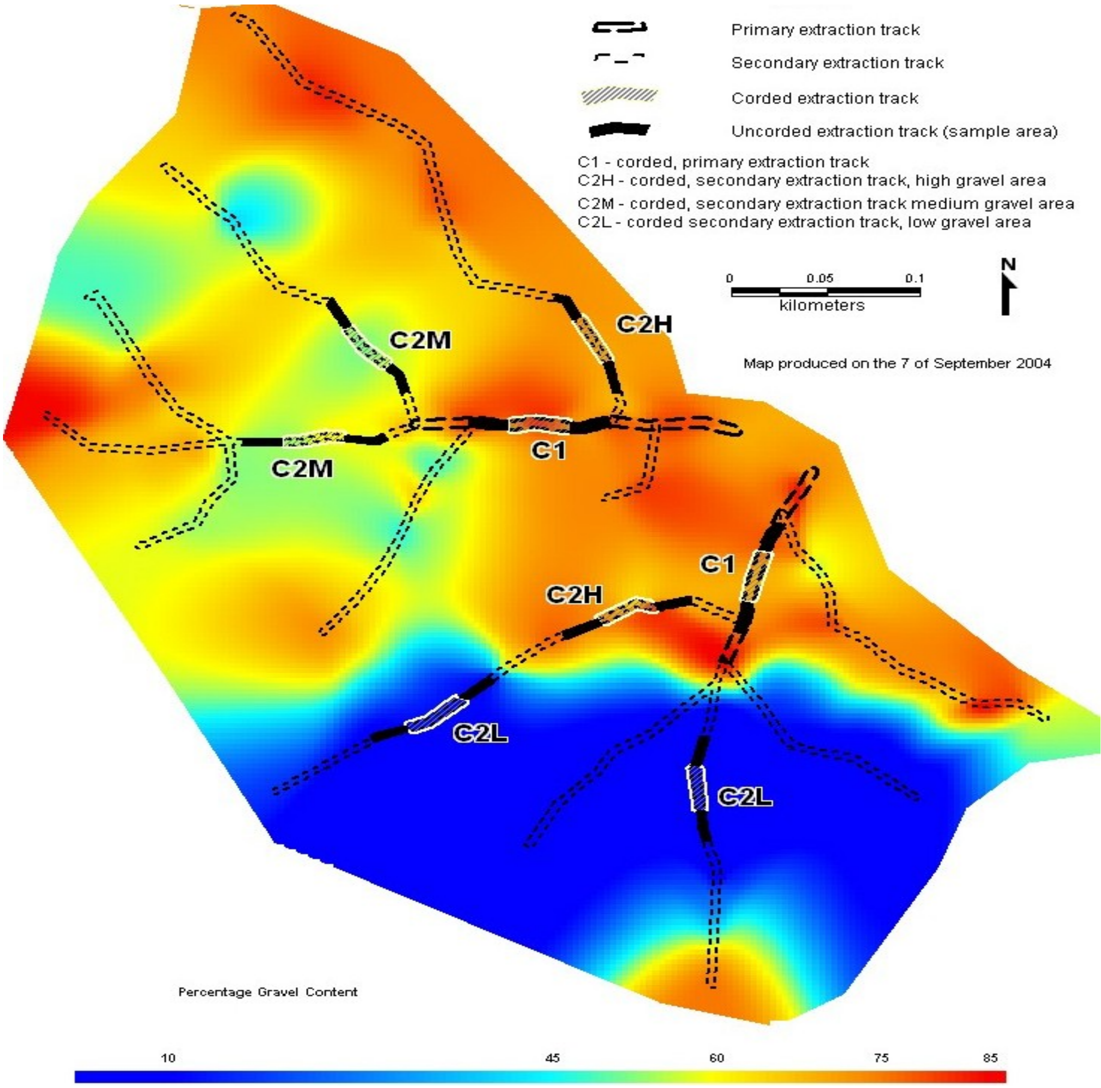


Fig. 4.1. The percentage gravel content of the surface soil across the site at Jolly, the layout of snig tracks proposed prior to harvest, and the location of the corded and uncorded snig track sections. Bulk density samples were collected on the corded sections and on the uncorded snig track at both ends of the corded sections. The gravel content was determined from sampling at 30 m intervals along the proposed snig track routes (Whitford et al., 2005).

4.5 Cording, matting and brushing

As previously outlined in Section 2.2.6, the techniques of cording, matting and brushing refer to the placement of small logs, understorey vegetation, bark and logging slash to create a physical layer over the ground. This layer spreads the ground pressure of the logging machinery and separates the soil surface from their tyres and tracks. These materials can be used either individually or in combination.

Cording and matting has been used very successfully in Victoria and Tasmania to ‘protect’ snig tracks and landings, particularly in the highly productive ‘ash’ forests. The technique is generally used to extend the harvesting period into the wetter ‘shoulder periods’ of autumn and spring, but can also extend harvesting into winter. It is often used in combination with shovel-logging, but not exclusively so. A typical harvesting system using the technique could include a tracked mechanical feller with ‘shovelling’ capacity, a grapple skidder (tracked or rubber-tyred) and a couple of tracked processing excavators on the landing. There may also be a second tracked excavator assisting with cording of snig tracks, and the shovelling of logs for easy skidder access from the corded surface. Specific system configurations are largely dependent on the nature of the resource (volume per hectare and piece size). Shovel logging relies on an excavator-based grapple to lift and move logs while the machine is stationary. Logs are passed from stack to stack or in a continuous ribbon across the coupe to the landing or corded snig track (Wilkinson, 2001) for distances of 200-300 m (CSIRO, 1997; Yankee, 2005). The low static ground pressure, due to their large tracks, and moving of logs by lifting or sliding across other logs can result in reduced environmental impacts. The capacity of cording and matting in combination with shovel logging to extend the logging season has eased production pressures, which in this wetter forest type are often affected by the variability of the weather. The productivity of these forests means that there is usually considerable unmerchantable short material (5m lengths - often wattle understorey) available to cord snig tracks, and longer pulpwood lengths (12m) for the temporary cording of landings. Matting of the cording with bark assists in ‘smoothing’ out the corrugated surface associated with the cording and improves the trafficability of the tracks. Brushing is generally used to extend snig tracks that are either only lightly used or are located on drier parts of the logging coupe. Cording and matting can be employed over the whole coupe, or only on a specified component of the coupe where local conditions, or forward planning for a wet weather contingency require it (DSE, 2004; Wilkinson, 2001; Forest Practices Board, 2000). These techniques have been very successful in minimising rutting, soil mixing and puddling, but there will be a degree of compaction. The level of compaction will depend on many factors and there is some scope to modify the application of the techniques to meet specific compaction standards.

In SW WA it is expected that lower per hectare volumes and a reduced availability of unmerchantable material for cording will make this technique less generally available as a management option. Application of the technique may be restricted to higher risk components of the snig track/landing network. In short-wood thinning operations, where forwarders are used, brushing of wheel tracks using thinning slash should be achievable during periods of higher soil moisture. This technique is effective in reducing soil disturbance and rutting.

4.6 Management systems

Management systems can significantly influence the nature and magnitude of soil disturbance and compaction. Costantini and Doley (2001) have detailed a number of possible approaches to designing these systems (Fig. 4.2) 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 three approaches have been identified and are detailed in the 2nd row of Fig. 4.2.

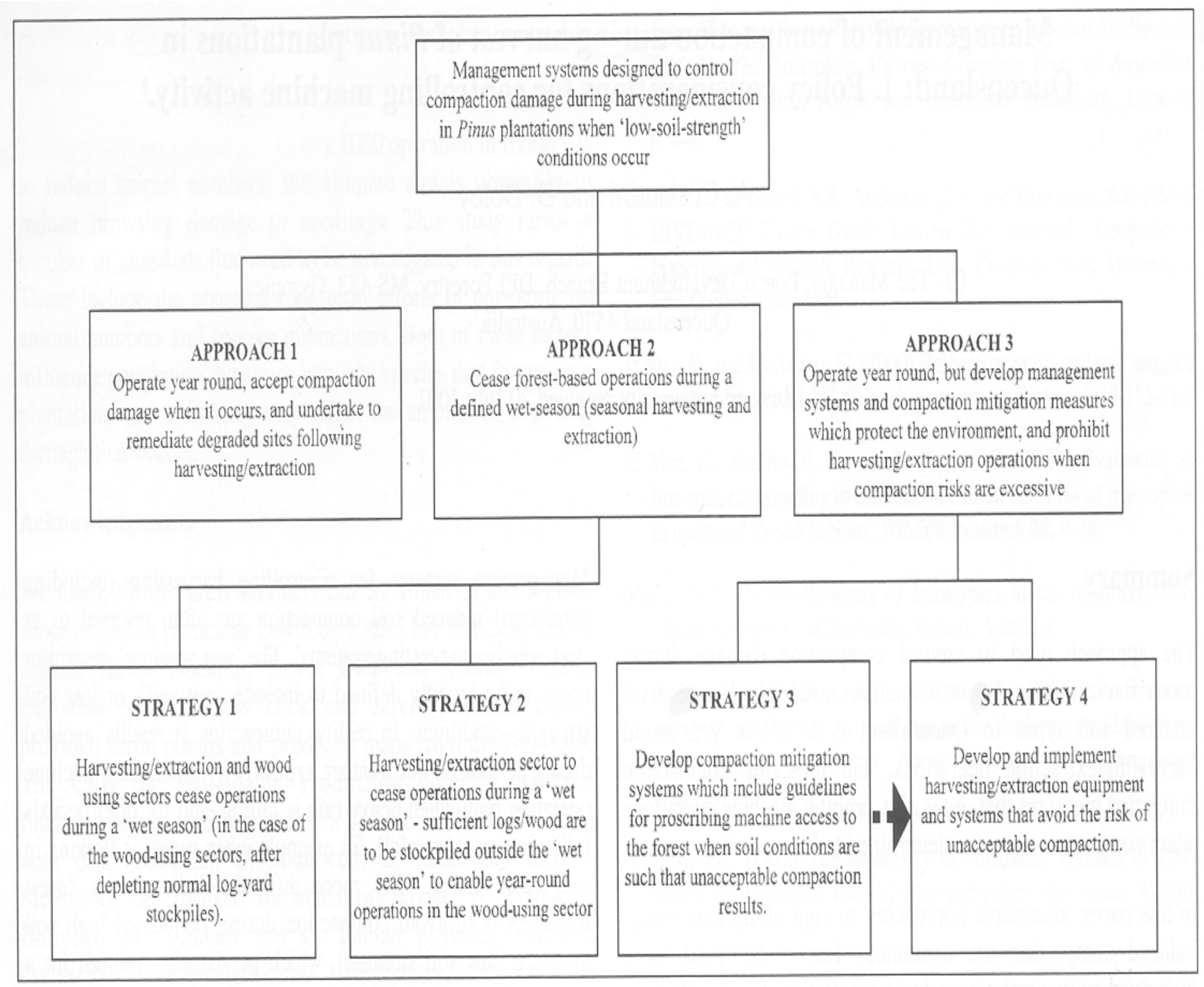


Fig. 4.2. Conceptual model of alternative approaches to controlling compaction damage that can result from forest harvesting conducted during periods of low-soil-strength (Costantini and Doley, 2001).

Approach 3 outlines the direction most relevant to this review and suggests that there are two broad strategies that should be considered. The two strategies can be viewed as being on a continuum, with Strategy 3 the short- to medium-term option and Strategy 4 the medium- to longer-term option. Strategy 3 optimises existing harvesting equipment while Strategy 4 requires enhancement of presently used harvesting systems, the development of low-disturbance-risk technology, research and development investment, and the use of adaptive management approaches to drive progressive improvement. Systems for identifying when harvesting-induced disturbance risks are excessive can be based upon predictive modelling approaches or approaches relying on observed real effects. This latter approach, described as "reactive' by Costantini and Doley (2001), allows harvesting operations to occur until an unacceptable result is observed, whereas the former approach relies upon predictions of likely soil disturbance. As outlined by Costantini, 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 disturbance effects and costs. Historically, the reactive approach has usually been adopted. This is because: (1) it is simpler and easier to adopt; (2) it satisfies the need for guidelines that can be applied consistently and uniformly, and hence equitably to a wide range of harvesting systems; and (3) it encourages and rewards operators who use 'disturbance-friendly' harvesting systems. In the first instance a combination of Approach 3 together with this reactive approach is likely to best suit the needs of SW WA forest land managers and local industry. However, as the data available to underpin a predictive modelling approach become more available and is refined, then, the approach is expected to change. Irrespective of which approach is used a clear definition of what constitutes excessive soil disturbance is needed to underpin any functional soil disturbance management system.

4.7 Restrictions during wet weather

As outlined in Section 3, avoiding machinery use on wet soils wherever possible is one of the most important management techniques for reducing soil disturbance and compaction. Identifying these 'wet soil' days at an appropriate scale for harvesting operations is often based on experience and is difficult to quantify. Rating models such as Thomasson (1982) have been developed to estimate the number of machinery days, when soils would not be susceptible to damage by traffic. However, methods such as this require considerable data and their accuracy is difficult to fully test.

The specific threshold values of soil moisture at which excessive soil compaction will occur are discussed in Section 5, and indicate some of the complexities associated with different soil types. The use of the Soil Dryness Index (SDI) in SW WA as a predictor of soil moisture conditions is discussed in detail below (see Section 6). A plan for the progression and development of the soil disturbance management system used in SW WA currently is provided in Section 12.

5. Factors, criteria and threshold values of soil trafficability

5.1 Factors affecting soil trafficability

The soil is tractable if a tractor or other forest machine can move on that soil to satisfactorily perform the function of the machine without causing significant damage to the soil (CSSS, 1967). Droogers et al. (1996) used trafficability to define the bearing capacity of soils. Droogers et al. (1996) defined trafficability as "the period during the year when soil traffic is possible without causing unfavourable compaction". In forest operations soil bearing capacity is usually considered as the maximum allowable wheel contact pressure. The actual wheel pressure, however, is difficult to assess, because the true contact area depends on tyre and soil properties.

Another term used to describe the bearing capacity of soil is vehicle mobility (eg. Ayres, 1975), in particular in the US military. The term workability is used to describe the soil characteristics for mechanised tillage. Workability is defined as "the period during the year when tillage is possible with positive effects on soil structure" (Droogers et al, 1996). Trafficability, vehicle mobility and workability are similar concepts; frequently these terms are not distinguished and only one threshold value for machinery accessibility is used (eg. Babeir et al. 1985; Rounsevell, 1993). For the purpose of this review the term soil trafficability is preferred. The soil trafficability can be split into two components. The first component is the threshold value for trafficability, expressed in moisture content or matric potential. That is, the value below which machine traffic is possible without damage (compaction) to soil. The second component is the period during which the soil is trafficable. It is a function of soil moisture regime and the threshold values.

Various factors affect soil trafficability including soil strength, stickiness, slipperiness, critical soil layer and soil moisture. These are discussed below.

5.1.1 Soil strength

Bearing and traction capacities of soils are functions of their shearing resistance. Soil shear strength can be predicted using Coulomb's equation:

$$S = C + \sigma \tan \theta \qquad (5.1)$$

where S = soil shear strength (kPa);

C = cohesion of soil (kPa);

σ = applied load (kPa); and

θ soil friction angle o.

This equation shows that the friction angle has more influence on shear strength than cohesion of soils. Soil cohesion and friction properties are dependent on particle size (see Table 5.1).

Table 5.1 Cohesive and friction properties of soils (Kuonen, 1983, cited by Saarilahti, 2002).

Soil property	Cohesive soils			Friction soils	
	Clay	Clay silt	Silt	Fine sand	Sand
Particle size (mm)	<0.002	<0.06	<0.02	<3	<6
Cohesion, (kPa)	25	20	0	0	0
Friction angle (^{O})	22	27	33	34	38
Soil moisture content (%)	47	25	32	17	13
Bulk density (Mg/m^3)	1.19	1.6	1.439	1.709	1.726

5.1.2 Stickiness

Stickiness may seriously hamper a vehicle operating in wet, fine-grained soil. Under extreme conditions, sticky soil can accumulate in vehicle running gears, making travel and steering difficult. Normally, stickiness is troublesome only when it occurs in soils of low-bearing capacity (normally, fine-grained soils). The rate of increase in stickiness of the soil as the moisture content increases depends on many factors such as silt and clay content, the degree to which the clay particles are bound to each other into stable granules and organic matter content of the soil (Russell, 1973).

5.1.3 Slipperiness

Excess water or a layer of soft, plastic soil of liquid limit overlying a firm layer of soil can produce a slippery surface. Such a condition may make steering difficult or may immobilize rubber-tired vehicles. Vegetation, especially when wet and on a slope, may cause immobilization of rubber-tired vehicles. Slipperiness is troublesome, even on soils with high-bearing capacities.

5.1.4 Critical soil layer

The critical layer is the layer in the soil that supports the weight of the vehicle in question. The depth of the critical layer varies with soil type, soil strength profile, the vehicle type and weight, and the number of passes involved (see Table 5.2). Anttila (1998) (cited by Sarrilahti, 2002) found that penetration resistance measured at 0.15 m depth had the highest predictive power when modelling for rut-depth. Sarrilahti (2002) recommended the use of an average penetration depth of 125 to 175 mm as the critical depth for Finnish moraine soils. Kogure et al. (1985) reported that a depth of 150 to 400 mm may be considered to be the most important in determining soil trafficability. Based on the ground pressure of the types of machinery used for harvesting operations in the forest of SW WA (Table 5.3), an average depth of 0 to 150 mm is recommended for critical soil depth in the upland sand and gravels; and 200 to 400 mm in karri loams and shallow duplex and clay soils.

Table 5.2 Critical depth (m) of different soil/vehicle combinations (cited by Sarrilahti, 2002).

Vehicle weight (kg)	Loose dry sand	Reading decrease in depth (abnormal profile)	Reading increase or remain constant	Peat, Muskeg
Wheeled vehicles				
Up to 22,500	0- 0.150	0.15 – 0.450	0.15 – 0.300	
Over 22,500	0- 0.150	0.225 – 0.525	0.225 – 0.380	
Tracked vehicle				
Up to 1,500	0- 0.150			0- 0.150
1,500 to 4,000	0- 0.150	0.075 – 0.380	0.075 – 0.225	0.075 – 0.225
4,000 to 7,000	0- 0.150	0.150 – 0.450	0.150 – 0.300	0.15 – 0.300
7,00 to 11,000	0- 0.150	0.150 – 0.450	0.150 – 0.300	0.225 – 0.380
11,000 to 45,000	0 –0.15	0.150 – 0.450	0.150 – 0.300	0.380 – 0.450
Over 45, 000	0- 0.150	0.225 0.525	0.225 – 0.380	

Table 5.3 Logging equipment used in SW WAA.

Machine type	**Application**	**Wheeled/tacked**	**Approx loaded ground pressure (kPa)**
Skidders	Snigging	Wheeled	255
Loader	Landing loader	Wheeled	310
Barkmate	Loads/docks	Tracked	40 (unloaded)
Harvester – 45 t	Harvesting mature trees	Tracked	70
Harvester – 27 t	Harvesting regrowth	Tracked	~70
Forwarder – 8 wheel	Carrying out regrowth and small logs	Wheeled	360
Forwarder - 6 wheel	Carrying out regrowth and small logs	Wheeled	~360

[A] Approx 75% of volume is felled by machine.

5.1.5 Soil moisture

Soil moisture and consequently changes in soil trafficability are dependent on weather conditions, especially rain. Increases in soil moisture due to rain result in slipperiness, stickiness and decreased strength. Dry periods produce opposite effects. The exception is loose sands where trafficability improves through an increase in cohesion during rainy periods and returns to a loose, less trafficable state during dry periods (Yea and Ahmad, 2005). Trafficability characteristics measured on a given date cannot be applied later unless full allowance is made for the changes in soil strength caused by changes in soil moisture.

The matric potential of soil water contributes to soil strength through its influence on the effective stress (Towner, 1961; cited by Wronski, 1985). The shear strength of an unsaturated soil is given by

$$S = C' + (\sigma - \chi\psi)\tan\theta \qquad (5.2)$$

where S = soil shear strength (kP);

C′ = effective cohesion of soil (kPa);

σ = applied load (kPa);

σ -$\chi\psi$ =effective load (kPa);

χ = dimensionless desaturation factors representing the fraction of the surface area in any plane through which the matric tension acts;

ψ = soil water matric potential (kPa); and

θ = soil friction angle (^{o}).

Typically, χ increases from c. 0.2 to 1.0 as the proportion of a saturated void space increases from 0.5 to 1.0 (Wronski, 1985). For a loam soil this range of moisture content corresponds to matric potentials of between –70 to 0 kPa (Williams and Shaykewich, 1970; cited by Wronski, 1985).

The substitution of S from equation 5.1 into 5.2 gives:

$$C = C' - \chi\psi\tan\theta \qquad (5.3)$$

The effect of soil moisture on shear strength is demonstrated in Fig. 5.1. The shear strength decreases exponentially with increase in soil moisture.

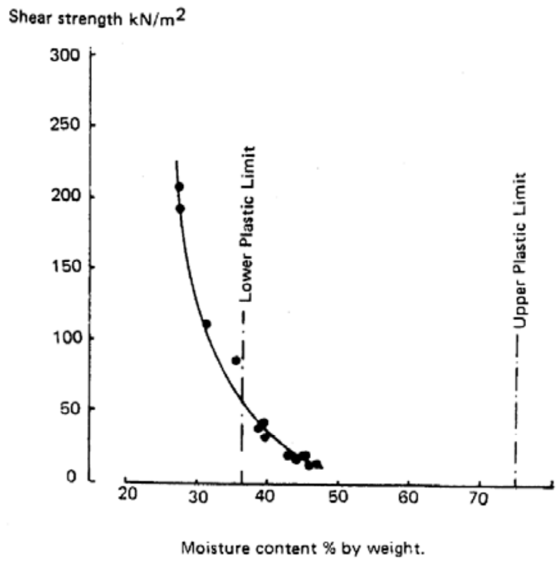


Fig. 5.1 Relationship between clod shear strength and moisture content (Godwin and Spoor, 1977).

The influence of soil matric potential on shear strength of a soil and hence on its bearing capacity is given by Terzaghi (1943) (cited by Wronski, 1985) equation for the bearing capacity Q_u of soil with a long foundation:

$$Qu = N_c C + \rho_a L N_q + \rho_a (B/2) N_p \qquad (5.4)$$

where N_c, N_q, N_P = semi- empirical dimensionless coefficients dependent on the effective friction angle of soil;

B = width of footing;

L = depth of the footing base below ground level;

ρ_a = soil bulk density; and

C = cohesion of soil.

Equation 5.4 can also be used to estimate the bearing capacity of a soil which has attained plastic limit equilibrium with a loaded wheel, where B is taken as the wheel width and L as the wheel sinkage (Steinhard, 1974; Wronski, 1985). In general the magnitudes of the coefficients in equation 3 are Nq ≈ N_P and $N_c > N_q$, and substitution of C from equation 5.3 into 5.4 gives the dependence of the bearing capacity of the soil on the wheel width (B), the sinkage (L), the soil matric potential (ψ), the effective friction angle (θ) and cohesion (C′) of the soil. For unconsoliated loam soils, Wronski (1985) used the values of θ = 30° (Lambe and Whitman, 1979), and at this angle N_q = 20, N_c = 30. He assumed ρ_a = 1.3 Mg/m^3, B= 400 mm and a typical wheel sinkage L = 150 mm. Using these values, the last two terms on the right-hand side of the equation 5.4 total approximately 85 kPa while the first term ranges between 0 and 800 kPa as the matric potential falls from 0 to -70 kPa (Wronski, 1985). Thus the cohesive force arising from matric potential in the soil can be a dominant factor determining the bearing capacity of the soil. The effect of soil moisture on bearing capacity of soil is illustrated in Fig. 5.2. This figure shows that the bearing capacity of soil decreases linearly with increases in moisture content.

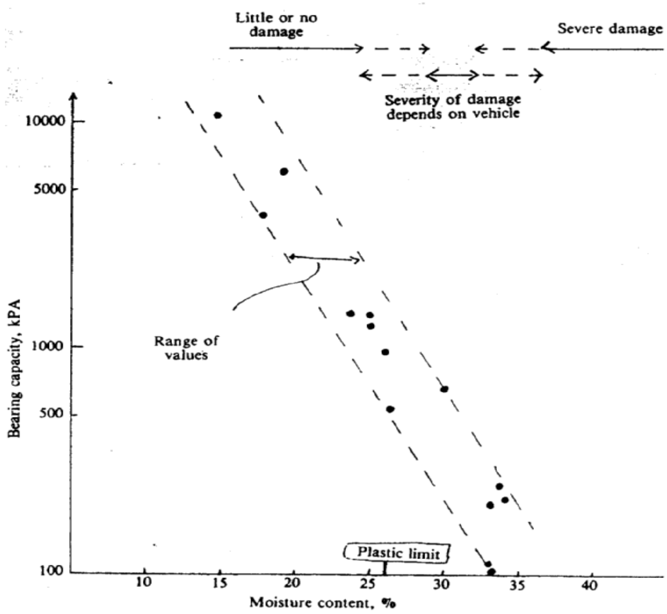


Fig. 5.2 Bearing capacity variation with moisture content. Superimposed is the range of moisture contents giving the extent of damage (Kirby, 1988).

For a given load and soil moisture content, clay soils will have significantly lower shear strength and therefore bearing capacity compared to that of sandy soils. At a given moisture content, trafficability on the soils of SW WA forests would be best on upland sands and gravels, followed by karri loams and then shallow duplex and clay soils.

Shear strength is usually measured in the field using either penetrometer resistance or a shear vane. Penetrometer resistance is the most popular measure. Penetrometer resistance depends on various factors including soil texture, organic matter content, soil bulk density and most importantly soil moisture content. Various authors have developed models for predicting penetration resistance using various independent variables including soil moisture, texture and soil bulk density (eg. Murfitt et al., 1975; Ayers and Perumpral, 1982; Witney et al., 1984; Freitag, 1987; Perumpral, 1987; Elbann and Witney, 1987; Dexter et al., 1988, Hinze, 1990; Hernandez et al, 2000; Vaz et al., 2001). However, the majority of these models are empirical. Dexter (1998) (cited by Saarilahti, 2002) presented the following general model for some Australian soils.

$$q = \exp^{(k+m-y+n.w)} \qquad (5.5)$$

where q = penetration resistance (MPa)

k, m, n = constant from Table 5.4;

γ = soil bulk density (Mg/m^3); and

w = soil moisture content, (%, w/w)

Table 5.4 Coefficients for the Dexter (1988) model.

Soil type and layer	k	m	n
Light clay loam, 0-50 mm	-7.3	6.0	-0.105
Loam, 50 –250 mm	-6.2	6.0	-0.105
Clay loam, 250 mm	-4.2	6.0	-0.105
Sandy loam, 0-50 mm	-6.3	5.0	-0.061
Sandy loam, 50 mm	-4.8	5.0	-0.061

Saarilahti (2002) compared these models for Finnish forest soils and found that prediction of penetration resistance varies considerably between models. However, predictions of penetration resistance using all of the above models suggested that penetration resistance decreased exponentially with increase in soil moisture (see Fig. 5.3). Measurement of soil strength using a shear vane has been related to penetrometer resistance by various authors (eg. Saarilahti, 2002). The relationship between the shear vane test and penetrometer resistance is demonstrated in Fig. 5.4.

During winter the soil strength of karri loams and shallow duplex and clay soils in SW WA forests is likely to be low and therefore harvesting of timber during these periods will reduce the trafficability significantly compared to that during harvesting in summer. Under these conditions, these soils may lose their ability to support the load resulting in rut formation and general deterioration in soil structure. On the other hand, the trafficability of upland sands and gravels may increase significantly during spring and winter due to increase in soil strength and therefore, harvesting may not cause excessive damage to these soils in SW WA forests. The threshold values of soil moisture at which movement of machinery during timber harvesting might cause excessive soil damage are discussed below.

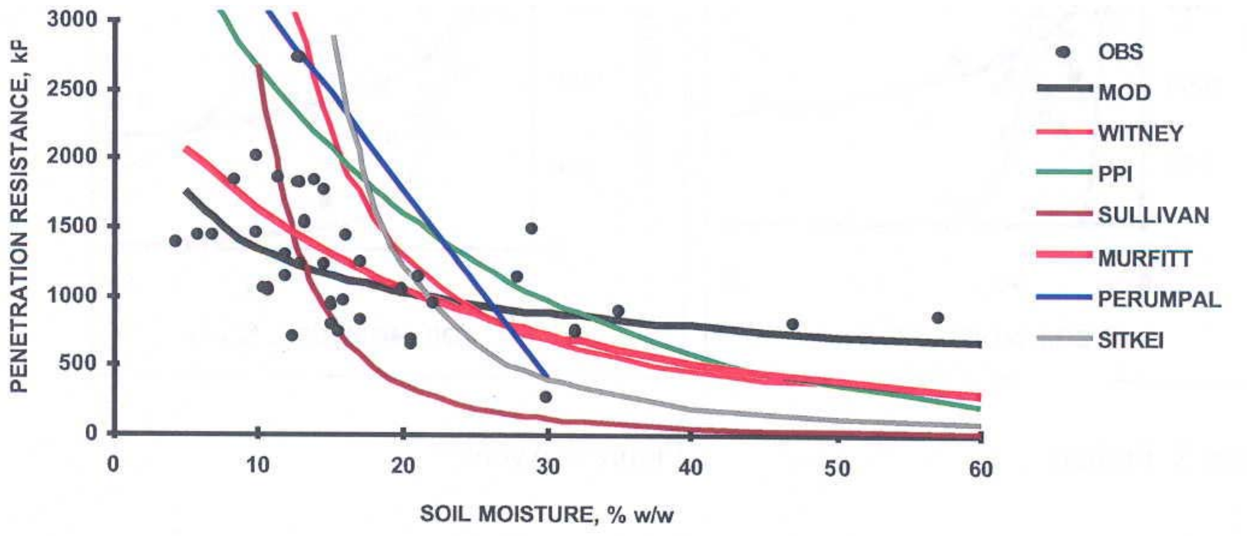


Fig. 5.3 Comparison of penetrometer resistance as a function of soil moisture content predicted using different models: Witney et al. (1984), PPI (2005), Sullivan (1999), Sitkei and Kiss (1986), Perumpal (1987), Mutfit et al. (1987) (Saarilahti, 2002).

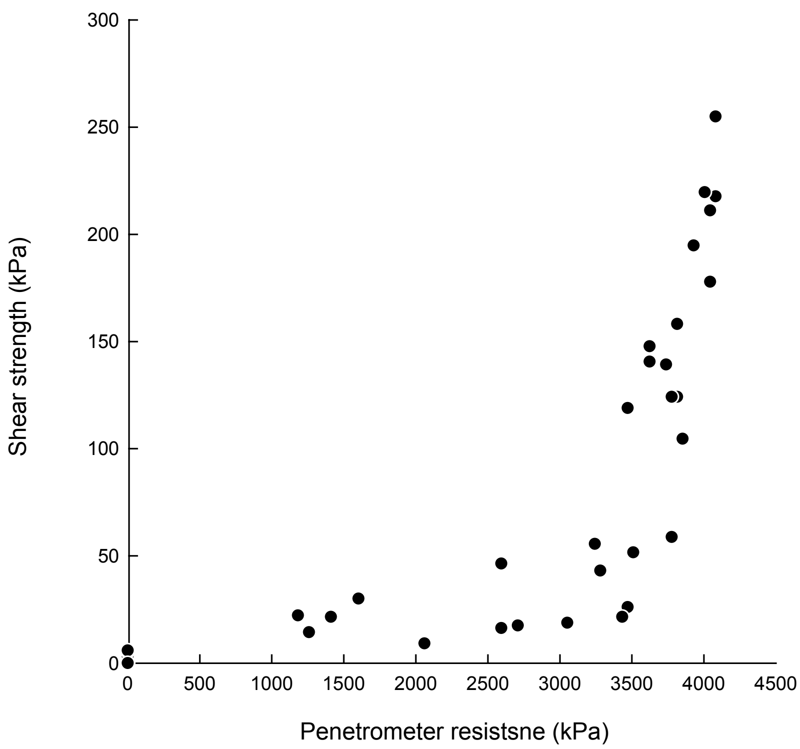


Fig. 5.4 Soil vane shear strength as a function of penetrometer resistance (Rab, unpublished).

5.2 Criteria and threshold values of trafficability

The threshold value for trafficability is defined as "the soil moisture status", expressed in moisture content or matric potential, at which soil traffic is possible without causing unfavourable compaction (Droogers et al., 1996). Various criteria have been used to assess the trafficability of soils including shear strength, critical moisture content for maximum bulk density, field capacity, saturation moisture content and combination of field capacity and rainfall amount. For a given criterion, different threshold values were used for different soil types, vehicle configurations and soil moisture content. These are discussed below with implications for SW WA forest soils.

5.2.1 Soil shear strength

Soil shear strength determines the bearing capacity and traction capacities of soils and therefore soil trafficability. The bearing capacities of various soils are presented in Table 5.5. This table shows that both soil type and moisture content significantly influence the bearing capacity of soils. As discussed earlier, the time of harvest is a critical factor, as large variations in bearing capacity can be expected, particularly in the shallow duplex and clay soil sites of SW WA forests. For example, a clay soil may have a ground bearing capacity of 800 kPa when dry in the summer period but this may fall to as low as 100 kPa when wet during winter. It can be concluded from the data presented in Table 5.5 that the average bearing capacity of both moist sandy soil and clay is about 250 kPa. Comparing the critical value of 250 kPa with the values of ground contact pressures imposed by various harvesting machinery used in SW WA indicates that both skidders and forwarders could severely damage soil during logging in wet weather, in particular during spring and winter.

Table 5.5 Bearing capacity of various soils (authors, cited by Saarilahti, 2002).

Source	Hyvarinen and Ahokas (1975)	Ragot (1976)	Risk
Soil description	Bearing capacity, kPa		
Gravel, fine		500	No
Gravel, dry		200 – 600	No
Gravel, moist	400 - 800		No
Sand, dry	150 - 250		Exist
Sand, moist	300 - 500	400	No
Clay, dry	400 - 1200	4000	Exist
Clay, moist	200 - 300	200	No go
Clay, wet	50 - 150	100	No go
Alluvial soils		50	No go
Peatland, wooded	40 -70		No go
Peatland, open	10 - 40		
Snow, virgin	10 - 30		
Snow old, -10C	50 -100		
Snow, hard packed, -10C	400-800		No go
Ice	1000 - 2000		

Owende et al. (2002) classified bearing capacity of soils into three categories: low (assumed < 40 kPa), medium (assumed 40 – 80 kPa), and high bearing capacity (assumed > 80 kPa) based on three soil parameters. The parameters used in classifying soils are Cone Index (CI), shear strength and deformation modulus (Elasticity value). Each of these can be measured quite easily in the field using portable equipment (Owende et al., 2002). The soil is classified into a bearing capacity category based on the “least common denominator” – i.e. the parameter value that falls into the lowest bearing capacity. The values of soil parameters associated with each classification are given in Table 5.6.

Table 5.6 Classification of the three bearing capacity (BC) categories based on three soil parameters.

Bearing capacity category [A]	**Cone index (kPa)** [B]	**Elasticity**	**Shear strength (kPa)**
Low – bearing capacity (<40 kPa)	<300	<20	<20
Medium – bearing capacity (40–80 kPa)	300 – 500	20 – 60	20 – 60
High – bearing capacity (>80 kPa)	> 500	> 60	> 60

[A] The soil is classified into a bearing capacity category based on the least common denominator – i.e. the parameter value that falls into the lowest bearing capacity.

[B] maximum value in the to 300 mm of the soil profile.

Various authors have used nominal ground pressure as an indicator of ground pressure by machinery. Owende et al. (2002) presented the following equations for determining nominal ground pressure.

For wheeled machines:

$$NGP = \frac{W}{rb} \tag{5.6}$$

where *NGP* = nominal ground pressure;

W = wheel load (kN);

r = wheel radius (m); and

b = tyre width (m).

For tracked machines:

$$NGP = \frac{W}{b}(1.25 + L) \tag{5.7}$$

where *NGP* = nominal ground pressure;

W = track load (kN);

L = length between the wheel centres (m); and

b = track width (m).

Examples of typical NGP ranges that may be encountered in common forest operations are given Table 5.7. The machines, depending on configuration, can impose nominal ground pressures ranging from a minimum of 30 kPa to as high as 70 kPa (see Table 5.8). In order to minimise soil surface rutting, the nominal ground pressure (NGP) should be matched to soil bearing capacity. The Finnish Forestry Development group defines ruts with economic and ecological consequences to be those exceeding 100 mm depth and extending for at least 50 m. Owende et al. (2002) reported that rutting is only considered to be a problem where it is greater than 100 mm deep for more than 10% of the total trail (snig track).

Owende et al. (2002) proposed the use of the ratio of Cone Index to NGP to define the operational limits and ranges for forest harvesting machines. Using the data of Wronski and Humphreys (1994) and Anttila (1998), Owende et al. (2002) developed a relationship between CI/NGP and rut depth (Fig. 5.5). Fig. 5.5 shows that the operational limit lies in the CI/NGP ratio of 3 to 7. Assuming 100 mm rut depth as the threshold value for economic and ecological consequences, this is achieved at a CI/NGP of 5. Owende et al., (2002) proposed the use of a CI/NGP value of 5 as the criterion for establishing the required NGP for a given vehicle operation on sensitive sites in Finland forests. A rut depth of 300 mm is currently used as a threshold in SW WA forests (Appendix 6, Conservation commission of Western Australia, 2005). Therefore, it is proposed to use a CI/NGP value of 3 as a criterion for establishing the required NGP for a given harvesting machine operation on karri loams and on duplex and clay soil sites in SW WA forests.

Table 5.7 Range of nominal ground pressure (NGP) values for people and machines (Olsen and Wasterlund, 1989; cited by Owende et al., 2002).

NGP (kPa)	Reference value
17	A person with boots, standing on two feet
35	A person with boots, standing on one foot
35 – 50	12 t forwarder with 5 t load

Penetrometer resistance has also been widely used for determining trafficability of field soil. Critical penetration resistance for soil trafficability can be found in the literature (eg., Rounsevell, 1993). However, values are obtained with a large diversity of penetrometer techniques. From comprehensive field measurements it appears that penetrometer resistances lower than 0.5 MPa are insufficient to support traffic and values higher than 0.7 MPa are sufficient (Van Wijk, 1988, cited by Droogers et al., 1996).

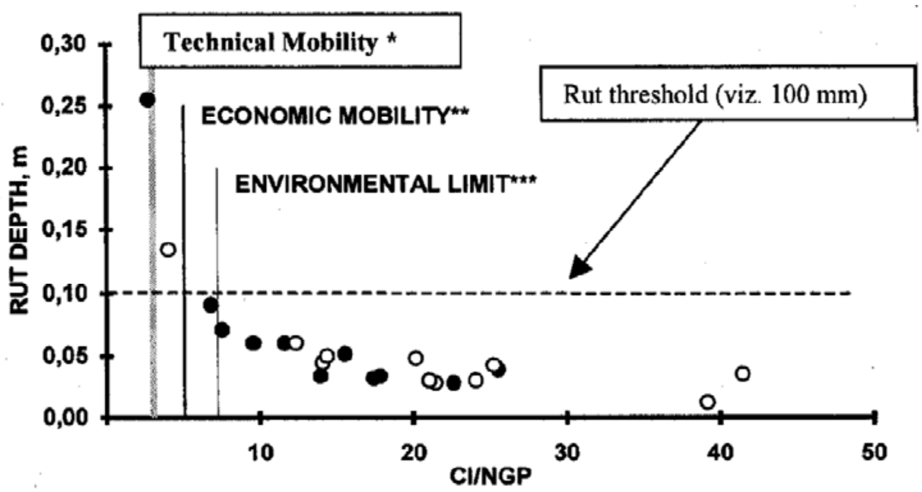


Fig. 5.5 Rut depth (m) versus Cone Index (CI)/Nominal Ground Pressure (NGP) ratio (Wronski and Humphreys, 1994; Anttila, 1998; cited by Owende et al., 2002).

*** the limit of vehicle mobility**
**** CI/NGP value of 5 gives nominal rut depth of 100 mm**
*** the CI/NGP ratio below which rutting develops.

Table 5.8 Calculated nominal ground pressures (NGP) for range of forest machines with and without a pay load (Owende et al., 2002).

Machine type (f=fowwarder) (h=harvester)	Empty weight (kg)	Payload (kg)	Total weight (kg)	No wheels	tyre size	Radius (m)	Tyre width (mm)	Band tracks fitted or not fitted (Yea/No)	Duals (Yes/No)	Tyre+track width (mm)	Track c-c (mm)	NGP (kPa)
Gremo 950 HPV (f)	10800		10800	8	600/50-22.5	0.585	600	No	No			38
Gremo 950 HPV (f)	10800	6000	16800	8	600/50-22.5	0.585	600	No	No			59
Gremo 950 HPV (f)	10800		10800	8	700/50-22.5	0.585	700	No	No			32
Gremo 950 HPV (f)	10800	6000	16800	8	700/50-22.5	0.585	700	No	No			50
Gremo 950 HPV (h)	14000		14000	8	600/50-22.5	0.585	700	No	No			49
Gremo 950 HPV (h)	14000		14000	8	700/50-22.5	0.585	700	No	No			42
Valmet 840 (series 2) (f)	15000		15000	8	600/50-26.5	0.667	600	No	No			46
Valmet 840 (series 2) (f)	15000	8000	23000	8	600/50-26.5	0.667	600	No	No			70
Valmet 840 (series 2) (f)	15000		15000	8	700/50-26.5	0.667	700	No	No			39
Valmet 840 (series 2) (f)	15000		15000	8	700/50-26.5	0.667	700	4 band tracks	No	900	1.51	25
Valmet 840 (series 2) (f)	15000	8000	23000	8	700/50-26.5	0.667	700	4 band tracks	No	900	1.51	37
Timberjack 770 (h), 6 wheel	13500		13500	2	650-26.5	0.666	650	No	No			53
Timberjack 770 (h)	10800		10800	4	650-26.5	0.666	650	No	No			61
Timberjack 810-B (f)	10500		12000	8	600/50-22.5	0.585	600	No	No			42
810-B (f) + Tracks	10500		12000	8	600/50-22.5	0.585	600	4 tracks over 8 wheels	No		1.3	24
810-B (f) + Tracks and duals	10500		13500	8	600/50-22.5	0.585	600	5 tracks+ extra wheels	Yes, 400 mm	1150	1.3	17
Valmet 860 (f)	15900		15900	8	700/45-26.5	0.666	700	No	No			42
Valmet 860 (f)	15900	8000	23900	8	700/45-26.5	0.666	700	No	No			63
Valmet 860 (f)	15900		17400	8	700/45-26.5	0.666	700	4 tracks over 8 wheels	No	900	1.51	26
Valmet 860 (f)	15900	8000	25400	8	700/45-26.5	0.666	700	4 tracks over 8 wheels	No			38
Valmet 911 (h), 6 Wheel	14500		14500	4	700/45-26.5	0.666	700	No	No			55
Valmet 911 (h), 6 Wheel	15500		15500	2	700/50-26.5	0.666	700	No	No			40
Valmet 911 (h), 6 Wheel	15500		15500	2	700/50-26.5	0.666	1170	Duals, extra 400 mm	Yes	1170		35

Table. 5.9 Soil physical properties, critical moisture content, maximum bulk density, and degree of saturation for 30 soils from Victorian Central Highlands forests (Rab, unpublished).

Site location	Sampling depth (cm)	Horizon	Texture	Coarse sand (%)	Fine sand (%)	Silt (%)	Clay (%)	BD (g/cc)	LOI (%)	OM (%)	OC (%)	MD (g/cc)	DS (%)	CMC (% wt.)	LPL (% wt.)	FC (%wt.)
Hellsgate	0-20	A	Loam	34.8	22.8	21.6	20.8	0.73	17.9	13	6.9	1.23	83.3	36.3	55.1	61.2
Hellsgate	50-70	B	Clay	29.9	14.2	16.1	39.7	1.05	9.3	1.8	0.93	1.53	84.7	23.4	33.8	42.7
New Turkey	0-20	A	Silty loam	28	18	30.1	23.9	1.21	9.3	5.3	2.8	1.54	86.0	23.4	32.9	31.8
New Turkey	65-80	B	Clay	15.4	10.6	9.6	64.4	1.18	10.2	1.3	0.65	1.43	92.8	29.9	42.7	42.9
Top Regen	0-20	A	Silty loam	6.8	42.2	40.4	10.6	0.75	17.2	10	5.4	1.12	79.3	40.9	65.3	58.8
Top Regen	35-55	B	Silty loam	5.5	49.3	35.4	9.9	0.87	12.8	5.7	3	1.25	84.4	35.7	49.4	57.4
Old Mill	0-20	A	Loam	44.8	23.1	17.1	15	0.62	18.4	13	6.8	1.15	81.0	39.9	64.1	52.6
Old Mill	70-90	B	Clay	22.9	12.5	9.4	55.2	1.41	10	1.4	0.7	1.51	80.7	23	39.4	26.9
Deception Spur	0-20	A	Loam	24.2	42.8	17	16	0.76	21.9	12	6.5	1.11	80.7	42.3	64	56.6
Deception Spur	35-60	B	Clay	4.8	18.2	20.2	56.9	1.1	12.3	1.7	0.87	1.39	77.7	26.6	44.6	40.5
Simpsons Road	0-20	A	Silty loam	7.7	32.9	35.5	23.8	0.94	13.4	7.6	4	1.33	82.2	30.8	45.9	41.6
Simpsons Road	50-70	B	Silty clay loam	5.9	35.5	27.7	31	1.27	9.4	3.3	1.7	1.52	86.6	24.3	36	30.3
Long Spur	0-20	A	Silty loam	19	36.5	27.1	17.4	0.94	17.4	9.7	5.1	1.23	79.4	34.6	57.7	49.5
Long Spur	35-55	B	Clay	24	15.6	17.3	43.1	1.36	9.3	1	0.5	1.55	80.6	21.6	42.9	31.1
Nine Mile Road	0-20	A	Silty clay loam	11	20	37	32	0.76	16	10	5.3	1.14	70.8	35.4	57.1	77.9
Nine Mile Road	50-80	B	Silty clay	8	18	33	41	1.13	13.3	6.7	3.5	1.23	83.7	36.5	51.9	55.1
Radford Road	0-20	A	Loamy sand	33	39	17	11	0.71	24.1	17	8.8	1	74.5	46.4	69.6	46.5
Radford Road	50-80	B	Loam	6	55	21	18	1.11	10.4	4.2	2.2	1.43	77.9	25.1	40.5	40.2
Silver Ridge Top	0-20	A	Silty loam	24	24	33	18	0.85	18.1	12	6.5	1.21	78.6	35.3	53.5	55.3
Silver Ridge Top		B	Clay	24	14	14	48	1.2	8.6	1.2	0.61	1.6	75.9	18.8	37.3	41.8
Woodmore	0-20	A	Silty loam	8	40	37	16	0.75	19.1	16	8.3	1.04	77.2	45.1	67	60.4
Woodmore	60-80	B	Silty loam	3	55	31	11	1.07	10	4	2.1	1.43	75.4	24.3	41.4	44.4
Siberia Pre-thinning	0-20	A	Loam	35.4	24.4	23.9	16.3	0.59	24.9	16	8.2	1.02	74.4	44.9	68.3	58.3
Siberia Pre-thinning	140-160	B	Loam	37.8	26.9	14.1	21.2	1.35	8.9	1.8	0.92	1.62	83.7	20.1	32	32.5
Back Block	0-20	A	Silty loam	16	29	33	22	0.7	20.3	17	8.9	1.05	75.8	43.6	67.2	65.8
Back Block	60-80	B	Loam	14	47	23	15	1.06	11.5	5.5	2.9	1.4	85.1	28.7	45.2	45.7
Turton's Track	0-20	A	Silty clay loam	1.5	20.2	40	38.3	0.87	15.5	9.5	5	1.18	78.4	36.9	50.2	57
Turton's Track	60-80	B	Silty clay	0.9	14.9	26.9	57.3	1.25	8.9	3.4	1.8	1.37	88.4	31.2	43	39.3
Seaview Ridge Road	0-20	A	Silty clay loam	2.3	30.3	39.5	28	0.89	11.1	7	3.7	1.31	72.2	27.9	44	55.3
Seaview Ridge Road	50-70	B	Clay	6.1	22.7	19.9	51.3	1.28	7.3	1.3	0.68	1.44	78.2	24.8	39.7	41.8

BD = bulk density LOI = loss on ignition, OM = organic matter, OC = Organic carbon, DS = Degree of saturation, MD = Maximum bulk density from Proctors compaction tests using 25 blows per layer; CMC = Critical moisture content for maximum bulk density; LPL = Moisture content at plastic limit; and FC = Field capacity, moisture content at –10 kPa

5.2.2 Critical moisture content (CMC)

The study of change in soil compaction levels with changing soil-water content is of interest so as to determine the critical water content for maximum soil compaction so that timber harvesting can be carried out at less than this water content. The traditional approach is to determine critical moisture content for maximum bulk density using a Proctor compaction test (see discussion earlier, Section 4). Rab (unpublished) determined CMC for 60 soils from mountain ash and mixed species forests in the Victorian Central and East Gippsland forests. He found that CMC for maximum bulk density varied from 39% to 49.2% for the topsoil and 24% to 48.5% for the subsoil depending on soil texture and organic matter content (see Table 5.9).

The values of CMC at which penetrometer or shear strength start to fall from the maximum can also be determined (see Fig. 5.6). The maximum penetrometer resistance and shear strength occurred at a lower soil-water content than that which produced the maximum bulk density and the shape of the soil strength-water content curve was flatter at or close to critical soil-water content. This phenomenon has been observed by others (eg. Ayers and Perumpral, 1982; Ohu et al, 1987). This is because at a soil-water content below the critical value, the bulk density has more influence on penetrometer resistance and shear strength than the soil-water content. At soil-water content near to the critical value the effect of soil-water on penetrometer resistance is greater, resulting in the flatter shape of the curves. At soil-water contents above the critical value, both penetrometer resistance and shear strength decreased more rapidly than bulk density due to a reduction in bulk density and increase in soil-water content.

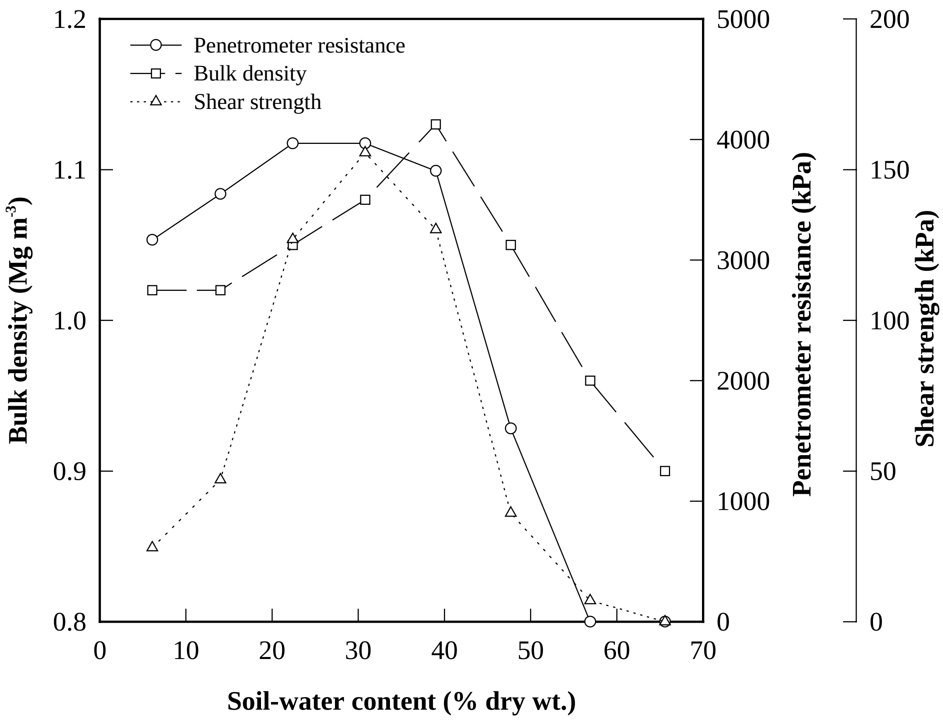


Fig. 5.6 Comparison of the response of bulk density, penetrometer resistance and shear strength as affected by soil-water content at 15 blows per layer for one soil (Old Mill - topsoil) (Rab, 1998a).

Puddling is most serious when soil moisture potentials are higher than field capacity because moist soil aggregates have low strength (Braunack and Dexter, 1978). Several authors have used a threshold values of degree of saturation at which maximum bulk density occurs. Aragon et al (2000) determined maximum bulk density and corresponding critical water content for 30 soils from Argentina.

The degree of saturation can be determined using the following equation (Hillel, 1980):

$$S = \left(\frac{CMC}{S_{CMC}}\right)100 \qquad (5.8)$$

where S = degree of saturation (%);
CMC = critical moisture content at Proctor maximum bulk density (% dry wt.); and
S_{CMC} = saturated soil moisture content at Proctor maximum bulk density (% dry wt.).

The volumetric soil moisture content at maximum bulk density can be determined using using:

$$S_V = \left(1 - \frac{BD_{\max}}{Pd}\right)100 \qquad (5.9)$$

where S_V = saturated soil moisture content at maximum bulk density (% vol.);
BD_{max} = bulk density of Proctor compacted sample (Mg/m^3); and
Pd = soil particle density, usually taken as 2.65 Mg/m^3

The S_{CMC} is estimated by dividing the S_V by the maximum by the maximum bulk density:

$$S_{CMC} = \frac{S_V}{BD_{\max}} \qquad (5.10)$$

Aragon et al (2000) found that the degree of saturation at maximum bulk density varied from 73.2% to 96.8%. For the Victorian forest soils, the line connecting the maximum bulk density versus critical soil water content ranged from 77% to 84% of the degree-of-saturation line (Rab, 1998a). Similar values have been reported for other soil types by Hamdani (1983), 76.9%; and Hillel (1980), 80%.

From this data it can be concluded that an 80% degree of saturation may be a suitable threshold value for determining trafficability of forest soils. However, there is a drawback in the method of determining threshold values of degree of saturation. The values of soil moisture content were determined using the Proctor compacted maximum bulk density values. As discussed earlier, the values of maximum bulk density are dependent on compactive effort. Therefore, the values of degree of saturation determined using the values of maximum bulk density would be different to those determined using bulk density values of undisturbed soils. For example, Rab (unpublished) found that values of degrees of saturation determined using bulk density values of undisturbed soils were significantly lower than those determined using the Proctor compaction maximum bulk density values. At this stage, it is recommended not to use 80% degree of saturation moisture content as a threshold value for SW WA forests.

5.2.3 Plastic limit

Soil trafficability is related to moisture content at the plastic limit (eg. Mueller, 1985; Mueller and Krestschmer, 1990; Smedema, 1993; Mueller and Schindler, 1998a; Mueller and Schindler, 1998b; Dexter and Bird, 2001; Mueller et al., 2003). The plastic limit is defined as the soil water content at which the soil can be rolled into a 'worm' about 3 mm diameter without breaking. The main advantage of the concept of using plastic limit is the opportunity to reliably check the soil behaviour in the field. However, this concept has some disadvantages. It is not applicable to non-cohesive soils and is difficult to apply if plastic limit is small (Dexter and Bird, 2001).

At the plastic limit, the soil is just lubricated enough to exhibit plastic deformation when a force is applied; cohesion is at a maximum near this point and therefore shear strength is at maximum (see above equation 5.2). Above this water content, internal soil friction falls, resulting in a sharp decline in shear strength to a very low level at the liquid limit. The plastic limit, therefore, represents the maximum water content at which a soil can be worked without the occurrence of structural damage (Boekel and Peerlkamp, 1965).

Many authors state that the threshold value of water content corresponding with trafficability is lower than the plastic limit (eg. Godwin and Spoor, 1977). There is no definite matric potential at which the plastic limit occurs, but it is nearly always drier than field capacity in temperate soils (Boekel and Peerlkamp, 1965, Archer, 1975), so that a wet loam or clay soil, just after drainage has stopped, is too wet for trafficking. Research conducted by various authors (Boekel and Peerlkamp, 1965; Boekel, 1979; Archer, 1975; Howard et al., 1981; Littleboy et al., 1998) suggests that the susceptibility of soil to physical deformation is dependent on the relationship between field capacity and plastic limit. The plastic limit of a soil is the minimum soil-water content at which puddling is possible. Boekel and Peerlkamp (1965) have suggested that (i) a soil is likely to be workable at water contents up to field capacity; (ii) damage occurs when a soil is worked at or above the plastic limit. Thus he argues that poor workability may be expected of a soil if the plastic limit is lower than field capacity. As a consequence for fine textured soils, the greater the ratio of plastic limit to field capacity the better the working properties and therefore, thus better the trafficability.

The plastic limit increases with increase in clay content and is noticeably influenced by variation in organic matter content (Archer, 1975). Increasing the soil organic matter content raises the plastic limit proportionally more than it raises the field capacity (see Fig. 5.7) so that a critical organic matter may be assigned to specific soils in order to maintain the plastic limit higher than the field capacity.

Mapfumo and Chanasyk (1998) studied the relationship between Atterberg limits (plastic limit and upper limit), agronomic limits (field capacity and wilting point) and the critical water content (moisture content at Proctor maximum bulk density) for three soils of different textures (sandy loam, clay loam and silt loam). They found that for the sandy loam and loam soils, the field capacity was close to the critical moisture content but lower than the plastic limit. They recommended that trafficking of these two soils at moisture contents close to the field capacity should be avoided since maximum compaction occurs at these moisture contents. Overall, the critical moisture content or field capacity is considered to be a better guide for trafficking of sandy loam and loam textured soils than the Atterberg limits. For the clay loam, field capacity was within the plastic range. Thus trafficking of this soil at field capacity would cause severe compaction. It is concluded that either field capacity or plastic limit, whichever is less, can be used as a guide to avoid trafficking at this moisture content and beyond.

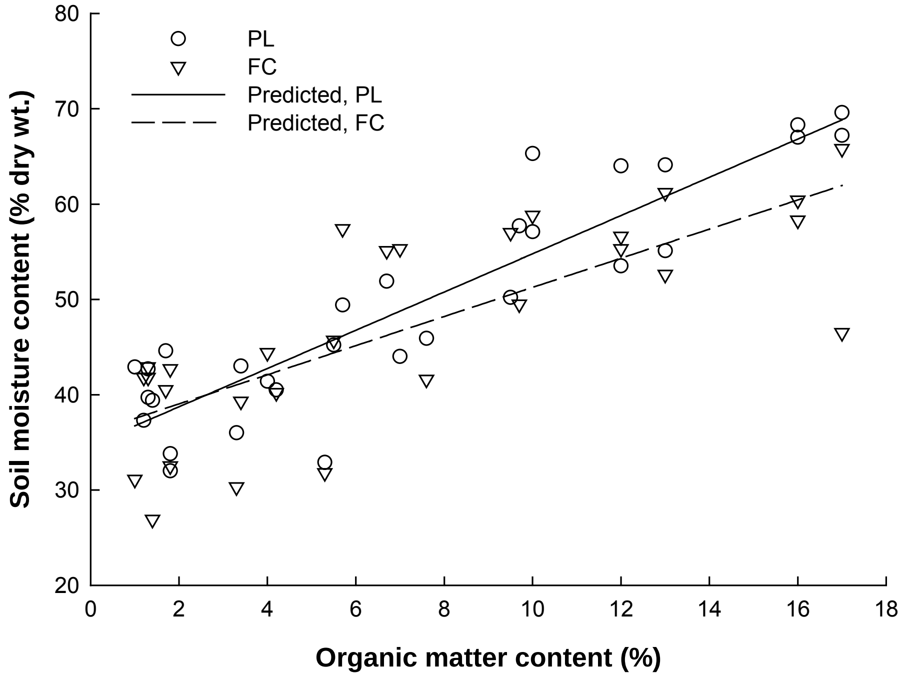


Fig. 5.7 Effect of organic matter (OM) on soil moisture content at plastic limit (PL) and field capacity (FC) of forest soils in the Victorian Central Highlands (Rab, unpublished).

Droogers et al. (1996) determined trafficability of loamy soils in the Netherlands using the plastic limit and penetrometer resistance as criteria respectively. They found that the threshold value of trafficability was −160 cm matric potential.

Rab (unpublished data) studied 60 soils from native forests in Victoria. He found that for the majority of soils the values of critical moisture content were less than the values of plastic limit. The values of plastic limit were greater than the values of field capacity (see Table 5.9).

Trafficking of upland sand and gravels of SW WA will have less impact if timber harvesting is carried out at or close to the plastic limit.

5.2.4 Field capacity

Various workers around the world have used the values of moisture content at field capacity or near field capacity as a criterion to determine the trafficability of both agricultural and forest soils. A comparisons of the values of CMC with field capacity by Rab (unpublished) for 60 soils from Victorian forests showed that at all sites, both topsoil and subsoil have field capacities (soil-water content at −10 kPa water potential) above the CMC. This shows that these soils have high potential for compaction if timber harvesting is carried out at a soil-water content at or near field capacity. However, all these soils are well drained and they should dry out to less than field capacity value by mid−spring.

Rutledge and McHardy (1968) determined the influence of soil moisture on shear strength of plastic soils in Alberta, Canada by using the empirical equation of Nicholls (1932):

$$Fs = \frac{Pu - M}{Pn}\left(0.06Pn + P + 1.8\right)$$

where *Fs* = shear strength (psi);

Pu = plastic limit;
M = soil moisture content (%);
Pn = plasticity number = 0.6C –12;
C = clay content (%); and
P = confining pressure (psi).

They assumed the soil confining pressure to be 16 psi, and the tractor operated with 1% slip, and the soil shear strength required to enable the tractor to develop a drawbar pull of 42.5% of its rear wheel weight was 11 psi, and 9.6 psi for tilled loam and Fall Rye seeding respectively. They reported that applying the above equation, a shear strength in this range would be developed at field capacity of most plastic soils. However, they concluded that machinery operations may be performed in coarse textured soils at moisture contents near field capacity without harm to soil structure. In finer textured soils, machinery operation at high moisture content is harmful to soil structure, and the 95% field capacity criteria must be used.

Bolton et al. (1968) considered a day as workday for tillage operations on silty clay and sandy soils if soil moisture in the top 15 cm layer was less than 80% of maximum storage capacity. For clay soils, the threshold value must be set at or below 78% of maximum storage capacity for all field operations. Seliri and Brown (1972) used 90% of field capacity in the top 12 cm of a soil with unspecified capacity; and Baier (1973) used 97.5% in 25 cm of a soil with a 5 cm field capacity.

In Canada, Brown and Van Die (1974) and Van Die and Brown (1974) (cited by Rounsevell, 1993) considered the moisture content criteria for workability (trafficability) in the spring to be 90% of field capacity in the top 12 cm of soil, whereas in the autumn it was 95%.

Matsumoto (1992) used a soil moisture level greater than 95% of field capacity as the criterion on all soils (sandy, loamy, clay) to determine an unsuitable workday in Mississippi forest.

Pote et al. (2000) investigated the relationship between climate and the pattern of workdays in the two states in USA. They used this information to estimate the number of potential workdays based on given of probability levels. They used the following assumptions to determine possible workdays in Mississippi and Alabama forests:

1. for the effective root zone of 75 cm, values of field capacity used for sandy soil, loamy soil and clay soil were 0.10 cm3/cm3, 0.20 cm3/cm3, 0.30 cm3/cm3 respectively;
2. the trafficability threshold was set for sandy soil at 95% of the field capacity, for loamy soil at 80% of the field capacity, and for clay soil at 65% of the field capacity;
3. soil moisture storage in all soil was at field capacity on the first day of the period of each simulation;

4. no accounting was made for the effect of slope in the analyses; and
5. all work days were of equal length.

5.2.5 Combination of field capacity and rainfall amount

The combination of soil moisture and rainfall amount has been used as a threshold for determining trafficability (Babier et al., 1985; Cornish, 1981; Cornish et al., 1981; Cornish, 1985). Babier et al. (1985) used a combination of soil moisture content in the top 30 cm soil layer, the amount of daily rainfall, snow on the ground, and daily air temperature as criteria to determine soil trafficability. The soil moisture criterion was expressed as a percentage of field capacity of the soil (99% of the field capacity value). If the soil moisture on a particular day was above this established criterion, that day was classified as a non-trafficable day. While the soil moisture was the primary ingredient in the trafficability criteria used in determining whether the day was trafficable or not, other conditions were also used. For example, on a rainy day, if the previous day was trafficable and today's rain was no more than 0.5 cm, the day was considered trafficable. For consecutive rainy days, if the number of rainy days was 3 days or more and today's rain was more than 0.13 cm, the day was considered a non-trafficable day even if the moisture content of the soil layers was less than the field capacity.

Cornish (1985) used records of forest closure periods and predicted rainfall to establish that forest closures were necessary in the Pine plantations in NSW when:

(i) soil moisture $\geq$ 330 - 340 mm in the surface meter and $\geq$ 10 mm rain fell in the day;
(ii) or soil moisture > 340 mm in the surface meter and $\geq$ 5 mm rain fell in the day, and
(iii) after (ii) and sometimes (i) , one more days of carry over closure may have been necessary.

5.2.6 Summary

It is concluded that soil moisture content at field capacity, saturation and plastic limit are the most useful criteria for determining soil trafficability of SW WA forest soils.

However, no information is available on the relationship between these criterion and trafficability of SW WA forest soils (but see Wronski, 1984). As an interim approach, it is recommended that "High Risk" thresholds be set at: 99% of field capacity for upland sands and gravels; 95% of field capacity for karri loams and duplex soils; and 90% of field capacity for clay soils during harvesting in autumn and summer. For spring and winter harvesting it is recommended that: 95% of field capacity be used for upland sands and gravels; 90% of field capacity for karri loams and duplex soils; and 85% of field capacity for clay soils. Detail for other risk classes are found in Table 5.10. These threshold values need to be refined on the basis of operational outcomes over a representative range of sites, seasons and operating systems.

Table 5.10 Proposed threshold values of soil trafficability (using field capacity, FC, as a criterion) for four risk classes, two seasons, and four major soil groups in SW WA forest.

Soil types/seasons	Risk class			
	Very high	High	Moderate	Moderate to low
Upland gravels and sands				
Autumn/summer	Saturation - FC	FC - 0.99 FC	0.99 FC - 0.95FC	>0.95 FC
Spring/winter	Saturation - 0.99 FC	0.99 FC – 0.95 FC	0.95 FC - 0.90 FC	>0.90 FC
Loams				
Autumn/summer	Saturation - FC	FC - 0.95 FC	0.95 FC - 0.90 FC	>0.90 FC
Spring/winter	Saturation - 0.95 FC	0.95 FC – 0.90 FC	0.90 FC - 0.85 FC	>0.85 FC
Duplex soils				
Autumn/summer	Saturation - FC	FC - 0.95 FC	0.95 FC - 0.90 FC	>0.90 FC
Spring/winter	Saturation - 0.95 FC	0.95 FC – 0.90 FC	0.90 FC - 0.85 FC	>0.85 FC
Clay soils				
Autumn/summer	Saturation - FC	FC - 0.90 FC	0.90 FC - 0.85 FC	>0.85 FC
Spring/winter	Saturation - 0.90 FC	0.90 FC – 0.85 FC	0.85 FC - 0.80 FC	>0.80 FC

6. Predicting trafficability periods using the Soil Dryness Index (SDI) model

The SDI is a soil water balance model, which is driven by rainfall and temperature, and is expressed as the nominal rainfall deficit from field capacity. The SDI model is based on Keetch Byram's Drought Index (KBDI) model (Keetch and Byram 1968). The SDI is expressed as the number of points of water (100 points are equal to one cm) required to bring the soil back to field capacity. In estimating SDI, a maximum soil moisture deficit of 200 mm was assumed for a 1 m soil profile depth. At field capacity the SDI equals to zero and any additional water is called runoff even if it is still in the soil. The SDI cannot be negative as it does not account for soil with a moisture content greater than field capacity. The SDI is assumed to be uniform over the area being considered.

6.1 Model description

The assumptions of SDI model are the same as the assumptions of KBDI. The assumptions used in KBDI are as follows (cited by Prudente, 1986):

1. The rate of moisture loss in a forested catchment/area is dependent on the density of the vegetation cover in that area. In turn, the density of the vegetation cover, and consequently, its transpiring capacity, is a function of the mean annual rainfall.
2. The vegetation-rainfall relation is approximated by an exponential curve in which the rate of moisture removal is a function of the mean annual rainfall.
3. The rate of moisture loss from soil is determined by the relationship between evaporation and transpiration (evapotranspiration relations).
4. The depletion of soil moisture with time is exponentially approximated using wilting point moisture as the lowest moisture level. Thus, the expected rate of drop in soil moisture to the wilting point, under similar conditions, is directly proportional to the amount of available water in the soil layer at a given time.
5. The soil has a capacity of 200 mm of available water. The thickness of soil that can hold 200 mm of water depends on soil type. Although the selection of 200 mm is somewhat arbitrary, a precise numerical value is not essential. The use of 200 mm of available moisture appears reasonable for fire control because Keetch and Byram (1968) observed that in many areas of USA, it takes all summer for the vegetation to transpire that much water.

The following equations are used to estimate SDI:

$$P_e = P - I - F_R \qquad (6.1)$$

where P_e = effective rainfall (mm),

P = daily rainfall measured in the morning (mm);

I = canopy interception loss (mm); and

F_R = flash runoff that produced by rain falling on soil, not already at field capacity, faster than it is absorbed by some layer in the profile. F_R is assumed to be zero for SW WA forest (Loh et al., 1984; Burrows, 1987).

The equation for SDI was given as:

$$SDI_1 - Pe = SDI_{am} \tag{6.2}$$

where SDI_1 = SDI value for the afternoon of day 1 (mm);

SDI_{am} is the SDI value for the morning of day 2 if P_e is less than SDI_1

If it is not, SDI_{am} is set to zero and the difference is called soil capacity overflow (the excess rain, drainage or surface flow, from soil whose whole profile is at or above field capacity). The SDI cannot be negative.

$$SDI_2 = SDI_{am} + ET_2 \tag{6.3}$$

where SDI_2 = SDI value for the afternoon of day 2;

ET_2 = daily evapotranspiration corresponding to the maximum temperature for day 2.

Substituting the value SDI_{am} from equation 6.2 into equation 6.3 gives

$$SDI_2 = SDI_1 - Pe + ET_2 \tag{6.4}$$

Substituting the value of P_e from equation 6.1 into above equation 6.4 and assuming F_R = 0 gives

$$SDI_2 = SDI_1 - (P - I) + ET_2 \tag{6.5}$$

6.2 Data requirements

Input parameters required for this model, (equation, 6.5) are daily rainfall and daily maximum temperature. Interception and evapotranspiration are estimated within the SDI environment. These are discussed below.

6.2.1 Interception

Interception, *I*, in this model is defined as the difference between the rainfall outside the canopy and the sum of throughfall and stemflow (Mount, 1972). For the purpose of calculating SDI, it is assumed that the drying of wet tree leaves has negligible effect on transpiration but that drying of wet low vegetation occurs at the expense of evapotranspiration. Interception is dependent on forest types, tree height and rainfall amount. Rutter (1963) (cited by Mount, 1972) showed that the annual interception loss from a pine forest in England was 32% of annual rainfall.

Mount (1972) derived various formulae for estimating the interception loss for mature eucalypts, mature pines and young pines forest types using the experimental data of Rutter (1963) and Bell and Gatenby (1969). Based on these equations, he developed equations for young pine forest in Lidsdale catchment of Tasmania taking into account tree height and crown cover. Smith (1974) and Langford and O'Shaughnessy (1978) conducted a detailed study on throughfall, stemflow and interception by native forests and conifer plantations in NSW and Victoria respectively. Langford and O'Shaughnessy

(1977) presented the following equations for estimating interception for various forest types:

$$I_{MS} = 0.176P + 1.36 \tag{6.6}$$

$$I_{H} = 0.106P + 1.22 \tag{6.7}$$

$$I_{MA} = 0.176P + 1.51 \tag{6.8}$$

$$I_{RA} = 0.150P + 1.09 \tag{6.9}$$

$$I_{RW} = 0.354P + 1.10 \tag{6.10}$$

$$I_{RP} = 0.164P + 1.49 \tag{6.11}$$

$$I_{DF} = 0.235P + 1.32 \tag{6.12}$$

where P = Rainfall (mm)

I_{MS} = Interception by mixed species (mm);

I_{H} = Interception by hazel (mm);

I_{MA} = Interception by mature ash (mm);

I_{RA}= Interception by regrowth ash (mm);

I_{Rw} = Interception by California redwood (mm);

I_{RP}= Interception by radiata pine (mm); and

I_{DF} = Interception by douglas fir (mm).

Interception loss data for the common forest types in SW WA was derived by Burrows (1987) based on Mount (1972). He divided the SW WA forests into four canopy types: Open wandoo (Eucalyptus wandoo), open jarrah, southern jarrah and karri 3 and 6; and karri 1 and 2 and pines (see Table 6.1). The amount of rainfall intercepted by the forest canopy is a function of canopy height, canopy cover and scrub cover. Burrows (1987) applied the following descriptions for the four canopy types:

(a) Open wandoo (*Eucalyptus wandoo*): canopy cover 20%, 40% scrub cover and very light (<30%) ground cover.

(b) Open jarrah: canopy cover 40%, 60% scrub cover and very light (<30%) ground cover.

(c) Southern jarrah and karri 3 and 4: canopy cover 40%, 60% scrub cover and dense (60%) ground cover.

(d) Karri 1 and 2[1] and pines: canopy cover 40%, 60% scrub cover and dense (60 - 80%) ground cover.

The role of litter depth in interception has not been accounted for in any of the above.

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[1] Karri forest types are described in Forest Fire Behaviour Tables for Western Australia (Sneeuwagt and Peet, 1976).

Table 6.1. Amount of rainfall intercepted by canopies of common forest types in the SW WA (Burrows, 1987).

When to use	Daily rainfall (mm)	Canopy interception (mm/day)			
		Open wandoo	Northern jarrah	Southern Jarrah karri 3 and 6 (a)	Karri 1 and 2 (a) pines
Section A	<1.0	0.1	0.2	0.2	0.3
(1) First wet day	1.1 - 2.0	0.2	0.4	0.5	0.6
(2) Consecutive wet days	2.1 - 3.0	0.3	0.6	0.8	1
when daily rain is	3.1 - 4.0	0.4	0.8	1.1	1.4
less than 2 mm after	4.1 - 5.0	0.5	1.0	1.4	1.8
the first wet day	5.1 - 6.0	0.6	1.2	1.7	2.2
	6.1 +	0.7	1.3	2.0	2.7
Section B (3) Consecutive wet days when each day's rain is greater than 2 mm or equal to 2 mm after the first wet day	>2 mm after the first	0.3	0.5	0.6	0.8

(a) Karri forest types are described in Forest Fire Behaviour Tables for Western Australia (Sneeuwjagt and Peet, 1976)

6.2.2 Evapotranspiration (ET)

The ET component is determined as a function of both maximum temperature and soil moisture deficit (i.e. SDI). This relationship is an input to the model as a table of ET values in which each row corresponds to an interval of SDI values and each column corresponds to an interval of maximum temperatures. Evaporation is satisfied entirely from the soil moisture store. Mount (1972) provided values of ET as both functions of daily maximum temperature and SDI for Tasmanian forests. Burrows (1987) divided the SW WA forests into six regions and presented ET values for each region as functions of daily maximum temperature and SDI. The ET values for Collie and Harvey forest districts are presented as an example in Table 6.2.

Table 6.2. Evapotranspiration as a function of maximum daily temperature and SDI (mm x 10) for Collie and Harvey forest districts, SW WA (Burrows, 1987).

	Maximum daily temperature (^oC)											
Feb - June	9+	12+	15+	18+	21+	24+	27+	30+	33+	36+	39+	42+
July - Jan	6+	9+	12+	15+	18+	21+	24+	27+	30+	33+	36+	39+
SDI	Evapotranspiration (mm)											
0	0.5	1.3	1.7	2.1	2.7	3.3	3.9	4.4	5	5.6	6.2	6.8
250+	0.3	0.8	1.1	1.4	1.9	2.4	3.1	3.7	4.3	4.9	5.5	6.1
500+	0.1	0.4	0.6	0.9	1.3	1.7	2.6	3.2	3.8	4.4	5	5.6
1400		0.2	0.3	0.5	0.6	0.8	0.9	1.1	1.3	1.4	1.5	1.7
1650+		0.1	0.1	0.2	0.3	0.3	0.4	0.5	0.5	0.6	0.7	0.8

6.3 Model output

The model predicts daily soil moisture deficit and expresses it as an accumulated soil dryness index value. The values of SDI cannot be negative. The SDI assumes a maximum soil moisture deficit of 200 mm independent of soil types. An SDI of zero means that soil moisture is at field capacity. At a maximum SDI value of 2000 (mm x 10), soil moisture equates to permanent wilting point.

6.4 Relationship between SDI and soil moisture

Various authors have compared measured soil moisture with SDI (Langford et al., 1978; Burrows, 1987). These authors found strong correlations between measured soil moisture and SDI for most of the drying cycles studied. The relationship between soil moisture and SDI was not sensitive at the wetter end of SDI, while the relationship was very good at the drier end. However, this shortcoming may be overcome by estimating SDI using real values of field capacity instead of a hypothetical value.

6.5 Relationship between SDI and soil damage

Critical evaluation of soil disturbance data for the 2004 winter harvesting cells and adaptive management trials indicated no relationship between SDI and soil damage. This is probably because harvesting in the wettest periods was confined to more robust[2] soils, cording was required in the wettest periods and snig track damage was recorded on the basis of snig track order rather than actual damage severity. However, a substantial body of literature exists to support the fact that soil moisture significantly influences soil profile disturbance, compaction and rut formation during timber harvesting (see discussion earlier, Section 3). The threshold values of soil moisture content at which severe compaction and/or rutting occur are discussed in Section 5. The threshold values of SDI for SW WA forests are presented later (see Section 6.9.4).

6.6 Application in SW WA forests

In the SW WA forests, the SDI model is used to plan the timing of prescribed burning in spring and autumn and plan the level of preparedness for wildfire emergencies. The Indian Ocean Climate Initiative (IOCI) is currently developing a forecasting system for SDI (IOCI, 2002).

Most recently, it has been used by CALM for predicting forest closure risk periods for machinery operations in SW WA forests (Appendix 6, CCWA, 2005). The SDI is used to set a threshold for the following risk levels for soil damage:

(a) High risk is when the SDI is less than 250 in spring or less than 100 in autumn. Soils are wet and soil damage is likely in parts of most coupes for operations that involve snigging.

(b) Medium to high risk is when the SDI is between 250 and 500 in spring or 100 and 500 in autumn. Soils are moist and soil damage is likely in parts of most coupes unless intensive management

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[2] Sands or soils with high gravel content.

action is taken to avoid such damage with particular attention to soil type, topography and position in the landscape.

(c) Medium risk is when the SDI is between 500 and 1000. Soils may be moist enough that soil damage could occur, depending on specific soil, management and vehicle factors.

(d) Low risk is when the SDI is greater than 1000. Soils are dry enough to enable operations with heavy machinery to proceed without compaction and rutting under normal conditions.

The Director of Forests or a delegated officer has the authority to set more specific SDI thresholds for particular soil types and the Conservation Commission is notified when this occurs.

6.7 Strengths

6.7.1 Simplicity

One of the major strengths of the SDI model relates to its mathematical simplicity and subsequent ease of use. Mathematical expression of this model is very simple and easy to understand. It does not require any sophisticated programming knowledge to run nor does it require any programming expertise. The simplistic equation structure enables a result to be obtained quickly and cost effectively. Once each of the factors has been assigned a value, the calculation of SDI involves simple arithmetic. The small number of input values also reduces the potential for introduction of prediction errors.

The model is run using a simple Microsoft Excel spreadsheet. The spreadsheet is already developed by the Bureau of Meteorology of Australia and adopted by all states in Australia including SW WA forest regions. This model can be run in any PC based computer and doesn't require a large amount of memory to run. The model can be run within seconds using more than one year of data.

6.7.2 Availability of input data

The SDI model has a simple structure that is consistent with the quality and extent of input data. As discussed earlier, it requires only two input parameters: daily rainfall and maximum temperature, which are readily available for most of the forest districts in SW WA.

The SDI is estimated for the location of the harvesting operation. A method has been developed to correlate the SDI at a field location where no weather data is available with that of the nearest weather record site (see discussion below).

6.7.3 Simple model output

The output provided by this model is the daily soil moisture deficit. Local CALM and FPC officers are quite familiar with the model output and its interpretation in relation to risk levels.

6.7.4 Other applications

The KBDI has been widely used the US in the last three decades for predicting fire risk periods in forests. The SDI has also been widely used in Australia in the past three decades for determining fire risk periods in forests. For example, wild-fire and flood forecasting by various authorities for fire danger rating, protective burning, declaration of local fire danger periods and recommending suitable intensities for patrol of going fires (Mount, 1972).

This model has also been used for purposes other than fire risk predictions. For example, Mount (1972) applied this model to predict runoff from a forested catchment in Tasmania. Langford et al. (1978) used the model to predict stream flow from the Slip catchment in Victoria. They concluded that the prediction of streamflow was reasonable compared to observed data.

Recently, it has been used for estimating grassland curing in Tasmania and New Zealand (Chladil and Nunez, 1995; Hosking, 1990). Hosking (1990) developed a Grassland Curing Index (GCI) based on SDI. The GCI was calculated as the accumulated daily increase in SDI from a nominal start date. Encouraging correlations have been found in Tasmania when GCI is used in conjunction with satellite imagery (Chladil and Nunez, 1995).

This model is adapted for use in irrigation systems in Tasmania. This adaptation has been recognised as the approved method for determining the water balance for wastewater re-use in Tasmania since 1994 (Dettrick and Gallagher, 2002).

Gellie (2003) (cited by Anonymous, 2003) analysed more than 40 years of climate data using the SDI and reported that for 12 years out of 46 years the SDI has exceeded 140 mm for 40 days in a year. He concluded that a value of SDI in excess of 140 mm will lead to wilting of trees, shrubs and curing of grasses in native forests and will lead to increased flammability and curing of live forest fuels. This implies that at a maximum SDI, soil moisture is at wilting point.

6.8 Weaknesses

6 8.1 Estimating ET

For the purpose of estimating ET, the SW WA forests are divided into the following six zones (Burrows, 1987):

- Zone 1- Busselton, Nanup and Kirup;
- Zone 2 – Wanneroo, Mundaring;
- Zone 3 – Collie, Harvey;
- Zone 4 – Dwellingup, Jarrahdale;
- Zone 5 – Walpole south, Manjimup west, Pemberton; and
- Zone 6 – Walpole north, Manjimup east.

For a given zone the values of ET are estimated as functions of both SDI and daily maximum temperature (see Table 6.2). The effect of soil moisture deficit (SDI) on ET will vary depending on microclimate, soil-water characteristics, soil texture and plant species.

The average values of field capacity and wilting point for sandy soils in SW WA are 0.10 m^3/m^3 and 0.08 m^3/m^3 respectively (AgET model, provided by Geoff Stoneman, CALM). The corresponding values for the clay soils are 0.38 m^3/m^3 and 0.24 m^3/m^3 respectively. The estimated values of available water (field capacity – wilting point) for the sandy and clay soils are 20 mm and 140 mm respectively.

In other words, the maximum values of SDI for these soils would be 200 and 1400 respectively. At a maximum SDI value, ET by plants growing in both sandy and clay soils will be close to zero or negligible and the plant is likely to wilt. Therefore, an SDI value of 200 in sandy soil will have the same effect as an SDI value of 1400 in clay soil. Thus, the characteristics of individual soils must be understood if SDI values are to be interpreted correctly.

Estimates of ET using the six tables provided by Burrows (1987) does not take into account variation in soil-water characteristics (eg. soil-moisture–matric potential, and soil moisture – hydraulic conductivity relationships), soil texture between various forest blocks within each region or tree species. In the SW WA, tree species vary from wet sclerophyll karri to dry sclerophyll jarrah, and marri to dry woodland wandoo.

For a given a plant species and soil type, ET is dependent on solar radiation, vapour pressure deficit, wind speed, temperature and relative humidity. These factors are not taken into account when estimating ET using the SDI model.

Table 6.3. Hydrological properties of various soil types in SW WA (from AgET 93 model soil input data file, Argent, 1999; model provided by Geoff Stoneman, CALM, WA).

Soil type	Thickness A- horizon (m)	Sat A- horizon (m^3/m^3)	FC A- horizon (m^3/m^3)	WP A- horizon (m^3/m^3)	Thickness B- horizon (m)	Sat B- horizon (m^3/m^3)	FC B- horizon (m^3/m^3)	WP B- horizon (m^3/m^3)	FC Deep soil (m^3/m^3)	WP Deep soil (m^3/m^3)	Ks A/B (mm/day)	Ks B/Deep (mm/day)
Upland sands and gravels												
Rocky or Stony	0.5	0.25	0.10	0.08	0.5	0.30	0.10	0.08	0.10	0.02	1	0
Sand-Gravel / Duricrust	0.6	0.38	0.24	0.07	1.5	0.35	0.12	0.04	0.35	0.10	3	50
Shallow Sand / Cemented Layer	0.6	0.40	0.15	0.05	1.5	0.38	0.25	0.12	0.18	0.08	5	30
Deep Sandy Gravel	1.2	0.38	0.19	0.06	1.5	0.43	0.32	0.12	0.40	0.28	5	20
Deep Sands	1.5	0.40	0.13	0.04	1.5	0.37	0.20	0.07	0.40	0.27	8	20
Loams												
Deep Loam Duplex	0.7	0.42	0.32	0.15	1	0.38	0.28	0.14	0.40	0.27	2	10
Loamy Earths and Gravels	0.8	0.42	0.26	0.08	1	0.38	0.28	0.14	0.40	0.27	3	10
Duplex soils												
Shallow Sandy Duplex	0.3	0.40	0.13	0.08	1.0	0.43	0.38	0.26	0.40	0.27	1	10
Duplex Sandy Gravel	0.5	0.40	0.25	0.04	3.0	0.42	0.38	0.18	0.40	0.27	8	2
Shallow Loam Duplex	0.3	0.42	0.32	0.15	1.0	0.38	0.28	0.14	0.40	0.27	2	10
Clay soils	0.8	0.38	0.36	0.24	1	0.38	0.25	0.14	0.40	0.27	1	15

Sat = soil water content at saturation; FC = soil water content at field capacity; WP = soil water content at permanent wilting point; and Ks = saturated soil hydraulic conductivity.

6.8.2 Assumptions for estimating SDI

One of the major weaknesses of the SDI model is that in estimating SDI, a maximum soil moisture deficit of 200 mm is assumed for a 1 m profile depth. In SW WA forests, 11 types of soil texture have been identified (see Table 6.3). The value of field capacity and wilting point, and therefore maximum soil moisture deficit, varies with soil texture, organic matter content and bulk density (see Tables 6.3 and 5.9). In addition, the substantial spatial variation in soil texture and its effect on values of field capacity and wilting point (and therefore, SDI) is not taken into account.

Another weakness of the SDI is that SDI cannot be negative. Any additional water above field capacity is called run-off even if it is still in the soil. In other words, if the moisture content of the soil is more than field capacity, the SDI would still be zero. This may be the reason why SDI is not sensitive at or near saturation and the model output is not sensitive at the wet ends of SDI. However, this may be overcome by setting a threshold value of soil moisture at or less than field capacity (eg. 0.95 field capacity).

6.8.3 Threshold values and risk classes

The SDI is used to set threshold values for the various risk levels for soil damage during timber harvesting in the SW WA forests (see Section 6.6). The current threshold values were assigned without taking into account the wide variation of soil types in the SW WA forests.

6.8.4 Error in predicted values

SDI significantly overestimates soil moisture at high values and underestimates at low values (Langford et al., 1978). The reason for this is that the increments of temperature and SDI for adjusting evapotranspiration are too coarse.

Although the fit between observed and modelled data was imperfect, the model was considered to be satisfactory for its intended purpose. It was noted that a disproportionate amount of the error variance in the estimation of interception, soil moisture, and streamflow was attributable to a small number of large errors. The model performed much better under average conditions than this extreme (Langford et al., 1978).

Like many other water balance models, the SDI model has been developed for specific types of catchment and could be very much in error if applied to catchments with completely different hydrologic regimes. For example, the SDI model would not be suitable for situations in which infiltration was a limiting factor because the model assumes all rainfall that reaches the ground, with the exception of flash runoff, enters the soil moisture store. For upland gravel and sands of SW WA forests, infiltration rates are extremely high (Loh et al., 1984; Burrows, 1987) and moisture storage capacities are so large that situations where runoff occurred because of limited infiltration would seldom occur. For shallow duplex and clays soils, infiltration rates and saturated hydraulic conductivity are likely to be low and therefore, both overland flows and subsurface lateral flows would be an issue, in particular during spring and winter.

6.8.5 Spatial variability

Currently, SDI values are estimated at a forest district level and these values are adjusted to local harvesting cell level without taking into account soil types or climatic variations (eg. solar radiation, wind speed, relative humidity). For example, an SDI value of 200 in Manjimup or Burnside assumes that 200 mm of moisture is required to bring the soil in each of these forest areas to field capacity although in reality this may not be the case as soil types may differ widely.

6.9 Recommendations for improvements

The weaknesses of the SDI (as discussed earlier) may be overcome in a number of ways including improving the accuracy of the estimated value of SDI and developing threshold values of SDI based on soil physical principles. The accuracy of the SDI model prediction can be improved by better estimation of ET values and calculating SDI values based on rainfall and temperature at the site rather than interpolating SDI. These are discussed below.

6.9.1 Method for estimating ET

The values of ET are estimated as functions of both SDI and daily maximum temperature for six zones (discussed earlier). The effect of solar radiation, vapour pressure deficit, wind speed, temperature and relative humidity were not fully taken into account when estimating ET using the SDI model. The ET values were derived based on the pan evaporation method and therefore these values would be significantly higher than the actual ET values. This will result in overestimation of SDI.

This may be overcome in a number of ways including determination of ET values for each forest block based on specific relationships between vegetation types and pan evaporation. Another way to improve the estimation of ET is to calculate potential evapotranspiration, ET_0, and then convert ET_0 into actual ET using the FAO 56 manual (Allen et al., 1998). The ET_0 may be estimated using Penman-Montheith (Allen et al., 1998), Priestley-Taylor (Priestley and Taylor, 1972) or Jensen-Haise (NESU, 2003) methods.

Penman-Montheith method

$$ET_o = \frac{0.408\Delta\left(Rn - G\right) + \gamma \frac{900}{\left(T + 273\right)} u_2 \left(e_s - e_a\right)}{\Delta + \gamma\left(1 + 0.34 u_2\right)} \qquad (6.13)$$

where ET_o = potential evapotranspiration (mm/day);

Rn = net radiation (MJ/m^2/day);

G = soil heat flux(MJ/m^2/day);

T = mean daily air temperature at 2 m height (^{o}C);

u_2 = mean daily wind speed at 2 m height (m/s);

e_s = mean daily saturation vapour pressure at mean dry bulk temperature (kPa);

e_a = actual mean daily vapour pressure (kPa);

$(e_s$-$e_a)$ = saturation vapour pressure deficit of the air;

Δ = slope of the saturation vapour pressure-temperature relationship (kPa/^{o}C); and

γ = psychrometric constant (kPa/ ^{o}C).

The psychrometric constant, γ can be estimated using

$$\gamma = \frac{c_p P}{\varepsilon \lambda} \tag{6.14}$$

where P = atmospheric pressure (kPa);

λ = latent heat of vaporisation, 2.45 (MJ/kg);

c_p = specific heat at constant pressure, 1.013x10^{-3} (MJ/kg/^{o}C); and

ε = ratio of molecular weight of water vapour/dry air = 0.6222.

Substituting the values of λ, cp and ε in the above equation z, the equation for estimating γ becomes:

$$\gamma = 0.665x10^{-3}\mathrm{P} \tag{6.15}$$

The atmospheric pressure, P, can be estimated using:

$$\mathrm{P} = 101.3\left(\frac{293 - 0.0065z}{293}\right)^{5.26} \tag{6.16}$$

where z = elevation above sea level (m).

Priestley-Taylor method

$$\mathrm{ET_o} = \frac{\alpha\Delta(R_n - G)}{\lambda(\Delta + \gamma)} \tag{6.17}$$

where ET_o = potential evapotranspiration (mm/day);

Δ = slope of the saturation vapour pressure-temperature relationship (kPa/^{o}C);

R_n = net incoming solar radiation (MJ/m^2/day);

G = soil heat flux (MJ/m^2/day);

λ = latent heat of vaporisation, 2.45 (MJ/kg);

γ = psychrometric constant (kPa/^{o}C); and

α = 1.26 given by Priestly and Taylor (1972).

Jensen-Haise method

This method requires measurements of daily solar radiation and average air temperature along with historical temperature data.

$$ET_O = C(T - T_x)R_S \qquad (6.18)$$

where ETo = potential evapotranspiration in langleys;

R_s = solar radiation in langleys;

T = average air temperature (^oC);

C = computer based long-term weather data for the site; and

T_x = computer based long-term weather data for the site.

The values of C and T_x can be determined using

$$C = \frac{1}{(C1 + C2 \times CH)} \qquad (6.19)$$

$$CH = \frac{50}{(e_2 - e_1)} \qquad (6.20)$$

$$T_x = -2.5 - \frac{0.14(e_2 - e_1)}{50} \qquad (6.21)$$

where C1 = 38 – (2^{o}C*elev in m/305);

C2 = 7.6^{o}C;

e_2 = saturation vapour pressure at mean maximum air temperature for the warmest month at the location; and

e_1= saturation vapour pressure at mean minimum air temperature for the warmest month at the location.

6.9.2 Spatial variability

The two million hectares of forests in SW WA is divided into six zones for the purposes of SDI calculation. Considerable weather variability may exist within each zone. This may result in a wide variation in moisture deficit within the zone. In the southwest of WA it is usual for conditions to be warmer and drier in the eastern and northern parts of the forest (Burrows, 1987).

Accurate measurement of this variability involves considerable cost to CALM or any other organisation. Currently, the Bureau of Meteorology of Australia is in the process of establishing remote weather stations at strategic locations (Peter Murray, CALM, pers. com). This will significantly improve the SDI estimation at remote locations in the SW WA forests.

Another way to improve the SDI is to estimate SDI at a harvesting cell level taking daily temperature into account. Daily maximum temperatures are recorded in a few locations within SW WA forests. Currently, SDI is calculated for six zones throughout the forest. A method has been developed to correlate the SDI at the field location with that of the nearest weather record site based on mean annual rainfall. Spatial variability of temperature is not taken into account.

The daily maximum temperature for a given harvest cell may be estimated based on the relationship between mean annual temperature and elevation. Langford used the following equation (Langford et al., 1978) to estimate daily maximum temperature in the Slip Creek catchment in Victoria:

$$T_2 = T_1 - 0.0054(l_1 - l_2) \tag{6.22}$$

where T_1 is the daily maximum temperature at site number 1(^oC); T_2 is the daily maximum temperature at site number 2 (^oC); l_1 and l_2 are the elevation of site 1 and 2 respectively (m). Similar or other types of relations may be developed for harvesting cells where no temperature data are available.

6.9.3 Methods for estimating SDI for different soil types in SW WA forests

Currently, there is no mechanism available to estimate SDI for a given soil type. The following method is recommended for estimating values of SDI for given soil types in the SW WA forests.

The SDI by definition is the amount of rainfall required to bring the soil profile back to field capacity. Mathematically it can be expressed as:

$$SDI = FC - MC \tag{6.23}$$

where *SDI* = defined in equation 6.5 (mm)
MC = soil moisture content (mm);
FC = Field capacity (mm); and

It follows from the equation 6.23 that at zero SDI, soil moisture is at field capacity, therefore, *MC* = *FC.* By knowing the values of *SDI* (using equation 6.5) and *FC* for a given soil type, the values of MC could be determined. These values of *MC* could be compared with the predetermined threshold values of *MC* (discussed earlier in Section 5) and consequently, a risk level could be assigned.

Alternatively, by assigning various threshold values of MC (MC_{th}), the threshold values of SDI (SDI_{th}) could be determined using:

$$SDI_{th} = FC - MC_{th} \tag{6.24}$$

The soil moisture deficit at a given threshold value of moisture content can determined using:

$$SMD_{th} = FC - MC_{th} \tag{6.25}$$

where SMD_{th} = Soil moisture deficit a given threshold values of soil moisture content for given soil type (m^3/m^3); and
MC_{th} = Soil moisture content at a given threshold for a given soil type (m^3/m^3).

The values of maximum soil water deficit can be determined using:

$$SMD\max = FC - WP \quad (6.26)$$

where SMD_{max} = Maximum soil moisture deficit for a given soil type (m^3/m^3); and
WP = Permanent wilting point of soil (mm).

The current threshold values of SDI for upland gravels and sands; duplex, loams and clay soils can be estimated using:

$$CSDI_{th} = \left(\frac{SMD_{th}}{SMD_{\max}}\right) SDI_{\max} \quad (6.27)$$

where $CSDI_{th}$ = Current threshold values of SDI for a given soil type (mm x 10); and
SDI_{max}= Maximum SDI value for the current SDI model, 2000 (mm x 10);

6.9.4 Threshold values and risk classes for various soil types in SW WA forests

Values of soil moisture and SDI at various field capacity thresholds

There is no field measured data available on hydrological properties of SW WA forest soils. Soil hydrological properties for 11 soil textures were obtained from the AgET model (Geoff Stoneman, pers. com.) soil input data file. These soils were grouped into four major soil types: upland gravels and sands, loam, duplex, and clays, which are relevant to SW WA forests (see Table 6.3). The average values of moisture content at field capacity and permanent wilting point for these four soil types were calculated. The average values of moisture content at field capacity (*FC*) for upland gravels and sand (A-horizon), loam (B-horizon), shallow duplex (B-horizon) and clay (B-horizon) soils were found to be 0.162, 0.280 and 0.347 and 0.250 m^3/m^3 respectively. The average values of moisture content at permanent wilting point for upland gravels and sand (A-horizon), loam (B-horizon), shallow duplex (B-horizon) and clay (B-horizon) soils were found to be 0.060, 0.140 and 0.190 and 0.140 m^3/m^3 respectively.

Values of soil moisture content at various field capacity thresholds (MC_{th}) were calculated for the above four major soil types using the average field capacity values above (see Table 6.4). These MC_{th} and corresponding *FC* values for four major soil types were then used for determining the threshold values of SDI (SDI_{th}) using the equation 6.24. The values of SDI (SDI_{th}) at various field capacity thresholds for four major soil types are presented in Table 6.4.

Table 6.4 Soil moisture content (m^3/m^3) and values of SDI (mm x 10) at various field capacity (FC) thresholds for four major soil types in the SW WA forests[A].

Threshold	Soil moisture content at various field capacity thresholds				SDI at various field capacity thresholds			
	Upland gravels and sands	Loams	Duplex soils	Clay soils	Upland gravels and sands	Loams	Duplex soils	Clays
FC	0.162	0.280	0.347	0.250	0	0	0	0
0.99 FC	0.160	0.277	0.343	0.248	16	28	35	25
0.95 FC	0.154	0.266	0.329	0.238	81	140	173	125
0.90 FC	0.146	0.252	0.312	0.225	162	280	347	250
0.85 FC	0.138	0.238	0.295	0.213	243	420	520	375
0.80 FC	0.130	0.224	0.277	0.200	324	560	693	500
0.75 FC		0.210	0.260	0.188		700	867	625
0.70 FC		0.196	0.243	0.175		840	1040	750
0.65 FC			0.225	0.163			1213	875
Wilting point	0.060	0.140	0.193	0.140	1020	1400	1533	1100

[A] *SDI* was calculated for a 1-m soil profile using the equation 6.24, $SDI_{th} = FC - MC_{th}$, *FC* is the field capacity (mm) and MC_{th} is the critical soil moisture content at a given threshold (mm).

Threshold values of SDI for the improved SDI

Method for improving the SDI model has been presented in earlier (see Sections 6.9.1, 6.9.2 and 6.9.3). The threshold values of trafficability for four major soil types, two seasons and four risk classes are recommended for SW WA forests (see Table 5.10). Using this information, the threshold values of SDI from Table 6.4 were classified into various risk classes according to pre-defined threshold values of risk classes. Recommended threshold values of SDI for four risk classes for four major soil types using best practice harvesting in SW WA forests is shown in Table 6.5. Two options, option 1- conservative, option 2- liberal, are presented.

Threshold values of SDI for the current SDI model

Currently, the SDI threshold values are used to define the four risk levels (Appendix 6, Conservation commission of Western Australia, 2005). However, there is no relationship available between these threshold values and soil trafficability criteria including plastic limit, critical moisture content, saturation water content and field capacity. As an interim approach, it is proposed to define the threshold values of SDI based on field capacity values for different soil types in SW WA.

Table 6.5. Threshold values of SDI (mm x 10) for various risk classes, four major soil types and recommended harvesting practices in SW WA forests using the improved SDI model [A]

Seasons/ Soil types	**Threshold values for improved SDI[A]**							
	Option 1- Liberal				**Option 2 - Conservative**			
	Risk class [B]				Risk class			
	Very High SDI class	High SDI class	Moderate SDI class	Mod. to Low	Very High SDI class	High SDI class	Moderate SDI class	Mod. to Low SDI class
Autumn/Summer								
Upland gravels and sands	0	0-15	15-80	>80	0	0-80	80-150	>150
Loams	0	0-150	150 - 280	>280	0	0-280	280 -425	>425
Duplex soils	0	0-175	175 - 350	>350	0	0-350	350 -520	>520
Clay soils	0	0- 250	250-375	>375	0	0-375	375-500	>500
Spring/Winter								
Upland gravels and sands	0-15	15-80	80 - 150	>150	0-80	80-150	150-240	>240
Loams	0-150	150-280	280 -425	>425	0-280	280 -425	425-560	>560
Duplex soils	0-175	175-350	350 -520	>520	0-350	350 -520	520-700	>700
Clay soils	0- 250	250-375	375-500	>500	0-375	375-500	500-625	>625
Recommended harvesting practice	No logging	Plan snig tracks Monitor frequently No logging where free water Cord if starting to rut or stop	Plan snig tracks Monitor less frequently No logging if free water	Plan snig tracks Monitor less frequently	No logging	Plan snig tracks Monitor frequently No logging where free water Cord if starting to rut or stop	Plan snig tracks Monitor less frequently No logging if free water	Plan snig tracks Monitor less frequently

[A] *SDI* was calculated for a 1 m soil profile using the equation 6.24, $SDI = FC - CMC$, *FC* is the field capacity (mm) and C*MC* is the soil moisture content at a given threshold (mm).
[B] Risk classes are defined in Table 5.10.

Soil moisture deficit at a given threshold value of field capacity was determined for four major soil types using threshold values of moisture content from Table 6.4 and equation 6.25. Maximum soil moisture deficit for these soil types was calculated using average values of moisture content at field capacity and permanent wilting point and the equation 6.26. The average values of moisture content at field capacity (*FC*) used for upland gravels and sand (A-horizon), loam (B-horizon), shallow duplex (B-horizon) and clay (B-horizon) soils are 0.162, 0.280 and 0.347 and 0.250 m^3/m^3 respectively. The average values of moisture content at permanent wilting point (WP) used for upland gravels and sand (A-horizon), loam (B-horizon), shallow duplex (B-horizon) and clay (B-horizon) soils are found to be 0.060, 0.140 and 0.190 and 0.140 m^3/m^3 respectively.

The values of soil moisture deficit at various field capacity thresholds as a proportion of maximum deficit were determined for four soil types. The soil moisture deficit values were then converted to threshold values of SDI for the current SDI model using the equation 6.27. The threshold values of SDI for four major soil types using current SDI are presented in Table 6.6.

Table 6.6. Soil moisture deficit at various field capacity thresholds as a proportion of maximum deficit and threshold values of SDI for four soil types in SW WA forests using the current SDI model.

Threshold	Soil moisture deficit at various field capacity thresholds as proportion of maximum deficit[B]				Threshold values of SDI for using current SDI model[C]			
	Upland gravels and sands	Loams	Duplex soils	Clays	Upland gravels and sands	Loams	Duplex soils	Clays
FC	0.000	0.000	0.000	0.000	0	0	0	0
0.99 FC	0.016	0.020	0.023	0.023	32	40	45	45
0.95 FC	0.079	0.100	0.113	0.114	159	200	226	227
0.90 FC	0.159	0.200	0.226	0.227	318	400	452	455
0.85 FC	0.238	0.300	0.339	0.341	476	600	678	682
0.80 FC	0.318	0.400	0.452	0.455	635	800	904	909
0.75 FC		0.500	0.565	0.568		1000	1130	1136
0.70 FC		0.600	0.678	0.682		1200	1357	1364
0.65 FC			0.791	0.795		0	1583	1591
Wilting point	1.000	1.000	1.000	1.000	2000	2000	2000	2000

[B] Calculated using the equations 6.25 and 6.26, corresponding soil moisture content and SDI values are given in Table 6.4.
[C] Assuming a maximum SDI value of 2000. The threshold values of SDI were calculated using the equation 6.27.

Recommended threshold values of SDI for four risk classes, four major soil types and two seasons (Table 5.10) and with best practice harvesting in SW WA forests are presented in Table 6.7.

Table 6.7. Threshold values of SDI (mm x 10) for four risk classes, four major soil types and recommended harvesting practices in SW WA forests using the current SDI model [A].

Seasons/ Soil types	Threshold values for four risk class using the current SDI model Risk class [B]			
	Very High	High	Moderate	Mod. to Low
Autumn/Summer				
Upland gravels and sands	0	0-30	30-160	>160
Loams	0	0-200	200-400	>400
Duplex soils	0	0-225	225-450	>450
Clay soils	0	0-450	450-680	>680
Spring/Winter				
Upland gravels and sands	0-30	30-160	160-320	>320
Loams	0-200	200-400	400-600	>600
Duplex soils	0-225	225-450	450-680	>680
Clay soils	0-450	450-680	680-900	>900
Recommended harvesting practice	Plan snig tracks Monitor frequently No logging where free water Cord if starting to rut or stop	Plan snig tracks Monitor less frequently No logging if free water	Plan snig tracks Monitor less frequently	Plan snig tracks Monitor less frequently

[A] *SDI* was calculated for a 1 m soil profile using the equation 6.27, *SDI = FC – CMC*, *FC* is the field capacity (mm) and C*MC* is the soil moisture content at a given threshold (mm).
[B] Risk classes are defined in Table 5.10.

7. Alternative water balance models for predicting soil trafficability

Determination of soil trafficability periods usually involves one of two general approaches. The first approach involves prediction and measurement of soil strength and the second, the application of a water balance model. The most popular around the world is the use of water balance models. This approach is discussed below with particular reference to SW WA forests.

7.1. General principles of water balance models

The soil-water balance takes into account precipitation, evapotranspiration, overland flows, subsurface lateral flows, soil-water storage and deep drainage (Fig. 7.1).

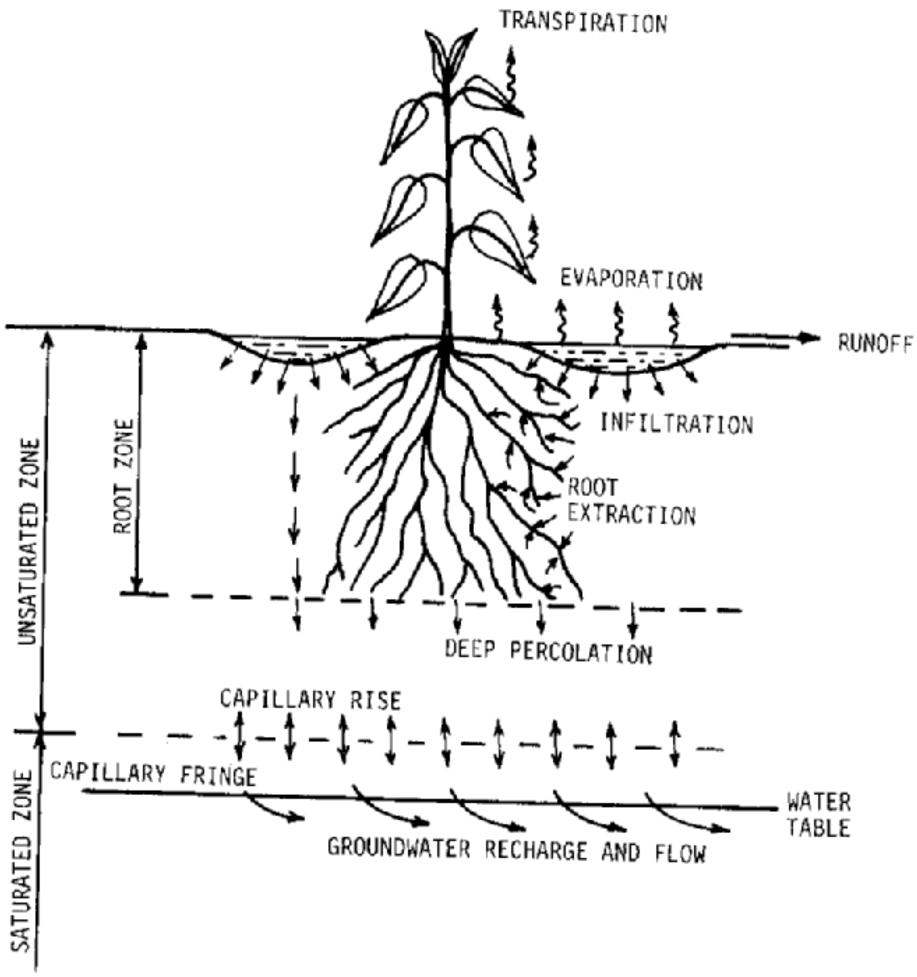

Fig. 7.1 Soil-water balance of the root zone (schematic) (Hillel, 1982).

The water balance components can be estimated using the integral form of the following equation:

$$\Delta\theta = P - I - ET - D - R - L \quad (7.1)$$

where $\Delta\theta$ = change in soil-water storage for a given profile;

P = precipitation;

I = interception by canopy;

ET = evapotranspiration;

D = deep percolation;

R = surface run-off; and

L = subsurface lateral flow.

In general, daily values of *P* are measured or generated using various climate models. The daily *I, ET, R, L* values are predicted using various sub-models. Usually, the *I*, *ET, R, L* and *P* values are used as input variables in the equation 7.1 to solve for soil-water redistribution and deep drainage, *D.* Over the last 50 years numerous models have been developed to solve the soil-water balance equation 7.1 at point, paddock and catchment levels.

In order to determine trafficability periods the threshold values of soil moisture at which machinery will damage soil (see Section 5) are compared with soil moisture conditions over an extended number of years. Soil water balance models have been used widely for predicting soil trafficability of both agricultural soils (eg. Shaw, 1965; Rutledge and McHardy, 1968; Rutledge and Russel, 1971; Selirio and Brown, 1972; Baier, 1973; Ayres 1975; Elliott et al. 1975; Ali 1977; Rosenberg et al., 1982; Babier, 1984; McCabe, et al., 1985; Wosten and Bouma, 1985; Mueller et al., 1990; Droogers et al., 1996) and forest soils (Cornish, 1981; Cornish et al., 1981; Cornish, 1985; Oskoui 1988; Matsumoto, 1992; Pote et al., 2000). For example, Babier et al. (1985) developed a simulation model (TRACTMOD) that can be used to predict the available field operation time for machinery as a function of weather and soil moisture conditions in the top 30 cm of the soil. The model was tested and validated by comparing its output with 11 years of observed workdays for central Iowa, USA. The agreement between observed and predicted trafficability conditions showed that the model was reasonably accurate in predicting trafficability conditions. The authors claim that although the model was developed for a particular location in Iowa, USA, it could be applied to any location worldwide if the data for the input parameters are available. Cornish (1985) develop a hydrological model for predicting trafficability of NSW forests. The models of Babier et al. (1985) and Cornish (1985) could be adapted for use in the SW WA forests.

However, to apply the above models or any other soil water balance model in the SW WA forests, it is important to understand how various components of the equation 7.1 are predicted and what are the underlying assumptions behind each of the sub-models.

It also essential to verify and parameterise the particular model for local conditions. These models also require a good input data set for accurately determining any particular component of the water balance model. Usually, there is a lack of soil and plant input data needed for various hydrological models in Australia, in particular for forested catchments. In this case, surrogates are used to generate soil and input data for models. The general principles of water balance models used by various authors are the same. However, different assumptions for estimating different components of the model (equation 7.1) and different inputs are used and there are differences in the accuracy of their estimates.

The specific objectives of this Section are to:

1. identify water balance models which may be applicable for determining trafficability of SW WA

forest soils; and

2. critically review relevant models for estimating various components of the equation (1).

Soil water balance models such as AgET, PERFECT and WAVES have been developed for predicting daily evapotrapiration, soil moisture distribution and deep drainage of agricultural catchments in Australia. These models could easily be applied for determining trafficability of SW WA forest soils. The TRACKMOD (Babier et al., 1985), Cornish (1985) and Pote (2000) models have been applied to determine trafficability periods of forest soils.

The Cornish (1985) and AgET models will be reviewed in detail below. The Cornish (1985) model was selected because it was used in forest in Australia (NSW). The AgET model was selected because it was developed for SW WA. The following criteria are used to assess which models are most applicable to SW WA forests:

- data requirement and data availability;
- output provided by the model;
- simplicity and ease of use;
- applicability to a range of land uses;
- other applications;
- weaknesses;
- strengths; and
- applicability to SW WA forests.

7.2 Cornish model

Cornish (1981) developed a water balance model for predicting daily soil moisture under *Pinus radiata* plantations at Tumut, NSW. The model inputs are daily rainfall and pan evaporation. The various components of the forest water balance are determined using appropriate relationships. The model has proved a reliable predictor of soil moisture during a 15 month verification period and has been used to indicate when the forest should be closed in order to minimise machinery damage during very wet conditions.

7.2.1 Model description

The general water balance equation may be written as:

$$\Delta\theta = P - R_O - I - ET - U \qquad (7.2)$$

where $\Delta\theta$ = daily change in soil moisture storage (mm);
P = daily precipitation (mm);
R_O = daily runoff (mm);
I = daily interception by canopy (mm);
ET = daily evapotranspiration (mm); and
U = daily deep drainage (mm).

7.2.2 Data requirements

The model inputs are daily rainfall and pan evaporation, and the various components of the water balance are determined using appropriate relationships. The input data required are volumetric soil moisture content to 1 m depth and the soil moisture content at saturation.

The value of daily R_O in equation 7.2 is estimated from a relationship between daily runoff, daily rainfall and soil moisture at the start of the day, derived from data obtained for a *P. radiata* catchment (Smith, 1972).

$$Ro = \left[\frac{P + 27.9 + 135 \ln\left(\frac{\theta}{\theta_{\max}}\right)}{25.5} \right]^2 \qquad (7.3)$$

If the numerator in equation (z) is ≤ 0, then it is made equal to 0.

where θ = mean volumetric soil moisture content to 1 m depth; and

θ_{max} = the soil moisture content at saturation.

The canopy interception, I, is estimated using the following relationship developed by Langford and O'Shaughnessy (1977).

$$I = 0.164P + 1.49 \qquad (7.4)$$

when $P \leq 1.78$ mm, $I = P$.

ET is estimated from measured daily pan evaporation values that were modified by seasonal factors similar to those observed by Smith (1974) and soil moisture depletion factors as discussed by Priestly and Taylor (1972).

$$ET = E_p f \frac{E_A}{ET_0} \qquad (7.5)$$

where E_p = measured daily pan evaporation (mm);

f = seasonal factors;

ET_0 = daily potential evapotranpiration rate; and

E_A = daily actual evapotranpiration rate; estimated using the following equation (Priestly and Taylor, 1972).

$$\frac{E_A}{ET_0} = 1 - 0.02(\theta_L - \theta) \qquad (7.6)$$

where θ_L = soil moisture (mm in top metre) below which $E_A < ET_0$; and

θ = actual soil moisture (mm in top metre), when $\theta_L \geq \theta$, then $E_A = ET_0$.

Substituting E_A from the equation 7.6 into equation 7.5 gives:

$$ET = E_p f\left[(1 - 0.02(\theta_L - \theta))\right] \qquad (7.7)$$

U was estimated from the following relationship obtained by optimization.

$$U = C(\theta - \theta_U)P \qquad (7.8)$$

where C = a constant, an optimized value of 0.0076 used; and

θ_U = a particular soil moisture determined by optimization.

7.2.3 Model output

The model output is daily soil moisture in various soil layers.

7.2.4 Strengths

This model makes a direct prediction of soil moisture content instead of an index, such as SDI. It is better than SDI in terms of estimating various components of the water balance model, in particular, evapotranspiration (ET), and runoff (RO) and deep drainage components. It takes soil moisture content into account. .

7.2.5 Weaknesses

The main drawback of this model is that it is developed for *P. radiata* at a specific location within NSW. It has not been tested or calibrated for other native forest species, soil types and climatic conditions. It also requires measurement of soil moisture content in the top 1 m of the profile. This model is not commercially available for public use.

7.2.6 Other applications

This model has not been used for other purposes. AS mentioned earlier, it has not been tested or calibrated for other native forest species, soil types and climatic conditions.

7.2.7 Availability of the model

This model is not commercially available for public use. However, similar types models, for example, WAVES (Zang and Dawes, 2003)) and PERFECT (Littleboy et al., 1989) are available free of cost.

7.2.8 Adoption in SW WA forests

This model could be adopted in SW WA forest with some modifications. For example, the ET can be estimated by using either Priestly and Taylor (1972) or Penman Monteith (Allen et al., 1998) equation, depending on availability of weather data in SW WA forests. The runoff, RO, can be assumed to be negligible due to flat topography and slope conditions ($<7^o$) of the SW WA forests. The deep drainage, U, can also be assumed to be negligible for the majority of SW WA forests due to drier climatic conditions, flat topography and well drained karri loam soils. The canopy interception may be estimated following Langford and O'Shaughnessy (1977) or Burrows (1987).

7.3 AgET model

AgET is a simple water balance model for comparing water balance components (i.e. evapotranspiration, runoff and deep flow) under different cropping rotations and management options in WA (Argent, 1999). The AgET water balance model is a product of Agriculture Western Australia, and was developed under the auspices of the Salinity Action Plan. The program leads the user through a series of steps by which climate, soil and cropping options are selected. Alternative options are compared through comparison of the evapotranspiration, runoff and deep flow components of the water balance.

It was developed as an extension tool to assist in the exploration of the water balance components associated with different planting and cropping options. AgET helps farmers and their advisors to understand how differing climates, plants, soils and rotations influence components of the water balance. The model uses ‘average’ climate, and ‘representative’ soil and plant information obtained within the agricultural areas of Western Australia.

7.3.1 Model description

The AgET water balance program uses a cascading, three-level "bucket" water balance. This balance is based upon the SOILWAT model of Parton (1978), and the balance of the SOILWAT module in APSIM (McCown et al., 1996) and PERFECT (Littleboy et al., 1992). The daily balance for any soil level is based upon the soil moisture available over the lesser of the soil layer thickness and the effective rooting depth of the crop in question. Thus, if a crop or plant has roots only in the A-horizon, the balance is performed on the A-horizon only, and any drainage from the A-horizon goes to the deep flow component.

The basic steps in the operation of AgET for each day are:

1. Determine rainfall for the day, with allowance made for runoff from intense summer storms
2. Determine evapotranspiration for the day. This is dependent upon the climate (evaporation), monthly crop factor (i.e. the ability of the plant to grow) and the moisture available in the soil.
3. Perform the water balance for the day by adding rainfall and subtracting evapotranspiration. This also determines if there is any surface runoff, how much moisture drains into different soil levels, and how much goes to deep flow.
4. Alter the current soil moisture levels to reflect the results of the daily balance.

The one-dimensional water balance of the AgET model can be described as:

$$\theta_2 = \theta_1 + P - AET \qquad (7.9)$$

where θ_2 = soil water storage in day 2 (mm);

θ_1 = soil water storage in day 1(mm);

P = effective rainfall after talking into account of runoff from intense summer storms (mm); and

AET = actual eavpotranspiration (mm).

The methods for estimating soil water redistribution and runoff are discussed below. The soil water balance is carried out for each of the three soil horizons. Firstly, water balance on the A-horizon is performed using the equation 7.9 then deep drainage and water in excess of AET are routed to the lower horizons (see below).

(i). If the storage, θ_2, is above saturation moisture content (θ_s), then the amount of water above θ_s goes to runoff, AET is fully met, and drainage (D_A) to the B-horizon is calculated as the lesser of the saturated flow (equivalent to saturated hydraulic conductivity at the A/B interface (KsatAB) (mm/day)) and the amount of moisture held between θ_s and the field capacity (FC) of the A-horizon (θ_s – *FC)*. The storage, θ_2, is then set to θ_s - D_A.

(ii) If θ_2 is below θ_s and above *FC*, then runoff is zero, AET is fully met, and drainage to the B-horizon store is calculated as the lesser of the unsaturated flow (calculated by KsatAB*[(θ_2 -FC)/(θ_s - FC)]^2) through the A/B interface and the amount of moisture held between θ_s and *FC*. The storage is then set to θ_2 - D_A.

(iii) If θ_2 is below *FC* and above the permanent wilting point (*PW*), then runoff is zero, AET is fully met, and drainage to the B-horizon is zero.

(iv) *If* θ_2 is below *PW*, then runoff is zero, AET is partially met, θ_2 is set equivalent to *PW*, and drainage to the B-horizon is zero.

Similarly, the balance on the B-horizon is performed using:

$$\theta_{B2} = \theta_{B1} + D_B - UAET \qquad (7.10)$$

where θ_{B2} = soil water storage for the B-horizon in day 2 (mm);

θ_{B1} = soil water storage for the B-horizon in day 1(mm);

D_B = drainage from A-horizon (mm); and

UAET = unmet actual eavpotranspiration (mm).

(i) If θ_{B2} is above the saturated moisture content of the B-horizon (θ_{Bs}), then *UAET* is fully met, and drainage to the Deep horizon, (D_B) is calculated as the lesser of the saturated flow and the amount of moisture held between θ_{B2} and *FC* of the B-horizon (FC_B). The storage for B-horizon is then set to θ_{B2} – D_B.

(ii) If θ_{B2} is below θ_{Bs} and above FC_B, then *UAET* is fully met, and D_B is calculated as the lesser of the unsaturated daily flow through the B- Deep store interface (calculated as for the A store) and the amount of moisture held between θ_{Bs} and FC_B. The storage for B-horizon is then set to θ_{B2} – D_B.

(iii) If θ_{B2} is below FC_B and above the permanent wilting point (PW_B) for B, then *UAET* is fully met, and drainage to the Deep-horizon is zero.

(iv) If θ_{B2} is below PW_B, *UAET* is partially met, θ_{B2} is set equivalent to PW_B, and drainage to the Deep-horizon is zero.

The balance for the Deep-horizon is performed over the depth of the roots in the horizon, with as much of the unmet AET as possible being used, and any moisture above *FC* going to deep flow (deep drainage).

7.3.2 Data requirements

The climatic data required to run the AgET model are mean annual rainfall, daily rainfall and pan evaporation.

AgET has rainfall and evaporation data for eighteen climatic regions (CVT) in SW WA. The CVT zones are used because they divide the south-west into rainfall regions that are immediately recognisable to farmers via the annual Crop Variety Sowing Guide. The zones are labelled as follows:

Zones

1	North
2	North central
3	Central
4	South central
5	South

Rainfall Regions

VH	Very High - greater than 750 mm (average annual rainfall)
H	High - 450 to 750 mm (>450 mm where there is no VH region)
M	Medium - 325 to 450 mm
L	Low - less than 325 mm

All data are stored in text files, and the details in the following sections allow these files to be updated and extended as new or more information becomes available.

In the climate data files, the ordering of regional information is very important. The CVT regions are always addressed in the following order:

1	H1	10	L3
2	M1	11	VH4
3	L1	12	H4
4	H2	13	M4
5	M2	14	L4
6	L2	15	VH5
7	VH3	16	H5
8	H3	17	M5
9	M3	18	L5

The soils data required for the model are:

- Initial soil moisture conditions of A, B and Deep horizons
- Thickness of the A horizon;
- Thickness of the B horizon;
- Saturation, drained upper (field capacity) and lower (wilting point) soil moisture limits for the A horizon;
- Saturation, drained upper (field capacity) and lower (wilting point) soil moisture limits for the B horizon;
- Drained upper (field capacity) and lower (wilting point) soil moisture limits for the Deep Storage soil below the B horizon;
- The saturated hydraulic conductivity for flow from the A to the B horizon (in mm/day);

- The saturated hydraulic conductivity for flow from the B Horizon to the Deep Storage soil (in mm/day); and
- The summer storm runoff threshold (in mm).

The above properties for the following 11 soils, which are relevant to SW WA forests, are built-in in the model (see Table 6.3).

- Rocky or Stony
- Sand-Gravel / Duricrust
- Shallow Sand / Cemented Layer
- Deep Sandy Gravel
- Deep Sands
- Deep Loam Duplex
- Loamy Earths and Gravels
- Shallow Sandy Duplex
- Duplex Sandy Gravel
- Shallow Loam Duplex
- Clay

The program may be run using the properties of these soils or measured soil properties can be used.

The daily maximum actual ET, AET_{max}, is calculated using:

$$AET_{\max} = 0.8Eo \qquad (7.11)$$

where E_0 = daily pan evaporation for day 2 (mm).

The value of AET_{max} is then reduced as a linear function of available moisture for moisture levels below 75% of the saturated moisture level (θ_s) (Denmead and Shaw, 1962; Chiew and McMahon, 1991).

The pan evaporation data are stored in the model. The evaporation data are ordered according to the region order specified previously, from H1 through to L5. The daily evaporation values for each region are representative values of pan evaporation. In running the model, the 365 daily values for the selected region are used in every year.

The crop data needed are the effective rooting depth and monthly crop factor for each crop or plant. In addition, data are also required on type and year of rotation. Rotation cycles of up to eight years can be set.

The built-in Crop File contains data for 24 alternative crops and plants (including bare soil) for each year of each rotation. If required, the effective rooting depth and monthly crop factor for each crop or plant can be changed.

7.3.3 Model output

The model outputs are daily surface runoff, evapotranspiration, soil storage change and deep flow. The daily water balance components of rainfall, runoff, evapotranspiration, soil storage change and deep flow are summed to provide monthly and annual data.

The summary table of results also lists the annual 75th, 50th and 25th exceedence percentile values for rainfall, evapotranspiration, runoff, deep flow and change in soil store, for the current and new rotation. These are a measure of how often certain values are expected to be exceeded. For example, the 75th percentile exceedence value of, say, rainfall, is the annual rainfall that is exceeded in 75% of years. The percentile values are shown as "No Data" for selected run time periods of less than eleven years. This means that the minimum simulation period is ten years.

7.3.4 Strengths

Simplicity

One of the major strengths of the AgET model is that it is a simple water balance model. It can be run using easy to follow step by step guidance provided in the technical manual or help file. It will require only a couple hours of self-learning to run the program. The programming logic of this model is very simple and easy to understand. It does not require any sophisticated programming knowledge to run nor does it require any programming expertise. The simplistic equation structure enables a result to be obtained quickly and cost effectively. This model can be run in any PC based computer and doesn't require any large memory to run. The model takes only a couple of minutes to run using more than 40 years of climatic data. The program is designed to run on Windows 95 or 98™3.

Availability of input data

As discussed earlier, all the input data of soil, plant and climate are provided with the model. These data could easily be modified if needed to suit the local conditions.

7.3.5 Weaknesses

The major drawback of this model is that it does not take into account canopy interception. AgET does not measure plant 'water use. It estimates total evapotranspiration (combined soil water evaporation, plant water use and direct water loss by evaporation and interception). It calculates potential ET by multiplying pan evaporation by 0.8. The potential ET (PET) is then converted to actual ET by multiplying PET with crop factors and further modified based on soil water deficit. It does not use the Penman-Montheith equation to estimate potential ET. AgET is a relatively simple one-dimensional model. It was designed to demonstrate processes and likely outcomes. AgET was not designed to solve the water balance for complex situations. It should not be used as a surrogate for other 'scientific' type models, which are specifically designed for this purpose. AgET cannot be used with accuracy unless realistic site data are used. It is not suited to areas where the root-zone and the watertable are in contact (eg. discharge areas), or where waterlogging, flooding and inundation significantly effect plant water use. This model requires a minimum period of ten years weather data for simulation.

7.3.6 Other applications

The water balance component of AgET balance was based on APSIM and PERFECT, models that are widely used in Australia. AgET was developed for the Sustainable Rural Development Program of Agriculture WA and is an initiative of the Salinity Action Plan.

[3] Windows 95 and 98 are trademarks of Microsoft Corporation

7.3.7 Availability of the model

This model is freely available to use. It is free of cost. Dr. Geoff Stoneman (CALM, WA) has a copy of this model. It was developed by staff within the Natural Resource Management Unit, Agriculture WA and colleagues in CSIRO and the University of Western Australia. The model was produced by the Centre for Environmental Applied Hydrology, University of Melbourne.

For further information please contact the following people (Agriculture WA staff unless otherwise noted):

Project Details	Richard George
Programming	Robert Argent (The University of Melbourne)
Climate data	Ian Foster, Les Heinrich
Soil data	Noel Schoknecht, Paul Raper, Greg Hamilton, Keith Smettem (UWA)
Plant data	David Hall, David Tennant, David Bicknell, Bob Nulsen, Frank Dunin (CSIRO)

7.3.8 Adoption in SW WA forests

This model could be adopted in SW WA forests with some modifications. For example, the model itself needs to be modified to account for canopy interception. Canopy interception may be estimated following Langford and O'Shaughnessy (1977) or Burrows (1987).

The potential ET can be estimated by using either the Priestly and Taylor (1972) or the Penman Monteith equation, depending on availability of weather data in SW WA forests, and then modifying the potential ET based on crop factors and soil water deficit (see Section 6.9.1).

Since the model has been mainly developed and tested for agricultural farming systems, it needs to be calibrated and parameterised before applying in the SW WA forests. Realistic site data on particular soil hydrological properties need to be measured for major soil types within the SW WA forest to improve the accuracy of the model predictions.

7.4 Summary

Both Cornish and AgET models are scientifically sound, simple to use and can easily be adopted in SW WA forests. However, the AgET model would be more suitable than Cornish model because of the following reasons: (i) the AgET model is developed for WA; (ii) it has been tests in SW WA; (iii) local CALM officers (Geoff Stoneman) are familiar with this model; and (iv) they have used it for preliminary investigation of hydrology of SW WA forests (Geoff Stoneman, pers. com.). However, it requires minimum of 10 years of weather data to run. The model is customised so that it can only be run for eighteen climatic zones within WA. The model in its present form is not suitable for day to day running at a given cell level. Therefore, source codes of the model need to be modified to account for the above drawbacks.

An interim approach, using either improved SDI (see Section 9.4 and Table 6.5) or current SDI model with revised threshold values (Table 6.7) may a better option.

8. Field methods for measuring soil moisture, indices of soil moisture and soil trafficability with reference to application in the forests of SW WA

Soil moisture is an important determinant of plant growth, and water movement through soils. It is an integral component of the plant-soil-atmosphere continuum. Soil moisture is one of the most critical factors that influence the degree and extent of soil profile disturbance, compaction, puddling and rutting, and thus trafficability during timber harvesting (discussed in Sections 2 and 3). Restriction of machinery movement during wet weather harvesting is one of the ways to minimise severe soil disturbance (see Section 4).

Generally, a threshold value of soil moisture content is defined as the moisture content at which severe soil disturbance may occur (Section 5). In order to develop strategies for minimising severe soil disturbance during timber harvesting, various risk periods are defined using the threshold value of soil moisture (discussed earlier in Section 6). The soil moisture content before timber harvest can be predicted for a given harvesting cell using various soil-water balance models (see Sections 6 and 7). Currently, in the SW WA forests, the SDI model is used for predicting soil moisture deficit and trafficability periods at a forest district level using climatic data (Conservation commission of Western Australia, 2005). Measurement of soil moisture before timber harvest in the SW WA forests is likely to help in applying and interpreting the SDI value at a harvest cell level.

The specific objectives of this section are to review:

(i) techniques for operational measurement of soil moisture with reference to SW WA forests; and
(ii) field methods for estimating indices of soil moisture.

Trafficability periods may also be determined by comparing measured values of shear strength with the threshold values of shear strength. If the measured values of shear strength fall below the threshold value then the day could be assigned as non-trafficable.

The third objective of this Section is to review field methods for measuring trafficability of soils.

8.1 Techniques for measuring soil moisture

There are many techniques available for determining soil moisture in the field, including:

- Gravimetric method,
- Neutron moderation method,
- Time domain reflectometry (TDR) method,
- Aquaflex sensor; and
- Capacitance based sensors.

Recently, a joint workshop on soil moisture measurement was conducted by the Victorian, Riverina and NSW branches of the Australian Society of Soil Science (ASSSI, 1999). The principles, operational procedures, strengths and weaknesses of the various techniques for measuring soil moisture were discussed in detail (ASSSI, 1999). In this report, a brief discussion on the above soil moisture measurement techniques with particular reference to application in the SW WA forests is presented.

8.1.1 Gravimetric method

This method is the most common method for estimating soil moisture in the field. This method involves taking a soil sample from the site in question. The sample is weighed, dried in an oven at 100 ^{o}C to 110 ^{o}C for 24 to 48 hours and then re-weighed (Reynolds, 1970a, 1970b; Gardner, 1986, cited by George, 1999a). The gravimetric soil moisture content is termed soil wetness and determined using:

$$W = \left(\frac{W_w - W_d}{W_d} \right) \quad (8.1)$$

where W = soil wetness (g/g);

W_w = weight of soil mass (g); and

W_d = oven dry weight of soil mass (g).

The effect of temperature range and drying time periods on the accuracy of soil moisture content was discussed in details by various authors (eg. George, 1999a). However, the most common temperature used for drying the soil sample is 105 ^{o}C and the drying time period used is 24 hours. In the field a sound method for collection and storage of samples is important in reducing error and increasing the accuracy of the actual determination (George, 1999a).

The gravimetric moisture content, w, can be converted to volumetric moisture content using:

$$W_v = W\rho_d \quad (8.2)$$

where W_v = volumetric soil moisture content (m^3/m^3); and

ρ_d = soil bulk density (Mg/m^3).

The gravimetric method is the most accurate method for determining soil moisture. This method is used in many field studies for calibrating other methods for measuring soil moisture. The major drawback of this method is that it takes at least 24 hours to obtain results. In addition, taking soil samples from depth is time consuming, in particular when a large number of samples are required to account for spatial variability.

This method is not considered suitable for operational measurement of soil moisture in the SW WA forests because of at least 24 hours time delay. However, the method may be applied in these forests on an occasional basis for use in calibrating values of SDI.

8.1.2 Neutron moderation method

The neutron moderation method (NMM) and gamma density probe are the two common instruments that fall into this category. The NMM is the most widely used in soil water measurement studies in Australia and throughout the world (George, 1999b) and is discussed below. The NMM technique is based on the measurement of fast moving neutrons that are slowed by an elastic collision with hydrogen particles in the soil. The technical details of the NMM method have been described by various authors (eg. Bavel et al., 1956; Williams et al., 1981; George, 1999b).

For using the NMM to determine soil moisture, aluminium access tubes (4 cm od) are usually installed at 2 to 6 m depths in the field. Readings of neutron probe counts are taken at various depths at regular time intervals. The neutron probe counts are converted into soil moisture content using a pre-determined *in-situ* calibration equation.

One of the major advantages of this method is that this allows rapid measurement of soil moisture as a function of depth and time. The NMM is very robust in operation and the field technique is well established. A good standard technique for installation allows rapid deployment of access tubes and relatively straightforward data collection (George, 1999b). Calibrations for many soils have already been developed (eg. McKenzie et al., 1990; O'Leary and Incerti, 1993; cited by George, 1999b).

The neutron moisture meter measures a large volume of soil compared to dielectric techniques in particular. The integration over a large volume of soil can be viewed as a positive aspect of the technique with respect soil heterogeneity (George, 1999b). However, in duplex soil or where there is sharp wetting front, the large measured volume can lead to difficulty in data interpretation (Williams et al., 1981).

Although this method has many advantages, soil moisture can only be measured at locations where access tubes are already installed. It will not be cost effective to install access tubes in every harvest cell for determining soil moisture using this method. Determining soil moisture using the NMM method at a depth less than 10 cm is not reliable. Another disadvantage is that it may be difficult to install access tubes in heavy gravely sites. However, installing access tubes at strategic locations within the uncut forest of SW WA for measuring soil moisture when required may be a cost effective option.

8.1.3 Time domain reflectometry (TDR) method

Time domain reflectometry (TDR) uses the dielectric properties of soil as the basis for determining soil moisture. The dielectric constant of a soil is an electrical property of its soil, water and ion content (Wood, 1999). It is a measure of how strongly the soil matrix is polarised when placed in an electric field. Dielectric constant values for water, soil and air are about 80, 5 and 1 respectively. Due to large differences in their respective dielectric constant values, by measuring the dielectric constant for the soil matrix the moisture content can be determined. A calibration is required to relate the measured soil matrix dielectric constant to soil moisture content.

The TDR technique is based on the reflection of a fast rise-time voltage pulse generated in either a step-wave or impulse formation. The travel time of the electromagnetic wave along probes buried in the soil is measured and the dielectric constant is calculated. The dielectric constant is then related to volumetric soil moisture either empirically or via various physically based models. Various authors have discussed the principles of TDR method (eg. Edis and George, 1999).

The TDR instruments may be operated in a portable or stationary capacity. In the field, stainless steel probes are generally of two forms, being either balanced (two-wire) or unbalanced (three-wire). Generally, two wire probes are used for portable measurement and the three wire probes for permanently placed probes (Edis and George, 1999). For a detailed discussion on this see Zegelin and White (1989).

One of the major advantages of the TDR method is that it does not generally require calibration. When used in conjunction with a multiplexer, a single TDR unit can be used to monitor several wavelength locations. Most TDR software allows the measurement of soil moisture at several locations, at selected time intervals, with data logging. This is very useful for monitoring profile wetting.

The major disadvantage of this method is the high cost associated with the purchasing of the TDR unit and stainless steel probes. It also requires permanent installation of stainless steel probes in the soil, which may be problematic at sites with high gravel content of the SW WA forests. However, the diameter of the stainless steel probes is significantly smaller than the aluminium access tubes that are required for the NMM method. Therefore, the TDR method would be less problematic than the neutron moderation method (discussed earlier) for measuring soil moisture at gravely sites in the SW WA forests. Installing the probes at strategic locations where weather stations are installed within the uncut forest of SW WA for measuring soil moisture when required may be a cost effective option. Alternatively, portable TDR units with two-wire probes may be used for determining soil moisture at a harvest cell level when required in the SW WA forests.

8.1.4 Aquaflex

The Aquaflex soil moisture sensors use the dielectric properties of soil as the basis for determining the amount of moisture in the soil. For detailed discussion on general principles, operation methods, installation, data handling and limitations of the Aquaflex soil moisture sensors see Wood (1999).

The Aquaflex soil moisture sensors, which are buried in the soil at a given depth, consist of a three metre long transmission ribbon and electronics to generate and monitor electrical pulses. The Aquaflex sensors use techniques similar to TDR, where rapid voltage transitions pass along a transmission cable and electronics record their velocities (Woodhead, 1994; Wood, 1999), The major differences between TDR and Aquaflex sensors are that: (i) the electronics in the Aquaflex sensors receive a transmitted pulse rather than a reflected pulse; (ii) the electrical pulse is transmitted at a different frequency which allows the sensor to be longer; and (iii) the transmission line is covered with a tough plastic coating (Streat Instruments, 1999; cited by Wood, 1999).

The advantages of the Aquaflex include (Wood, 1999): (i) reliability; (ii) large sampling area; (iii) speed of measurement; (iv) no radiation source; (v) high resolution; and (vi) allowance for soil conductivity and temperature.

The disadvantages of the Aquaflex sensors as described by Wood (1999) include (i) non-linearity of calibration curve; (ii) soil disturbance during installation; (iii) sensors connected to loggers by cabling; and (iv) spatial variability of soils and crops. In addition, the installation of the Aquaflex sensors in a site with high gravel and stone content in the SW WA forests may present problems.

The Aquaflex sensors are unlikely to be suitable for operational measurement of soil moisture at a harvest cell level in the SW WA forests. As discussed earlier, the portable TDR with two-wire probes would be better compared to Aquaflex sensors for operational measurement of soil moisture in SW WA forests.

8.1.5 Capacitance based sensors

EnviroSCAN, Gopher and Diviner are three capacitance based sensors used widely in Australia. The EnviroSCAN was the first capacitance based system that was utilised widely by researchers and farmers for on-farm, continuous soil moisture monitoring. This system is suited for permanent in-situ continuous monitoring of soil moisture at a number of depths within the profile. The Gopher and Diviner apply the same principle of measurement as the EnviroSCAN, however, they have been designed as a portable instrument, which is moved from site to site after a soil profile has been recorded (Orloff, 1999). Aleemullah (1999) and Hughes (1999) have discussed the theory, principles and installation of EnviroSCAN sensors in detail.

The principle of measurement applied by the Gopher and the Diviner are the same, however, there are some fundamental differences in the two systems with respect to their operational features. These are discussed in detail by Orloff (1999). The generic benefits of capacitance apply to both sensors, however, there are a number of refinements to the operational features of the Diviner that make the system more repeatable and user friendly (Orloff, 1999).

The main weakness of the capacitance techniques, described by Orloff (199), is the relatively small zone of the influence of the capacitance probes, their sensitivity to the region immediately adjacent to the probe, the effect of the access tube on its performance and its sensitivity to air gaps surrounding the probes. The access tubes need to be installed with care so that no or a very minimum gap is left between the soil and access tubes. This may present a serious problem when installing access tubes in the SW WA forests, in particular in sites with high gravel and stone content. Due to this limitation, the capacitance-based sensor may not be suitable for measuring soil moisture in the SW WA forests.

8.1.6 Summary

Aquaflex and EnvrioSCAN units are suitable for permanent in-situ continuous monitoring of soil moisture at a number of depths within the soil profile. The Gopher, Diviner and neutron probe have been designed as portable instruments, which are moved from site to site after the soil moisture profile has been recorded. The TDR can be installed semi-permanently or used for one-off measurements. The determination of soil moisture using the TDR or neutron moister meters are likely to be relatively more accurate than that determined by the Aquaflex and capacitance based sensors. All of these instruments are mainly designed for on-farm irrigation scheduling. These instruments are not designed for one-off measurement except the TDR with two-wire probes. Most of these instruments require installing either access tubes or sensors in the soil for monitoring of soil moisture content. It will not be practicable or cost effective to install either access tubes or sensors at the harvest cell level for continuous monitoring of soil moisture in the SW WA forests.

Methods that may be appropriate for measurement of soil moisture in the SW WA forests include:

1. Installing neutron probe access tubes or TDR probes at strategic locations where weather stations are installed and monitoring soil moisture as a function of depth and time when required.

2. Using the TDR with two-wire probes for measuring soil moisture before harvest at various locations within a given harvest cell.

8.2 Field methods for estimating indices of soil moisture

Soil moisture is one of the important factors that influence trafficability of soils during timber harvesting. The threshold value for trafficability can be defined as “the soil moisture status”, expressed in moisture content or matric potential, at which soil traffic is possible without causing unfavourable compaction (Droogers et al., 1996). The criteria and threshold values, which are used for assessing the trafficability of soils with reference to SW WA forests, have been discussed in detail in Section 5.

There is a body of literature, which suggest that maximum soil damage occurs when soil is at or near its plastic limit. Puddling and severe rutting occurs when moisture content of the soil is at saturation.

The value of SDI between field capacity and saturation is zero. Usually, the SDI is estimated at a forest district level and then transferred to a harvest cell level based on rainfall at a nearby weather station. It was observed in the field that sometimes the SDI model might esimate a zero value at a forest district level based on rainfall and maximum temperature, but at a particular harvest cell, soil may not be at field capacity or saturated. In this situation, verification of the estimated SDI value with a field measurement of soil moisture is likely to improve confidence in the SDI model and help forest managers to make a decision at the cell level. A field method for estimation of both saturation moisture content and plastic limit will help to verify the SDI value at a harvest cell level. These are presented below.

8.2.1 Saturation moisture content

Bulk soil consists of soil particles (solids), air and water (see Fig. 8.1). After heavy rainfall or irrigation, all the air space in the soil is usually filled with water and the soil moisture content at this stage is considered to be at saturation. In 1-3 days after heavy rainfall, depending on soil type, water from large pores (macropores) is drained out due to gravitational flow and only micropores (pore size <30 μm in diameter) are filled with water. The moisture content of the soil at this point is considered to be at field capacity. In the field, whether soil moisture content is at saturation or not can be determined by physically grabbing a handful of soil and squeezing it between the thumbs. Since there is no air available in the bulk soil at saturation, some water should come out from the sample after squeezing. After squeezing the soil sample, if there is a sign of water between the finger gaps then it could be safely assumed that the soil is at saturation. A representative sample of soil tests is required to account for spatial variability in the harvest cell.

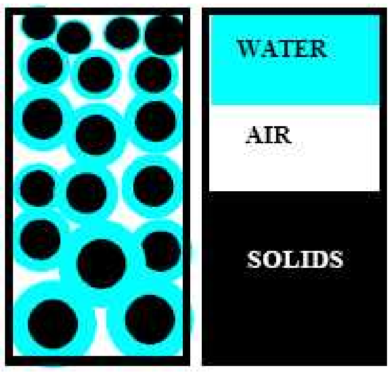

Fig. 8.1. Components of bulk soils in the field

8.2.2 Plastic limit

The plastic limit describes the state of the soil at the lower limit of plasticity. The upper limit of plasticity is called the liquid limit. The difference between them is the plasticity index (Marshall and Holmes, 1979). A soil with moisture content above its plastic limit, exhibits soil particles that begin to stick together (Sticky limit).

The plastic limit of a soil is the minimum soil-water content at which puddling is possible and the maximum soil-water content at which the soil is friable (discussed in Section 5). It is defined as the water content at which the soil can be rolled into a "worm" about 3 mm diameter without breaking. The plastic limit of a soil can be determined in the laboratory (Lamb, 1951). About 15g of air dry soil is moistened by adding a few drops of distilled water and mixed thoroughly. The moist soil is then rolled on a glass plate with the hand until it forms a "worm" of 3-mm diameter. The soil is rolled further until the 3-mm diameter "worm" shows sign of crumbling. The water content of the crumbling soil is determined and taken as the plastic limit of the soil. Four determinations of plastic limit are usually required for each soil horizon.

The same principles could be applied to determine the plastic limit of soil in the field before harvest. First determine whether moisture content of the soil is at saturation or not using the above technique. If the moisture content of the soil is not at saturation then carry out the test to determine whether the soil moisture content is at plastic limit or not. Take about 15g of soil from a given location within the harvest cell. Without adding any water into the sample, try to roll the soil sample on a glass plate with the hand. If it is not possible to roll the soil then it can assumed that the moisture content of the soil is less than the plastic limit. If it is possible to roll the soil sample then continue until the 3-mm diameter "worm" shows signs of crumbling. At this point, it could be assumed that the moisture content of the soil is at plastic limit. Carry out a number of tests to account for spatial variability within a harvest cell. It is not possible to determine the plastic limit of sandy soils using this technique.

Measurements of saturation moisture content and plastic limits need to be taken at various sites in the critical soil layer (see Section 5.1.4).

8.3 Field assessment of soil trafficability

The bearing capacity or traction capacity of a soil determines its ability to support traffic during timber harvesting. In the US military, trafficability is defined as the capacity of soils to support military vehicles. As discussed earlier (Section 5), bearing and traction capacities of soils are functions of their shear strength. Soil shear strength can be measured using different test apparatus, and the results are very dependent on the soil loading conditions and measuring methods. The methods include:

- triaxial tests; and
- direct shear test.

Triaxial tests are generally laboratory tests to assess the cohesion and friction component of the soils under different loading conditions. In direct shear tests, soil reactions are recorded under vertical load only. In the field, shear strength is usually measured using either a cone penetrometer or a shear vane. Penetrometer resistance is the most popular measure. Shear vane and penetrometer resistance is dependent on various factors including soil texture, organic matter content, soil bulk density and most importantly soil moisture content. These factors are discussed in detail in Section 5. In this Section, operational procedures and limitations of these two methods with particular reference to SW WA forests are presented.

8.3.1 Shear vane test

The shear vane test is commonly used to estimate the *in-situ* undrained shear strength of soft to firm cohesive soils. It is also used in some laboratory methods (CECW-EG, 1992). This test should be used with other tests when evaluating the soil shear strength. The test may be performed by hand or may be completed using sophisticated equipment. Details of the test are provided in ASTM D 2573. The vane tester consists of a metal rod, with shear wings, which are pushed into the soil to a certain depth. The rod is turned using a recording torque meter, and the torque is recorded. In simpler versions, only the maximum torque is read. Based on that, soil maximal shear strength is calculated.

The equation for undrained shear strength is given as:

$$C_u = \left(\frac{T_v}{K_v} \right) \tag{8.3}$$

where C_u = shear strength (ksf);

T_v = van torque (kips.ft); and

K_d = constant depending on the dimensions and shape of the vane (ft^3).

The constant K_v may be estimated for a rectangular vane causing a cylinder in a cohesive soil of uniform shear strength by:

$$K_v = \frac{\pi}{1278} \frac{{d_v}^2 h_v}{2} \left[1 + \frac{d_v}{3h_v} \right] \tag{8.4}$$

where d_v = measured diameter of the vane (inch);

T_v = van torque (kips.ft); and

h_v = measured height of the vane (inch).

The advantages of the shear vane test are that: (i) it is a simple device; (ii) relatively easy to use; and (iii) cost of purchasing this equipment is relatively low (current market price is about $A1000.0).

The major limitation of the shear vane is that it covers only a very small sampling area (about 10 cm^2). A patch of root mat or a small area of gravel may significantly influence the reading of the shear vane. The other factors that influence shear vane tests results are soil texture, soil moisture content and bulk density. The effect of soil moisture on soil shear strength has been discussed in Section 5. The shear strength decreases exponentially with increase in soil moisture content (see Fig. 5.1).

There is a lack of information on threshold values of shear strength at which soil is trafficable for various soil and machinery types in the SW WA forests. The SW WA forest soils are highly variable in terms of gravel content, soil moisture and root mat of the surface soils. Therefore, the shear vane test is unlikely to provide meaningful results for determining trafficability of gravely soils of SW WA forests.

8.3.2 Cone penetrometer test

The cone penetrometer is the principal instrument used in evaluating soil trafficability, in particular in the US military. The US military has developed a test kit for determining soil trafficability for military vehicles (US Military, 2005). Similar principles may be applied for determining the trafficability for harvesting machines currently used in SW WA forests. As an example, the typical cone penetrometer, which is used in the US military, is described below. It consists of a 30-degree cone of ½-square-inch base area, an aluminium or stainless steel shaft 19 inches long and 5/8 inch in diameter, a proving ring, a micrometer dial, and a handle (see Fig. 8.2). When the cone is forced into the ground, the proving ring is deformed in proportion to the force applied. The amount of force required to move the cone slowly through a given section of soil is indicated on the dial inside the ring. This force is considered to be an index of the shearing resistance of the soil and is called the Cone Index (CI) of the soil in that plane.

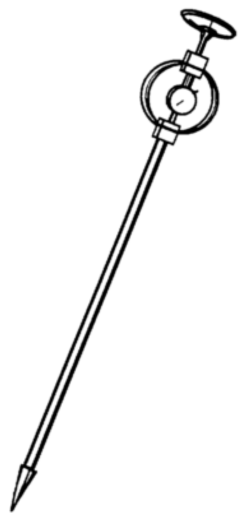

Fig. 8.2 An example of a typical cone penetrometer

A CI ranging between 10 and 300 psi in the critical layer is required to support most military vehicles (US Military, 2005). Except for a few vehicles, a CI below 10 psi is considered to be non-trafficable and a CI above 300 psi is considered trafficable to all but a few vehicles for 50 passes. However, at these threshold values, harvesting machinery may cause severe soil damage.

The advantages of the cone penetrometer test are that: (i) it is a simple device; (ii) relatively easy to use; (iii) it has been used widely for other purposes including soil compaction and root growth studies; and (iv) cost of purchasing this equipment is relatively moderate (current market price is about $A2000.0). A cheaper version of the cone penetrometer may also be available in the market.

The limitations of the cone penetrometer are that: (i) it covers only a very small sampling area; (ii) the test results are influenced by soil texture, soil moisture content, organic matter content, bulk density and gravel content. However these factors do not represent a limitation if the penetrometer is used to estimate site trafficability at a particular time. The effect of soil moisture on cone penetrometer resistance has been discussed earlier in Section 5. Penetrometer resistance decreases exponentially with increase in soil moisture content (see Fig. 5.3).

8.3.3 Summary

The cone penetrometer is likely to provide more meaningful results on soil trafficability than the shear vane for karri loams and podsolic soils of jarrah forests in SW WA forests. Thus the cone penetrometer is recommended for determining the trafficability of these soils during timber harvesting.

The shear vane can also be used with limited success for measuring trafficability of gravelly soils in SW WA forests (Whitford, pers. com.). However, this test should be used with other tests when evaluating the soil shear strength. The number of measurements required to account for the spatial variability of soils in terms of the above properties need to be determined.

As discussed earlier, the SW WA forest soils are highly variable in terms of gravel content and soil moisture. When using the both cone penetrometer and shear vane for assessing soil trafficability care needs to be taken to avoid solid objects, and a representative range of samples need to be taken to account for spatial variability. Both penetrometer and shear vane methods are not likely to provide meaning full results for soil with more than 30% gravel content (Kim Whitford, pers. com.).

From comprehensive field measurements, it appears that penetrometer resistances lower than 0.5 MPa are insufficient and values higher than 0.7 MPa are sufficient to support harvesting machinery (see Section 5). These limits usually make it possible, while gathering data for trafficability evaluation, to classify large areas as above or below the critical range without extensive testing.

Further research is needed to determine the threshold values of shear strength at which soil is trafficable or non-trafficable for various soil and machinery types in the SW WA forests.

9. Gravel content as an index of soil trafficability in SW WA forests

The soil moisture, texture and gravel content are the most important factors affecting both soil compactibility and trafficability. The effects of soil moisture and texture on soil compactibility and trafficability are discussed in Sections 3 and 5 respectively. The effect of gravel content on soil compactibility and trafficability is presented here.

9.1 Effect of gravel content on trafficability of soil

Gravel content, as one of the constituents of the bulk soil, contributes to the soil bulk density. Generally, the greater the gravel content, the greater the bulk density of the soil. Theoretically, the effect of soil bulk density on bearing capacity can be explained using the following equation (see equation 5.3, Section 5).

$$Qu = N_c C + \rho_a L N_q + \rho_a (B/2) N_p \qquad (9.1)$$

where Qu is the soil bearing capacity;

N_c, N_q, N_P = semi- empirical dimensionless coefficients dependent on the effective friction angle of soil;

B = wheel width;

L = wheel sinkage;

ρ_a = soil bulk density;

C = cohesion of soil.

This equation shows that the bearing capacity of soil increases linearly with increasing bulk density. Since bulk density increases with increasing gravel content, increasing gravel content is likely to increase the bearing capacity of a soil. The bearing capacity determines the trafficability of soils (see Section 5.1). Therefore, an increase in gravel content is likely to improve soil trafficability.

Data on bearing capacity of both dry and moist gravel is presented in Table 5.5. Ragot (1976) reported that bearing capacity of dry gravel varies from 200 to 600 kPa. Hyvarinen and Ahokas (1975) reported that bearing capacity of moist gravel varies from 400 to 800 kPa. Using bearing capacity as a basis, Saarilahti (2002) classified various soil and gravel types into three trafficability risk categories: no risk, risk exit and no go (Table 5.5). He reported that both dry and moist gravel fell into the no risk category.

The range of values of bearing capacity of gravel reported by these authors, 200 to 600 kPa, is significantly greater than those reported for moist clay (200 to 300 kPa), wet clay (50 to 150 kPa), and dry sand (150 to 250 kPa), by the same authors. Based on the above research findings, it can be concluded that during spring and winter, upland gravels are likely to have better trafficability compared to that of karri loams and podzolic soils in the SW WA forests.

9.2 Effect of gravel content on soil compactibility

Several authors have studied the effect of gravel content on soil compactibility and rutting (Wronski, 1984; Whitford, 2001; Whitford et al., 2005). Soils with a high gravel content have generally been observed to be more resistant to rutting and mixing under moist conditions than the more loamy soils with lower gravel content (Wronski, 1984; Whitford, 2001). Wronski (1984) reported for gravelly sandy clay loams in karri forest at Treen Brook in SW WA that as the gravel content declined below 55% by weight, the soil became more susceptible to rut development. He also reported that for sites with less than 55% gravel, poor trafficability and rut development may be expected for vehicles exerting up to 200 kPa average ground pressure once matric potentials in the main zone of shear failure beneath the wheel exceed –3.0 kPa.

Forest Practices Code BC (1999) reported that soils with more than 70% gravel content have a low susceptibility to compaction and the influence of soil texture would be negligible (see Table 9.1).

Table 9.1. Susceptibility of soils to compaction and puddling based on texture (Forest Practices Code BC, 1999).

<table>
<tr><th colspan="2" rowspan="2">Soil texture[A]
(0-30 cm)</th><th colspan="2">Relative compactibility</th></tr>
<tr><th>(H-horizons <20 cm)</th><th>(H-horizons ≥20 cm)[B]</th></tr>
<tr><td colspan="2">Fragmental
(subsoil composed of coarse fragments, fragments >2 mm diameter, >70%)</td><td>Low</td><td rowspan="5">Very high</td></tr>
<tr><td rowspan="4">Coarse fragments (<70%)</td><td>Sandy
S, LS</td><td>Low</td></tr>
<tr><td>Sandy loam
SL, fSL</td><td>Moderate</td></tr>
<tr><td>Silty/ loamy
SiL, Si, L</td><td>High</td></tr>
<tr><td>Clayey
SCL, CL, SiCL, SC, SiL, SC, SiC, C</td><td>Very High</td></tr>
</table>

[A] Soil texture abbreviations: S – sand; LS – loamy sand; CL – clay loam; SL – sandy loam; fSL – fine sandy loam; C – clay; L – loam; Si – silt; SiC – silty clay; SiL – silty clay, SiL – silt loam; SC – sandy clay; SCL – sandy clay loam; SiCL – silty clay loam;

For the purposes of this key, fSL, "fine sandy loam," means the soil contains 30% or more fine or very fine sand, or more than 40% fine and very fine sand combined. Fine sand is 0.25-0.10 mm in diameter, very fine sand is 0.1-0.05 mm in diameter.

[B] The H-horizon is mainly composed of organic matters, or of peaty forest floors> 40 cm thick, (including Folisols < 40 cm). It has very low strength and compressibility properties and is susceptible to rutting because it's low load-bearing strength material makes it easy to displace. Otherwise, it is some kind of transformation zone between vegetation and soil, and biological processes (roots, microbes and nematodes) renovate it continuously.

Whitford et al. (2005) studied the effect of pre-harvest soil gravel content on soil bulk density due to timber harvesting in SW WA forests. They found that gravelly soils generally attained levels of soil compaction after timber harvesting that were similar to those measured in soils with low gravel contents (see Table 9.2). They found no evidence that surface soils with high gravel content were resistant to compaction during timber harvesting under moist soil conditions. They did not quantify the effect of soil moisture content and number of machinery passes on rut development. The soil textures also were not reported for the study sites. The difference in findings on the effect of gravel content on soil compactibility found by Wronski (1984) and Whitford et al. (2005) may be attributed to the differences in soil moisture content, number of machinery passes and soil texture between these study sites.

Table 9.2 Effect of pre-harvest gravel content on soil compaction due to timber harvesting in the Jolly forest block during the 2004 harvesting season (Whitford et al., 2005).

Snig tracks gravel content	Pre-harvest bulk density (%)	Pre-harvest bulk density (Mg/m^3)	Post-harvest bulk density (Mg/m^3)	Increase in bulk density (Mg/m^3)	Percent increase in bulk density
Primary	69 ± 1	0.65 ± 0.02	0.88 ± 0.05	0.28 ± 0.05	50.7
Primary	69 ± 1	0.65 ± 0.02	0.88 ± 0.05	0.28 ± 0.05	50.7
Secondary	67 ± 1	0.57 ± 0.03	0.85 ± 0.02	0.28 ± 0.04	54.8
Secondary	39 ± 2	0.69 ± 0.04	0.94 ± 0.06	0.25 ± 0.07	40.1
Secondary	4 ± 1	1.09 ± 0.06	1.31 ± 0.07	0.22 ± 0.07	21.8

9.3 Summary

Currently, gravel content is used as a gauge of trafficability under moist soil conditions in SW WA forests. It is recommended to continue the use of gravel content as an indicator of soil trafficability during harvesting in SW WA forests, in particular during spring and winter.

Traditionally, gravel has been used to improve the trafficability of dirt forest roads worldwide. However, there is a paucity of information on the threshold values of gravel content at which soil compacts or ruts (but see Wronski, 1984; Forest Practices Code BC, 1999). As an interim approach, a threshold gravel content value of 60% is recommended for snig tracks that can be trafficked throughout the spring and winter periods when SDI is low.

10. Classifying of SW WA forest soils into similar compactibility and trafficability groups

10.1 Climate and soils

The south-west of Western Australia has a Mediterranean climate with a rainfall in the forest areas ranging from 600 - 1300 mm per annum, most of which occurs between May and October (Gentilli, 1989). There is a strong rainfall gradient with reducing rainfall from the west and south-west coast towards the inland. Mean annual evaporation ranges from 400 mm in the south to 800 mm in the north.

The soils of the forest area are principally determined by the degree of dissection of the Darling Plateau. The northern jarrah forest is dominated by lateritic uplands where the soils consist of sandy gravels overlaying the lateritic duricrust. On the slopes this gives way to sandy gravel duplex soils overlaying kaolinitic clay. The broad valley floors are characterised by yellow duplex soils or orange earths. In the deeply incised river valleys the soils consist of red and yellow earths derived from the country rock with some gravel colluvial from the lateritic upland. (Churchwood and McArthur, 1980; Churchwood and Dimmock, 1989).

In the southern parts of the forest the lateritic duricrust decreases in elevation and has been more extensively eroded. Red and yellow duplex soils (podsols) begin to dominate south of Manjimup and there are also relatively extensive areas of red earths extending from the valley to the ridge tops in the vicinity of Pemberton. The podsols have a sandy and sandy gravel surface but are relatively shallow to clay. The red earths (known as karri loams) vary from sandy loams to loams with a gradual transition to clay at about 50 cm (McArthur and Clifton, 1975; Bradshaw and Lush, 1981; Christensen, 1992).

The pattern of forest type is strongly influenced by soil type. The lateritic duricrust tends to be dominated by jarrah in relatively pure formation, with the proportion of marri increasing on the slopes with duplex soils. Karri dominates on the red earths of the southern forest and occurs in mixture with marri on the red duplex soils. Karri also occurs on the red soils derived from the emergent granite-gneiss insolbergs of the southern coastal plain. To the north of the karri distribution, blackbutt and bullich occur on the red, brown and yellow earths. Wandoo occurs in the broad valleys to the east of the jarrah forest on orange earths with a shallow depth to clay.

In the Blackwood Plateau (also known as the Donnybrook Sunklands) to the west of the Darling Scarp there is little topographic relief and the soils are dominated by yellow duplex soils in broad depressions separated by a low divide of gravely sands on the lateritic duricrust (Churchwood and McArthur, 1980). The depressions have a shallow depth to clay and the water table is close to the surface in winter.

This wide range of soil characteristics and the climate within which they occur leads to substantial variation in soil trafficability and the number of days in the year when it can be satisfactorily worked.

10.2 Soil compactibility mapping

Soil compactibility varies according to soil texture and organic matter content as discussed earlier (see Section 4). At the most detailed level, 19 general soil texture grades are recognised (Northcote, 1975). These may be grouped into any number of categories depending on what is practical to recognise, map and use. Table 10.1 shows how these soils may be grouped into six, five and four texture groups. Local soil types can then be fitted into each of these various texture groups according to the relative susceptibility of soils to compaction.

While recognising that soil texture is a critical characteristic in terms of compactibility and trafficability, consideration has also been given to the significance of soils with a very high gravel content and depth to clay. The table shows how the 14 texture grades of SW WA soils (Argent, 1999) fit into the more general texture grades. These have also been grouped into four categories.

As a first stage approach to mapping WA forest soil groups into trafficability classes we have used readily available mapped information on vegetation and landform to infer these characteristics at a landscape scale. For this purpose we used existing maps of Vegetation Complex (Mattiske and Havel, 1998) and Forest Associations (Bradshaw et al*.,* 1997). Vegetation complexes provide a seamless coverage of State Forest and are derived from an attribution of vegetation to landform, while forest associations are based on direct mapping of forest types. We initially defined and delineated upland sands and upland gravels from Vegetation Complex and separated the remaining area according to Forest Association. The groupings (in decreasing order of trafficability) were based on:

- *Lateritic uplands* – aims to capture the lateritic duricrust and deep well-drained gravels of the Darling plateau and includes Vegetation Complex D1, D2, D3, D4, HR, BE1, BE2, Y5, MH, WG. Aims to exclude other undulating uplands but will include small areas of upland sands overlaying the duricrust.
- *Blackwood Plateau uplands.* Aims to capture the uplands soils on lateritic duricrust in the Blackwood Plateau and includes Vegetation Complex KI. Undulating lower ridges and slopes are excluded.
- *Upland sands* – includes Vegetation Complex CR, CF (there are probably others which could be identified with a more thorough examination)
- *Red loams* – identified as pure karri from Forest Associations. Some karri/marri forest is occurs on red loams but the soil type associated with karri/marri mixtures is more variable. Red karri loams may occur in all positions in the landscape. Confining the group to pure karri represents a conservative estimate.
- *Duplex soils*. These are principally podsols with a sandy or gravel sand surface but are relatively shallow to clay. They occur on slopes, broad flats and valley floors sometimes with a relatively high colluvial gravel content. These were initially divided into ‘other karri’ and ‘other jarrah’ types.
- *Blackwood Plateau shallow to clay*. This includes the remainder of the jarrah forest in the Blackwood Plateau on duplex soils on low ridges, slopes and depressions but also includes some red and yellow earths in the valley systems.

- *Clays*. These are delineated on the basis of wandoo types. While occurring on orange earths in the broad valleys they are shallow to clay with very poor trafficability when wet. This area is largely irrelevant to harvesting.

Table 10.1 Trafficability and compactibility of various proposed categories of SW WA forest soils for combined texture and local soil groups.

Trafficability	Compactibility	Texture groupings			Local soil groupings	
		4 texture groups	5 texture groups	6 texture groups	6 soil groups	4 soil groups
Excellent	Low	Stony/ Sandy	Rocky or Stony Sand-Gravel / Duricrust Shallow Sand /Cemented Layer	Sand Loamy sand Clayey sand	Lateritic uplands	Lateritic uplands Upland sands, Blackwood Plateau uplands
			Deep Sandy Gravel Deep Sands	Sandy loam Fine sandy loam Light sandy clay loam	Upland sands	
		Loam	Shallow Loam Duplex Shallow Loam / Hardpan Deep Loam Duplex Loamy Earths and Gravels	Loam Loam, fine sandy Silt loam Sandy clay loam	Blackwood Plateau uplands	Red loams (Karri loam)
		Sandy duplex/ Clay loam	Earthy Sands Shallow Sandy Duplex Duplex Sandy Gravel Deep Sand Duplex	Clay loam Silty clay loam Fine sandy clay loam	Red loams (Karri loam)	Shallow to clay (duplex soils under jarrah and karri, Blackwood Plateau shallow to clay)
		Clay	Clay	Sandy clay Silty clay loam Light clay Light medium clay	Shallow to clay (duplex soils under jarrah and karri, Blackwood Plateau shallow to clay)	Clay (orange earths under wandoo)
Very poor	Very high			Medium clay Heavy clay	Clay (orange earths under wandoo)	

The first three categories are considered to be relatively robust in terms of winter trafficability, the third is moderately robust while the remainder are highly susceptible to soil damage in winter. These categories contain the following areas of State forest:

- Lateritic uplands 396,000 ha
- Blackwood Plateau uplands 64,000 ha

- Upland sands 9000 ha
- Red loams 30,000 ha
- Shallow to clay – karri 49,000 ha
- Shallow to clay – jarrah 373,000 ha
- Shallow to clay - Blackwood Plateau 116,000 ha
- Clay (wandoo) 39,000 ha

For operational purposes we believe that these soils can be further grouped into four categories as follows:

1. Lateritic uplands (Darling and Blackwood Plateaux) and Upland sands
2. Red karri loams
3. Duplex soils (shallow to clay), Blackwood Plateau shallow to clay,
4. Clay (shallow to clay under wandoo)

The above categories should be regarded as preliminary at this stage and refinement may be possible with further examination. A section of the map is illustrated in Fig. 10.1. The map covering State forest is held within CALM's Forest Management Information System (FMIS) under the file name SOILGROUP4.

The Department of Agriculture is the custodian of soil mapping in Western Australia and has developed seamless soil maps covering the forest area. They are able to produce soil maps at a range of resolutions (Schoknecht et al., 2004). Datasets that include a full range of soil attributes have been proportionally attributed to each identified map polygon. Soil attributes have been obtained from field sampling. Soil maps of state forest are also generally based on landform at the landscape scale (similar to the basis for the Vegetation Complex maps) but attributed according to soil type rather than vegetation. Data in this form may be able to be grouped in ways that are more directly related to soil behaviour. It is also possible to develop a range of derived data sets including susceptibility to compaction. The potential of this mapping for use in harvesting activities should be examined in more detail.

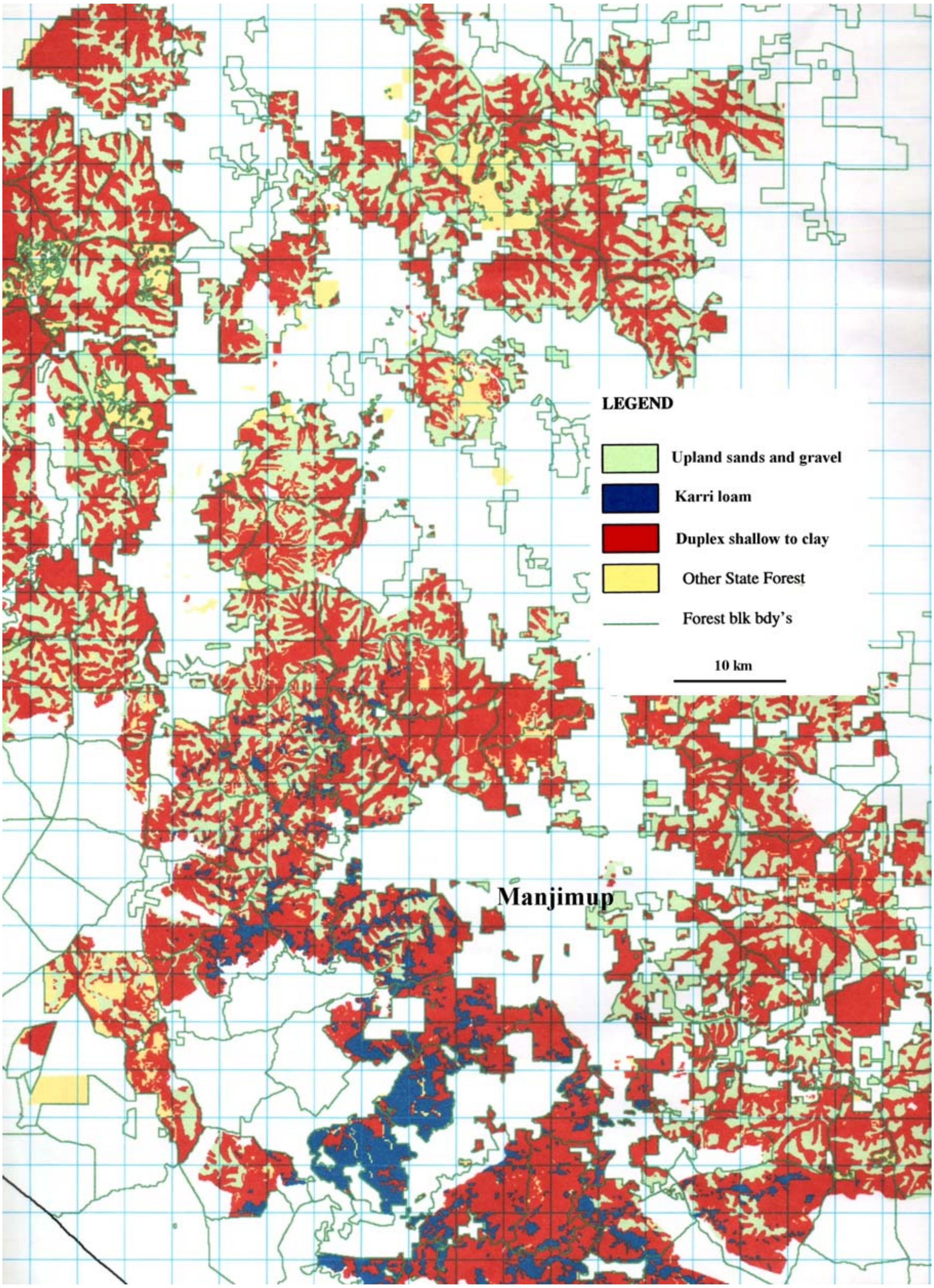

Fig. 10.1 Map of soil trafficability using 4 local soil categories in SW WA forests(There are no examples of clay (wandoo) soils shown in this sample).

11. SW WA soil disturbance management system

11.1 Objectives

Protection of soil is one of several key objectives of the Forest Management Plan 2004-2013 and is expressed as: "*An overall aim of the plan is to protect soil and water resources on land to which the plan applies."* It goes on to say *"Past soil management strategies have been reactive to soil damage as a result of compaction, puddling and mixing. The plan seeks to adopt a more proactive approach to reduce the occurrence of soil damage."* The Issue Paper, which preceded the FMP, provides further insight into the intent. It says the strategy should be to *" Schedule silvicultural operations that require heavy machinery, including timber harvesting, for times when dry soil conditions prevail, except for specified circumstances."*

Key Performance Indicator 21 says that *"Soil damage not to exceed prescribed maximum levels (see Appendix 6)."* Appendix 6 then goes on to provide both a prescription for operations and the limits of various types of soil damage.

The objective is therefore interpreted in terms of minimising damage to that which is achievable by best practice, with specified limits to damage being seen as an acceptable maximum, rather than an acceptable goal.

The Forest Management Plan attempts to define best practice through the prescription provided in Appendix 6 of the plan. This interpretation of the objectives has important ramifications in the way operations are conducted and monitored and the way in which stakeholders see their goals or targets and there is a need for further clarification of the intent.

11.2 Present soil management prescription

The soil management system is specified in Appendix 6 of the Forest Management Plan. As a part of the Plan it has legal authority and can only be varied under specified conditions. These prescriptions will apply until the Soil and Water Conservation Guidelines are prepared and approved following the review currently underway. Appendix 6 specifies the conditions under which harvesting operations may take place and specifies the maximum damage limits that will be permitted within individual harvesting cells[4] .

11.2.1 Prescription for harvesting

The prescription centres on the activities that may occur under different levels of estimated SDI. The key components are summarised below:

High risk period (SDI<250 in spring, SDI<100 in autumn)

- Skidding not permitted
- Forwarder operation for first thinnings in karri is permitted – within damage limits

Medium to high risk period (SDI 500-250 in spring, SDI 100-250 in autumn)

[4] A cell is a discreet part of a coupe varying in size from about 5 to 50 ha and usually bounded by stream reserves, coupe boundary or a major log road.

- Schedule best soil types and topography for operations
- Landings and primary snig tracks to be corduroyed (can be waived by the Director of Forests)
- Snig tracks planned – herringbone pattern
- Operations to be contained within specified damage limits

Medium risk period (SDI 500-1000)

- Snig tracks planned – herringbone pattern
- Operations to be contained within specified damage limits

Low risk period (SDI>1000)

- No restrictions unless SDI is reduced by 400 by a rainfall event (then apply Medium rules)
- No requirement to plan snig tracks
- No monitoring of damage levels is required

Further detail is provided in the Interim Manual of Procedures (CALM, 2004). SDI is calculated on a daily basis for specific localities on the basis of the previous day's SDI, rainfall and temperature. SDI is calculated for six localities and the SDI ascribed to the harvest area is based on the nearest locality (CALM, 2004 Appendix 3). The intention is that future calculations will be based on a much larger number of weather stations than used previously, and extrapolated across all forest areas on the basis of rainfall isohyets. SDI is not estimated for different soil types and it is not verified in the field.

Appendix 6 makes provision for amending the conditions of harvesting with the approval of the Director of Forests with advice to the Conservation Commission. From June to September 2004, fifty three amendments were approved. The most common variation was the reduction of the Medium to High Risk period from 500 to zero, particularly with soils with a high gravel content (generally >45%). In some situations the requirement to corduroy was removed or varied. Only 33 of these variations were acted upon because delay in harvesting resulted in a higher SDI applying at the time of harvest in the remaining cells.

11.2.2 Limits of damage

Appendix 6 specifies the following damage limits:

Landings	Jarrah	1.5%
	Karri thinning	1%
	Karri clearfell	3.5% (previously 5%)
Rutting	Gravel and sand	150 mm max for 20m[5] on feeder snig tracks
	Other soil	300 mm max for 20m on feeder snig tracks
Severe disturbance (D3)	Jarrah	2%
	Karri pre-log	1%
	Karri C/F	2% (including 'pre-logging'[6])
	Karri thinning	1%

[5] Interpreted as any contiguous 20 m section on all snig tracks.
[6] Pre-logging is the removal of a lower storey of regrowth (usually pole sized trees) prior to the clear felling of larger trees. The purpose is to reduce felling damage to smaller trees and improve operator safety.

Moderate disturbance (D2)	Jarrah	8%
	Karri pre-log	5%
	Karri C/F	15% (including 'pre-logging')
	Karri thinning	8%

Total disturbance other than landings [7]

	Jarrah	10% (previously 10% including landings)
	Karri	17% (previously 15%)
	Karri thinning	9% (previously 10%)

Total damage limits are essentially the same as those that have applied since the late 1970s, except that limits have been placed on various types of damage and limits to rutting have been introduced. While the basis of these maxima are not described it is assumed that it is based on what is achievable with care at times when the soil is reasonably trafficable. There is no explicit consideration of acceptable limits based on future productivity or their relationship to potential targets for soils, water, biodiversity or other sustainability criteria that may eventuate as part of the Montreal Indicator Process or Environmental Management Systems such as the Australian Forestry Standard, ISO 14001 or Forest Stewardship Schemes.

11.2.3 Defining damage

Appendix 6 classifies 'Moderately disturbed' soil as damaged – it is defined as "Topsoil mixed with subsoil (A-horizon dominant) or the topsoil partially removed. 'Severely disturbed' soil, also classified as damaged, is defined as "Topsoil completely removed and subsoil exposed or the topsoil mixed with subsoil (B-horizon dominant), or the subsoil disturbed, or the subsoil mixed with parent material, or the subsoil partially removed" (italics are our words).

Table 11.1 describes soil disturbance categories in more detail. These descriptions are a modification of those of Rab et al (1998), Rab (1999) and Raison and Rab (2001). This system is based on visible descriptions of disturbance and makes no specific attempt to quantify compaction *per se*. Compaction may be inferred in the category of 'Moderately disturbed' by the inclusion of mixed soils beneath a snig track as category D2 (LMS and TDS).

The consistency and accuracy with which this visual system can be applied in the field is a critical issue. Clearly, the system needs to be applied by fully trained and unbiased field observers.

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[7] Under the 2004 rules, the cumulative figure only applied if the individual limits of D2 and D3 were not exceeded. This is discussed in a later section.

Table 11.1. Categories and sub-categories of soil disturbance from Appendix 4 of Procedure Manual (CALM, 2004).

Soil disturbance category		Soil disturbance sub-category (type of mixing/removal)	
Undisturbed		Litter layer intact	
Lightly disturbed	D1	Litter layer broken/partially removed	LR
		Litter completely removed and topsoil exposed	TE
		Litter mixed with topsoil in general harvest area	LM
		Topsoil disturbed in general harvest area	TD
Moderately disturbed	D2	Litter mixed with topsoil on snig track[8]	LMS
		Topsoil disturbed on snig track	TDS
		Topsoil mixed with subsoil	TM
		Topsoil partially removed	TR
Severely disturbed	D3	Topsoil completely removed and subsoil exposed	SE
		Topsoil mixed with subsoil	SM
		Subsoil disturbed	SD
		Subsoil mixed with parent material	SC
		Subsoil partially removed	SR
Very severe disturbance	D4	Subsoil removed and parent material exposed or mixed with subsoil parent material	PE
Other	O	Corded primary snig or forwarder track [9]	CST1
		Corded secondary snig or forwarder track [10]	CST2
		Rock	R
		Stump or log	SL
		Tree	T
		Other non-soil occurrence	ON

[8] Includes Forwarder wheel tracks though it appears that this may not have been consistently applied.
[9] Categorised as D2 from October 2004.
[10] Categorised as D3 from October 2004.

Variations to these descriptions were applied from October 2004, when all sites beneath a primary snig track, whether corded or not, were regarded as damage class D3, and all areas beneath a secondary or lower order snig track (corded or not) were regarded as category D2, based on the results from compaction studies in the Barlee trial. This is recognition of a desire to account for compaction that may not be adequately represented by disturbance descriptions. This has ramifications in the application of damage limits described above, particularly in relation to D3 limits. For example, this approach provides little incentive to minimize damage to snig and forwarder tracks via techniques such as cording and matting or by dry soil harvesting. This is discussed in a later section.

11.2.4 Monitoring of damage

The requirements for monitoring soil damage are broadly specified in Appendix 6 and described in more detail in Procedure Manual (CALM, 2004). The key requirements are summarised below.

Other than low risk (SDI<1000)

Daily visual inspection by Forest Products Commission (FPC) staff

Weekly formal survey by FPC staff.

Spot checks by CALM staff at critical periods

Low risk (SDI>1000)

No requirement

Formal survey method

A formal survey is carried out on a harvest ‘cell’ basis and damage percent is calculated for each cell.

The formal survey is based upon:

Evenly spaced transects at right angles to the main snig tracks

Damage class defined at sample points (20 cm diameter) every 1m.

Surveys to be submitted to CALM.

Initial survey – 500 m

Survey length 500m. If limits are exceeded or likely to be exceeded, close operation or increase sampling; otherwise continue operation.

Second stage sample – increase to 1000 m

If limits are exceeded or likely to be exceeded, close operation or increase sampling; otherwise continue operation.

Final sample – increase to 2500 m

If limits are exceeded or likely to be exceeded, close operation; otherwise continue operation. It is estimated that 2500 samples are required to achieve an error of ±2% in damage estimates for an individual cell.

11.2.5 Results for 2004

Surveys of soil disturbance results for 68 cells during 2004 are presented in Tables 11.2, 11.3 and 11.4. These indicate that damage levels were generally well below the permissible maximum. One (corded) cell of karri exceeded the permissible D3 damage but had less than the permissible total damage.

Table 11.2 Average percent damage by cell (not weighted by cell area), excluding landings. [A]

	D2	D3[B]	Total
Jarrah	3.24%	0.66%	3.90%
Karri clearfelling	4.91%	1.15%	6.06%

Table 11.3. Percent damage for cell with highest total damage excluding landings. [A]

	D2	D3 [B]	Total
Jarrah	8.1%	1.69%	9.7%
Karri CF	9.3%	3.93%	13.22%

Table 11.4. Percent damage for cells that exceeded damage limits. [A]

	D2	D3	Total
Jarrah	0%	0%	0%
Karri clearfelling	3.93*% (1 cell)	0%	0%

[A] Source data: Peter Murray, Department of CALM, WA

[B] Includes percentage of corded primary snig track

Results for karri thinning operations with a forwarder have not been included above. Where forwarder operations were accompanied by brushing, soil mixing did not occur or could not be seen beneath the brushing although compaction of varying degree does occur. The most appropriate way of assessing disturbance under these conditions was still being developed during the 2004 season and results are not available.

Part-way through the monitoring period, primary snig tracks were assigned a D3 damage category and secondary and other snig tracks assigned a D2 category based on the soil compaction studies in the Barlee harvesting trials. This is likely to have resulted in a higher D3 figure than would have been determined by visual evidence alone, though this can not be determined with certainty.

11.3 Harvesting operations

Harvesting operations in Western Australia are carried out by contractors to the Forest Products Commission. There are eight operators contracted to deliver 745,000 t of logs to a variety of customers in the south-west. Under the Forest Management Plan (2004-2013) the area cutover annually will vary according to the forest condition and silvicultural objective. Approximately 10,000 hectares per annum of jarrah forest is likely to be harvested, with total removals ranging from 20 tonnes per hectare to over 120 tonnes per hectare. In the karri forest, clearfell operations are likely to be undertaken in approximately 400 hectares per year (yielding over 250 tonnes per hectare) with thinnings up to 1000 hectares per year (yielding 70 to 120 tonnes per hectare).

Current contracts state that it is expected that logs will be supplied "*on an average 5 day week basis based on 150 working days per year*" and "*It is probable that harvesting will be stopped from time to time during the period between mid-June and mid-October approximately for environmental protection reasons.*" Harvesting may be stopped in order to avoid soil damage or to minimise the spread of *Phytophthora cinnamomi*.

A variety of logging equipment is used (Table 5.3). Approximately 75% of felling is now carried out by machine harvesters.

11.4 Trials

Trials of cording and matting of snig tracks and landings were carried out during 2004 (Whitford et al, 2005). The results of these trials indicated that:

- Gravel soils resisted rutting and mixing but compaction was similar across soils of varying gravel content (soil texture was not accounted for),
- Cording resulted in a small reduction in compaction in both jarrah and karri sites compared to uncorded tracks,
- Cording reduced the proportion of area affected by rutting in karri sites,
- Cording costs were approximately $15 per linear metre,
- The cost of cording varied from about $9/m^3$ for 150 m^3/ha removed to $4/m^3$ for 220 m^3/ ha.

The compaction results above contrast with those observed in the regrowth ash forests of Victoria (Campbell, 2003, 2005) where compaction under cording was substantially less than that for conventional snig tracks. This difference may have been due to puddling under cords due to free water retention on gentle slopes in SW WA. As discussed earlier, (see Sections 2 and 3) the level of compaction depends on soil moisture content at the time of the harvesting operation, soil texture and number of times machine passes over an area. The differences in level of compaction between corded and uncorded tracks in SW WA forests may be partly due to differences in the above factors. However, the success of cording depends on careful design, construction and maintenance to drain free water away from cords and minimize puddling.

Operational trials were also conducted whereby proposed snig tracks were surveyed for gravel content and sites with a gravel content of less than 50% were avoided. This was considered to be a successful means of improving snig track trafficability and reducing rutting, though it does not affect the percent damage.

Operational trials of 'shovelling' logs (lifting logs in step fashion rather than snigging them) to snig tracks was effective in reducing soil damage and was feasible for logs up to about 1500 mm diameter.

11.5 Issues and opportunities for improvement

11.5.1 Objectives

The Forest Management Plan objectives in their present form appear to place priority on achieving best practice (i.e. minimising soil damage), but the Performance Indicator implies an acceptable standard that may be higher than the achievable minimum. This can create uncertainty in the minds of operators who may be aggrieved at being expected to expend significant effort and funds to carry out a prescribed practice that may achieve levels of damage well below that required by the Performance Indicators. There would be benefit in clarifying the intent of the objectives and whether the emphasis is on following a prescribed practice or achieving the specific outcome of minimizing damage.

11.5.2 Prescription for harvesting

SDI is used as the primary determinant of what harvesting activities are permitted and what monitoring requirements should be implemented. Several shortcomings of the present method for calculating SDI have been identified in the report. These include: a lack of discrimination between soil types; an apparent insensitivity at low SDI, in particular the differences in soil moisture that occur during the drying period in spring as opposed to the wetting period in autumn; the error in modelling SDI at a specific location based on regional climate data; and the difference between the modelled SDI and the actual SDI or soil moisture at a localised site with varying soil type and topography.

Potential improvements to the estimation of SDI have been discussed in Section 6 and are summarised below:

- Increase in the number of weather stations and development of an algorithm to extrapolate SDI to other areas of the forest will improve reliability at the site level.
- Improvements to the evapotranspiration component of the SDI calculation.
- Relate SDI to soil type through the use of Field Capacity for a particular soil type or group of soil types.

Rutting can be assumed to occur between Field Capacity (FC) and saturation moisture content, and therefore the SDI at which rutting will occur for a particular soil may be estimated. Soil damage risk periods may be associated with a nominated fraction of FC and related to SDI in a similar fashion (See Section 6 for further detail).

However the estimation of SDI (even with the improvements foreshadowed), will remain a modelled estimate for a broad soil group. As such we are of the view that while SDI will provide valuable information for planning purposes, it cannot be expected to provide an accurate estimate of soil moisture (and therefore risk of soil damage) at the site level. If SDI is to remain the primary basis for prescriptive control (as opposed to its use as part of a guideline) we believe there is a need to incorporate some form of local field verification at least beyond any SDI limit that might be determined as ‘no-go’ period for harvesting on particular soil types.

Methods of field verification by direct measures of soil moisture indices and strength have been discussed in some detail in Sections 8.2 and 8.3. They provide opportunities for improvement by enabling verification of:

- SDI zero;
- Soil saturation;
- Soil field capacity; and
- Soil strength.

The current prescription imposes no restrictions on the method of harvest and no requirement for monitoring during summer harvesting. We do not consider that this is an adequate strategy for minimising soil damage during summer harvesting. The reasons for this are that:

- some parts of the landscape remain wet during the summer period;
- wetter parts of the landscape will be targeted for summer logging and more so as restrictions on winter logging are tightened;
- some soils are more prone to compaction than others (for example, podsols are more prone to compaction than uplands sands and gravels even when logged during summer);
- compaction prone soils will be targeted for summer logging;
- damage to soil structure by mixing can occur in summer though the risk of compaction is less;
- planned snig track design reduces disturbance at any time of the year and is a worthwhile routine practice;
- monitoring of damage levels in summer provides an essential base for striving to achieve best practice; and
- a lack of monitoring can lead to complacency in operations.

We are therefore of the view that there should be no distinction between the presently ascribed 'low' and 'medium risk' period except perhaps that formal surveying would only be required at the completion of harvesting.

An SDI system that recognises different soil characteristics will lead to the necessity to change the risk periods for different soil types. In doing so it will present the opportunity to remove some inconsistencies and some unnecessarily prescriptive requirements. For example, the current distinction between the use of Forwarder and Skidder in the high risk period is unclear, given that a Forwarder is quite capable of causing severe damage and rutting in certain circumstances, though unlike a Skidder, damage is restricted to the wheel tracks. Trials with brushing the tracks of the Forwarder appear to have been highly successful in minimising rutting and mixing in red loams though this will not necessarily translate to the shallower soils that are more typical of much of the younger karri regrowth that will be harvested in future years. In these circumstances Forwarder activity will be proscribed by maximum damage limits. It would appear that there is a case for treating Skidder operations in the same way i.e. if techniques can be successfully applied to minimise damage (such as cording) then they could be allowed to operate in what is currently the high risk period on certain soil types.

The requirement to design snig tracks on a herringbone pattern is considered to be an anomaly since it is not always the most effective design for different coupe shapes. This requirement takes on greater significance given the legal status of the prescription and strict adherence may not produce the best outcome. We believe that while there should be a requirement to design snig tracks to minimise damage and duplication, the specific design should not be specified in a legal context.

The present prescription specifies that snigging may only take place in the Medium to High Risk period if cording is undertaken. During 2004, snigging with cording was permitted in periods of lower SDI on some soil types. However, snigging without cording in these periods was not permitted on other than the most robust soils so that there was no opportunity to test conditions under which rutting may have begun to occur or when it would have exceeded the allowable limit. The results (Figs. 11.1 a, b, c) indicate that cording *per se* is unlikely to reduce overall soil damage, but it will allow harvesting to be conducted for longer periods in moist soil conditions without excessive rutting. However the cost per cubic metre for cording in areas of low volume per hectare that is typical of current harvesting operations is substantial and may well exceed the cost of alternatives such as stock-piling. If that is the case it effectively extends the 'no-go' period to SDI 500. This is a considerable imposition on industry when the opportunity to harvest within the damage limits has not been tested.

The alternative approach below might be considered:

Stage 1 – Minimising the area damaged

- Plan and implement snig track layout to minimise the area damaged (e.g. by duplication) for all operations throughout the year.
- Monitor operations throughout the year.
- Use appropriate machinery for the task (e.g. mechanical harvesting, use of shovelling, use of forwarders rather than skidders where appropriate).

Stage 2 – Minimising severity of damage

- Determine a 'no-snigging' period for major soil groups based on estimated SDI for their measured or estimated Field Capacity (this might be converted to a calendar period);
- Determine a 'high risk period' based on a fraction of the FC (see Section 5.2.6 and Table 5.10);
- Monitor individual sites closely during the high risk period, including field estimation of FC or soil strength;
- Outside the 'no-snigging' period, allow snigging to the point where rutting begins to occur (i.e. well before rutting limits are reached);
- At this point stop the operation and only proceed with the approval of the Director of Forests (e.g. where the operation could be completed without exceeding limits); or
- Carry out cording of snig tracks and proceed with the operation.

Stage 3 - Monitoring and improvement

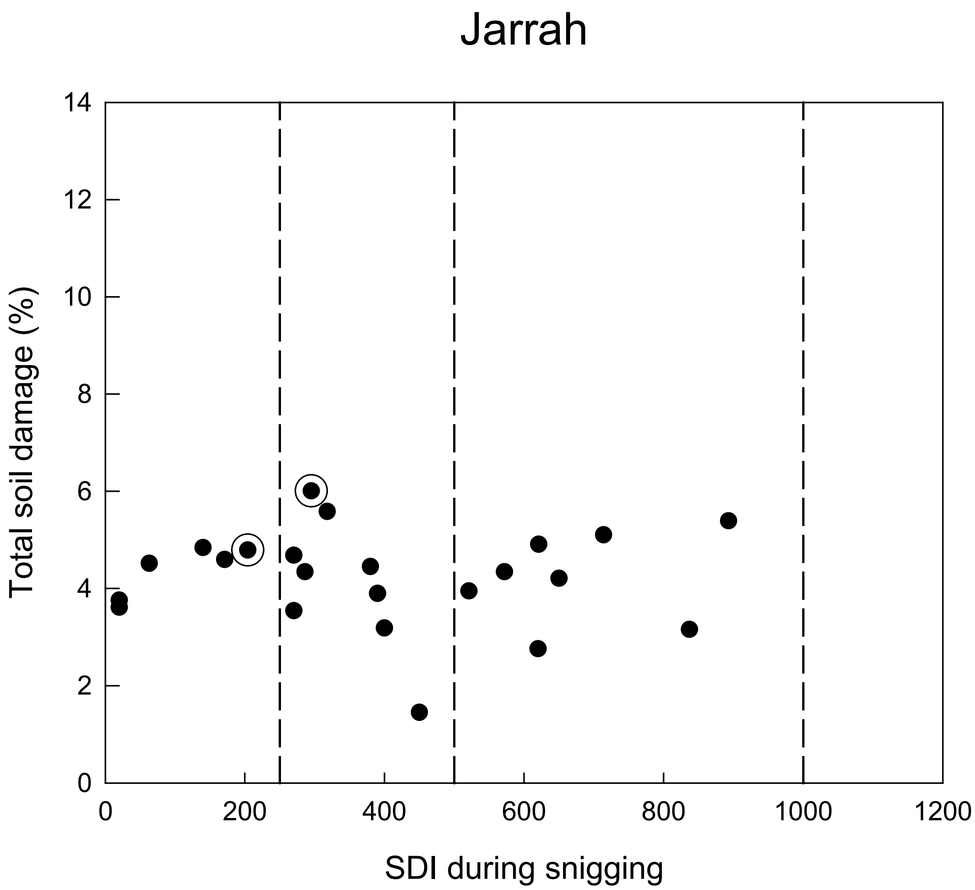
- Monitor damage outcomes and relate them to planning guidelines and operational practices at all sites.
- Use these on-ground outcomes for collaborative and continuous improvement of guidelines and practice.

This approach maintains the central objective of preventing snigging in the high risk period appropriate to the major soil groups; it implements best practice during the remainder of the year; and provides the opportunity and an economic incentive for operators to conduct their operations with the minimum impact on soil. It would allow the operator to make the decision about whether to stockpile or cord or use a combination of the two, based on physical evidence of soil damage rather than a prescription based on a prediction of SDI which is itself based on a prediction of the impact of snigging on soil damage. The system shifts the emphasis on SDI from a control system to a warning system, thereby making its precision less critical. In addition, it promotes a process of continued improvement based on actual on-ground outcomes rather than a control system based on penalties for violation of prescriptions.

11.5.3 Damage limits

The levels of total damage observed during 2004 are in most cases substantially lower than the allowable limits and lower than that which has occurred in the past (Tables 11.2, 11.3, 11.4, Fig. 11.1, a, b). This is due to a combination of factors including:

- the planning of snig track layout;
- the greater use of mechanical harvesting and ‘shovelling’ of logs to the snig tracks, thereby reducing snigging activity in the general harvesting area;
- lower volume per hectare being removed;
- the restriction of harvesting in the wettest periods to specific sites with higher gravel content; and
- high levels of scrutiny of harvesting activities aimed at reducing damage.



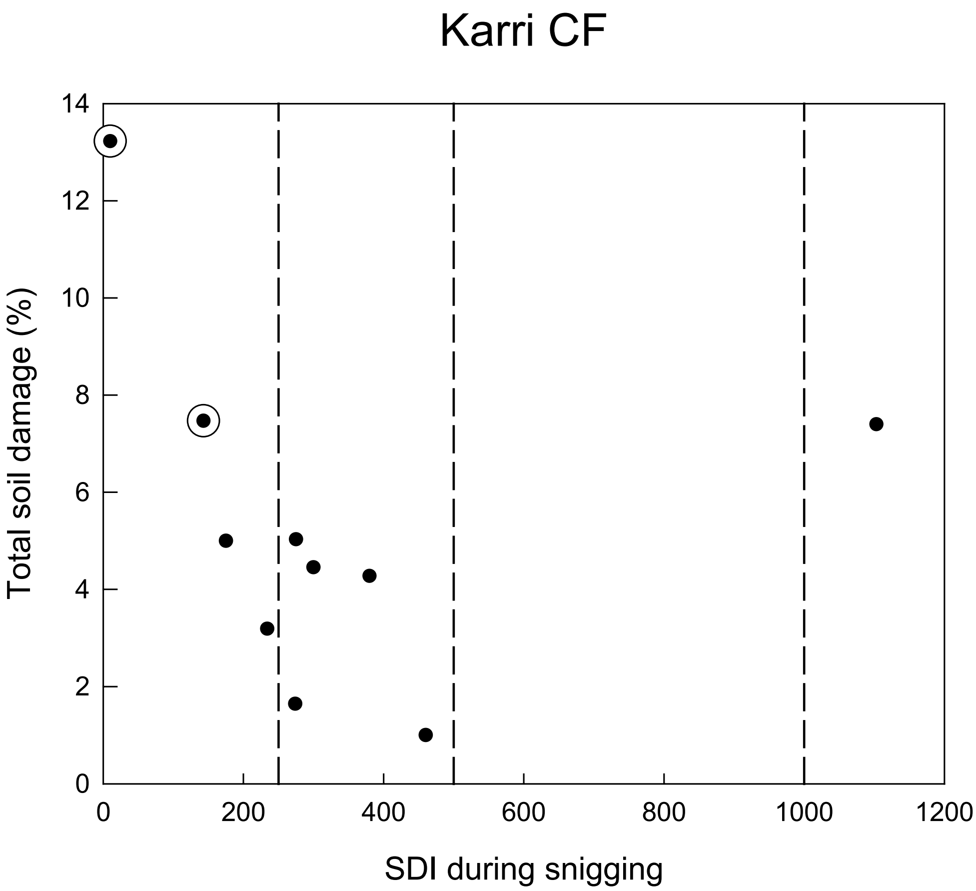


Fig. 11.1 a, b Total soil damage (D2 + D3) as percentage of cell area for all cells for which the SDI at the time of harvest is known. Circled points are cells where cording was carried out.

The results indicate that there is no relationship between damage levels and modelled SDI for 2004, but this is at least partly due to the fact that areas harvested in wetter periods were on selected soil types. It has not been possible to obtain data to relate soil groups to levels of damage.

In some situations the severity of damage, in particular to primary snig tracks, has been reduced by the use of cording or brushing. However in the case of cording this has not been reflected in the results since primary snig tracks, whether corded or not, were regarded as being severely damaged. Since corded tracks are wider than uncorded tracks this has led in some cases to higher recorded levels of damage. This is discussed more fully in the section on defining damage.
The levels of damage recorded in 2004 suggests that ‘best practice’ under current circumstances can result in lower levels of damage than has previously occurred and there may be a case for reviewing the allowable damage levels, especially in karri. However the determination of acceptable damage levels and the method of assessment and assignment of damage are directly linked. In our view there are still areas to be resolved in damage assignment and for that reason any changes to acceptable damage levels should be deferred until those areas are fully resolved and tested.

There may be a case to base the damage limits on soil type rather than jarrah and karri but it has not been possible to evaluate this to date.

An anomaly exists in the 2004 interpretation of damage limits which provides a disincentive to reduce damage severity. This occurs because D2 (moderate damage) and D3 (severe damage) was regarded as exclusive. Damage limits for jarrah for example allowed for 2% D3 and 8% D2 damage. However a situation that results in 0% D3 and 10% D2 damage was regarded as a breach even though the damage is less severe. We understand that this is to be rectified for 2005.

11.5.4 Defining damage

The present method of assessing soil assigns categories on the basis of visible evidence of disturbance and designates some of these categories as damage (Table 11.1). There is no attempt to quantify compaction *per se*. In the absence of simple, direct field measures of compaction (such as bulk density or shear strength) the assessment method makes the inference that disturbed soil beneath a snig track will be compacted. In the categories described in Table 11.1 above, topsoil that is mixed with litter or subsoil is categorised as damage if it is on a snig track (categories LMS and TDS), and therefore assumed to be compacted, but not damaged if it was in the general harvest area (LM and TD). In our view a further category of damage should be included to cater for sites where there is obvious *in-situ* compaction such as beneath a snig track, but with no mixing of soil (new categories LRS and TES).

In practice this issue has been partly addressed by the variation to the classification of 1st October 2004 where all snig tracks regardless of soil disturbance description are regarded as damaged. In this determination all primary snig tracks were defined as severe damage (D3) and all other orders were defined as moderate damage (D2) including sites under cording. The likely impact of this ruling is to assign a level of D3 that may not exist in reality. It may also increase the apparent level of damage of corded sites relative to uncorded on the basis that the corded tracks are wider than conventional snig tracks. While this may be a simpler system to apply it cannot be done in isolation from pre-defined limits to damage.

A further anomaly occurred in karri thinning. Where forwarder operations were accompanied by brushing, soil mixing did not occur or could not be seen beneath the brushing and was therefore not included as damaged even though it was clearly compacted. The inclusion of a category TES described above should resolve this anomaly.

Some clarification is also required. For example, 'topsoil mixed with subsoil' is included as both moderate and severe damage. Presumably the distinction is based on the dominance of topsoil or subsoil in the mix but this is not stated. This is a critical issue to be resolved to ensure that what may be considered 'desirable disturbance' is not included as damaged soil.

In our view it is not logical to automatically include primary snig tracks as D3 and other orders as D2 simply on the basis of assumed levels of compaction. We see a major distinction between compaction, which may be ameliorated more readily by natural means or by scarifying or ripping; and profile mixing or puddling, where profile re-establishment may take many rotations to restore. A preferred assessment would be to class snig track sections that are compacted as D2 (including all corded tracks) and sections that are profile mixed as D3.

11.5.5 Monitoring damage

The combination of visual assessment and progressively more intense formal assessment is a logical approach. However the recording procedure is complex and it is evident that there were major problems in having the surveys carried out in a reliable and consistent fashion. Rutting in particular was poorly recorded so that its significance and its value as a signal of severe damage could not be evaluated from the 2004 surveys. It is unclear how much of this is due to the complexity of the procedure or the adequacy of training. Given the fact that harvesting, monitoring and damage limits are prescribed within a legal context it is important that they are applied in a consistent and reliable fashion. There appears to be a need for greater training and standards control in the application of the monitoring. For example, visual identification and separation of topsoil and sub-soil, especially in gradational soils.

A shortcoming of the present survey procedure is the time taken to carry it out and the bias that can be introduced if survey lines run parallel to snig tracks. We suggest that an alternative procedure be considered. This would involve the GPS mapping of log landings and major snig tracks, from which can be calculated the percentage of the cell damaged by intensive extraction operations. Line assessment can then be confined to the general harvest areas (which may include minor snig tracks), with re-assignment of snig track damage levels being carried out where necessary. This record of extraction routes can then be stored (in, for example, the SILREC system) for use in future harvest planning as discussed elsewhere.

The final results of surveyed damage levels and the dates of major snigging activities (or the SDI relating to those dates) for each cell have not been maintained in a readily available form. We strongly recommend that this information be recorded as part of the sign-off procedures and that a summary of performance be maintained as part of a continuous improvement monitoring procedure.

For the reasons discussed earlier, we are of the view that monitoring of all operations should be conducted, regardless of the risk period.

11.5.6 Accumulation of damage

Un-repaired compaction will take many years to restore while profile-mixed and puddled soils are not repairable in realistic time scales. The avoidance of damage accumulation over several harvesting events is arguably a more critical issue than the fine tuning of current damage levels. While the use of old snig tracks is encouraged it has had limited success because of changed road patterns, different harvest cells and the difficulty of finding old tracks in dense scrub. However we suggest that there is opportunity to improve this for future operations. We recommend that current snig tracks and landings be located by GPS and recorded for use in future harvest planning. The mechanism to archive these records already exists in CALM in the form of the SILREC system.

The view has been put that there will always be change to future harvesting patterns that limit the value of using old snig tracks and landings. However we would argue that the importance of accumulation is such that re-use (even of 're-habilitated' tracks) should be seen as a major factor to be considered in planning harvest operations and that there needs to be compelling reasons not to use old snig tracks. This is particularly pertinent to karri forest where harvesting operations may occur at 20 - 30 year intervals, i.e. much more frequent intervals than the expected recovery time.

11.6 Adaptive management

We consider that an adaptive and collaborative approach to development of the soil management system (SMS) in SW WA is essential to progress.

Management may be defined as the on-going development of planning, operating and performance monitoring systems to meet specified objectives of management. Adaptive management involves:

- Clear definition of objectives and their associated performance measures;
- Collaborative development of guidelines for planning and operations; and
- Continuous improvement based on monitoring and evaluation of on-ground outcomes and operational experience.

This approach is embodied in Environmental Management Systems (EMS) such as the Australian Forestry Standard (AFS), ISO 14001 and Forest Stewardship Council systems. These systems provide a powerful vehicle for collaborative development, communication and certification of Sustainable Forest Management in systems such as those for soils in SW WA. Fig. 11.2 shows the key stages involved in the management process as specified in Criterion 1 of the Australian Forestry Standard.

We see that the purpose of our report and its recommendations is to provide input to the adaptive management process and to promote a collaborative approach to systems development. Issues arising from the review of the SMS have been identified along with suggestions for action in the following Section.

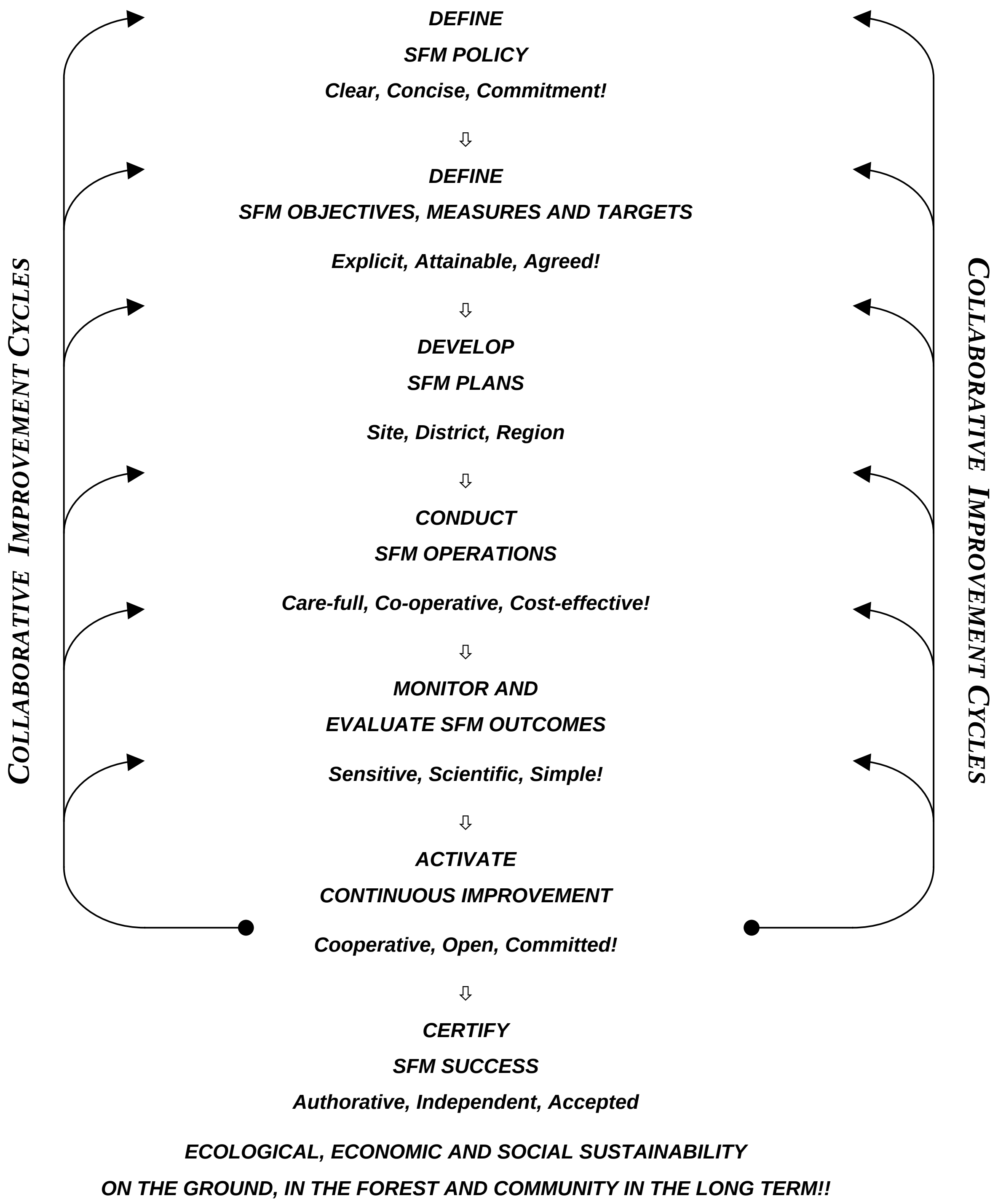


Fig. 11.2 SFM systems development flow chart for adaptive management (Campbell, unpublished).

12. Plan for the progression and development of a soil disturbance management system

This section is intended to provide a summary of the steps recommended for the continued development of a soil disturbance management system. The background to the recommendations made here are covered in detail in other Sections of the report and are referred to under each item.

The issues identified below should be considered in the context of a process of continuous improvement rather than an expectation that a definitive system be developed and rigidly implemented. To facilitate the process of continuous improvement, systems and prescriptions that are developed should so far as is possible remain outside legally enforceable codes. We also believe that the development of a soil management system will be more effective and efficient if it is seen in the light of a co-operative development involving the Department of Conservation and Land Management, Forest Products Commission and the harvesting contractors.

To facilitate on-going improvement in both predictive methods and in harvesting techniques, the proposed Soil and Water Guidelines should be developed in a way that allows for regular update with a minimum of bureaucratic or procedural delays.

12.1 Objectives

The objectives of the soil management in their present form would benefit from a clarification of intent as discussed in sections 11.1 and 11.5.1. It should be made clear whether the emphasis of the system is on following prescribed practice, achieving best practice and continuous improvement, or on meeting a specified maximum level of damage. We believe that this is necessary to guide future development.

12.2 Prescription for harvesting

The present soil disturbance management system centres on the prevention or limitation of harvesting activity based on a predicted soil condition that will occur under a predicted level of SDI. This report has recommended a number of ways in which the prediction of SDI may be improved and recommended an objective basis for defining risk periods according to soil group and season (see section 6.9). While these recommendations should result in an improved prediction of soil condition and the outcome of logging they will nevertheless remain a prediction.

In addition to the changes referred above we recommend that the system be further developed to incorporate a field verification phase that can be used to verify soil condition at the cell level on an particular day when harvesting is contemplated (see Section 8). A further stage in the process should include closer monitoring of the impact of actual harvesting activity. We recommend that the decision to log or not to log be based on these results rather than the estimated SDI.

The recommendations concerning thresholds that have been made in this report have been based on objective parameters but have not been tested in operations and must be regarded as interim recommendations. Whatever thresholds are adopted for guiding logging operations, there is a need to develop a monitoring system that provides feedback of predicted soil conditions versus actual conditions, and predicted harvesting impact versus actual impact. To facilitate this there will be requirement to provide for on-going trials of operations that are outside the permissible conditions for routine operations in order to test a wider range of conditions without compromising routine operations.

Further discussion on opportunities for improvement in this area can be found in section 11.5.3.

12.3 Harvesting technique

Harvesting techniques involving snig track planning; 'shovelling' of logs; cording, matting and brushing have all been trialled in 2004 with varying degrees of success. A review of approaches adopted elsewhere have not revealed other significant techniques or machinery that are likely to be relevant or economical in SW WA conditions. However the new techniques that have been adopted should continue to be reviewed and improved. A necessary part of this process is the installation of targeted trials to acquire objective data on specific aspects of any new approach that is adopted.

A soil management system should incorporate continuous review of new techniques that are attempted elsewhere and new machinery that becomes available over time.

12.4 Damage limits

In the context of continuous improvement, the limits of acceptable damage should also be subject to regular review so that they can be adjusted to be close to that which is reasonably achievable with best practice. However, damage limits, damage definition and the method of assessment are directly linked. For that reason damage limits should not be considered for amendment until issues relating to definition and assessment have been resolved.

While we understand that the inclusion of the soil management system within the legal framework of the Forest Management Plan may make amendment difficult, we nevertheless recommend that the possibility of amendment is an essential part of adaptive management and should be incorporated in the proposed Soil and Water Guidelines.

In the interim we recommend that the literal interpretation of the permissible damage by damage type (discussed in the final paragraph of Section 11.5.3) be more liberally interpreted so that it is more compatible with the spirit of the regulation.

12.5 Defining soil damage

The present system of defining soil damage on the basis of soil disturbance is based on a well recognised process of visual features. However it does not incorporate any direct measure or description of compaction, one of the most significant aspects of soil damage. This aspect must be inferred on the basis of evidence of traffic (i.e. snig tracks). While this a realistic approach to the problem, there are anomalies and inconsistencies in the way that this is interpreted at present and these need to be rectified. There is also the opportunity for wide variation in interpretation of damage that relies on the visual evidence of the relative proportion of profile mixing. This is particularly so in gradational soils where horizons are not sharply defined and differences are often interpreted on the basis of colour change, where colour change in the A horizon may be confused with the mixing of the

A and B horizons. There is a real risk that 'desirable' disturbance and 'damaging' disturbance may be interchanged (see Sections 11.2.3 and 11.2.5 for further discussion).

Anomalies also arise where snig track damage levels are defined solely on their order. While this may have been done on the basis of simplicity or to overcome the anomaly of a rigid interpretation of permissible damage levels by category, it does not provide a sound basis for objective comparison of operations, for example between the impact of dry and moist soil operations.

The method of damage assessment is based on a subjective visual assessment of disturbance and visual cues of the amount of traffic. There is an urgent need for staff training to ensure that the interpretation is consistent and to this end there should be a core of highly trained staff to maintain consistent standards.

There is also a need to consider how other soil disturbing activities (e.g. silviculture, and fire management) are incorporated into the damage assessment.

12.6 Soil mapping

There are broad groups of soils that are demonstrably more resistant to damage than others for harvesting under the same weather conditions. This report has highlighted how this can be related to the different Field Capacity of these soils (Section 5.2).

As a part of this review we have made a preliminary attempt to categorise the forest soils of SWWA into four groups using readily available information that has been mapped to a 'landscape' resolution (see Section 10 and Fig. 10.1). We are of the view that mapping to this resolution is appropriate for planning purposes and overlaying this information with proposed harvest areas will provide useful guidance for trafficability. However this mapping was undertaken as a preliminary exercise and improvements are likely to result from a more careful examination of the components of each soil group and a program of field verification and longer term monitoring of actual outcomes after logging.

Further improvement in soil mapping at the landscape level may result from an examination of the soil data sets managed by the Department of Agriculture (Schoknecht et al., 2004). Soil maps may be produced at a variety of resolutions, identifying polygons for which soil attributes have been obtained from field sampling. They indicate the proportion of each polygon that is expected to contain a full range of soil attributes. It is also possible to develop a range of derived data sets including susceptibility to compaction. The potential of this mapping for harvesting activities should be examined in more detail.

We are of the view that it is unlikely to be cost-effective to undertake a program of soil mapping at a resolution less than landscape scale. A more productive approach is likely to be the use of maps of the form above for planning purposes, associated with specific monitoring of soil characteristics and trafficability indicators at the coupe scale (see Sections 8.2 and 8.3).

12.7 Predicting risk period

Relating risk period (through SDI) to a specific soil group will make a substantial improvement to the concept and credibility of risk period. Further refinements to SDI have been discussed in Section 6 and are summarised below:

- Increases in the number of weather stations and an algorithm to extrapolate SDI to other areas of the forest will improve reliability at the site level.
- Improvements can be made to the evapotranspiration component of the SDI calculation.
- Risk period, SDI and soil type can be related through the use of Field Capacity, allowing different SDI's to be used for different soil types for similar degrees of risk (see Section 5.2.6).

While other models are available for predicting soil moisture, we believe that the simplicity of the SDI is a considerable advantage, and that the refinements listed above will provide sufficient improvement to the SDI system to allow it to be used as a valuable planning tool. This is particularly the case if SDI is used as a predictive warning system coupled with field verification; and not as a rigid decision trigger in its own right.

12.8 Confirming risk period

SDI and all other soil moisture prediction models are subject to a range of errors associated with the extrapolation of weather parameters, fine scale differences in soil type, and the algorithms used to predict drainage, overland flow, interception and evapotranspiration. There are therefore limits to the results that can be expected from any model. For that reason we believe that there is a need to develop a field methodology to determine whether or not the threshold of trafficability has actually been reached at a particular site at a particular time i.e. to confirm the predicted condition.

We recommend that two stages be considered:

- The establishment of soil moisture measuring sites over a range of soil type and localities that will not be disturbed. These may be used to measure moisture content and over time provide a basis for correction of the SDI at the wet end of the scale (see Section 8.1).
- Develop a methodology to determine field indices of trafficability at the cell level that can be used to confirm whether trafficability thresholds have been reached on a particular day. This should be aimed at providing a definitive answer to the question of whether to proceed with logging, rather than depending on a estimated SDI (see Sections 8.2 and 8.3)

12.9 Monitoring soil damage

We believe that there is potential to do soil damage at any time of the year, and for that reason the planning of snigging operations and the monitoring of results should be implemented all-year round, with appropriate variation for frequency of observations.

Soil damage usually affects a relatively small proportion of a harvest cell (Table 11.2). Since the maximum number of sample points (2500) are required to estimate damage to within 2% (CALM 2004), the sampling error associated with the estimate of damage will be large. Where there is a limit of 2% D3 damage, for example, the error could be of similar magnitude. This is an important issue to be considered if these samples are to be used as a basis for determining a breach of the specified damage limits. Establishment of samples of this size is very time consuming and every effort should be made to improve efficiency. The linear nature of most of the damage presents a potential source of bias in the present system. A stratified system employing a combination of snig track 'mapping' and inter-snig track point sampling should be examined as an alternative (see Section 11.5). Such a system should also incorporate an observed evaluation of damage category on snig tracks, rather than an inferred category, including forwarder operations.

12.10 Accumulation of damage

Accumulation of damage over several harvesting cycles is a critical issue (see Section 11.5.4). The development of any system should place a strong emphasis on re-using old snig tracks and landings. Systems should be developed to capture and store this information for later use. Operational rules should be examined to ensure that they provide adequate incentive for re-use of old snig tracks.

Consideration should also be given to the degree to which landings and snig tracks should be regarded as part of the permanent infrastructure in areas subject to harvesting as it is in some other countries.

12.11 Operational research and development trials

The current prescription relating to risk period and operational practice has been based on a limited amount of objective data. The operational costs or the environmental costs of inappropriate settings are considerable. Data is not only required to provide a more objective basis for the prescriptions and limits but also as a basis for continuous improvement.

Limits of damage based on measured environmental impacts, such as might be pursued as part of the Montreal Indicators, are likely to remain elusive for a long time to come. We are of the view that information that should be collected as part of this process should be primarily directed towards reducing damage *per se* over the long term rather than attempting to quantify the absolute effects of certain levels of damage.

- We believe that priorities for operational trials and targeted monitoring should be directed towards Improving the understanding of the impact of harvesting on different soil types with the benefit of objective field-based measurement of moisture conditions.
- Testing operational limits with the benefit of objective measures of trafficability.
- Understanding the impact of snig track design and various machine configurations.
- Continue to improve understanding the relationship between visual evidence of damage and actual impacts, particularly in relation to compaction and other SFM outcomes related to ecosystem regeneration, soil recovery and ecosystem health and vitality.
- Conduct annual workshops at practitioner, planner and policy levels to report, review and re-develop the soil management system for sustainable forest management in SW WA

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15. Glossary

Bearing capacity: In forest operations soil bearing capacity is usually considered as the maximum allowable wheel contact pressure. Another term used to describe the bearing capacity of soil is vehicle mobility, in particular in the US military.

Bulk density: Bulk density is defined as the mass of oven dry soil per unit volume of soil.

Cone index: When the cone penetrometer is forced into the ground, the amount of force required to move the cone slowly through a given section of soil is indicated on a dial. This force is considered to be an index of the shearing resistance of the soil and is called the cone index of the soil in that plane.

Cone penetrometer: The cone penetrometer is the instrument used to measure soil resistance (measure of soil strength) in the field.

Critical moisture content: When soil is compacted at a given load, soil bulk density initially increases with increasing in moisture content, reaching a maximum bulk density then decreases. The critical moisture content is the moisture content at which bulk density reaches maximum.

Critical soil layer: The critical layer is the layer in the soil that supports the weight of the vehicle in question.

Degree of saturation: Degree of saturation is the ratio of amount of moisture at a given moisture content and the moisture content at saturation.

Evapotranspiration: Evaporation in the field can take place from plant canopies, from the soil surface, or, more rarely, from a free-water surface. Evaporation from plants is called transpiration. When the surface is partly bare, evaporation can take place from the soil as well as from plants. It is generally difficult to separate these two interdependent processes. These two terms are lumped together and treated as if they were a single process, called as evapotranspiration.

Field capacity: Field capacity is used to describe the amount of water held in the soil after water has drained away by a gravitational force. For all practical purposes, the downward movement has stopped. Field capacity is usually used to define the upper limit of plant available water.

Hydraulic conductivity: Water can move through soil as saturated flow, unsaturated flow, or vapor flow. Saturated flow takes place when the soil pores are completely filled (or saturated) with water. Unsaturated flow occurs when the larger pores in the soil are filled with air, leaving only the smaller pores to hold and transmit water. Vapor flow occurs as vapor pressure differences develop in relatively dry soils. Vapor migrates from an area of high vapor pressure to an area of low vapor pressure. Hydraulic conductivity is a soil property that describes the ease with which the soil pores permit water (not vapor) movement. It depends on the type of soil, porosity, and the configuration of the soil pores.

Infiltration rate: The infiltration rate is defined as the volume flux of water flowing into the profile per unit surface area.

Infiltration: Infiltration is the term applied to the process of water entry into the soil, generally by downward flow through all or part of the soil surface. The rate of this process, relative to the rate of water supply, determines how much water will enter the root zone, and how much, if any, will run off. The ease or difficulty with which water can pass into and through a soil profile is important so as to avoid detrimental effects such as compaction, surface smearing and other properties that generally lead to structure decline.

Matric potential: Matric potential characterises the tenacity with witch soil water is held by the soil matrix.

Permanent wilting point: The moisture content of soil at which plants remains permanently wilted unless water is added to the soil is called permanent wilting point or permanent wilting percentage. Just as field capacity has been widely used to refer to the upper limit of soil water storage for plant growth, the permanent wilting percentage is used to define the lower limit.

Plastic limit: Soil trafficability is related to moisture content at the plastic limit. The plastic limit is defined as the soil water content at which the soil can be rolled into a 'worm' about 3 mm diameter without breaking. At the plastic limit, the soil is just lubricated enough to exhibit plastic deformation when a force is applied; cohesion is at a maximum near this point and therefore shear strength is at maximum. Above this water content, internal soil friction falls, resulting in a sharp decline in shear strength to a very low level at the liquid limit. The plastic limit, therefore, represents the maximum water content at which a soil can be worked without the occurrence of structural damage.

Potential: The physicochemical condition or state of soil water is characterised in terms of its free energy per unit mass is termed as potential.

Saturation: Saturation is defined as the condition in which all the soil pores are filled with water.

Shear strength: The strength of soil is the maximum shear stress it can sustain, or the shear stress acting on a shear slip surface along which it is failing.

Shear vane: The shear vane is the instrument used to measure shear strength of soil in the field.

Slipperiness: Excess water or a layer of soft, plastic soil of liquid limit overlying a firm layer of soil can produce a slippery surface. Such a condition may make steering difficult or may immobilise rubber-tired vehicles.

Soil compaction: Compaction is a process that leads to densifiation of soils as a result of the application of stresses, usually of short duration, resulting from passes of vehicle traffic. Soil compaction occurs when a soil is subjected to an external pressure that exceeds its strength. The result is compression of the soil due to the rearrangement of soil particles and a decrease in pore volume. In forestry, compaction can occur as a result of the movement of the harvesting and snigging machinery and logs over the soil. Compaction can also occur naturally in soils over longer periods as a result of settlement and slumping.

Soil displacement: Soil displacement is the mechanical movement of soil by equipment and logs. It involves excavation, scalping, exposure of underlying material and burial of topsoils.

Soil disturbance: Soil disturbance is usually defined in terms of mixing and/or removal of litter and soil, which may change the physical, chemical or biological properties of a soil. Soil disturbance can be used as an index of environment impacts due to logging. Soil disturbance is one of the important factors, which determines the extent and degree of erosion.

Soil moisture content: Soil moisture content is the proportion of water in the soil. It is usually expressed as per unit mass or volume of soil.

Soil puddling: Soil puddles when it is wet. Puddling is most serious when soil moisture potentials are higher than field capacity because moist soils aggregates have low strength. During puddling, soil aggregates are sheared and the structure that they contribute to soil is destroyed. Volume change is assumed to be small because the soils are nearly saturated, with no air space to displace.

Soil structure: Soil structure is defined as the spatial arrangement of individual soil particles. In general, there are three broad categories of soil structure – single grained, massive, and aggregated. When particles are entirely unattached to each other, the structure is completely loose, as it is in the case of coarse granular soils or unconsolidated deposits of desert dust. Such soils were labelled structure less or single grained structure. On the other hand, when the soil is tightly packed in large cohesive blocks, as is sometimes the case with dried clay, the structure can be called massive. When soil particles are associated in quasi-stable small clods known as aggregates or peds, this structure is called aggregated, is generally the most desirable for plant growth. Soil characteristics such as water movement, aeration, bulk density, and porosity are influenced by the overall aggregation or arrangement of the primary soil separates.

Soil texture: The term soil texture refers to the size range of particles in the soil, i.e., whether the particles of which a particular soil is composed are mainly large, small, or of some intermediate size or range of sizes. The traditional method of characterising particle sizes in soils is to divide the arry of possible particle sizes into three conveniently separable size ranges known as texture fractions or separates, namely, sand, silt, and clay.

Stickiness: Stickiness may seriously hamper a vehicle operating in wet, fine-grained soil. Under extreme conditions, sticky soil can accumulate in vehicle running gears, making travel and steering difficult. Normally, stickiness is troublesome only when it occurs in soils of low-bearing capacity (normally, fine-grained soils).

Trafficability (Soil trafficability): Soil is tractable if a tractor or a forest machine can move on that soil to satisfactorily perform the function of the machine without causing significant damage to the soil. Trafficability can be defined as: the period during the year when soil traffic is possible without causing unfavourable compaction. The trafficability can be split into two components. The first component is the threshold value for trafficability, expressed in moisture content or matric potential, stating whether trafficking is possible. The second component is the period during which the soil is trafficable, which is a function of the soil moisture regime and the threshold values.

Workability (Soil workability): Workability is defined as the ease with which operations to produce a satisfactory seed-bed or to harvest a root crop, can be undertaken. Workability may also be defined as “the period during the year when tillage is possible with positive effects on soil structure”. The soil is workable when a fine tilth can be produced. For workability, soils must be sufficiently dry to crumble and not too wet to smear. The threshold value for workability is defined as ‘the soil water status, expressed in soil water content or soil matric potential, at which tillage is possible with positive effects on soil structure’. If the soil is drier than the threshold value tillage can be undertaken without structure deterioration.