**Effects of deep ripping on cropping soils and crop production**

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## Introduction

This review covers some of the research on problems associated with dense subsoils in Australia, with limited reference to overseas research.

The loosening of dense subsoils to improve plant growth is not a new practice. 'A subsoil-loosening plough was described in Britain in 1835 (1), and another was built in North America in 1845 (2). In the early 1920's, experiments were done at Rutherglen, Victoria, to investigate deep ripping to 55 cm for grapevines, and "trenching", as it was called, became common practice (J. Gibbs, personal communication 1985). In the 1950's and 1960's, a series of experiments on deep tillage for dryland crops were done in Victoria (unpublished reports). Little benefit was observed, and the experiments did little to change farmers' practices.

It appears that the early work was done in response to observations on impeded drainage or penetration of plant roots, and there would have been little or no data on which to base the need for subsoil loosening. There has been a resurgence of interest in subsoil loosening in Australia over the last 10 years. In view of the costs involved, compared with the possible returns, it is important to quantify plant requirements in subsoil structure and chemistry, the effectiveness of management practices in meeting the plant requirements, the longevity of the effects, and their influence on productivity and the environment.

Soil has been defined as compacted when the proportion of total (or air-filled) pore volume to total soil volume is inadequate for maximum crop growth (3).

*Plant root requirements*

The ideal subsoil is soft, porous, permeable and well-drained, well-aerated and non-dispersive; chemical and biological properties and top-soil should also be ideal (4). Such conditions would permit plant root systems to develop to their optimum. The optimum size of the root system is probably governed by climate and seasonal rainfall distribution, as well as nutrient supplying ability of the soil. In most of the cropping areas of Australia, rainfall quantity or distribution are less than ideal. In this situation we require soils which will accept and store rainfall in the root zone, minimising losses by runoff, evaporation and drainage. Root systems should then be large enough to use most of the stored water by the time the plants reach maturity. Too large a root system can be detrimental, as it is possible for plants to use stored water too rapidly, leaving insufficient for growth later in the season (5).

Generally, we require crops to have deep root systems. Cereal roots have been reported to 4 m depth in Nebraska (6). Commonly, root depths are less than this; in Australia, the greatest reported depth was probably 2.9 m (7), while other reports indicate cereal root depths between 0.3 and 2.1 m (8, 9), and legume roots between 0.45 and 1.9 m (10, 11, 12, 13). It appears that our crops frequently are restricted with regard to root depth. Soil water and soil chemistry will often be the limiting factors (6, 14), but will be considered here only in so far as they are relevant to the topic of deep ripping.

For plant roots to be able to grow in soil, they require water, oxygen, and a soft soil, or one containing interconnected pores with diameters similar to those of the roots. Roots will not grow into dry soil layers. At the other extreme, roots cannot survive in a saturated zone unless it is aerated, or unless the roots produce aerenchyma. In Britain, restricted growth from an inadequate oxygen supply is unlikely if soil has a gas-filled pore space greater than 10% and no saturated aggregates larger than 9 mm diameter (15).

However, there is no constant relationship between air-filled pore space and the degree of anaerobiosis which can develop, as temperature affects the rate at which oxygen can be consumed in a soil (14). Ethylene in soil can also limit root growth (16). Waterlogging and compaction are probably the most common causes of anaerobiosis in soil.

The pressures required to reduce root extension rates may be quite small; in ballotini, root extension of barley plants was reduced nearly 90% by 0.1 MPa pressure (18), and it appeared that roots could not penetrate pores of smaller diameter than the roots. In soil, root elongation was reduced 80% by 0.4 MPa (19). Barley root diameters were given as 0.4 mm (seminal axes), 0.7 mm (nodal axes), 0.2 mm (first-order laterals) and 0.1 mm (second-order laterals) (14). Continuous pores of these diameters are thus required for unhindered penetration of soil by roots. Lupins may have thicker roots and may exert higher pressures, but there is little data.

Mechanical resistance influences growth of roots in many soils (20). Growth of pea radicals in saturated clay ceased at a penetrometer resistance of 2.4 MPa, equivalent to a water-filled voids ratio of 0.81. Penetrometer resistance increased exponentially as voids ratio decreased, and remoulded clay gave higher resistance than aggregated clay (20). It must be noted that root tips encounter less resistance than probes when penetrating dense soils, thus penetrometers give only comparative, not absolute, guidance as to the forces which roots experience. Values of penetrometer resistance at which root elongation ceased were often between 2.5 and 5 times the maximum pressure which roots can exert (21). Root growth is generally assumed to be seriously restricted at penetromer resistances about 2 MPa.

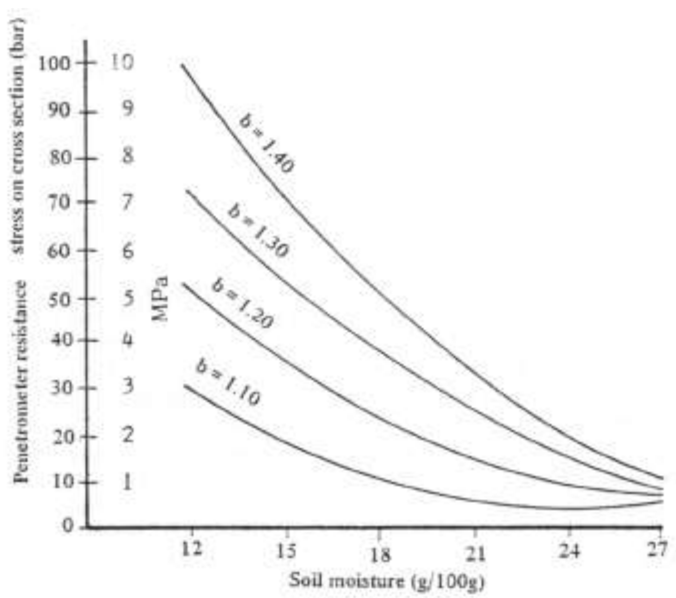


**Fig. 1 Effect of soil moisture cn resistance offered by soil to penetration by a metal probe at four bulk densities (b g cm-3) (Gooderham and Fisher 1975) (27).**

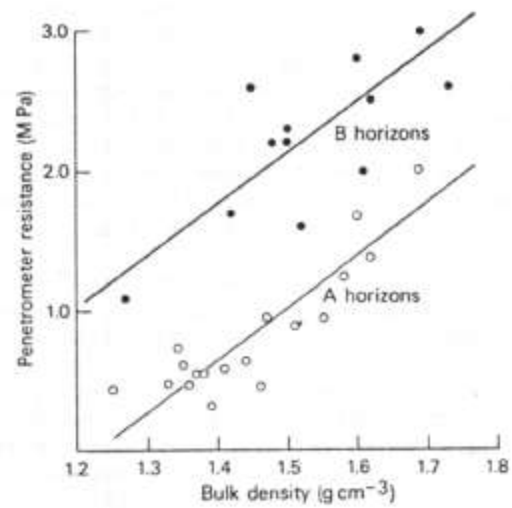


**Fig. 2 Relationship between bulk density and penetrometer resistance at field capacity for the surface soil using a 5 mm diameter 60? probe in the laboratory and for the subsoil using an 8 mm diameter probe in the field ( Greacen 1981) (29).**

Penetrometer resistance varies greatly with soil water content (Fig. 1) (27, 28), but more directly with soil water suction, thus measurements should be made at field capacity in the field, or at -10 kPa suction in the laboratory. Resistance is also closely related to soil bulk density (Fig. 2) (29), which in turn is related with organic matter and total porosity in soil. Personal observation suggests that in some situations, penetrometer resistance may also be related with the degree to which soil particles are cemented, and the strength of the cementing agents may vary according to how long they have been wet or dry.

*Diagnosis in the field of subsoil structure problems*

Probably the best method of assessing root growth in subsoil is visual assessment of root distribution in pits, following careful preparation of the pit face. Pits provide a basis for determining root sampling intensity by coring. If root depth or quantity is seen to be limited, biological or chemical causes, or limitations due to water must be taken into account. Physical limitations can sometimes be seen (Fig. 3) (30). Platy structures with horizontal orientation of peds, or massive layers of low porosity, sometimes have plant roots growing horizontally above them. Often root growth proliferates above a restricting layer and roots may be thickened or contorted at the interface (these symptoms may have other causes, however). Root growth through such layers may be restricted to cracks and channels left by worms or roots. The pit method is laborious, destructive, and not easily replicated so it is impractical on a large scale. Where compaction caused by animals or machinery is under investigation, however, it can be done on a miniature scale by excavating blocks of undisturbed soil to about 20 cm depth for replicable observation (31).

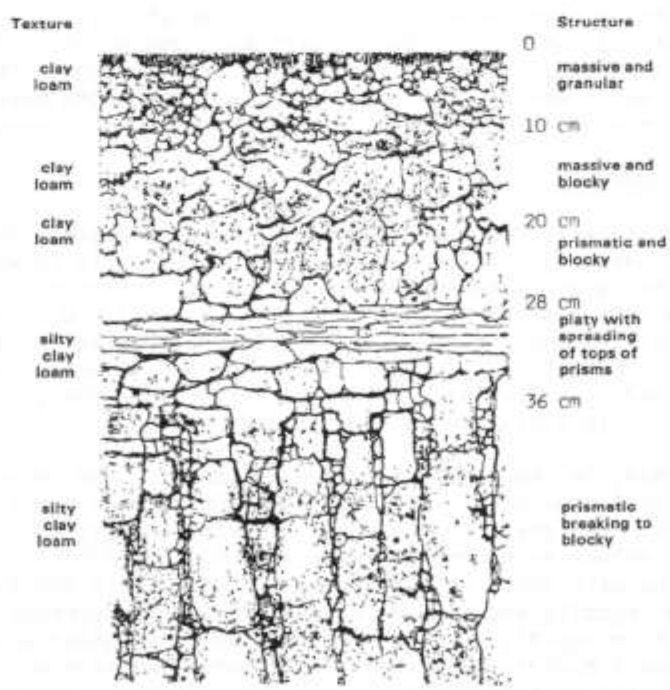


**Fig. 3a Typical chalky boulder clay profile with very good stable structures under arable cultivations. Extensive fissuring with vertical fissures close together.**

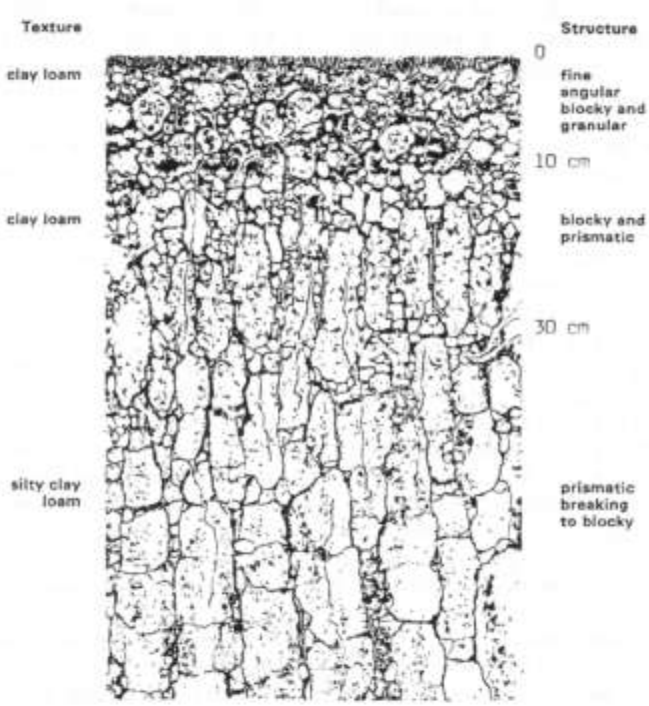


**Fig. 3b A typical chalky boulder clay with normally good structures but damaged by ploughing and pressure when too plastic (Anon. 1970) (30).**

Sampling roots by coring is also useful, but often seems to underestimate root maximum depth. Sampling variation can be large and often it is not possible to take an adequate number of cores to an adequate depth. Large-diameter cores give lower sampling variation than do small cores.

Other methods for measuring root distribution have been reviewed (14), and mini-rhizotrons (clear tubes inserted at an angle into soil) can also be useful (A. Troughton, personal communication) (22).

'Penetrometer resistance can also give an indication of subsoil structure which would limit root growth. Ideally the measurements should be done at field capacity in the field. They are useful experimentally in making comparisons between treatments, particularly as recording penetrometers are now available (23, I. Grevis-James, personal communication 1986), and many replications can be made. Differences in soil-water content and potential must be recorded if results are to be used predictively (24). As a diagnostic tool for extension purposes however, they have a number of limitations, and caution must be exercised in interpreting results. They give no indication of discontinuity of pores, nor can they detect very thin layers that are compacted or smeared. Accepting the limitations, however, even a simple pointed steel probe can indicate the relative hardness of soil layers, permitting the areal extent of hard layers to be readily assessed.

Soil bulk density measurements are essential in measuring soil water or quantities of nutrients in soil. They are of limited value in assessing structure, because while they are related to total porosity of soil, they are not necessarily related to macro-porosity which is important (25). So also are air-filled porosity and pore continuity (24).

Measured water permeabilities are likely to be associated with soil structure classes (26). Sorbtivity and hydraulic conductivity measurements at a range of tensions can permit estimation of the effective pore sizes which conduct water in soil (G.J. Porch, personal communication 1982). The methods applied to subsoils could give valuable information on the continuity of pores in which roots could grow, but again the methods are laborious, hence may be of more value in research than in extension.

*Causes of dense subsoils*

Subsoils may be naturally dense. The proportions of different types of clay minerals, and of sand and silt particles affect the density to which they can be packed. Moisture content strongly influences the degree to which soils of varying textures can be compacted (Fig. 4) (32). Wetting and drying affect swelling and shrinking of clay, and biological activity affects porosity. Cementing by organic compounds and silicon, calcium, iron, manganese and aluminium also affect density. The extent of naturally impervious subsoils in Australia has been mapped (33).

Dense soils may also be induced by tillage and traffic, and by grazing when soils are wet. Hoof pressures exerted by standing animals were: cow,

192 kPa; sheep, 83 kPa; goat, 60 kPa (34). Walking animals would exert more pressure. These values were compared with values of 30-150 kPa exerted by tractors. Grazing with sheep at increasing stocking rates was shown to increase bearing capacity and soil bulk density, and to decrease hydraulic conductivity (0-6 cm depth), with the problems being greatest when soils were wet. Increased bearing capacity (penetrometer resistance) results in the soil being better able to carry traffic; but surface compaction reduces clover growth (35) and penetration of water.

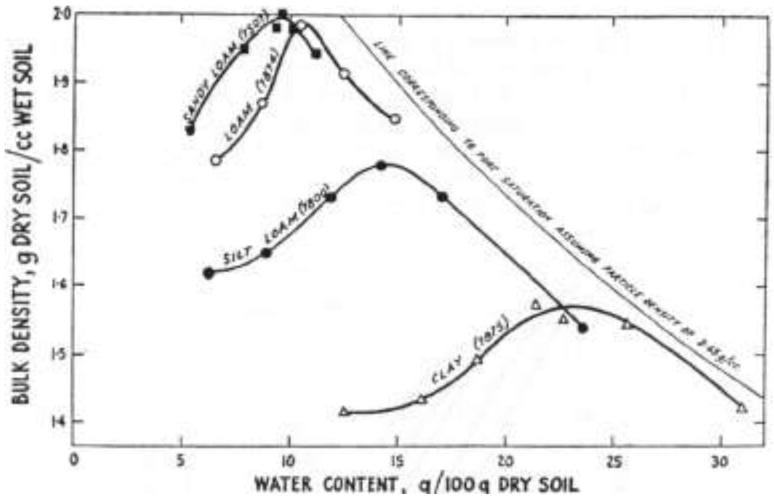


**Fig. 4 Compaction of soil in relation to its water content (compaction done by method of Proctor 1933) (Marshall 1959) (32).**

Soil compaction by agricultural vehicles has been researched and reviewed extensively, and reportedly is understood better today than ever before (36, 37, 38, 39, 3, 40, 41, 42). Traffic patterns in different tillage systems have been described; modern tillage systems lend themselves to a logical reduction in overall effort, by reducing the area treated to that which becomes compacted. Further advances in minimum tillage were expected from improved designs in tillage traffic systems (39). If compaction cannot be avoided, it should be limited in area by a suitable choice of traffic system. Soil water storage and some soil physical changes under tillage were reported for a soil at Katherine, Northern Territory, indicating large differences in the tillage requirements of bands of trafficked and untrafficked soil. The fraction of a field which requires loosening by tillage could be as small as one-eighth, with better tillage systems (36).

Pressures on the soil surface from wheels and tracks depend on characteristics of the wheel or track, and of the soil surface; pressure distribution within the soil is a function of pressure patterns on the surface, and to only a minor extent, of the physical characteristics of the soil (3). For pneumatic tyres, the average pressure exerted on the soil surface approximates the inflation pressure. Increasing the load (up to 1 t) has little effect on the pressure exerted, as the tyre flattens sufficiently to spread the load. Tyre wall stiffness, lug design, and very soft soil cause some deviation from the above generalisation. The depth to which wheels sink affects the area of tyre-to-soil contact, hence it affects the pressures exerted. Soil near the edge of a wheel can flow to the side, thus pressures at the edge are lower than those under the centre. If a load is distributed over a wider area (reducing surface pressure), maximum pressure at shallow depth will be decreased but not in proportion, while at great depth there will be almost no change in maximum pressure in response to the surface load redistribution, as subsoil pressures are related to total load. Pressures can be transmitted deeply into soil; about 100 kPa at 25 cm, and about 50 kPa at 50 cm depths were reported. Pressures into subsoil are not transmitted vertically, but spread out at an angle about 30?.

Soil-working implements also generate soil compacting pressures; 240-440 kPa on a plough-share was reported.

Changes in soil density or porosity in response to pressures (Fig. 5) depend partly on soil moisture, shear deformation, soil texture and structural stability, vibration, repeated loading, and the time over which the load is applied. Soil sensitive to shear deformation (unstable structure) developed a more highly compacted zone deeper in the profile than was expected. The volume of lost porosity due to wheel traffic approximates the volume of the rut formed by the wheel. The importance of shearing forces in deforming soils was also discussed.

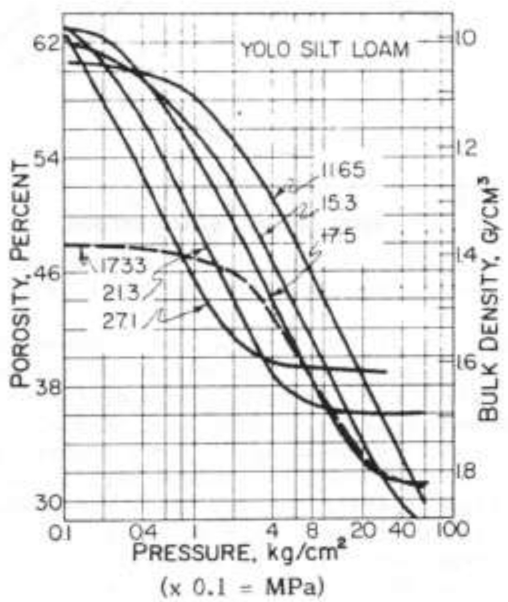


**Fig. 5 Typical semi-logarithmic pressure-porosity relationship for agricultural soils. The dashed line represents data from a sample preconsolidated by natural field conditions and transferred intact to the static compaction cylinder for test (Chancellor 1975) (3).**

Another review on compaction considered' soil and wheel characteristics, compaction under tyres and other running gear, and incidence and control of compaction in crop production (40, 41, 42). A wide and confusing variety of methods, units and expressions for studies on compaction were reported. Techniques were considered which might be used to predict compaction by wheels. Tyre inflation pressures, speed of travel, number of passes of equipment, and wheel slip, were all important with regard to compaction. It was suggested that tyre contact pressures should be kept below 100 kPa to avoid increases in soil bulk density. For tractor tyres, there was no clear relationship between inflation pressure and soil contact pressure, over a range of soil conditions. At high loads, soil response may be related more with the load per se than with the contact pressure. It was considered that avoidance of subsoil compaction will be more important in the future, as compaction may persist many years.

A third review concluded that continuation of the trend to larger and heavier machinery appears to be in jeopardy with recognition of (1) total axle loads as the basic cause of subsoil compaction and (2) the nearly opposite soil requirements for effective performance of wheels and crops (43). Flotation tyres reduced contact pressure at the soil surface, but total axle load was the dominant factor in pressures at 18-50 cm depth. Axles loads >6 t may compact soil below 40 cm depth. Management to control compaction was discussed.

*Soil area covered by traffic*

The area of soil covered by tillage tools and traffic wheels varies widely.

For seeding, a direct drilling system could entail one pass with a wide boom sprayer and one pass with a modified combine fitted with narrow points on the sowing boots only. A tractor towing a 4 m-wide combine would cover 38% of the land with wheelmarks (A. Makin, personal communication 1987). With narrow points (4 cm) and 17.8 cm row-spacing, only 22% of the land would be contacted by tools. Using a full combine with 10 cm points, all of the land would be covered twice by tools (225% coverage). For seeding with a full tillage system in Victoria, there could be between 4 and 10 operations (44). The area covered by wheelmarks would be considerable, but there appear to be no published data for Australia. In Britain, 5 operations prior to seeding results in 91% coverage of the soil with wheelmarks (Fig. 6) (45). The area compacted is wider than the width of the tyres (3), thus practically all of the subsoil would have been subject to compactive forces. The unknown loads on subsoil due to tillage tools would be additional.

The time taken for subsoils to recover from induced compacted can be very long; times have been quoted up to 50 or even 100 years (42).

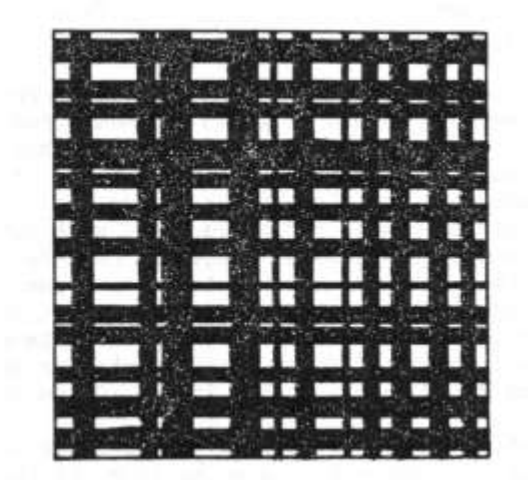

**Fig. 6 Example of pattern of tractor wheel tracks over an area 9 m by 9 m during traditional seedbed preparation (fertilizer distribution, harrowing twice, sowing, rolling; 91% coverage including overlap) (Soane 1975) (45).**

*Effective loosening of subsoils*

Natural forces which may loosen dense subsoils include drying and wetting which cause shrinking and swelling of some clay minerals, and the action of roots and other organisms living in soil. (Freezing and thawing is unimportant in most of Australia).

Deep tillage in one form or another will be the quickest way to loosen subsoil (even if not the cheapest). Deep ploughing, chisel ploughing, and subsoil-mixing have been used. The commonest form of deep tillage is deep ripping or subsoiling. The basic aim of deep ripping is to loosen compacted subsoil without inversion, to permit free movement of air, water and roots within the profile. Unless there is a restricting layer in the soil, no response can be expected from deep ripping (47).

Deep ripping is not a new practice. A deep ripper described in Britain in 1835 (1) had two interesting features (Fig. 7). It was intended to follow the common plough (in the furrow) operating to 40-45 cm depth, and it had a wing near the point. Later work has shown that these features reduce draught and increase the volume of soil loosened.

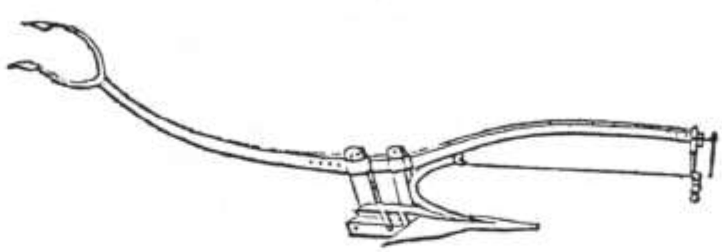

**Fig. 7 A subsoil plough invented by Mr. Smith, Deanston, Britain (Anon. 1835) (1).**

Design of implements should achieve cracking and upward movement of subsoil (47). The point of the shoe should be 20-25? from the horizontal; a smaller angle produces insufficient lift, while steeper angles may result in subsoil compaction round the shoe. Increasing length and width of the shoe increases soil displacement, but also increases draught. The standard or tine should be sharp at the front, and be equipped with some form of release mechanism to provide protection against immovable objects. The tine must be long enough to allow the uplifted soil to clear the frame. Hydraulic controls should provide for constant depth, not constant draught. Disc coulters permit trash to be cut, leave a more level surface, and most importantly they reduce draught. Power requirements for deep rippers are high; about 50, 65 and 85 kW to rip to 50, 75 and 100 cm depths was quoted.

The depth of deep ripping should be related to the depth of the restricting horizon; 7-10 cm below a plough-pan ensures maximum lifting. Width between tines should be adjusted according to depth of operation, so that the soil zones lifted by adjacent tines just overlap at the surface.

Soil moisture influences the effectiveness of deep ripping. Too much moisture results in compaction at the bottom of the ripped zone. Although it is often stated that the soil should be dry for optimum shattering, in Australian hard-setting soils, very dry conditions result in large subsoil clods being formed, with high draught and rapid point-wear. Subsequent cultivation to reduce clods may cause recompaction; subsoil clods may also settle and pack together again. Ideally, there should be enough moisture to permit effective loosening; close to the plastic limit, or around pF 3 has been quoted (48).

Frequency of the need for deep ripping depends on soil type, climate and management. With bad management or unstable soil structure, the effect can be lost within a season. Waterlogging reduces longevity of the effect also. Traffic can recompact loosened soil to the full depth of ripping, and tillage can reform a tillage pan in one season (49, 50). Reduced tillage and traffic systems can increase longevity of the effect of loosening. Natural hardpans may not reform after ripping. Thus, the effect of ripping may last less than a season or it may last many years.

The effects of deep ripping are to increase permeability of soil. Infiltration rate, percentage of large pores, water-holding capacity, depth and rate and distribution of root penetration, have all been reported to increase when compacted layers have been loosened in optimum moisture conditions. No crop response or even yield reductions have been recorded where compacted layers were not identified or where the subsoil was too wet. (In Australia, yield depressions have been recorded where deep ripping was followed by long dry periods permitting increased water loss).

Large differences in the effectiveness of deep ripping can be achieved through appropriate design and configuration of points and tines (51). Each tine has a maximum useful working depth; below this depth soil compaction rather than loosening occurs, and specific resistance (unit draught) increases greatly. This critical depth depends on tine geometry and soil conditions. Increased critical depth and soil disturbance, and lower specific resistance can be achieved by attaching wings to the tines and through the use of shallow tines working ahead of the deep ones, thus the effective working width can be almost doubled for little increase in draught (Fig. 8). At least one commercially-available machine incorporates these features, or the modifications can be done on the farm (G. Spoor, personal communication 1980). Breaking soil in tension maintains structure and reduces draught greatly; one machine is designed with this in mind (52, 48).

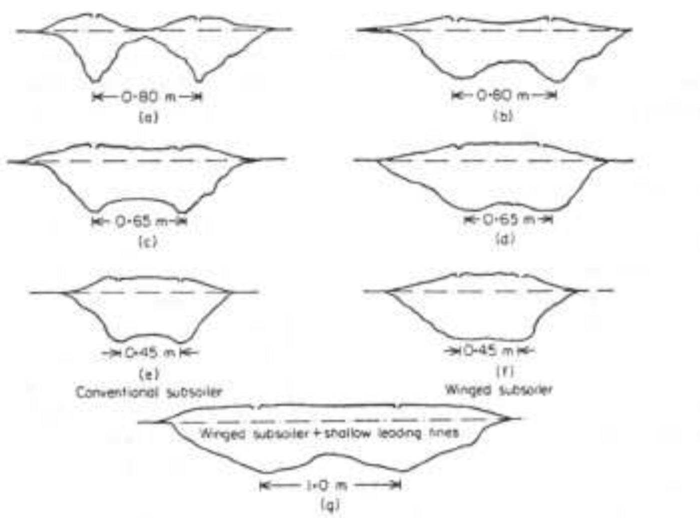


**Fig. 8 Effect of the spacing between subsoiler tines on soil disturbance (Spoor and Godwin 1978) (50).**

Some Australian subsoils become extremely hard when dry, consequently are slow to wet. Deep ripping is then an expensive and slow process, and the need to wait for rain conflicts with land preparation for normal sowing operations (53). Timing of deep ripping within the farm rotation is important. It may be difficult to achieve optimum moisture conditions through the soil profile, and timing will often be a compromise which varies with annual rainfall distribution patterns, to fit in ripping without detriment to following crops. Probably the ideal is to aim for a topsoil dry enough to permit good traction without damage to soil structure, with adequate moisture in the subsoil. This may often be achieved in Spring, where there is a phase of annual pasture. Without follow-up rains, this will lead to the subsoil drying out, which may be detrimental to plant growth in the following year in drier areas, but not in wetter areas. Perennial plants would often be killed by such treatment.

For perennial plants, ripping before sowing or before the wet season would be necessary. In cereal cropping areas, it may be necessary to fit in ripping between harvest and the following sowing time, if possible taking advantage of any summer rains.

Some practices may help to improve efficiency of deep ripping where subsoils are extremely hard. Loosening the soil surface will reduce draught for deep ripping. If shallow leading titles cannot be fitted, shallow ripping may be followed by deeper operation on a second pass to achieve the same object and to reduce wear and breakages. In both cases, traction on the loosened soil may become a problem. Possibly the second pass could be done in a second season. Ripping then cross-ripping at right angles is much more efficient at loosening subsoil than is re-ripping in the same direction (H. Austen, personal communication 1980). On a compacted, dispersive soil (red-brown earth), gypsum applied in autumn reduced penetrometer resistance in subsoil in the following spring (Ellington, unpublished report 1986) so it may also reduce resistance to a deep ripper.

*Deep ripping and stability of soil structure*

Some soils have structure which is stable, and their aggregates can resist compactive forces to some extent and do not collapse when they are wet.

Deep ripping dense layers in these soils should produce beneficial long-term effects.

Other soils may have weak structure; disturbance and rapid wetting can seriously damage their structure, so it is common that they have compaction problems. However, deep ripping without due consideration can lead to deterioration instead of improvement of their subsoil structure.

Management, including deep ripping, of such soils in Australia has been reviewed (54, 55). The problems have been clearly defined, and the key to improving these soils was said to lie in increased biological activity (4). For the sodic red-brown earths, aggregate stability must be improved. Macro-aggregates (>0.25 mm) are improved most by organic matter, roots and fungal hyphae (56). Micro-aggregates (<0.25 mm) are improved in stability by organic matter and polyvalent cations, of which calcium is probably the most important in the present context, but aluminium and iron are probably underestimated (57). High concentrations of electrolytes (salts) in solution can also reduce dispersion. Aggregates, when wetted, may first of all slake (break into smaller aggregates); then disperse (micro-aggregates disintegrate completely and release clay particles). Dispersion is serious, or even disastrous as far as soil structure is concerned. Slaking and dispersion are worst when soil is wetted rapidly, when it is saturated for long periods, and when soils have been worked or disturbed.

Management to improve structural stability and prevent clay dispersion of the sodic red-brown earths centres on improving organic matter inputs, supplying calcium (as gypsum), minimising soil disturbance, minimising extremes of wetting and drying, and preventing rapid wetting and water-logging. For deep ripping to be effective in the long term, attention must be given to these points. In practical terms it means using gypsum, minimum tillage, controlled traffic, crop rotation with grain legumes, stubble retention (preferably on the soil surface), including additions of organic matter or a pasture phase to improve organic matter inputs, structural stability and soil nitrogen. The essentials of this system are already in use (58).

Another group of soils which present problems with regard to effectiveness of deep ripping are soils which are strongly acid below the surface.

Acidity in itself can inhibit root growth of some plants in these soils (59, 60), and can reduce or eliminate crop responses to loosening compacted subsoil (61, 62). Surface-applied lime can sometimes ameliorate the subsoil acidity (63), but lime can sometimes be slow to move into the subsoil (64) and crop responses to deep ripping and to liming can be disappointing. Small-scale experiments indicate that incorporation of lime or gypsum into the subsoil can ameliorate the problems (59, 60, 65, 66). Machines have been built to test the effectiveness of injecting lime or other materials into acid and compacted subsoils in the field (67, 68, 69).

With regard to induced soil acidity in Australia (70, 71, 64), one can speculate on a possible relationship between the development of subsoil acidity and the presence of degraded structure of topsoil and of subsoil. Soil with degraded structure may be leached more completely than soil with a well-developed structure, through which much water would pass in preferred pathways. Additionally, aggregates may release nitrate to a leaching stream only by diffusion, instead of by mass movement. Thus, if leaching of nitrate is reduced in well-structured soil, then development of acidity associated with nitrate leaching will be reduced, and the converse would apply where soil structure is degraded, unless the soil had become almost impermeable. In a survey (31), many areas with hardpans were found to be more acid than areas without hardpans in the same paddock.

*Soil and crop responses to deep ripping in Australia*

Crop responses to loosening subsoils which are too dense will be observed only to the extent that compaction per se is the problem affecting plant growth, and to the extent that it is ameliorated by treatment. If other factors are limiting plant yields, they will limit responses to soil loosening, and must be identified and ameliorated, as well as ameliorating the compaction problem. In Australia, water supply will often be the main limiting factor. Subsoil loosening cannot increase the water supply, but it may increase the efficiency with which water is used by plants. Some factors reported to reduce responses to deep ripping were soil acidity, waterlogging, drought, diseases, and weeds (63). Longevity of the responses are affected by management - for example, the package of treatments used at Tatura (58) - which must be based on an understanding of the processes involved.

Effects of deep ripping here will be considered on red-brown earths, clay soils, and on other soil types.

Red-brown earths

Most of the red-brown earths used for cropping in Australia are sodic, and clay tends to be dispersive (72). The use of calcium compounds on these soils has been studied intensively.

A scheme was proposed for predicting dispersive behaviour and gypsum requirement of these soils, based on 6 classes. The scheme does not fit red earth and black clay profiles, nor soils with much free lime or exchangeable aluminium (73), but seems to hold considerable promise and is being evaluated for a wide range of soils. Calcium compounds, with or without organic matter, are the only materials likely to benefit structural stability of these soils (74, 75). Gypsum was shown to increase exchangeable Ca to 25 cm depth, and reduced exchangeable Mg and Na to 15 cm depth 5 years after 15 t $ha^{-1}$ gypsum was applied to the surface. Half of the gypsum may have been leached below 25 cm or even 1 m depth. Current methods for predicting gypsum requirements were shown to underestimate amounts required to lower ESP to <6 and E Mg P to <25 (76).

Physico-chemical and management studies of red-brown earths showed that leaching could occur to 80 cm depth, gypsum lowered soluble salts in the profile, but Ca-Na exchange was mostly limited to the 0-10 cm horizon (77, 73, 78). The amount of dispersible clay in subsoil was suggested as a useful characteristic, as it appears to govern swelling, porosity, water retention capacity, hydraulic conductivity, friability and modulus of rupture (79). Both coagulation and cementation of clay are important (80). Gypsum effects on structure depend partly on the types of clay minerals present (81).

Experiments with crops have shown variable responses to ameliorative treatments. Deep ripping with a slanted-leg implement reduced subsoil density and doubled water infiltration, but failed to increase wheat yield in a wet season. Rainfall runoff and soil loss were halved. Gypsum improved water-stable aggregates but reduced wheat yields (82, 83). Other work showed wheat yield increases after deep ripping were greater when followed by no cultivation than when soil was subsequently cultivated (84). After deep ripping, cultivation was shown to increase soil penetration resistance compared with direct drilling, and in wheelmarks, resistance was higher than in unripped soil. Gypsum reduced penetration resistance but increased wheat yield only in the presence of lime and deep ripping, possibly because of an effect on soil acidity (63).

On irrigated red-brown earths, deep ripping and gypsum almost doubled tree growth, while mixing A and B horizons and adding organic matter more than doubled growth (85). Subsoil mixing by deep ploughing, together with gypsum, increased cotton yield from 39 to 220 bolls m-2. Repeated gypsum applications were necessary, as part of the improvement was due to the electrolyte effect (86).

The Tatura system of soil management includes soil modification to 60 cm (ripping), hilling the surface soil into permanent untrafficked beds, zero cultivation, straw mulch and frequent watering. This trebled yields of peaches (87). The soils remained well drained and aerated, and penetration resistance remained below 1 MPa at -10 kPa matric potential.

Lucerne also responded to subsoil modification on these soils, with yield increases up to 57%, as a result of improved water penetration and subsequent use by the crop (88). Untreated soil had a low saturated hydraulic conductivity (25 mm d-I) and high penetrometer resistance (>1.4 MPa at -10 kPa matric suction). Treatment reduced penetration resistance to 0.4-0.8 MPa and markedly increased root quantity in the modified zone, but did not improve roots to the quantity or depth found in well-drained light-textured soils. Much of the benefit seemed to come from the use of gypsum, while deep ripping gave a further yield increase only with spray- and not with flood-irrigation (89).

Other work on irrigated red-brown earths (Lemnos Loam) in Northern Victoria aimed to determine whether management systems for continuous double-cropping or crop/lucerne rotations could be developed (90). A range of treatments including deep ripping, organic matter additions, and irrigation treatments were examined. Soil strength was reduced by ripping, but it was concluded that further improvements in oxygen supply and drainage, and reductions in soil strength will be required before these subsoils become suitable for active root development. A later report suggested that soil conditions and crop yields continued to improve as time progressed (91). On pasture, how-ever, total profile modification had no effect on production, and subsequent treading by cattle reduced pasture production by 12% in the third year. The effect of treading was confined to the top 15 cm of soil, but grazing was only allowed when the soil was dry (92), unlike the situation in farm practice.

A new method of soil amelioration is the use of gypsum-enriched slots cut 0.4 m into subsoils (93). This technique, without deep ripping, improved infiltration, aeration, and drainage, and increased sorghum growth.

Clay soils

The main problem with many of the cracking clay soils is that they swell on wetting, often preventing water penetrating deeply, hence available moisture may be low (33). Cracking is very important in this regard, especially in irrigated agriculture where cracks may not be allowed to develop (94). Zero tillage may help to improve rainfall infiltration by maintaining continuity of cracks (95).

In extensive research on a brown clay used for cotton-growing (96) treatments included deep ploughing and deep ripping, gypsum and organic matter (96, 97). Deep ripping improved porosity of subsoil but the effects were lost by the end of the second season. Significant interactions of tillage x depth occurred on soil water and water entry. Cotton yields were increased about 15% in year 1, but in year 2 only a combination of deep ploughing and deep ripping increased yield. Gypsum increased yield in both years, despite an increase in terminal (tip) damage of plants in year 1, but did not ameliorate the rate of structure decline after deep tillage.

In reviewing the management of vertisols in irrigated agriculture, the consequences of tillage at inappropriate moisture contents were noted (98). Deleterious effects on soil and plants occurred after just one season of cultivating soil when wet (99). Compaction effects on these soils may be deeper (20-40 cm) than on lighter textured soils. Persistence of deep tillage effects was likely to be greater, the greater the degree of soil disturbance, and when the layer disrupted was genetic rather than induced by management.

Traffic effects were examined; no direct evidence was found of compacted subsoil following treatments, but first-year cotton sites had subsoil with a better physical condition than sites which had been trafficked for several years (100).

In other work on structurally degraded vertisols, again, cotton yields were increased by deep ripping or gypsum, and subsequent wheat yields were also increased, with benefit/cost ratios of 3:1 (ripping) and 1.1:1 (gypsum) (101). Enhanced water intake was thought to be the most important mechanism, but again the effect was short-lived. Effects on bulk density lasted longer. It was concluded that chisel ploughing to 25 cm may be the most economical treatment for these soils, together with crop rotation (drying the subsoil) instead of continuous cotton, and minimum traffic and tillage (86). Yield increase from sunflowers grown on unstable grey clay occurred both with gypsum and deep tillage, because of reduced crust strength and increased water in the profile (102), and residual effects were still seen after 4 years. Oxygen deficiency after waterlogging is also important in unimproved clay soils (103).

Other soils

Soils with periodic subsurface waterlogging due to impermeable subsoils are widespread in Australia (33).

Physical and chemical aspects of soil suitability for irrigated cropping in the lower Burdekin Valley (Queensland) were reported in detail (104). Soils are grey clays, solodics and solodized solonetz, with problems associated with high proportions of exchangeable sodium and magnesium leading to low

plant-available water capacity. Many of the soils could be modified by deep ripping and subsoil mixing, with gypsum to prolong the beneficial effects. Soils likely to respond are those with slow water recharge of subsoil and those with restricted root ramification, indicated by slow water extraction below 40 cm depth. Deep ripping is difficult to quantify, and it was suggested that best results would be obtained on duplex soils with impermeable subsoils. Other information for the Burdekin-Elliot River area was given, with measurements of water, salts, roots, and penetrometer resistances (105). Among their conclusions was one that massive profile disruption of duplex soils would double the available soil water store to the depth of ripping.

In Western Victoria where waterlogging is a problem, some research on duplex soils has been initiated by Gardner (personal communication 1984) at Horsham and Hamilton. Few results are available as yet, but it seems that other problems occur as well as dense subsoils. Other work by Bakker and Van der Graaf (personal communication 1985) aims at alleviating the waterlogging; for lucerne, there was good evidence that deep ripping made more water available.

In the higher-rainfall areas of Victoria, over many years crops have shown patches of stunted, yellow growth. Research in the North-East showed that this could not be alleviated by nitrogen fertiliser, but observations suggested that it was alleviated for one or sometimes two years after a period of pasture. Further observations in 1978 and 1979 indicated that the problem was associated with stunted root growth and shallow hardpans or layers of compacted soil. In 1980 a crop survey was done in North and North-East Victoria to determine the extent, severity and possible causes of the stunted growth (31).

The lost yield potential amounted to 25% of the total for the area, with a value of $9.5 million, and it occurs to a greater or lesser extent every year.

In a set of test strips, mean yields of grain in green areas was 1.9 t ha1, and in yellow areas it was 0.6 t ha11; adding nitrate fertilisers raised yield of the latter only to 0.9 t ha .

The main problems were found to be hardpans in 64% and soil acidity in 41% of the paddocks. Rotation of cereals with legumes or other crops was inadequate on 55% of the paddocks examined. The problems were thus a mixture of soil physical, chemical and biological problems, and research has since been done on all of these aspects.

On a fertile, slightly acid soil, deep ripping through a dense subsoil layer increased yields of wheat or lupins over a period of 4 years. Ripping above the hard layer had no effect. Cultivation after ripping began to form a hardpan even in the first year, and this subsequently reduced saturated hydraulic conductivity of the subsoil(50). Over 4 years, ripping followed by direct drilling produced 1.2 t ha more grain than when followed by cultivation, and 4.2 t ha more grain than the cultivated control. In another experiment, deep ripping increased wheat yields by about 0.5 t ha-1 , and lupins on ripped ground used almost as much soil water as did a cover of grey box trees (106).

Waterlogging can reduce beneficial effects of both lime and deep ripping. Where waterlogging occurred on an acid compacted soil, subsoil drainage increased responses to deep ripping and lime from wheat, barley, oilseed rape, lucerne and clover/ryegrass pasture. Lupins (L. albus) responded positively to deep ripping and negatively to lime (107).

Where compaction problems were confounded with acidity and low fertility, deep ripping gave variable responses without lime, but gave wheat yield increases of about 40% with lime applied (108, 63, 109). Responses continued over a 6-year period. There were few significant interactions on yields between deep ripping and lime or a range of nutrients, although nitrogen and magnesium uptakes were increased by deep ripping. It was thought that manganese toxicity would be decreased more by improved soil physical conditions than by liming in acid soils (110).

Deep ripping with slurry injection of gypsum, lime and brown coal decreased rainfall runoff, soil loss, waterlogging, and drought stress, and increased soil water use. Wheat grain yield was increased about 30% (Ellington, unpublished report 1987).

In the above experiments, deep ripping did not affect the incidence of cereal root diseases (111). However, in Western Australia, it was concluded that deep ripping can reduce incidence or severity of a range of diseases (112).

In Western Australia, responses to deep ripping have been measured on a range of soil types (61). Light-textured soils gave 25% crop response to deep ripping, but acid subsoil prevented responses from occurring. Duplex or gravelly soils gave variable responses. It was suggested that sands compact worse than other soils. Compaction due to a tractor was measured with a penetrometer (113) and reduced wheat yield markedly on a sand plain soil. Unit draft measurements for ripping in this soil type were 5-22 kN $m^{-2}$ for 10-40 cm depths, and were decreased by increasing tine spacing (114).

**Economics of deep ripping**

Whether deep ripping leads to increased productivity or profitability depends on many factors. The extent to which subsoil compaction restricts growth, and the degree to which it is ameliorated, will be the main factors. Other factors may limit responses to loosening of soils and may need to be ameliorated. The costs of the operation and the value of the extra product are vitally important, together with the longevity of the response, which is affected by soil type and management.

Use of contract or purchased equipment, and size of operation affect costs. In Victoria, contract charges for deep ripping are up to $50 per hour. For a farmer cropping 1,000 ha and who already owns a large tractor, and needs only to buy a ripper, the cost could be as low as $17 per hectare (R. Ashby, personal communication 1986). The cost per hectare varies widely, depending on severity of conditions, as time taken could be 1-4 ha $h^{-l}$. Ripping when soil is too dry tends to be expensive, and costs can be reduced by operating in the correct soil moisture range. Use of the techniques outlined by (51) can further reduce costs markedly, but it appears that few people are using these techniques in Australia.

Some economic analyses are available. One analysis concluded that ripping was only marginally profitable, with the assumption that wheat yields were increased by 0.2 t $ha^{-1}$ (first year), 0.1 t $ha^{-1}$ (second year) and no yield increases thereafter (115). Another analysis suggested that with ripping cost at \$35 $ha^{-1}$ (range \$25-\$45 $ha^{-1}$), and with varying yields and responses to ripping, return on outlay could vary from a loss up to 220% gain (116), but longevity of effect was not allowed for. In Victoria, an analysis was based on net present value (117) in an example where both lime and deep ripping were required. The results suggested that after liming, deep ripping would need to lift yield by a further 10% to be profitable. Actual yield responses to ripping were 30% and 40%, almost doubling net present value after 4 years. Speed and width of operation also affect costs appreciably (118).

**Conclusions**

Crop yields are likely to be restricted by soil compaction if penetrometer resistance at field capacity is near or over 2 MPa. This is a generalisation, and better methods are needed to predict responses to subsoil loosening. Crop yields can be increased by loosening such dense soils.

Cereal roots have diameters of approximately 0.4 mm (seminal axes), 0.7 mm (nodal axes), 0.2 mm (first-order laterals) and 0.1 mm (second-order laterals). Continuous pores of these diameters are required for unhindered penetration of soil by roots.

Subsoil compaction may be natural or induced by management. Controlled traffic and reduced tillage systems can reduce the recurrence of soil compaction problems. Wheel traffic causes compaction in proportion to the total axle load; altering wheel dimensions will have little effect on compaction at depth, particularly at high loadings. Shear forces and soil structural stability also influence compaction. Tillage tools can create high loads and shear forces. Induced compaction may have deleterious effects lasting up to 100 years.

Deep rippers (subsoilers) are used to loosen dense subsoils without inversion. Loosening the soil from the top downwards, and in tension, reduces the power requirement for deep loosening. Other factors reducing the unit draught requirement are the use of shallow leading tines or discs, and the attachment of wings to the point of the tine, permitting wider tine spacing. Each tine design has a critical depth which depends on tine geometry and soil conditions. Working below the critical depth increases draught greatly and causes subsoil compaction.

Soils with unstable structure and dispersive clay (for example, red-brown earths) may collapse when wetted after deep ripping. Such soils require special management if they are to be deep ripped. The use of calcium compounds and organic matter, stubble retention, and minimum traffic and disturbance are part of the management, to improve soil biological activity. Clay soils which are irrigated may require a rotation which permits periodic drying, to permit crack formation. Soils containing little clay with a 2:1 lattice cannot easily be improved in structural stability. Organic matter will generally be the important binding agent. In some situations, subsoil mixing may bring a useful proportion of suitable clay minerals into an unstable horizon.

Many soils, however, have structure which is stable, and the effect of loosening dense layers in them may last long periods provided that management does not cause recompaction. Structural improvement lasting at least 6 years has been reported.

When dense subsoils are loosened, stabilised if necessary, and appropriate post-ripping management is used, most crops will give economic responses. Increases of 220% of outlay, or a doubling of net present value, have been reported.

Factors in soils other than compaction per se may need to be ameliorated to obtain or maintain yield responses to s'lbsoil loosening. These factors may include salinity, alkalinity, soil aciLity and associated toxicities and deficiencies, and flooding or waterlogging. To maximise responses, other management factors will need to be optimised; cultivars, plant populations, time of sowing, fertiliser and plant protection. Frost, drought and disease can also limit responses.

**Acknowledgements**

The research for this paper was funded by the Wheat Research Committee of Victoria.

Many colleagues around Australia provided information, and their input is acknowledged with thanks.

While the paper was being written, my field research was continued by members of the Plant Research Group at Rutherglen, in particular Mr. G.W. Ganning, and thanks also are due to them.

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