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Compaction of Forest Soils. A Review

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Abstract

The problem of soil compaction in forestry differs from that in agriculture because of differences in the nature of the crop, in particular the weight and size of the plant members and the length of time that they persist. The roots compact the soil as they increase in size, but they also transmit the weight of the tree and forces generated by the wind onto the soil. There are important differences in management practices; in forestry modern harvesting machines apply heavy loads and, for reasons of cost, tend to be kept in operation throughout the year. As a consequence the structure of the soil suffers some damage, often manifested as compaction.

Compaction arising from such sources may reduce the growth of the current trees or trees subsequently planted on the site. But it is difficult to predict the extent of such reduction, if any, because of the complex of interactions involved. Important factors concerned, namely, the soil water regime and the organic matter content, are emphasized. A conceptual model is proposed as a predictive tool.

The mechanics of soil compaction, the effects of compaction on the physical properties of the soil, and techniques for the prevention and amelioration of compaction of forest soils, are discussed.

Introduction

When soil is compacted, soil strength is increased and total porosity is reduced at the expense of the large voids. Thus volumetric water content and 'field capacity' are increased, while air content, water infiltration rate and saturated hydraulic conductivity are decreased. Consequently surface runoff of water may increase and tree growth may be reduced because of a reduced water supply, restricted root space and poor aeration. In contrast soil compaction may increase traction and therefore the efficiency of vehicles moving on roads and snigging tracks in the forest. Forest soils may be compacted by grazing animals and by the roots of the trees themselves, but more noticeably by vehicles used for a range of mechanized forest operations. The compaction of agricultural soils has received considerable attention, and much of this research is relevant to compaction of forest soils. However, there are several reasons why compaction of forest soils is exceptional and deserves study in its own right. Tree roots persist and apply mechanical forces for long periods of time compared to those with annual crops. The felling and snigging of large trees imposes unique loads on the soil. Harvesting machinery may be very heavy and, combined with the pushing and pulling and lifting of logs, may exert large pressures on the soil. Some harvesting operations may greatly disturb the soil. Usually harvesting operations in forests are not as evenly spread over the area as in mechanized operations in agriculture, and consequently the degree of variability and heterogeneity of compaction and soil disturbance is greater in forests. Amelioration of compaction in forests by deep working is more difficult than in agriculture because of the presence of stumps and large roots. Many of our water supply catchments are in forests and soil compaction may affect water quality.

In this review we discuss (1) the mechanics of soil compaction, (2) the causes and extent of soil compaction in forests, (3) the effects of soil compaction on the physical properties of the soil, (4) the consequences of compaction to root growth, and (5) techniques for prevention and amelioration of soil compaction.

Mechanics of Soil Compaction

Compaction involves a rearrangement and bringing of the solid particles of the soil closer together and consequently an increase in the bulk density. Bulk density is commonly used as a measure of compaction, with the upper limit being determined largely by the shape and size distribution of the ultimate soil particles. For mixtures of fine sand and a silty clay soil, Bodman and Constantin (1965) give values of maximum density for a range of prepared soils as shown in Table 1. These values reflect the effect of particle size distribution or texture on the maximum density attainable in a soil.

Table 1. Data for fine sand/silty clay mixtures

Texture:	Silty clay	Clay loam	Sandy clay loam	Sandy loam	Loamy sand
Sand/silty clay	0/100	20/80	40/60	60/40	80/20
Bulk density (g cm^{-3})	1·42	1·53	1·69	1·77	1·85
Clay (%)	50	40	30	20	10
Liquid limit (%)	57	50	43	37	30
Plastic limit (%)	27	26	25	24	23

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. Description of the relationship between strength and compaction depends largely on soil mechanics theory. In soil mechanics, the state of compaction of a soil is described by the void ratio e rather than the bulk density, and this practice is followed here. Void ratio is the volume of voids associated with unit volume of the solids. Thus $e = (\rho_s/\rho_a) - 1$, where ρ_s is the real density of the soil grains and ρ_a is the bulk density. In the discussion that follows we discuss, firstly, relationships between void ratio and applied pressure with the overriding effect of the water content of the soil and the nature of the applied forces; secondly, soil strength and the bearing capacity and resistance to penetration of the soil; and finally, the time dependence of the compaction process.

Relationships between Applied Pressure and Void Ratio

The void ratio of a saturated soil undergoing uniaxial compression for the first time is considered to be linearly related (over a wide range of compression) to the logarithm of the applied pressure P (line AB in Fig. 1a).

Thus

$$e = e_0 - I_c \ln P/P_0,$$

where I_c is the compression index ($I_c = -\mathrm{d}e/\mathrm{d}\ln P$), and where e_0 is the void ratio at arbitrary pressure P_0 and $P > P_0$. BC in Fig. 1*a* represents the swelling curve on unloading, where I_s is the swelling index ($I_s = -\mathrm{d}e/\mathrm{d}\ln P$). The same relationship has been applied to unsaturated soil being compressed in a consolidometer (Greacen 1960*a*), and in a triaxial cell during compression with plastic failure (Farrell and Greacen 1966; Kumar and Weber 1974). Compaction of unsatuatred soil under an applied static pressure and an applied pressure with shear is shown in Fig. 1*b*. Consideration of these realtionships is important, as compaction of both saturated and unsaturated soil occurs in forests.

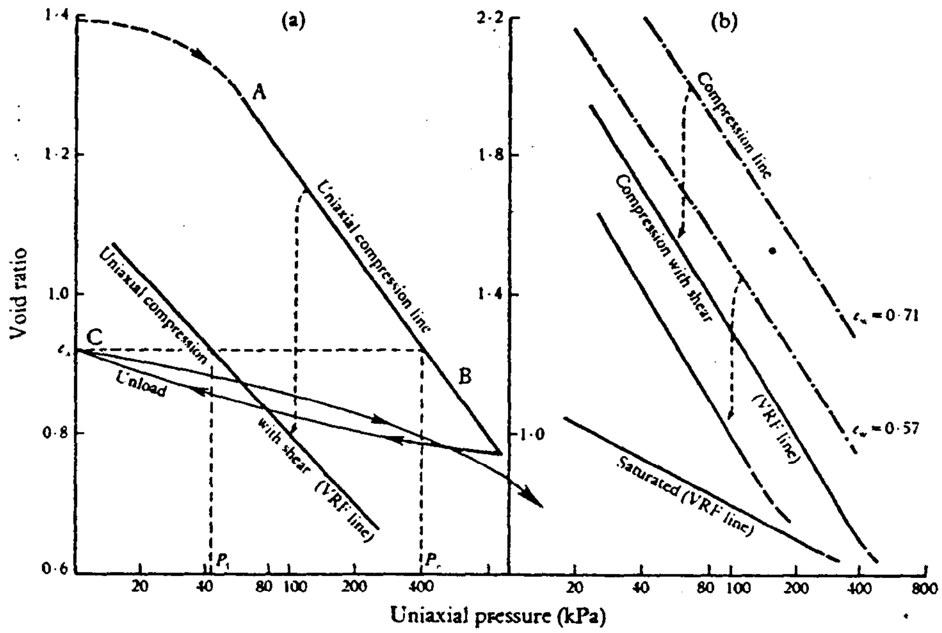

Fig. 1. Diagram of void ratio–pressure relationships for a clay soil under uniaxial pressure without shear and with shear to failure for (*a*) the saturated condition and (*b*) the unsaturated condition at two water contents expressed as e_w, the volume of water per unit volume of solid. The saturated VRF line is common to both (*a*) and (*b*), but note the change in scale.

In saturated soil a decrease in soil water pressure u has the same effect on volume change as an increase in an externally applied pressure or mechanical stress. Terzaghi (1923) showed experimentally that the amount of one-dimensional consolidation in a saturated soil depended on the effective stress σ', where $\sigma' = \sigma - u$, σ is the applied stress and u is the pressure in the soil water. The relationship is also valid for negative pore water pressure or suction, provided the system remains water filled (Childs 1955).

In unsaturated soil, the voids contain both air and water, and the suction is regarded as acting over a fraction χ per unit area of the soil. The effective stress is now given as $\sigma' = \sigma - \chi u$, with χ varying from near zero in dry soil to 1 at saturation. Williams and Shaykewich (1970) presented an S-shaped relationship similar for two soils between χ and the degree of saturation.

Application of the above Terzaghi model to compaction in unsaturated soil is not fully understood, but it appears to describe compaction in a qualitative way. As the suction increases in an unsaturated bed of aggregates or peds, χ can remain equal to 1 within the individual peds but approach zero for the bulk soil. Thus, during compression, there may be a negligible increase in the effective stress on the bed due to an increase in suction but a considerable increase in resistance to the crushing of the peds. Dexter (1975) and Braunack and Dexter (1978) tried to account for this behaviour by generalizing the compacting pressure as P/Y, where Y is the tensile strength of the peds which determines their crushing strength under compression. It will be appreciated that the tensile strength Y, and other strength parameters such as cohesion c, and the unconfined compressive strength σ_{uc} (Barley and Greacen 1967) are all directly proportional to the compacting pressure P and depend strongly on the water content expressed as e, as shown in Fig. 1.

Braunack and Dexter (1978) do not use the classical semi-log compression relationship; instead, they describe compression by an exponential expression, as

$$H/H_i = A+B\exp[a(P/Y)-b(P/Y)^{\frac{1}{2}}],$$

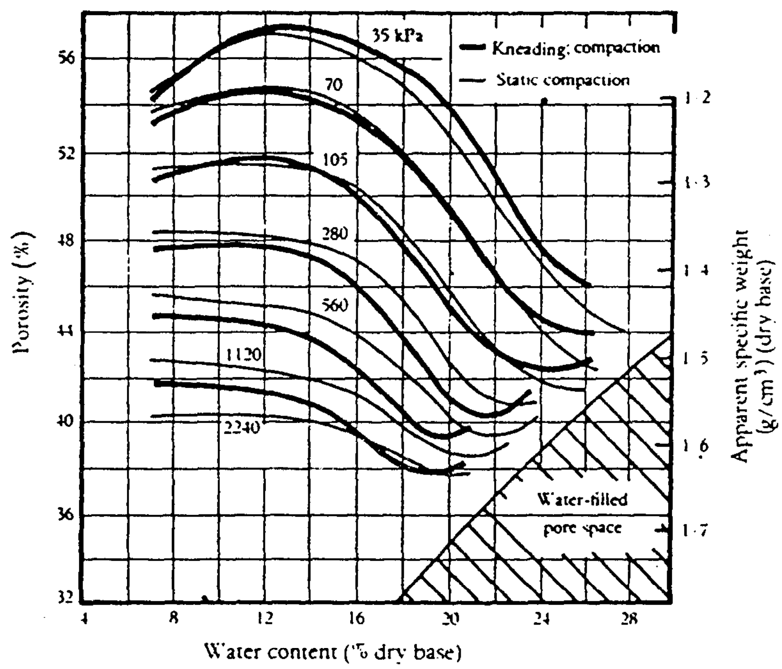

Fig. 2. Compressibility of a loess soil by static and kneading compression in relation to the water content (data of Soehne 1958).

where H and H_i are the height and initial height of the sample, A is a constant and $B = 1-A$; a and b are parameters which are approximately constant for a particular soil over the useful range of water content. If Y is known as a function of soil water suction and water content, the above equation allows calculation of the critical water content above which specific vehicles will cause unacceptable compaction. Braunack and Dexter (1978) give an example.

Other empirical expressions have been developed for the pressure–volume relationship in agricultural soils (Soehne 1958; Kuipers 1959; Koolen 1974), and different experimental methods have been developed which imitate the actual process being studied. The Proctor test (Proctor 1933) and the kneading piston test (Soehne 1958) boht simulate impact forces or momentary applications of pressure such as would be generated in the soil by moving wheels and the felling of trees. Fig. 2 from Soehne (1958) gives results of such tests. As a case of particular interest, they show that when clay soils are compressed, the drainage rate may limit the rate of compaction as saturation is approached. The application of a shear stress to a soil in equilibrium with an applied static load may cause considerable further decrease in void ratio. This is of particular relevance to compaction of forest soils, because many mechanized operations in forests generate large shear stresses. In the above methods, except for the triaxial test, the pressures on the sides of the sample and hence the shear stresses are not known, and direct application of the results to a particular field problem is uncertain.

Kumar and Weber (1974) separated the compression of unsaturated soil in a triaxial cell into two phases; firstly, hydrostatic or all-round compression, and secondly, compression by a deviator or shear stress. They found that the shear stress, $\tau = (\sigma_1 - \sigma_3)/2$, caused additional compression even when the mean stress, $\sigma_m = (\sigma_1 + 2\sigma_3)/3$, was held constant. σ_1 is the major principal axial stress and σ_3 is the minor principal all-round stress. Void ratio was a linear function of $\ln \sigma_m$ for both methods of compression, and with the same slope, similar to the results shown in Fig. 1*b*. Compaction varied with the stress path being used, but was uniquely related to $\sigma_m + 3/2\tau_{max}$, a result close to that obtained by Chancellor and Korayen (1965). Greacen (1960*a*) showed that unsaturated soil undergoing compression with shear arrived at an ultimate void ratio, that was effectively constant, in equilibrium with the compressive stress. The results when plotted fall on a line parallel to the normal compression (without shear) line. This line has been called the void ratio at failure (VRF) line.

The strength or the compressive force that a soil can withstand at a given bulk density is determined by the geometry and mineralogical composition of the soil grains. Greacen (1960*b*) defined the strength of unloaded aggregates at void ratio e_a as the equivalent pressure P_c on the normal consolidation curve, or as the equivalent pressure at failure P_f on the VRF line (Fig. 1*a*). Following Croney and Coleman (1954), the Atterberg limits, which reflect soil composition, also lie on the VRF line, the liquid limit LL at P_f of approximately 1 kPa and the plastic limit PL at about 100 kPa. Using this liquid limit relationship in equation (1), we obtain

$$\ln P_f = (e_{LL} - e)/I_f.$$

This gives the equivalent compressive strength P_f at any void ratio e for a soil with LL expressed as e_{LL} and a compression with a failure index I_f. If compressive strength at the PL is taken as approximately 100 kPa, as suggested by Greacen (1960*b*), I_f can be expressed in terms of the plasticity index PI. Preferably I_f can be estimated from the liquid limit as $I_f = 0{\cdot}9(\text{LL} - 10)$, where I_f is given as kPa^{-1} and LL as g water per 100 g soil on an oven-dry weight basis (Terzaghi and Peck 1948, p. 67).

The theoretical basis discussed above applies equally to unsaturated soils, but quantitative description is less certain because of difficulty in determining the effective area coefficient χ. Data from Farrell and Greacen (1966) for three soils also suggest linear relationships between compression behaviour and the Atterberg limits of unsaturated soils (Fig. 3).

Swelling can be predicted from the clay content and the plasticity index (Seed *et al.* 1964). But caution is required in the direct application of Atterberg limits in swelling as clay fabric or structure, which is destroyed in the Atterberg test, can have an effect on the swelling behaviour of a clay. Differences in the swelling behaviour of natural and remoulded soils are expressed in differences between extensibility tests on natural soils and swelling tests on remoulded soils (Franzmeier and Ross 1968). Swelling and other natural forms of volume change are important because they regenerate compacted soils.

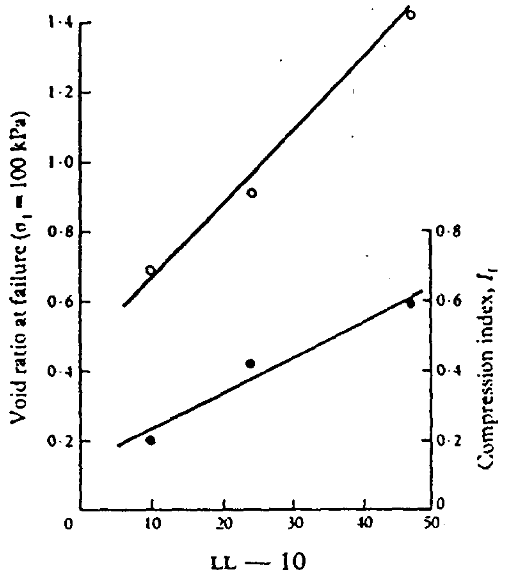

Fig. 3. Relationships between the liquid limit (LL) and the VRF line (o) (see Fig. 1) for three soils in the unsaturated condition. Soil water potential of −30 kPa. (Based on data and Fig. 2 of Farrell and Greacen 1966). ● Compression index.

Soil Strength and the Bearing Capacity and Resistance to Penetration

Consideration of soil compaction in terms of soil strength is important in this discussion because strength determines the resistance that the soil offers to compaction by machinery and penetration by tree roots. The resistance of soil to deformation is described basically by the empirical strength parameters cohesion c and the coefficient of friction usually expressed as $\tan\phi$, where ϕ is the angle of internal friction. These are derived from applying Coulomb's law to the results of direct shear tests as

$$\tau = c+\sigma_n \tan\phi .$$

In sands and in clays undergoing virgin or initial compression, $c = 0$ and τ is determined directly by an apparent ϕ and the applied normal stress σ_n. For overconsolidated soil, i.e. soil that has previously been compressed at greater than current load, which is the common condition for agricultural and forest soils, cohesion can be the dominant component of strength. Cohesion can be considered as frictional strength remaining in the soil from the original overconsolidation pressure. Hvorslev (1937) described cohesion in overconsolidated soil as

$$c = c_0\exp(-e_f/I_c),$$

thereby relating c to e_f, the void ratio at failure, which is an index of compaction similar to bulk density, c_0 is a constant for a particular soil, and I_c is the compression index described above. This has been discussed more fully by Barley and Greacen (1967).

In sands, cohesion is negligible, and shear strength is determined by ϕ, which increases with bulk density, and by the load on the soil normal to the direction of shear. Bjerrum *et al.* (1961) examined friction angles in sands of particle size 60–200 μm, which is similar to that of the dune sand soils on which radiata pine plantations have been established in western Victoria and the south-east of South Australia. They found $\phi = 40°$ at maximum ρ_a of $1{\cdot}67\ \mathrm{g\,cm^{-3}}$; this decreased linearly to $\phi = 30°$ at $\rho_a = 1{\cdot}45\ \mathrm{g\,cm^{-3}}$. For $\rho_a < 1{\cdot}4\ \mathrm{g\,cm^{-3}}$ ϕ decreased rapidly to 20°. The effect of this increased rate of change in ϕ on soil strength at a density of about $1{\cdot}4\ \mathrm{g\,cm^{-3}}$ is shown in Fig. 2 of Sands *et al.* (1979). Similar relationships between ϕ and ρ_a also occur in fine-textured soils (Chancellor 1971). Changes in ϕ and c with ρ_a are reflected in soil consistence. Consistency tests made by hand in the field simulate the unconfined compressive strength σ_{uc} measured in a triaxial cell, where the load to fail a cylinder of soil is determined at zero ambient load; $\sigma_{uc} = 2c\sqrt{N_\phi}$, where N_ϕ, the flow value, is equal to $\tan^2(45+\phi/2)$. Consistency values range from *soft* at $\sigma_{uc} < 50$ kPa to *hard* at $\sigma_{uc} > 4000$ kPa.

Stress conditions on a soil which cause failure are determined by the strength parameters c and ϕ, from Coulomb's equation above, as

$$\sigma_1 = \sigma_3(N_\phi)+2c\sqrt{N_\phi},$$

where σ_1 is the major principal stress and σ_3 is the minor principal stress. Bearing capacity q (kPa), which is a measure of the load a soil will support without deformation, is derived from the above as

$$q = cN_c+\rho_a DN_q+\rho_a(B/2)N_\rho,$$

where the coefficients N_c, N_q, and N_ρ are the bearing capacity factors for shallow footings of depth D and width B where the soil fails in general shear, i.e. the failure planes reach the surface. Their values depend on the angle of friction ϕ and are quite easily calculated. For $\phi = 0$, $N_c = (3/2)\pi+1 = 5{\cdot}7$, $N_q = 1$ and $N_\rho = 0$. Thus for clays, for which $\phi = 0$, for a surface load, $D = 0$, we obtain $q = 5{\cdot}7c$ (Terzaghi 1943). For a soil with a friction angle $\phi = 34°$ as commonly occurs in surface soils, $N_c = 41{\cdot}9$, $N_q = 29{\cdot}3$ and $N_\rho = 36$. For this soil $q = 41{\cdot}9c+36(B/2)\rho_a$, which shows how rapidly q increases with increasing values of ϕ. $c = 0$ in sands and therefore $q = \rho_a(B/2)N_\rho$. When sand becomes submerged, ρ_a changes from about 2 to 1 because of the buoyancy effect and the bearing capacity drops by 50%. In unsaturated sands a small, but important, cohesion develops due to the suction in the pore water. This cohesion falls to zero on saturation and the bearing capacity is considerably reduced (Sands *et al.* 1979). These effects have considerable practical significance when considering logging on waterlogged sands.

The same approach can also be used to calculate the resistance of a soil to a penetrometer, which is treated as a deep foundation ($D/B \geqslant 4$ to 10, depending on ϕ). Under the action of a penetrometer the soil yields in local shear failure, i.e. the failure planes do not reach the surface and the soil must be compressed to accommodate the volume of the penetrometer; the soil deforms as it does under a deep foundation. For calculating the bearing capacity of deep foundations, Terzaghi (1943) allows for the compressibility of the soil by assigning lower limiting values c' and ϕ' as $c' = (2/3)c$ and $\tan\phi' = (2/3)\tan\phi$. More recently Meyerhof (1961) has given revised values of the bearing factors for cones and circular footings which are applicable to penetrometers, but still based on the Terzaghi approach.

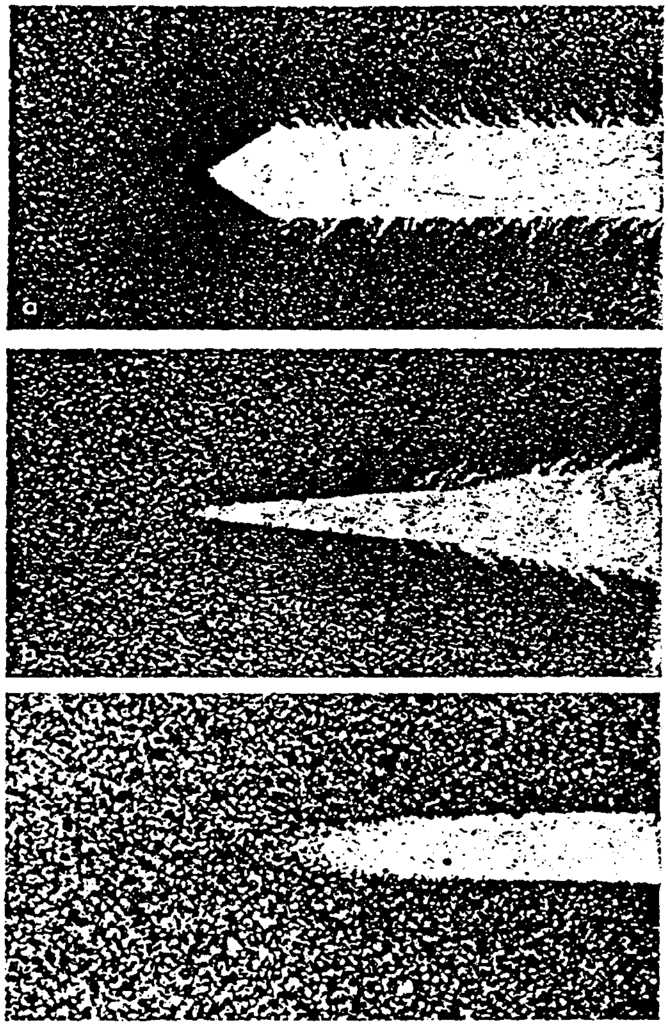

Fig. 4. Radiographs showing the distribution of bulk density around channels made in soil by (*a*) a 3 mm diameter blunt probe (included semi-angle 30°C), (*b*) a 3 mm sharp probe, semi-angle 5°, and (*c*) a 1 mm root of *Pisum sativa*. (Relevant data in Greacen *et al.* 1968. X-ray technique from Greacen *et al.* 1967.)

While the above bearing capacity theories are satisfactory for engineering purposes in well-compacted soils, they do not give sufficient emphasis to soil compressibility in normal agricultural and forest soils. Farrell and Greacen (1966) presented a theory of soil resistance to penetration based on the pressure required to expand a spherical cavity in a compressible plastic-elastic medium. This was later extended by Greacen *et al.* (1968) to the expansion of a cylindrical cavity in soil. Density patterns arising from cylindrical expansion of the cavity for a finely tapered probe and a plant root, and from spherical expansion for a blunt probe are shown in Fig. 4. The model predicted point resistance within 10% of measured values for several soils at different void ratios and water contents. From the data of Farrell and Greacen (1966) it can be determined that for remoulded surface soil in equilibrium with a compacting load σ_1, the point resistance of a penetrometer is approximately $10\sigma_1$. Thus soil being compacted by the tyre of a vehicle applying a pressure of 250 kPa will eventually reach a state of compaction at equilibrium which will have a penetrometer resistance q_p of 2500 kPa; this value is often regarded as being critical for the growth of plant roots.

The Time Factor in Compaction

Compaction relationships have been treated above as equilibrium states between void ratio and external stresses as they occur in remoulded or disturbed soil. In reality, compaction is a time-dependent process, and the duration of loading may often be of the order of only parts of seconds. Also, soil undergoing compaction is rarely completely remoulded. Thus in the equilibrium-state analysis we are dealing with the ultimate condition that will be arrived at under a particular loading requirement for the soil of particular water content and composition. Analyses of some time-dependent processes in compaction have been made, but in general the tendency has been to rely on empirical experiments in the laboratory and in the field. Dexter and Tanner (1974) compared the change in compaction with time of undisturbed samples of two soils, a sandy loam and a clay, when the external pressure was increased suddenly from 30 kPa to 1000 kPa. The compression half-time, i.e. the time for half the volume change to occur towards the final equilibrium volume, was for the sandy loam about 5 s and for the clay about 200 s. They give loading times of 5×10^{-1} s for tractor tyres, 10^0 to 10^2 s for foot traffic, and 10^4 to 10^6 s for plant roots. This suggests that soils with compression half-times > 100 s would avoid much of the compaction due to machine traffic. Vomocil *et al.* (1958) found only negligible effects of tractor speed up to 20 km h^{-1} on the compaction of cultivated Yolo loam. They concluded that most of the possible compaction must have occurred even with the short duration loading at 20 km h^{-1}. But the high compressibility in the cultivated condition and the overriding effect of soil water content severely limited the sensitivity of the experiment.

Because of changing conditions, especially soil water content and loading, empirical experiments have only limited application and should not be extrapolated beyond the test conditions. The same restriction applies to all models of soil compaction, but a more soundly based understanding of the mechanisms involved allows a better planning of management strategy when we are dealing with long-term trends towards ultimate conditions.

Causes and Extent of Compaction of Forest Soils

The energy required to compact soil may arise from rainfall, growth of plant roots, foot traffic from both man and animals, and from the weight of the vegetation and the soil itself. However, the main forces causing compaction of agricultural and forest soils come from machinery used to manage and harvest the crop. Mechanization of some forest operations has greatly intensified over the last decade, particularly in plantations, and forest managers are currently expressing concern about the compaction of forest soils and its consequences. There is a considerable literature on the compaction of soil by vehicles in agriculture where the major cause of compaction is the rear wheel of the standard rubber-tyred agricultural tractor. Much of this research is relevant to vehicles used in forests.

Kerruish (unpubl. data) discussed mechanized forest operations in Australia as related to soil compaction and presented data on the approximate contact pressures (excluding shear) of a range of machines used in the logging of forests.

Cable systems, Skyline rig	0 kPa
Flexible-tracked skidder	30–40
Crawler tractor	50–60
Rubber-tyred skidder	55–85
Forwarder with rear bogie	85–100
Forwarder with single rear axle	105–> 125

These contact pressures were derived by dividing the weight of the machine by the total ground contact area and were not intended to take into account other pressures generated by the movement of the vehicle and the handling of the logs. Frequently in logging operations one axle (usually the rear) supports considerably more load than the other. In a forwarder most of the weight of the logs is carried by the back axle, and contact pressures may be reduced by using a bogie. Uneven axle loads are also pronounced in skidders where a component of the weight of logs being skidded is supported behind the rear axle. Parsons (personal communication) calculated that a JD 740 skidder of 6441 kg operating weight operating at full load would have a pressure of approximately 26 kPa under the front tyres and of approximately 80 kPa under the rear tyres. In addition shear stress is generated by the moving tyre or tread and is greatly added to by any pushing and pulling activities of the logging

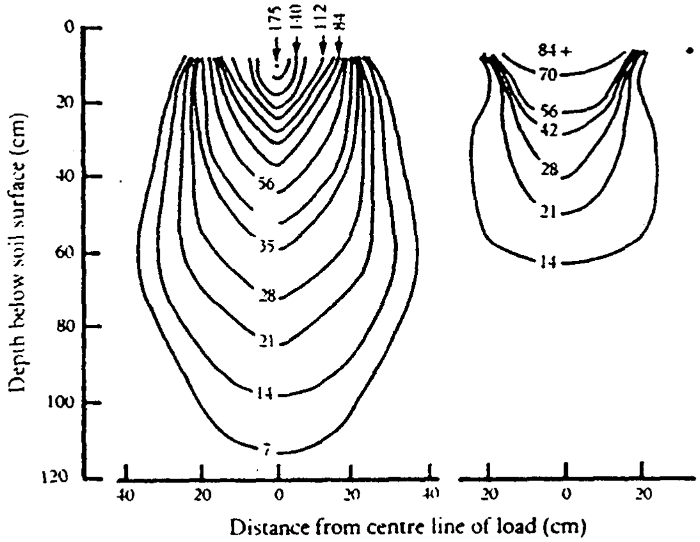

Fig. 5. Isograms of vertical stress (σ_z) perpendicular to the direction of travel in Congaree silt loam. (Data of Reaves and Cooper 1960.) Left: 13–38 tyre. P51. Right: 12 in. track. P31. (1636 kg dynamic load; 682 kg D′ bar pull.)

vehicle. Thus significant shear stress will be generated by skidders as used in plantations, and crawlers tractors as used in Australian native forests. Since soil failure is the rule under traction and assuming a friction angle of 45° for unsaturated soil, shear forces of 80 kPa would be expected for the example given above. As discussed above (Fig. 1*b*) this can have a compaction effect equivalent to more than doubling the static normal load. The studies of Davies *et al.* (1973) and Raghaven *et al.* (1977) identified wheel slip on agricultural tractors as causing significant compaction, and wheel slip from forest vehicles should therefore contribute to compaction. Pressures generated in the soil can be considerably greater than nominal contact pressures, depending on tyre geometry and nature of the operation. Pressures in the soil of up to five times the nominal contact pressures have frequently been recorded under the back wheels of agricultural tractors (Cohron 1971). Bekker (1956) discussed the optimum tyre design for reducing soil compaction. An account of machines used in the logging of Australian forests and the nature of their operation is given by Cameron and Henderson (1979).

While pressures from the wheels are concentrated in the soil immediately under the tread, they can be detected at considerable depth in the profile. Danfors (1974) measured soil compaction under 16 ton loads at 50–60 cm depth that still remained after 3 years; soil movement was detected at 120 cm depth. He concluded that with heavy loads, it is largely the load and not the contact pressure that is decisive for the magnitude of the stress at depths ⩾40 cm. Above this depth a considerable decrease in stress is obtained using equipment with a low surface pressure. In Fig. 5 vertical stress distribution under small loads is shown for tracked and rubber-tyred vehicles which have different contact pressures (Reaves and Cooper 1960).

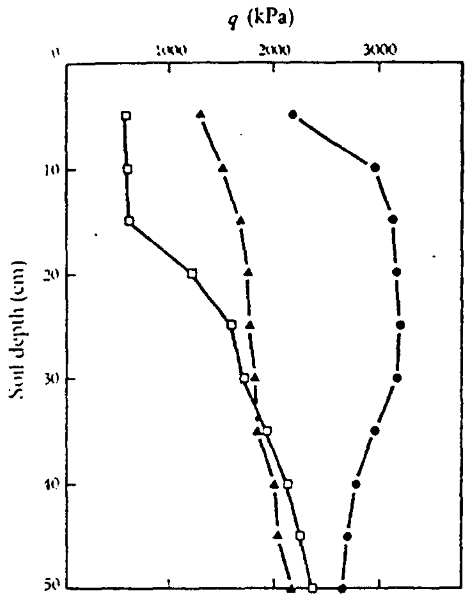

Fig. 6. Changes in soil strength q (kPa) with depth (cm) of Mt Burr sand on a logging road (●), after 10 passes with a JD 740 rubber-tyred skidder pulling full-length logs of radiata pine (▲), and adjacent undisturbed soil (□). (Each point was the mean of six observations, and q was measured as resistance to a penetrometer).

Another aspect of damage to soil by traffic is that of wheel sinkage. In the general case, sinkage is accompanied by compaction, but, as discussed above, in very wet to saturated soils, drastic sinkage may occur with general shear failure without compaction due to poor drainage in the soil under the load. In such cases the soil structure is destroyed with accompanying ill effects on infiltration and increased runoff. Cohron (1971) gives methods for predicting sinkage of wheels in clay and sand.

Though many forest managers are aware that soil compaction is occurring as a result of logging and harvesting operations, the degree and extent of such compaction is not well documented. van der Weert (1974) reported up to 30% increase in soil bulk density following the mechanical clearing of forest in Surinam. Steinbrenner and Gessel (1955) reported soil compaction and associated damage to soil structure following the tractor logging of Douglas fir in Washington State. Dickerson (1976) demonstrated a 20% average increase in soil bulk density after tree length skidding in pine-hardwood stands in Mississippi. Skidding in red pine stands in Minnesota increased soil bulk density (Mace 1970), with full tree skidding increasing bulk density twice as much as tree length skidding. Compaction of sandy soils under radiata pine forests in South Australia has been demonstrated by Sands *et al.* (1979). The effect of a rubber-tyred skidder on soil strength of a representative soil of the area is shown in Fig. 6. (previously unpublished data of the authors).

Froehlich (1973) in a review of the effects of forest management on soil physical properties in western U.S.A. concluded that under tractor logging 50% of the area is disturbed and 25% can be considered as compacted. Kerruish (unpubl. data) presented data (Table 2) on the range of mechanized operations used in Australian forests, the ground contact pressures of the vehicles associated with these operations and the number of passes of those vehicles over the same ground during the course of the operation.

Table 2. Mechanized operations in Australian forests

Forest type	Operation	No. of passes	Approximate contact pressure (kPa)
Plantation	Initial clearing	1–4	55
	Ploughing	1	55
	Planting	1	55
	Thinning	6–300	0–125
	Clear-felling	2–300	0–125
Native forest	Selective logging	2–50	50–80
	Clear-felling	2–300	0–80

All of these operations could cause soil compaction to some degree but, although there are no comparative data, it appears that thinning and clear felling operations would be the most likely to cause compaction.

A potential source of shear stress in forest soils is the movement of tall trees by the wind. The extent and significance of such forces in causing soil compaction has not, to our knowledge, been evaluated. The normally loaded weight of the forest crop should not cause significant compaction. For example, Sands *et al.* (1979) calculated that the normally loaded weight of a very productive radiata pine forest of fresh weight 2000 t ha^{-1} would be equivalent to about 14 cm of soil at a wet density of 1·4 g cm^{-3}; if 20% of the area is carrying the weight, the calculated pressure would be increased fivefold. The impact from the felling of large trees is another potential source of compaction but this aspect has not been studied.

Pressure exerted by the growing tree might also be an important factor in compaction. Penetration of the soil by a root and its subsequent enlargement can compact the soil in the immediate vicinity of the root. Greacen *et al.* (1968) showed that for fine metal probes and pea roots there was significant compaction of a compressible loamy sand up to a distance of one diameter from the surface of the root (Fig. 4). For the fine roots of crop and forage plants this action is considered meliorative for soil structure, since the roots soon decay and leave vacant channels which improve porosity and increase permeability.

The roots of forest trees may persist for many decades and grow to considerable size with rather more extensive effects than those of crop plants. Ryan and McGarity (1978) found that the soil around the tap root of a flooded gum (*Eucalyptus grandis*), 2 m diameter, compacted a brown forest soil from a bulk density of 1·1 to 1·4 g cm^{-3} over a radial distance of *c*. 2 m from the surface of the root, agreeing roughly with the effect of metal probes cited above.

In contrast to the compressible fine-textured soils above, the sands of some South Australian forests are classed as incompressible, with maximum density being closely approached at 1·55 g cm^{-3} (Sands *et al.* 1979). For a sand initially at a density of $1 \cdot 45\ \mathrm{g\,cm^{-3}}$, the cylinder of soil compacted to $1 \cdot 55\ \mathrm{g\,cm^{-3}}$ must be four times the diameter of the tap root merely to accommodate the volume of the root. For a hypothetical pine plantation of site quality 5, clear-felled at 44 years and with roots still persisting from trees felled at age 15 years and later thinnings, the total volume of tap roots could be 15% of the above-ground yield or $250\ \mathrm{m^3\,ha^{-1}}$ (P. Zed, personal communication).. This would require compaction of 30% of the area from a bulk density of $1 \cdot 45$–$1 \cdot 55\ \mathrm{g\,cm^{-3}}$ to a depth of 2 m to accommodate this root volume. Values considerably lower than this (6–9%) can be estimated from root profiles described by Ashton (1975) for *Eucalyptus regnans* growing in a compressible krasnozem in Victoria.

Such estimates of compaction should allow for the fact that some of this soil deformation will go to raising the soil surface, and where this occurs the extent of compaction will be reduced. But this aspect of soil compaction by forest trees is largely undocumented, as indeed is the overall importance of roots in modifying soil structure and compaction. On the other hand, the roots themselves have a reinforcing effect on the soil; for example, the bearing capacity of soils containing root networks of spruce was shown to be up to 70% greater than in similar soils without roots (Bjorkhem *et al.* 1975).

The susceptibility of a soil to compaction strongly depends on the amount of organic matter in the soil. There are frequent examples where the addition of organic matter to soil has improved structure and reduced compaction (Larson and Allmaras 1971). Soils rich in organic matter are also more difficult to compact. Increased organic matter in sandy soils under radiata pine forests in South Australia was associated with reduced bulk density, reduced compaction under a given load, and increased water retention and unsaturated hydraulic conductivity (Sands *et al.* 1979). Mulqueen (1973) found the bearing capacity was increased when subsoil (deficient in organic matter) was mixed with topsoil (rich in organic matter). Free *et al.* (1947) and Bodman and Constantin (1965) found the addition of organic matter increased the water content at which maximum bulk density was achieved.

The state of compaction in forest soil also depends on the presence and activity of soil fauna. Soil fauna play an important role in breaking down refractory litter on the forest floor and incorporating this into the soil mass, thereby improving its organic matter status. The tunneling of surface-voiding earthworms can reduce compaction and improve porosity (Barley 1961). Dexter (1978) demonstrated that earthworms could penetrate soil having a penetration resistance up to 3000 kPa, and that they did so by ingesting soil particles rather than pushing them aside. When such species void on the surface, the soil loosening effect becomes obvious.

The effect of water content on the strength of soil has been described in terms of soil mechanics theory above, with water content being a major determinate of soil strength. At low suctions and high water content, soils have low resistance to deformation and are prone to compaction. Steinbrenner (1955) found that logging in Washington State in winter when the soils were wet caused a significantly greater reduction in infiltration rate than logging in the summer when the soil was dry. He found that one passage of the 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. Hatchell *et al.* (1970) reported greater decrease in air-filled pores and infiltration rate on wet soils than dry soils following logging of loblolly pine. Steinhardt and Trafford (1974) found that drainage of wet clay subsoils reduced compaction from tractor traffic. Sands *et al.* (1979) reported that sandy soils under radiata pine plantations in South Australia were considerably more prone to compaction when wet.

Effects of Compaction on Physical Properties of the Soil

The effect of soil compaction on soil strength has already been discussed, and this section deals mainly with compaction effects on the water and aeration status of the soil.

When soil is compacted, the total porosity is reduced at the expense of the macropores, i.e. pores that are drained of water at nominal field capacity. Such reduction in macroporosity has been demonstrated in forest soils following logging activities by Steinbrenner (1955), Steinbrenner and Gessel (1955), van der Weert (1974), Dickerson (1976) and Sands *et al.* (1979). Continued reduction in the volume and shape of macropores may inhibit gaseous exchange between the soil air and the atmosphere, whether this be by mass flow or diffusion. Aeration in soils has been extensively reviewed by Grable (1971) and Cannell (1977).

Because micropores are relatively less affected by compaction, the proportion of micropores is increased. This has been demonstrated in forest soils following logging activities by van der Weert (1974) and Dickerson (1976). An increased proportion of micropores means the soil behaves as if it were of finer texture. The volumetric water content at nominal field capacity is increased, thereby increasing the volume of water per unit volume of soil that is available to tree roots. This has been demonstrated in forest soils by van der Weert and Lenselink (1972) and Sands *et al.* (1979). Hill and Sumner (1967) showed that with continued compaction a point is reached where the reduction in total porosity dominates the relative increase in the proportion of micropores, after which the volumetric water content at field capacity becomes less. This is particularly so in soils having a particle size distribution which packs to high bulk density. The relationship between bulk density and water retention in soils has been further examined by Box and Taylor (1962) and Archer and Smith (1972). Jakobsen (1973) developed appropriate mathematical relationships for use in plant growth models.

The effect of compaction on hydraulic conductivity and infiltration can be predicted from the change brought about in the size and geometry of the voids. Compaction usually reduces infiltration rate (Gaheen and Njoes 1977) and saturated hydraulic conductivity (Harrod 1975; Rasmussen 1976; Gaheen and Njoes 1977). However, because compaction increases the proportion of micropores, the reduction in unsaturated hydraulic conductivity is less marked than that of saturated, and there may even be an increase in unsaturated hydraulic conductivity (Kemper *et al.* 1971; Sands *et al.* 1979). Markedly reduced infiltration rates have been found following logging in Douglas fir (Steinbrenner and Gessel 1955) and loblolly pine (Hatchell *et al.* 1970). Steinbrenner (1955) reported successive decreases in infiltration rate with each passage of a logging tractor over a forest soil. Compacted soils are often layered with one layer being more compact and less permeable than the other. Warkentin (1971) discussed water movement through such soils; he concluded that field capacity is determined by the distribution of microporosity as well as the unsaturated hydraulic conductivity and its ordering between the layers.

Soil compaction can increase surface runoff because of reduced infiltration rate. However, runoff is affected by other factors besides compaction in logging operations. Hatchell *et al.* (1970) described how surface water may accumulate in depressions and ruts following logging of low-lying forested sites, thereby giving localized pockets of soil having poor aeration. van der Weert and Lenselink (1972) and Dickerson (1976) found increased runoff following logging activities, but a significant component of this was due to the removal of vegetation. Compaction can increase soil erosion when it increases runoff. However, because of increased strength, compacted soils have lower erodibility, and consequently may suffer less erosion for the same amount of runoff. Thus compaction can increase or decrease soil erosion depending on circumstances. For example, Liew (1974) reported less erosion on tractor paths after logging of forested slopes and attributed this to the greater soil compaction under the tracks. For similar reasons compacted soils may be more resistant to wind erosion.

The Consequences of Compaction to the Growth of Forest Trees

There appears to be an optimal bulk density, or range in bulk density, above and below which a decrease in plant yield occurs. Usually compaction of 'natural' or untilled soils decreases yield but not always. In literature surveyed between 1970 and 1977, there were 117(24), 12(1), 8(0) and 5(1) studies of the effect of compaction on crop yield showing yield reduction, yield increase, both yield reduction and increase, and no effect on yield respectively. The bracketed numbers refer to the number of tree species. Growth reduction has been reported in economically significant forest species such as *Pinus radiata* (Potter and Lamb 1974; Minko 1975; Berg 1975; Sands and Bowen 1978), *Pinus elliottii* (Haines *et al.* 1975), *Pinus taeda* (Foil and Ralston 1967; Hatchell *et al.* 1970; Duffy and McClurkin 1974), *Pinus ponderosa* (Trujillo 1976), *Pinus nigra* var. *maratima* (Berben 1972, 1973), *Picea abies* (Sokolovskaya *et al.* 1977), and *Pseudotsuga menziesii* (Berben 1972, 1973). Seed germination and seedling emergence may be adversely affected by soil compaction (Taylor 1971) and so therefore natural regeneration in forests may be affected (Sokolovskaya *et al.* 1977).

Compaction effects on root growth may be a complex interaction between soil strength, water and nutrient availability, and aeration.

Roots must overcome the strength of the soil to penetrate pores of smaller diameters than themselves. Because compaction both increases soil strength and decreases the number of macropores, the rate of root elongation and therefore root length is reduced. Typically elongation rate is reduced exponentially as soil strength (as measured by resistance to a penetrometer) is increased, but there is a critical, albeit ill-defined, resistance q_c above which root penetration effectively ceases. Greacen *et al.* (1969) tabulated q_c values ranging over 800–5000 (mean 2500) kPa depending on species, soil type, and penetrometer characteristics. Relationships between root growth and soil strength are largely unknown for forest tree species. Zyuz (1968) reported abundant pine roots in soils of strength less than 1700 kPa, but that penetration was restricted above 2500 kPa. Gayel and Voronkov (1965) found that roots of *Pinus sylvestris* in sandy soil behaved similarly. The penetration of roots of radiata pine into sandy soil in South Australia was found to be greatly restricted at soil strengths greater than 3000 kPa (Sands *et al.* 1979). The data of Greacen and Gerard (previously unpublished) shown in Fig. 7, give the relationship between the frequency of rooting of radiata pine and strength of two sandy soils. Though rooting was much reduced at soil strengths above 3000 kPa, a small number of roots still penetrated soil with strengths up to 7000 kPa. Specific soil strength–root elongation relationships depend on the type of penetrometer and its method of application, and caution is needed when comparing data obtained with different instruments (Taylor 1971). The penetration of soil by mycelial strands of mycorrhizal fungi associated with radiata pine roots is also restricted in compacted soils (Skinner and Bowen 1974).

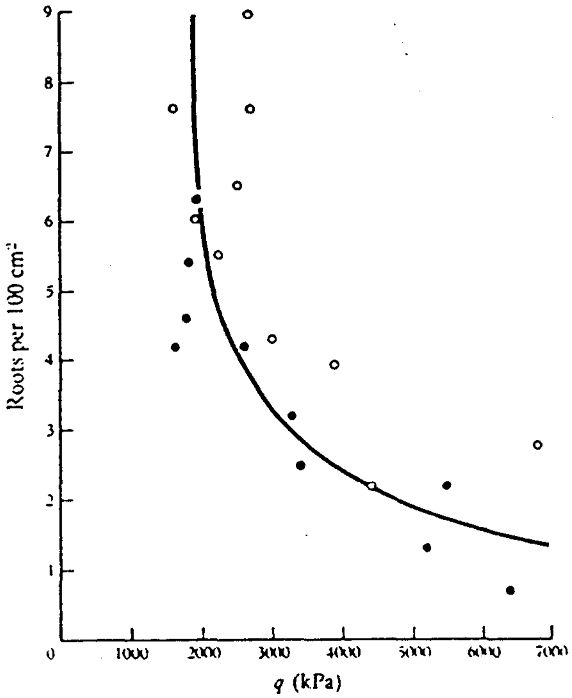

Fig. 7. The relationship between frequency of roots (no. per 100 cm²) of radiata pine and soil strength q (kPa) of Mt Burr sand (o) and Young Sand (•). (q was measured as resistance to a penetrometer.)

A feature of compaction in the field is its spatial variability both vertically and horizontally. This variability tends to be systematic in agriculture where mechanized operations are spread in a systematic manner over the area. However, this variability is more random in forest operations, particularly in unevenly aged stands, where mechanized forest operations are less evenly spread over the area. Roots will preferentially penetrate pockets of lower strength and structural weaknesses such as fissures and interfaces between structural units (Haans *et al.* 1973). Sands *et al.* (1979) demonstrated preferential penetration by roots of radiata pine into soil pockets of lower strength, and Sutton (1969) showed how spruce roots preferentially penetrated the interface between soil peds. Thus roots may be able to penetrate a layer of increased mean strength without serious growth loss if there are sufficient zones of weakness in the layer. Soil strength usually increases with depth and a decrease in rooting frequency with depth would be expected on this basis alone.

Because soil strength usually decreases as soils become wetter, it is not immediately obvious whether better root growth in wet soil is due to lower soil strength, better soil water status, or a combination of both. Greacen and Oh (1972) considered that pea roots could osmoregulate to maintain turgor over a range of soil water potential from –280 to –800 kPa, and consequently that root penetration was determined solely by soil strength and was independent of soil water potential. This is supported in peanut and cotton roots by the data of Taylor and Ratliff (1969). In contrast, Gardner and Danielson (1964) and Mirreh and Ketcheson (1973) reported that corn roots grew more slowly in media at constant strength when the soil water potential was reduced below –100 kPa. Perhaps trees, which are perennials, are less susceptible to growth reduction following soil compaction than annual plants because of the greater chance that their roots have of meeting wet soil (lower resistance) over the extended growing period. However, information is needed on the timing of root growth in forest species. Soil compaction may reduce macroporosity to the extent that growth or even survival of roots is determined by oxygen availability when the soil is wet. This will occur when the oxygen requirements for respiration in the soil exceed the rate at which oxygen in the soil air can be replaced from the atmosphere. Broadly speaking, this occurs when air-filled porosity is less than approximately 10% (Grable 1971; Greenwood 1975), although the situation is considerably more complex than this (Cannell 1977; Smith 1977). Because of their longevity, trees often experience oxygen deficiency (or carbon dioxide excess) at some time, and some are specifically adapted to tolerate low partial pressures of oxygen in the soil. Such adaptations include the development of air spaces in the stele of *Pinus contorta* (Coutts and Philipson 1978), and the development of adventitious roots, rhizosphere oxidation, specific carbon dioxide tolerance and accelerated anaerobic respiration in other tree species (Hook and Brown 1973). Comparative effects of aeration on growth within genus *Eucalyptus* have been described by Boden (1963), Parsons (1968), and Ladiges and Kelso (1977).

When soils are compacted, significant reduction in root growth often occurs before aeration becomes a problem. For example, Sands and Bowen (1978) found that compaction of sandy soil from a bulk density of 1·35–1·6 g cm^{-3} caused an 87% decrease in the dry weight of roots of radiata pine seedlings when the air-filled porosity at 1·60 g cm^{-3} was 21%. Warnaars and Eavis (1972) attempted to partition the effects of soil strength and aeration on the root growth of pea, corn, and grass, and also found that increased soil strength caused the major reduction. However, they reported that reduced aeration progressively limited root growth when air-filled porosity was less than 25%.

It is difficult to predict the effect of soil compaction on growth in the field because of the interactions involved. An increase in soil strength following compaction may give a more compact root system occupying less volume of soil (Sands and Bowen 1978), but this does not necessarily mean that shoot growth will be reduced. If air, water, and nutrients are in plentiful supply, and root length is sufficient to meet the requirements of the shoot, then top growth need not be impaired as a result of the restricted root system. Under these circumstances compaction may even be beneficial. Plant water supply could be improved because of the greater water retention and hydraulic conductivity. The uptake of mobile ions (e.g. nitrate), which mainly move in the soil by mass flow, could be improved. The uptake of less mobile ions (e.g. phosphorus, copper and potassium), which move in the soil mainly by diffusion, could also be improved because compaction increases the apparent diffusion coefficient of ions as well as packing more ions into a given volume of soil (Kemper *et al.* 1971). With continued compaction, diffusion would ultimately decrease because of the increased tortuosity of the diffusion path (Graham-Bryce 1963; Phillips and Brown 1965). However, if water and/or nutrients within the soil volume occupied by the restricted root system become limiting, then shoot growth will be inhibited unless further soil can be explored by roots. Under these circumstances a reduction in effective root space imposed by increased soil strength will inhibit shoot growth. Parish (1971) and Goss and Drew (1971) have discussed some of these interactions further.

When these interactions are considered together with the great spatial variability in soil compaction in the field, it is not surprising that results from experiments designed to test the effects of compaction on growth in the field appear to be inconsistent. Usually compaction reduces uptake of nutrients, particularly phosphorus (Khanna *et al.* 1974; Smittle and Williamson 1977), but this is not always so (Flocker and Nielsen 1962). Added fertilizer may (Juang 1972; Krejair and Petrikova 1973; Chaudhary and Prihar 1974) or may not (Tveitnes and Njoes 1974) help compensate for growth reduction caused by soil compaction, depending on the circumstances. Parish (1971) argued that compaction should reduce uptake of the immobile phosphorus more than that of the mobile nitrogen, and cited references showing compaction with increased nitrogen : phosphorus ratios in the plant. Compaction can reduce mineralization and nitrification of soil nitrogen (Whisler *et al.* 1965). Rosenberg and Willits (1962) found compaction increased the yield of barley in a sandy soil because of improved water retention, but decreased it in a silt loam because of poor oxygen diffusion. Compaction effects on water supply to the crop may depend on the frequency, intensity and amount of rainfall. In a dry year, soil water may limit growth of a tree whose root system is restricted by compaction. In a wet year, soil water may be adequate and the lower strength of the soil may encourage further root exploration. However, for rainfall above a certain intensity, runoff may be increased because of the reduced infiltration rate and soil water may again become limiting. Excess rain may cause waterlogging and associated aeration problems in the rooting zone if compaction has produced a layer of reduced permeability to water.

It should be appreciated that tree growth following thinning in plantations or logging in uneven-aged stands can be reduced by factors other than compaction. Soil disturbance resulting from these operations damage or sever tree roots, most of which are concentrated near the surface. Olson (1952) described such damage to western white pine following skidding and piling of slash with a dozer.

Because of these complexities, meaningful data on the effects of compaction on the growth of forest trees are rare, and such data are necessary to determine to what extent preventative and curative measures are worthwhile. From estimates of the aerial extent of compaction (Froehlich 1973) and from data on growth-reduction associated with increased bulk density, a 15% reduction in volume yield due to compaction from tractor logging can be predicted (H. A. Froehlich, personal communication). It appears that forest soil research has reached the stage where a formal systems analysis and modelling approach would be profitable.

Persistence, Prevention, and Amelioration of Compaction of Forest Soils

The extent to which compacted soil will recover depends on the soil type and the degree of compaction. Clay soils, which swell and shrink, may recover, or partly so, with subsequent wetting and drying. Recovery, if any, from sandy soils is slower.

Ivanov (1976) found logging of spruce forests caused compaction and that the time for the original bulk density to be restored was 5–7 years for well-drained soils and approximately 15 years for semi-hydromorphic soils. Thorud and Frissell (1976) artificially compacted soils ranging from sandy loam to loamy sand under mature oak forest. They found recovery between 5 and 9 years in the 0–8 cm zone, but no recovery over this period in the more compacted 15–25 cm zone. Hatchell *et al.* (1970) found no recovery one year after vehicular compaction in a loblolly pine forest, but reported that severely disturbed soils that had been logged over a 19 year period did recover slowly. They considered the average time of recovery for log decks to be 18 years, and cited Perry (1964) as estimating that 40 years would be necessary for full recovery of infiltration capacity on an old forest road. Dickerson (1976) estimated that recovery of wheel-rutted and log-disturbed soils would take about 12 and 8 years respectively following tree-length skidding on soils ranging from loamy sand to silty clay loam. Our unpublished data show extraction tracks on sandy soils under radiata pine forests in South Australia which have not been used for 50 years or more are still compacted compared to surrounding soil. Even if soil eventually recovers from compaction, significant growth reduction may occur during the early years which could be critical in determining the overall productivity of a forest plantation.

Though techniques for prevention and amelioration of soil compaction are available, the forest manager will need to be convinced that the exercise is worth while. Unfortunately, as described above, detailed information on the relationships between field compaction and tree growth is not yet available. Also, any improvement in tree growth from managing soil compaction would probably not be as spectacular as that gained from fertilization or weed control. However, several techniques for prevention and amelioration are simple and inexpensive, and could be easily incorporated in an overall management strategy. Others are more expensive and the relative economy of using such techniques would need to be examined in more detail. It should be appreciated though that slow but continued irreversible compaction of sandy soils under our forests may present a problem of considerable significance in the long term, even if the short term consequences appear insignificant. Soil compaction may be prevented to varying degrees by (1) managing natural soil factors and (2) traffic control. Once compaction has occurred it may be ameliorated to some extent by (3) mechanical loosening of soil.

(1) *Managing natural soil factors.* The importance of soil organic matter in increasing resistance to compaction has already been discussed. The maintenance of organic matter in forest soils should be a long-term management aim. This is particularly so in sandy soils which are low in clay content and almost entirely dependent on organic matter as a source of nutrients and for exchange capacity, as well as for adequate water retention and transmission, and resistance to compaction. Under these circumstances any process other than logging which removes organic matter from the site, such as fierce slash burns, should be avoided. If techniques become available, the management of soil fauna to promote rapid breakdown and incorporation of litter into the soil mass would be valuable. Liming may aid here to some degree. Earthworms should be encouraged. The incorporation of added organic matter with depth associated with deep ripping may help rehabilitate badly degraded sandy soils, but this is likely to be expensive as a forestry operation. Probably a long-term rotation with pasture is the best way

to improve organic matter status at a practical level. Rotation with legumes should improve the nitrogen status of the soil as well. Lucerne, which is deep-rooting, has been used successfully in agriculture for ameliorating compacted subsoils (Talha *et al.* 1973).

(2) *Traffic control.* Certain soils, such as texturally well-graded soils high in silt and low in organic matter, are more susceptible to compaction than others and particular care needs to be taken when logging on these soils. Wetter soils are more prone to compaction and the avoidance wherever possible of logging wet soils is probably the single most important management practice for prevention or reduction of compaction damage.

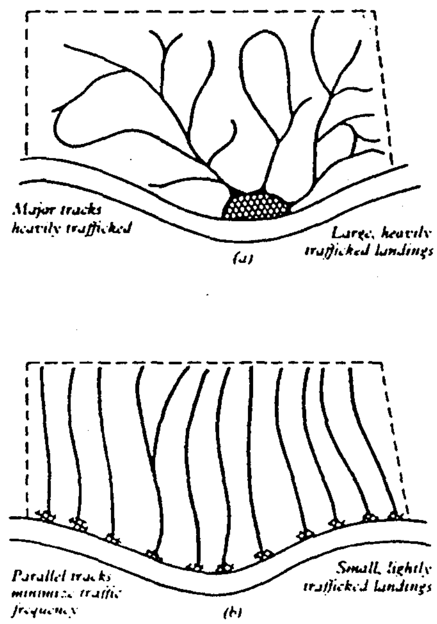

Fig. 8. Patterns of snig tracks: (*a*) a branching pattern as often seen in operations in native forests, and (*b*) a parallel pattern as often seen in operations in plantations. (Kerruish, unpubl. data.)

Wherever possible, machines that cause less compaction should be used. Usually specific design to reduce compaction is incompatable with machine efficiency and, since harvesting is an expensive component of the overall forestry operation, usually some compromise will need to be reached. In any case there is a lack of data on the relative merits or otherwise of the various machines available. Obviously the machine must be considered, together with the soil type and condition, and the nature of the operation. For example, a pulling machine with associated large shear stresses could cause as much compaction as a heavier lifting machine that covers the same ground on fewer occasions. The fewer the number of passes and the faster a vehicle moves, the less time compactive pressures are exerted on the soil; but these pressures may be magnified by bumping at high speed. Some logging operations disturb a smaller area of soil than others (Lull 1959). Under some circumstances greater compaction of a smaller area may be preferable to less compaction of a greater area. The extent and degree of compaction will depend on extraction patterns. Frequency of passes will be less on parallel than branching tracks as shown in Fig. 8 from Kerruish (unpubl. data). As mentioned earlier, very heavy machines may cause compaction at depth irrespective of the contact pressure. Specific comparative studies on the effect of different logging systems and strategies in Australian forests on soil compaction are almost non-existent. Such studies are necessary if traffic control is to be used successfully as a management tool to reduce soil compaction. It should be appreciated that this is only one of many aspects that need to be considered when logging. Cameron and Henderson (1979) give a comprehensive account of environmental considerations necessary when harvesting in Australian forests.

(3) *Mechanical loosening of soil.* Shallow compacted soils are often ripped prior to plantation establishment. Cockroft and Tisdall (1978) reported a greater than 400% increase in yield of peaches over commercial orchards by deep ripping to 60 cm and injecting gypsum as a slurry in compacted clay subsoils and confining traffic to tracks on exposed subsoil. Berg (1975) used deep ripping of soil compacted by heavy logging machinery and reported improved growth of radiata pine seedlings as a result. Minko (1975) showed improved growth of radiata pine seedlings in the nursery following subsoiling (ripping the subsoil without disturbing the topsoil) of compacted nursery beds. Potter and Lamb (1974) described root configuration of radiata pine seedlings transplanted to compacted gravelly soils that had been ripped. Other soil loosening treatments such as ploughing (Sokolovskaya *et al.* 1977), disking (Dickerson 1976), and mounding (Haines *et al.* 1975) may successfully alleviate compaction under some circumstances. It is important though to understand the mechanics for any particular situation. Where the soil has been degraded as shown by a large reduction in organic matter, it is possible that the state of compaction at equilibrium with the natural forces on the soil will already be critical. Effects of cultivation in loosening these soils will be short-lived and indeed may be counterproductive.

Conclusions

The disturbance of surface soil by modern heavy machinery is sometimes strikingly obvious, but chronic changes in soil structure due to traffic are not necessarily so obvious and might because of this have more serious and lasting consequences. Compaction of forest soils and the effect on current and long-term productivity depends in a complex way on various interacting factors such as climate, soil properties and management practice. Compaction has been described in a previous section as an equilibrium state problem, but it is not known whether a bulk density–strength equilibrium is ever reached under a constant system. Furthermore, there does not appear to be a cut-off point of soil strength for root growth, and roots continue to penetrate, although very slowly, soils of quite high strength. Thus the problem tends to be not one of clear-cut answers but one of more stable trends.

It was suggested above, that simulation of the forest soil system by means of a mechanistic model might be the best way to describe soil compaction under different management practices and to predict whether the effects of a practice might be detectable in tree performance and productivity. The principal factors and interactions involved are shown schematically in Fig. 9. The soil water regime, expressed as the annual course of soil water content, plays a dominant role in the system and is the most important consideration in the tactics of forest management. Thus a tree growth model based on water use may be developed.

The hub of such a program depends on establishing a model of the forest water balance, such as that of Nnyamaki and Black (1977), but incorporating root resistance terms (Meyer *et al.* 1978) to predict water use as an index of tree growth. The effect of compaction could be predicted in terms of how it affects soil porosity (and thus infiltration, water retention and aeration) and soil strength, and thereby effective rooting volume and root growth (Greacen and Hignett 1976).

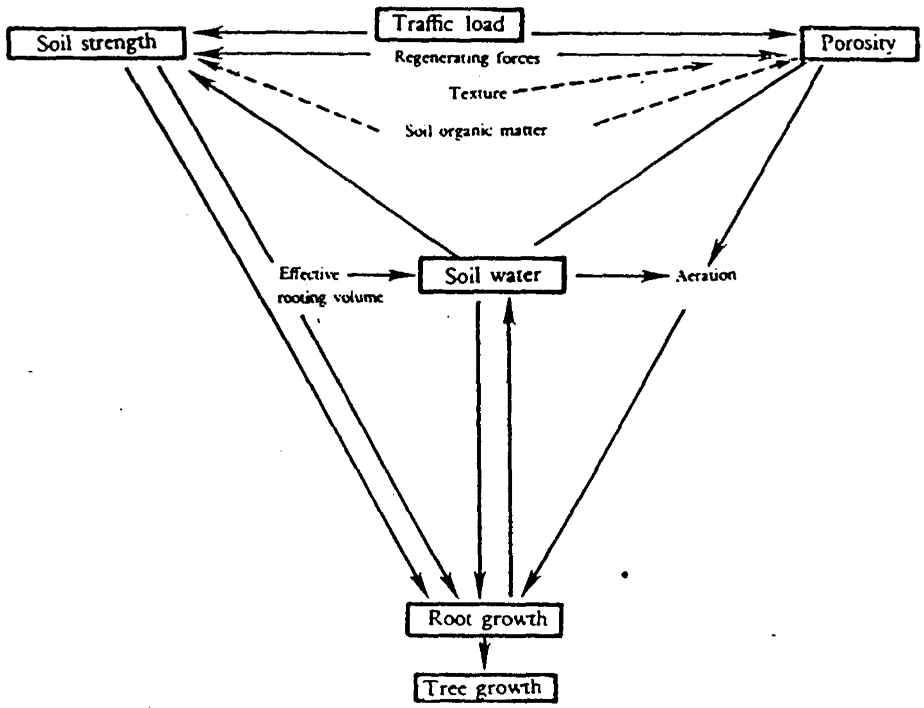

Fig. 9. Interacting effects of soil compaction on root growth.

Necessary subprograms would be:

(1) *Simulation of the course of soil organic content.* Clarke and Russell (1977) present differential equations linking crop practice, yield and soil organic matter trends with time. Their model includes decomposition and terms for addition from the growing crop and from non-crop sources, and offers the possibility of predicting soil organic matter under long-term monoculture and under rotation systems.

(2) *Prediction of porosity as a function of applied load, as modified by soil texture, water content and soil organic matter.* Both water content and organic matter can be influenced to some extent by management. Mathematical relationships between applied load, such as from logging vehicles, and porosity were suggested above. It is possible that the modifying effect of texture and organic matter may be described quantitatively in terms of the Atterberg limits and the compression and swelling indices or, in the case of sands, by their effect on compressibility. The effect of changes in soil porosity following compaction on the hydraulic properties of the soil has been described numerically by Jakobsen (1973), Douglas and McKyes (1978) and Sands *et al.* (1979).

(3) *Prediction of soil strength as a function of applied load and soil water content.* Relationships between the ultimate equilibrium bulk density and the applied load have been described for saturated and unsaturated soils. Some of these require further development and testing. Methods for describing changes in soil compaction with time under intermittent traffic and, in the reverse direction, under the natural regenerative forces in the soil, would also be required.

(4) *Prediction of the effect of soil strength on the rate of root elongation, and therefore root growth, as modified by aeration.* Data on the root growth of some agricultural crops and limited data on forest root growth (e.g. pine roots) are available. Detailed information is needed on the seasonal root growth behaviour in forest species.

The spatial heterogeneity of compaction in forests as typified in Fig. 8 presents some difficulty in modelling the overall forest system. Where the dimension of the heterogeneity pattern is of the same order as that of an individual root system, as for example in a plantation, it is possible that a one-dimensional model, with the roots having access to a decreasing volume of soil as the soil compacts, might be appropriate. In an uneven-aged stand, the pattern of heterogeneity could be greater than tree spacing and stratification of the forest on the basis of traffic could be required in the model.

While a satisfactory model of the forest system is still some way from being realized, sufficient information is available for an attempt at a crude model. At worst this would indicate where deficiencies lie and how to obtain information on the complex processes going on in the forest, and hopefully would provide a method for integrating this information to provide a general understanding of the system and a sound basis for planning forest management strategy.

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