# INCREASED MECHANISATION AND SOIL DAMAGE IN FORESTS — A REVIEW

R. WINGATE-HILL and B. F. JAKOBSEN

CSIRO Division of Forest Research, P.O. Box 4008,
Canberra, A.C.T. 2600, Australia

(Received for publication 2 December 1981; revision 30 July 1982)

ABSTRACT

Changes are caused in material on the forest floor and in the underlying soil by various types of machine traffic during ground-based logging operations. The extent, duration, and effect on tree growth of these disturbances vary, but wheeled and tracked machines and operating procedures can be modified to minimise the detrimental effects.

## INTRODUCTION

Mechanised tree harvesting with ground machines usually involves considerable traffic by heavy equipment. Under certain conditions this traffic breaks the litter layer and may cause soil movement, compaction, wheel rutting, and root damage to the trees, all of which can lead to reduced future productivity of the site. In most thinning operations, the effects of reduced competition on trees next to the wheel ruts outweigh to some extent the adverse effects due to soil compaction and root damage (Carter 1980; Moehring & Rawls 1970); nevertheless the benefits expected from thinning are reduced because of the soil damage involved. The scope for choice of different techniques and operational patterns in logging is substantial and, as they all tend to differ with respect to the intensity and areal extent of traffic movement, their effects on surface soil disturbance and subsoil compaction are very variable.

## SOIL DISTURBANCE AND THE EFFECTS OF MACHINES ON FOREST SOILS

For the purposes of this paper, disturbance is taken to mean any direct movement or compression of soil or surface litter during mechanised thinning and harvesting operations.

Disturbance to the forest floor is highly variable in extent and intensity because, as pointed out by Froehlich (1974), it depends on such factors as topography; soil type, depth, and moisture content; amount of litter or slash; harvesting machine weight and running gear; amount, size, and type of timber removed; pattern of extraction tracks and frequency of entry.

The areal extent of disturbance has been measured by a number of researchers, mainly in skidding operations (e.g., Froehlich 1974; Steinbrenner & Gessel 1955; Carter

1979; Hatchell *et al.* 1970; Campbell *et al.* 1973). The general picture appears to be of a relatively small area very heavily disturbed (1 to 3% of the total) on and around log dumps, a larger area of primary trails (3 to 20%) less disturbed, and a generally larger area (8 to 45%) in secondary trails with a low level of disturbance.

Litter and humus lying on the mineral soil are generally the first materials to be disturbed in a logging operation. Fries (1974) concluded, from measurements along tracks after thinning operations in Sweden, that the frequency of rupture and compression or removal of the humus layer increased more or less linearly with transported volume (number of machine passes × volume of load). Disturbance was determined largely by the soil bearing capacity (an index based on soil type, moisture content, and rainfall), being more prevalent where bearing capacity was low, but much reduced where logging slash was present. Hassan (1978) found a similar beneficial effect on bearing capacity from the "root mat layer" during skidding operations on a highly organic soil. Fries (1974) showed that, as one would expect, root damage was strongly correlated with track depth and that risk of root damage increased with increasing tree diameter and decreased with the distance of the tree from a track.

Many forest soils naturally have a low density A-horizon, which may become very soft when its water content is high. A low density soil will compact under the pressure from a wheel and thus gain in strength, as long as there is some air volume in the soil. At the point of saturation compaction will stop because the water is incompressible and drainage is too slow relative to the duration of traffic load to be of any significance. If the soil strength is still less than the machine ground pressure, soil will be squeezed out of the wheel track and ruts will form. Many soil types have a stronger B-horizon, giving sufficient thrust for the machine to proceed in the wheel ruts.

Several factors predispose soils to damage by traffic. The most significant is soil water content (Weaver & Jamison 1951). Many soils are strong enough to resist compaction under a moderate tyre pressure at water contents up to field capacity. A reduction of gravimetric water content of 3–6% will double the strength of many soils (Jakobsen 1973). Soil organic matter increases the soil compressive strength, the elastic recovery of soil after release of stress, and its air-filled porosity at field capacity (Sands *et al.* 1979; Howard *et al.* 1981). Fine-textured soils (clays) generally have a higher porosity after compaction than lighter sandy soils, but aeration problems and low hydraulic conductivity may still be much more severe on the clay soil despite the higher porosity. Heinonen (1979) and Howard *et al.* (1981) suggested a concept of a "normal bulk density" depending on soil type as a useful reference to evaluate degree of soil compaction. Well-graded soils with 10–15% clay and a significant content of coarse sand and gravel and low in organic matter may compact to extremely high densities at their optimal water content, and are more desirable as road material than for tree production.

Soil bulk density is the most commonly used indicator of soil compaction and results are often expressed as a percentage increase in bulk density compared with undisturbed soil nearby. Almost without exception logging causes an increase in bulk density, but of course the values are very variable: Campbell *et al.* (1973), Dickerson (1976), Froehlich (1974), and Steinbrenner & Gessel (1955) gave data from measurements on areas where skidding with wheeled machines was used; Jakobsen & Moore (in prep.) and Miles (1978) studied areas where tracked skidders were employed; Carter (1979) took measurements in tracks made by wheeled forwarders in a *Pinus radiata* D. Don pine plantation. In all areas high soil moisture contents at the time of logging led to increased soil disturbance and high bulk densities. Quoted percentage increases in the top 10 cm of the soil profile range from 2% on lightly used tracks to 44% on major tracks. Care must be used in interpreting these data, however, because bulk density is often decreased in the surface soil layers due to slippage of tyre treads or track cleats and maximum bulk densities occur some distance below the bottom of track ruts, often 10 to 20 cm below (Raghaven *et al.* 1976).

Predictably, bulk densities in the upper part of the soil profile increase with number of passes and total transported weight. The increase in soil density (and the wheel rut depth) may be approximately proportional to the logarithm of the number of passes, as can be derived from data of Fries (1974) and Hatchell *et al.* (1970). Under certain soil conditions increasing soil strength with an increasing number of passes in the same track will cause a reduction of soil-tyre contact area with consequent increased ground pressure. This leads to an even higher final soil density, which will be reached only after a large number of passes. Repeated traffic on an almost waterlogged clay soil may not cause an immediate increase in soil density, but rather soften the soil by dispersion of the aggregates (Emerson 1977) and thus lead to boggy conditions.

In skidding operations soil between the machine ruts is heavily disturbed but bulk density increases are generally not as large as those in the wheel or track ruts. Even in the absence of skidding, however, increases in soil bulk density occur 1½ tyre widths or more from the tyre centre line (Raghaven *et al.* 1976). Where wheels and tracks have been compared (Fries 1974; Omberg 1969) there appears to be an interaction between soil bearing capacity and type of running gear. On low bearing capacity areas (in Swedish forests) tracked machines tended to cause less disturbance and sink less than wheeled machines, probably because of generally lower ground-pressures, whereas on soils with a high bearing capacity the reduced deformation of soil and the litter layer caused more of the weight of tracked machines to be supported on their cleats. According to Omberg the resulting high stresses led to a "cutting" of the surface material which was then sheared off during the generation of tractive forces and deep ruts were formed.

King (1979) measured soil compaction caused by five different types of felling and bunching machines used in thinning pine plantations. On only two of his six sites (where soil moisture content was close to the plastic limit) was there a significant increase in bulk density at 5 cm depth caused by passage of the machines. The soil on all sites was well protected by the needle layer but his results indicate that skidding and forwarding are the operations most likely to cause severe soil disturbance.

The ground pressure exerted by a wheel on the soil surface will spread out and attenuate with depth in the soil (Soehne 1958). For the first depth interval equal to approximately half a tyre width (often 20–30 cm for logging machines), the attenuation is less than 20% of surface ground-pressure which in this zone is the most important factor for soil compaction. At depths of 50 cm and more, when the tyre load is several tonnes and the surface ground-pressure is within the normal operating range (100–

190 kPa), total load on each wheel is the most important factor in determining soil compaction.

Under these heavy loads significant stresses extend into the subsoil, although often density and strength of this subsoil are high enough to resist compaction. However, certain sedimentary and aeolian soils with a low-density subsoil and high ground-water table may be compacted to a depth of 1 m or more (Eriksson *et al.* 1974) and, even when the increases in subsoil density are small, degradation of soil structure by compactive forces may have adverse effects on soil hydrological properties and on tree growth.

Eriksson (1975/6) detected compaction-induced changes, after very heavy traffic, down to 1 m in a clay soil, and Greacen & Sands (1980) measured increases in penetrometer resistance, compared with undisturbed areas, down to more than 50 cm on a logging road on a sandy soil, and to 35 cm after 10 passes with a rubber-tyred skidder.

Soil recovery from compaction varies with soil type. Sandy soils, if they ever recover completely, do so more slowely than clay soils. Greacen & Sands (1980) found unused extraction tracks on sandy soils under *P. radiata* stands still significantly compacted after 50 years, and Munns (1947) noted visible effects of compaction on pioneer routes 100 years after they were last used. Miles (1978) presented data which show only a limited reduction in bulk density within and between extraction track ruts on sandy loam and silty loam soils at depths from 0 to 23 cm, 18 years after logging. Hatchell *et al.* (1970) and Dickerson (1976), from measurements on surface (0–5 cm) soils with a wide range in textures, concluded that wheel-rutted soils took 12 to 18 years to recover whereas areas between ruts needed approximately 8 years. Recovery rate also changes with depth, lower horizons taking very much longer to return to their former state than more superficial layers. For example, Froehlich (1979) found that in a sandy clay loam soil densities in skid trails at 7.6 to 15.9 cm and 22.9 to 30.5 cm depths were 18% and 9% greater, respectively, than those of adjacent undisturbed soils 16 years after logging.

Soil compaction may have a positive effect on traffic tolerance, but it will usually have negative effects on the site quality for tree growth. When soil is compacted, saturated hydraulic conductivity and soil air volume are decreased and penetrometer resistance (which can be taken as a measure of resistance to root penetration) is increased (Jakobsen & Moore in prep.). Penetrometer resistance increases exponentially with increasing soil density (Sands *et al.* 1979), so that even a small increase in soil density, as a result of an increasing number of machine passes in the same track, may bring it into the range where soil resistance is critical for root penetration.

The highest degree of compaction occurs in the top 30 cm of the soil profile. This zone normally contains 70–90% of the total root mass (Kalela 1949; Kostler *et al.* 1968) and is by far the most important zone for the nutrient supply to trees. Furthermore this layer is important for the infiltration of water during short-duration high-intensity rainstorms because in its natural condition it has a high hydraulic conductivity and high water storage capacity, both of which may be greatly reduced by compaction.

There are numerous reports of growth reduction after logging; for example, Greacen & Sands (1980), in a literature survey spanning the period 1970 to 1977, noted 117, 12, 8, and 5 studies of the effect of compaction on crop (tree) yield showing yield reduction, yield increase, both yield reduction and increase, and no effect on yield, respectively. It is not clear what they mean by "yield" because many of the references seem to be to studies where reduced establishment or growth rate of seedlings in compacted soil was observed. Nevertheless growth reduction was found in a number of economically significant species such as *P. radiata, P. elliottii* Engelm., *P. taeda* L., and *P. ponderosa* Laws. The extent of growth reduction in mature trees is of great interest. Froehlich (1979) and Carter (1980) both studied the problem in pine stands (*P. ponderosa* and *P. radiata,* respectively), by subjectively assessing the level of soil disturbance due to thinning some years after it had occurred, then using stem analysis techniques to determine growth rates before and after logging. Competition indices were employed to allow for differential competition effects on control and trackside trees. Froehlich calculated that trees close to moderately compacted areas of soil showed a 6% reduction in growth rate whereas trees adjacent to heavily compacted areas suffered a 12% reduction over a 16-year period. Carter concluded that (during a 6-year period) the yield from trackside trees was 23 to 32% lower than from trees unaffected by vehicle tracks, but in this study rut damage at the time of thinning was very severe. Moehring & Rawls (1970) studied the problem by setting up a replicated experiment with known levels of compaction applied both when the silt loam soil on which they worked was wet and when it was dry. The soil was compacted on one, two, three, or four sides of selected trees by six passes with a TD9 crawler tractor pulling three 16-foot (4.8-m) logs. Dry weather logging did not affect tree growth but compaction on three or four sides of trees in wet soil conditions reduced annual basal area growth by 36% and 43% respectively over a 5-year period.

## MEANS OF REDUCING SOIL DISTURBANCE

In the following section various ways of reducing soil disturbance (movement of soil or litter and soil compaction) are discussed on the assumption that any reduction is beneficial to the soil. Whether the beneficial effects are significant in terms of tree growth and whether the costs of obtaining these benefits are justified are questions which cannot be answered at present. These are pertinent questions because all the means of reducing soil disturbance discussed below ultimately involve increases in operating costs which must be weighed against resulting future changes in site productivity.

Average contact pressures between vehicle running gear and the soil, plus a limited number of soil properties (such as moisture content, texture, cone penetrometer resistance), have been used for predicting bulk density changes caused by traffic (Amir *et al.* 1976; Blackwell & Soane 1981). Unfortunately contact pressures are by no means uniform and although methods have been developed for calculating pressure distributions at the soil-wheel interface (Gee-Clough 1976) and deeper in the soil (Yong *et al.* 1978) they are as yet cumbersome. The relation between compression-induced soil changes and tree growth is by no means well understood, hence for some time to come the forest manager will have to rely heavily on his own judgment in deciding how far to go in modifying his mechanisation methods and/or equipment to avoid causing damage to the forest soil.

## Choice of Machines and Running Gear

Thinning and harvesting machines use the forest floor for support, as a resisting medium for traction, and for directional control. In providing support the soil is frequently compressed and ruts may form. During the process of developing tractive or steering forces the soil beneath a tyre or track frequently fails partially or completely and this leads to slip. Wheel slip increases soil compaction (Raghaven *et al.* 1978), often causes rut formation, and frequently produces considerable disturbance of litter, slash, or soil along extraction tracks. Jakobsen (1968) found that the combination of slip-induced shear stresses and normal stresses from wheel loading could double soil compaction as measured by bulk density changes, compared with the effect of normal static stresses alone. It is an unfortunate fact that maximum tractive efficiency (T.E. = drawbar power/input power to drive wheels) of wheeled machines generally occurs in the range 10 to 18% slip (Dwyer *et al.* 1975), and Raghaven *et al.* (1978) found that slip-induced compaction reached a maximum in the range 10 to 50% slip for soil types ranging from clay to sand. It appears that if surface soil compaction caused by wheel slip is to be avoided completely there will inevitably have to be some sacrifice in T.E. Vertical vibration is a factor rather like slip which augments the action of vehicle weight in causing soil compaction. It also reduces T.E. (Wong 1971) and on both counts should be minimised where this is feasible.

In the practical situation, machine choice involves a whole series of compromises. Some of those relevant to the present discussion are illustrated in a compact way in Figs. 1 and 2 taken from Reece (1970). Figure 1 shows the generally accepted "best" choice of running gear for various soil conditions in relation to operating requirements, ignoring monetary considerations. Fig. 2 is concerned with choice of vehicle form for similar operating conditions. Assume, for example, a vehicle is required to carry very heavy loads on soft soils. A relatively slow-moving tracked machine is usually the only solution, but expensive (Column 1). On soils with higher strength the conventional rear-wheel-drive agricultural tractor is an economical solution for tractive purposes, load carrying, and self propulsion, and it can generally travel faster than the track-laying vehicle (Column 2). These figures do not necessarily take into account detrimental effects of machines on the soil; for instance, in Fig. 1 the use of a high-pressure tyre to carry a heavy load at relatively high speed on a hard fine-grained sandy soil may cause irreversible compaction in the lower horizons, but operationally it is currently accepted as the most appropriate choice.

Where lighter machines can be used economically in preference to heavier ones they should be chosen because they will cause less surface and sub-soil compaction in susceptible soils. Unfortunately the traction developed by a driven wheel or track is largely dependent upon the load it carries, certainly in frictional (sandy) soils, so that reducing the weight of a machine is likely to reduce its tractive performance as well, unless engine power is a limiting factor.

The choice between tracked or wheeled machines is often difficult to make. For given over-all dimensions and gross weight a tracked vehicle will generally have a larger contact area than a wheeled vehicle. Average ground pressure, sinkage, and rolling resistance of the tracked vehicle will also be lower, and thus slip is usually reduced

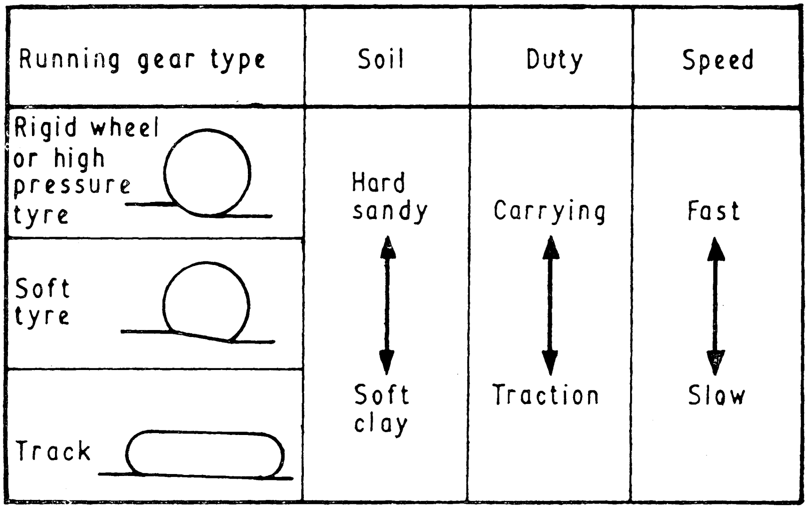


FIG. 1—Choice of running gear (from Reece 1970).

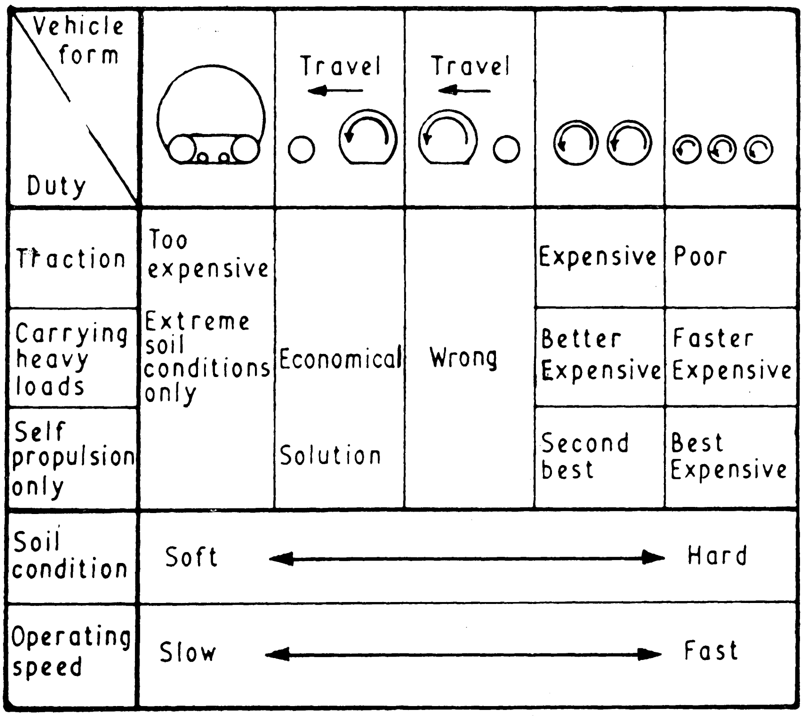


FIG. 2—Choice of vehicle form (from Reece 1970).

compared with an equivalent wheeled vehicle. All these factors favour the tracked machine in terms of causing potentially less soil damage. However, tracked machines are often more costly to buy and operate and less versatile than comparable wheeled vehicles. Also, as noted earlier, where soil bearing capacity is relatively good tracks may cause more soil disturbance than wheels. Two broad design parameters can be changed to improve tracklayer performance in this respect. Wong (1978) stated that track sinkage and motion resistance depend on maximum pressures below tracks, not on average values, and some tracks have a more uniform longitudinal pressure distribution than others – for example, designs with overlapping track rollers (Rowland 1972). Articulated steering of tracked machines is more desirable than the usual skid steering over rough terrain because it gives the vehicle better mobility and manoeuvrability and causes less soil disturbance (Wong 1978). One of the conclusions from a study by McMorland (1980) indicates that the use of smaller tracked machines can significantly reduce soil disturbance during skidding. The areas logged with small (47–48 kW) tractors showed approximately one-third less disturbance than those where large (54–58 kW) tractors had been used. Most of the reduction was attributed to narrower and more widely spaced skid tracks.

Apart from choosing tracked vehicles to reduce average ground pressures exerted by harvesting machines, there are a number of ways of mitigating the detrimental effects of wheeled machines on forest soils. These methods generally rely on increasing ground contact area for a given load or improving the tractive performance of the tyres so that a certain tractive effort can be obtained with a reduced wheel loading.

Both these benefits can be achieved, in varying degrees, by using flexible tyres at moderate-to-high deflections. Radial ply tyres are more flexible than cross plies and, except at high inflation pressures, usually have higher coefficients of traction at a given slip (C. of T. = thrust developed by wheel/vertical load on wheel). Numerous comparative tests have been carried out and increases in C. of T. range from 5 to 18% or more depending upon the level of wheel slip and type of supporting surface (for example, *see* Gee-Clough *et al.* 1977b).

Reducing tyre inflation pressure to the lowest value recommended for the load to be carried will increase contact area and reduce topsoil compaction, but the increased risks of tyre side-wall damage must be borne in mind. Gee-Clough (1980) has shown the detrimental effect on tractive performance, apart from damage to the soil, of using high load capacity, high inflation-pressure, earthmoving tyres instead of agricultural tyres for off-highway operations.

There is, in fact, an inherent conflict between the tyre requirements for a good off-road vehicle and one for highway use (*see* Figs. 1 and 2). Some forest machines often have to work on both types of surface and one way of at least partially reconciling these conflicting needs would be to use a "central tyre inflation/deflation system", which allows the operator to change tyre inflation pressures on the move. These systems are already widely used on military vehicles (Czako 1974). The benefits would be improved tractive performance and reduced surface soil compaction which would have to be weighed against increased machine complexity and cost.

Oversizing drive-wheel tyres by increasing diameter and width is another means of decreasing average ground pressures, provided wheel loads are not increased, because lower inflation pressures can be used (Taylor *et al.* 1967). A rather extreme form of this change in tyre specification is to use the comparatively very wide "Terra Tires" (D'Avello 1964) or equivalent. These tyres when used on skidders are operated at only 35 to 70 kPa compared with conventional tyres at 120 to 175 kPa and so compaction in surface soil layers is likely to be much reduced. FERIC in Canada is currently testing these tyres on wheeled skidders (Mellgren 1981). Preliminary results on very soft ground indicate increases in productivity of up to 60% and 20 to 30% savings in fuel consumption which must be set against an increase in cost for new tyres of 3 to 4 times and, possibly, a shorter tyre life.

Fitting dual tyres instead of singles to powered axles is a method used in agriculture to increase tractive performance (Southwell 1964; Gee-Clough 1980) and popular belief is that duals also reduce surface soil compaction. However, Dickson *et al.* (1979) showed that duals operating at the same inflation pressure as single drive-wheel tyres on a freshly cultivated loamy sand soil simply produced shallower ruts with a cross-sectional area 55% greater than corresponding wheel ruts and only a very slight decrease in soil compaction on the rut centre lines. On the other hand, when duals are used at a lower pressure than normal significant decreases in soil stresses and compaction effects can be obtained on soft soils (Soehne 1958; Eriksson *et al.* 1974) and the reported decreases in rut depth may be significant in a forest situation in terms of root damage.

The replacement of rubber tyres by wide steel cage wheels is another means of reducing soil compaction and new designs appear to be increasing their value in this respect (Dickson *et al.* 1979), but in forestry operations they are probably only appropriate for machines which work exclusively on soft soils for relatively long periods and where machine width is not a limiting factor. Of course this applies to dual or extra-wide tyres as well.

Instead of modifying wheeled machines to achieve extra flotation and reduced compaction intensity on soft soils, an alternative approach is to accept that soil damage will occur on tracks, to limit their extent, and use wheel systems to give high C. of T. with some prospect of reducing or at least limiting total machine weight. Many studies have shown the advantage, in terms of T.E., of using multi-powered-axle vehicles on deformable soils (e.g., Holm 1969). The improved performance is due to reduced rolling resistance and greater strength of the compacted soil in the floor of the rut from the leading wheel. Four-wheel-drive skidding tractors, processors, and forwarders with tandem drive wheels are examples of the use of this principle on forest harvesting machines.

Various "add-on" devices have been designed for increasing the T.E. of wheels. Southwell (1964) measured the increase in traction which could be obtained on a range of soil types in different moisture conditions by using 10 different traction aids including chains, strakes (metal "teeth" which can be easily extended beyond the tyre periphery to penetrate the soil), and half-tracks. Chains produced only minor improvements in C. of T. and drawbar power/tractor weight ratios. Strakes and half-tracks were the most effective devices and, on the grounds of ease of fitting and removal, cost, and performance, Southwell recommended strakes as the best alternative. Chains and half-tracks are used on tree-harvesting machines but strakes are not. Perhaps they should be tried as a means of increasing traction in soft soil conditions without resorting to adding extra weight by ballasting and so increasing the likely amount of soil compaction.

Lugs on pneumatic tyres cause stress concentrations in the soil which can lead to local severe compaction. Fortunately, in hard dry conditions when most of the load is supported on the treads the surface soil is probably not badly affected. In wetter conditions when the soil is more susceptible to damage, sinkage and soil movement ensure that wheel loads are much more evenly distributed over the contact area, hence the detrimental effect of lugs is reduced (Soehne 1958). Of course, flexible smooth tyres would be the ideal, but lugs are required to improve traction, except possibly in dry hard soils (*see* Biller & Hartman 1971). From the soil damage point of view treads should be as shallow as possible provided slip is not increased significantly. Gee-Clough *et al.* (1977a) have shown, for a range of agricultural soils, that there is no advantage in terms of C. of T. or T.E. in having treads higher than 20 mm. One would expect, although it has not been proved, that wider treads covering more of the tyre surface may lead to some reduction in surface soil compaction. Taylor (1976) found only small reductions in C. of T. in good traction conditions (< 20% slip) using such tyres instead of conventional agricultural tyres. The advantage claimed for wide-tread tyres was a substantial increase in wear life.

## Modification to Methods of Operation

Moisture content is certainly one of the most important factors in soil damage caused by wheeled or tracked equipment (e.g., Amir *et al.* 1976). Probably the single management change which could have the greatest beneficial effect is to stop logging when soils are too wet, especially on the more susceptible soils described earlier. What is "too wet" is, however, difficult to define. For soils containing > 15% clay, maximum compaction tends to occur at moisture contents near the lower plastic limit (Baver 1961), so operations involving very heavy equipment or many passes along tracks should, if possible, be discontinued as long as soil moisture is above these values. Organic matter raises the lower plastic limit moisture content and is beneficial in reducing the susceptibility of clay soil to compaction. Organic matter also has a beneficial effect in sands (Sands *et al.* 1979) and every effort should be made to retain it. Methods include not burning litter during site preparation; where soils are acid, liming to increase the pH and promote micro-organism activity, so increasing litter decomposition rates; planting pasture, especially legumes, between successive tree crops.

The use of slash on extraction tracks is also beneficial in this respect, but more immediately by physically protecting the soil. The effect can be very marked with wheeled machines in wet conditions (Fries 1974) but much less so where tracked vehicles are used on drier soils (Jakobsen & Moore in prep.). Various methods of drainage are widely used in agriculture to reduce high soil moisture contents and susceptibility to compaction (Eriksson *et al.* 1974); unfortunately the application of many of these techniques to forest situations is probably limited.

Any reduction which can be obtained in skidding forces is useful in that it will probably lead to less slip-induced soil compaction and may even allow the use of lighter machines, which cause less soil damage. The importance of not working on wet soil is emphasised by the highly significant increase in skidding forces at higher soil moisture contents recorded by Garlicki & Calvert (1969) and Perumpral *et al.* (1977). Skidding downhill, where possible, instead of uphill or along level ground, will reduce skidding forces (Herrick 1955). However, on steep slopes concentration of runoff water which may cause erosion, and the inevitable soil movement in skid tracks when trying to reduce speed, can be as detrimental as the more usual slip of wheels or tracks. Herrick also demonstrated the marked reduction in skidding force requirements which can be obtained by using arches instead of complete ground skidding.

The form and orientation of timber for skidding can have very significant effects. Garlicki & Calvert (1969) found that the power requirement for full-tree skidding of red pine on flat sandy soil was approximately double that needed for skidding of tree lengths. In another study on white spruce, Calvert & Garlicki (1968) measured a 14–16% increase in power requirement when skidding tree-length logs small-end first instead of the more usual method of butt-end first.

There is probably scope for reducing soil disturbance by modifying traffic patterns within the forest. Arndt & Rose (1966) from the development of a theory for the effect of variable traffic compaction on the over-all relative magnitude of soil properties of a field, pointed out that as the likely effects of soil compaction become more severe it is increasingly important to reduce the proportion of compacted ground by more careful selection of a traffic system. An example of this approach was given by Bradshaw (1979). He reported a reduction from 22% to 4% in skid track area for conventional skidding compared with pre-planned skid trails and winching of logs to the tracks on a partial-cut pine stand. Unfortunately production rates dropped by 11% and costs increased by 29%.

Some potential for reduction in the area of extraction tracks and in the intensity of compaction effects by cutting down the number of machine passes would appear to be possible in mechanised thinning and forwarder extraction operations – for example, the use of long-reach feller bunchers and long-reach cranes or winches (Fries 1974; Leidholm 1977), so that extraction track spacings can be increased and perhaps, where possible, planning of tracks with exits/entrances at both ends to avoid extreme soil disturbance at one end (Carter 1979). Militating against this last suggestion, however, is the general finding that the majority of any compaction effects occur during the first few machine passes (*see* for example, Eriksson *et al.* 1974) so that the most practical option may be to concentrate machine traffic on very limited areas and accept that considerable soil disturbance will occur. There is a striking parallel here with the current trend in some European and North American farming areas to adopt the "Tram-line" technique whereby all wheel traffic is confined to definite tracks (Basford 1979), one major object being to reduce the areal extent of wheel compaction.

## CONCLUSION

Compaction of forest soil is a problem which will most probably intensify as mechanisation of tree harvesting increases. There is ample evidence that soil disturbance and compaction can adversely affect tree growth and long-term productivity of a site, but the effects are variable and have not yet been well quantified. Until this is done the economic justification for and implementation of the ameliorative measures described in this paper are likely to be limited.

## REFERENCES


AMIR, I.; RAGHAVAN, G. S. V.; McKYES, E.; BROUGHTON, R. S. 1976: Soil compaction as a function of contact pressure and soil moisture content. **Canadian Agricultural Engineering 18(1):** 54–7.

ARNDT, W.; ROSE, C. W. 1966: Traffic compaction of soil and tillage requirements. II. A theory for the effect of variable traffic compaction on the overall relative magnitude of soil properties of a field. **Journal of Agricultural Engineering Research 11(3):** 176–7.

BASFORD, W. D. 1979: Tramlines – the right lines? **The Agricultural Engineer 34(3):** 81–3.

BAVER, L. D. 1961: "Soil Physics", Chapter 4. Third ed. J. Wiley and Sons, New York.

BILLER, C. J.; HARTMAN, R. L. 1971: Tractive characteristics of wheeled skidder tyres. **Transactions of the American Society of Agricultural Engineers:** 1024–26, 1033.

BLACKWELL, P. S.; SOANE, B. D. 1981: A method of predicting bulk density changes in field soils resulting from compaction by agricultural traffic. **Journal of Soil Science 32:** 51–65.

BRADSHAW, G. 1979: Preplanned skid trails and winching versus conventional harvesting on a partial cut. **Oregon State University School of Forestry, Research Note 62.**

CALVERT, W. W.; GARLICKI, A. M. 1968: Tree-length orientation and skidding forces. **Pulp and Paper Magazine of Canada** (June): 62–4.

CAMPBELL, R. G.; WILLIS, J. R.; MAY, J. T. 1973: Soil disturbance by logging with rubber-tired skidders. **Journal of Soil and Water Conservation 28:** 218–20.

CARTER, P. R. 1979: Logging input studies I and II. **Forestry Commission of New South Wales, Project Nos. 020/1.01 and 1.02, Progress Report.**

——— 1980: Variations in tree growth with proximity to outrows and levels of soil disturbance. **Forestry Commission of New South Wales, Internal Report.**

CZAKO, T. F. 1974: The influence of inflation pressure on cross-country performance. **Journal of Terramechanics 11(3, 4):** 13–23.

D'AVELLO, F. S. 1964: Terra tires. **Journal of Terramechanics 1(4):** 107–16.

DICKERSON, B. P. 1976: Soil compaction after tree-length skidding in Northern Mississippi. **Soil Science Society of America Journal 40:** 965–6.

DICKSON, J. W.; HENSHALL, J. K.; O'SULLIVAN, M. F.; SOANE, B. D. 1979: Compaction effects under commercial and experimental cage wheels in comparison with rubber tyres on loose soil. **Scottish Institute of Agricultural Engineering Dep. Note SIN/261 (unpubl.)**, 9pp.

DWYER, M. J., EVERNDEN, D. W.; McALLISTER, M. 1976: Handbook of agricultural tyre performance (2nd ed.). **National (U.K.) Institute of Agricultural Engineering Report No. 18.**

EMERSON, W. W. 1977: Physical properties and structure. **In** Russell, J. R.; Greacen, S. L. (Eds) "Soil Factors in Crop Production in a Semi-arid Environment". Queensland University Press, Brisbane.

ERIKSSON, J. 1975/76: Influence of extremely heavy traffic on clay soil. **Grundforbattring 27(1):** 33–51.

ERIKSSON, J. HAKANSSON, I.; DANFORS, B. 1974: The effect of soil compaction on soil structure and crop yields. **Swedish Institute of Agricultural Engineering Bulletin 354.**

FRIES, J. 1974: Views on the choice of silvicultural methods and logging technique in thinning. **"Aspects of Thinning", Forestry Commission Bulletin No. 55.**

FROEHLICH, H. A. 1974: The influence of different thinning systems on damage to soil and trees. **"Aspects of Thinning", Forestry Commission Bulletin No. 55.**

——— 1979: Soil compaction from logging equipment: effects on growth of young ponderosa pine. **Journal of Soil and Water Conservation (Nov-Dec):** 276–8.

GARLICKI, M.; CALVERT, W. W. 1969: A comparison of power requirements for full-tree versus tree-length skidding. **Pulp and Paper Magazine of Canada** (July): 83–6.

GEE-CLOUGH, D. 1976: The Bekker theory of rolling resistance amended to take account of skid and deep sinkage. **Journal of Terramechanics 12(2):** 87–105.

——— 1980: Selection of tyre sizes for agricultural vehicles. **Journal of Agricultural Engineering Research 25:** 261–78.

GEE-CLOUGH, D.; McALLISTER, M.; EVERNDEN, D. W. 1977a: Tractive performance of tractor drive tyres. I. The effect of lug height. **Journal of Agricultural Engineering Research 22:** 373–84.

——— 1977b: Tractive performance of tractor drive tyres. II. A comparison of radial and cross-ply carcass construction. **Journal of Agricultural Engineering Research 22:** 385–95.

GREACEN, E. L.; SANDS, R. 1980: Compaction of forest soils. A review. **Australian Journal of Soil Research 18:** 163–89.

HASSAN, A. E. 1978: Effect of mechanisation on soils and forest regeneration. I. Coastal plain organic soil. **Transactions of the American Society of Agricultural Engineers:** 1107–12.

HATCHELL, G. E.; RALSTON, C. W.; FOIL, R. R. 1970: Soil disturbance in logging. **Journal of Forestry** (Dec.): 772–5.

HEINONEN, R. 1979: The notion of normal bulk density in arable soils. **Proceedings of the 8th ISTRO Conference Stuttgart-Hohenheim:** 87–90.

HERRICK, D. E. 1955: Tractive effort required to skid hardwood logs. **Forest Products Journal (Aug.):** 250–5.

HOLM, I. C. 1969: Multi-pass behaviour of pneumatic tyres. **Journal of Terramechanics 6(3):** 47–71.

HOWARD, R. F.; SINGER, M. J.; FRANTZ, G. A. 1981: Effects of soil properties, water content and compactive effort on the compaction of selected California forest and range soils. **Soil Science Society of America Journal 45:** 231–6.

JAKOBSEN, B. F. 1968: Mechaniske egenskaber hos nogle danske jorde. Thesis, Royal Veterinary Agricultural University, Copenhagen.

——— 1973: Interrelations of soil physical characteristics **Acta Agricola Scandinavica 23:** 165–72.

JAKOBSEN, B. F.; MOORE, G. A.: Effects of two types of skidders and of a slash cover on soil compaction by logging of mountain ash (in prep.).

KALELA, E. K. 1949: On the horizontal roots in pine and spruce stands. I. **Acta Forestalia Fennica 57:** 1–79.

KING, A. L. 1979: Measuring soil compaction in mechanically thinned pine plantations. **American Society of Agricultural Engineers Paper No. 79-1600.**

KOSTLER, J. N.; BRUCKNER, E.; BIBELRUTHER, H. 1968: "Die Wurzeln der Waldbaume". Paul Dasey, Hamburg-Berlin. 284p.

LEIDHOLM, H. 1977: Time consumption and skidding resistance when winching stems and trees. **Skogshogskolan Research Note 113.**

McMORLAND, B. 1980: Skidding with small crawler-tractors. **Forest Engineering Research Institute of Canada Technical Report No. TR-37.**

MELLGREN, P. G. 1981: High flotation tyres for logging machines. **Forest Engineering Research Institute of Canada Internal Report.**

MILES, J. A. 1978: Soil compaction produced by logging and residue treatment. **Transactions of the American Society of Agricultural Engineers:** 60–2.

MOEHRING, D. M.; RAWLS, I. W. 1970: Detrimental effects of wet weather logging. **Journal of Forestry** (March): 166–7.

MUNNS, E. N. 1947: Logging can damage the soil. **Journal of Forestry 45:** 513.

OMBERG, H. 1969: The formation of tracks made by forwarders on forest soil. **Proceedings of IUFRO Meeting on "Thinning and Mechanisation", Stockholm, Sweden:** 144–50.

PERUMPRAL, J. V.; BALDWIN, J. D.; WALBRIDGE, T. A.; STUART, W. B. 1977: Skidding forces of tree-length logs predicted by a mathematical model. **Transactions of the American Society of Agricultural Engineers:** 1008–12.

RAGHAVAN, G. S. V.; McKYES, E.; BEAULIEU, B. 1978: Clay soil compaction due to wheel slip. **Transactions of the American Society of Agricultural Engineers** 646–9, 653.

RAGHAVAN, G. S. V.; McKYES, E.; CHASSE, M. 1976: Soil compaction patterns caused by off-road vehicles in Eastern Canadian agricultural soils. **Journal of Terramechanics 13(2):** 107–15.

REECE, A. R. 1970: Tractor design: looking back and thinking forward. **Farm Machine Design Engineering (Dec.):** 32–4.

ROWLAND, D. 1972: Tracked vehicle ground pressure and its effect on soft ground performance. **Proceedings of the Fourth International Conference of the International Society for Terrain Vehicle Systems, Stockholm, Sweden.**

SANDS, R.; GREACEN, E. L.; GERARD, C. J. 1979: Compaction of sandy soils in radiata pine forests. I. A penetrometer study. **Australian Journal of Soil Research 17:** 101–13.

SOEHNE, W. 1958: Fundamentals of pressure distribution and soil compaction under tractor tires. **Agricultural Engineering** (May): 276–81, 290.

SOUTHWELL, P. H. 1964: An investigation of traction and traction aids. **Transactions of the American Society of Agricultural Engineers:** 190–3.

STEINBRENNER, E. C.; GESSEL, S. P. 1955: The effect of tractor logging on physical properties of some forest soils in Southwestern Washington. **Soil Science Society of America Proceedings 19:** 372–6.

TAYLOR, J. H. 1976: Comparative traction performance of R-1, R-3 and R-4 tractor tyres. **Transactions of the American Society of Agricultural Engineers:** 14–16.

TAYLOR, J. H.; VANDEN BERG, G. E.; REED, I. F. 1967: Effect of diameter on performance of powered tractor wheels. **Transactions of the American Society of Agricultural Engineers:** 838–42.

WEAVER, H. A.; JAMISON, V. C. 1951: Effects of moisture on tractor tire compaction of soil. **Soil Science 71:** 15–23.

WONG, J. Y. 1971: Effect of vibration on the performance of off-road vehicles. **Society of Automotive Engineers Paper No. 710224.**

——— 1978: "Theory of Ground Vehicles", Chapter 4. John Wiley and Sons, New York.

YONG, R. N.; FATTAH, E. A.; BOONSINSUK, P. 1978: Analysis and prediction of tyre-soil interaction and performance using finite elements. **Journal of Terramechanics 15(1):** 43–63.