THE EFFICACY OF THREE TECHNIQUES TO ALLEVIATE SOIL COMPACTION AT A RESTORED SAND AND GRAVEL QUARRY

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ABSTRACT

Reinstated soil at restored sites often suffers from severe compaction which can significantly impede root development. Several methods, such as ripping and complete cultivation, are available to alleviate compaction that may occur as a result of soil reinstatement. This paper examines the effectiveness of the industry standard industrial ripper and a prototype modern ripper, the Mega-Lift, in comparison with the recommended best practice method of complete cultivation. An investigation of the penetration resistance of the soil at a restored sand and gravel quarry was carried out using a cone penetrometer and a 'lifting driving tool' (dropping weight penetrometer) three years following cultivation. All the cultivation treatments reduced soil compaction to some degree compared to the untreated control plot. However, the penetration resistance values suggest that rooting would be restricted at relatively shallow depths in the plots cultivated using the industrial and Mega-Lift ripper; penetration resistance exceeded 2 MPa within the first 0.33 m. Complete cultivation maintained penetration resistance values of less than 2 MPa within the depth limit of the penetrometer of 0.42 m. In addition, the results from the 'lifting driving tool' indicate that soils treated using complete cultivation remained significantly looser than those treated with the ripper to a depth of at least 0.80 m. The results demonstrate that complete cultivation remains the most effective method of alleviating soil compaction on restored sites, although it is recognised that its relatively high cost may restrict the uptake of the technique.

Keywords: soil compaction, industrial ripper, complete cultivation, restored soils

INTRODUCTION

Soil compaction is a common problem on restored sites and often occurs during soil stripping, storage and reinstatement as part of the excavation, restoration and after-care stages of mineral extraction. The risk of soil compaction can be minimised by following best practice guidance at all of these stages, such as that detailed in Moffat and McNeill (1994). Despite these guidelines, many restored sites still suffer from severe soil compaction that will require alleviation prior to vegetation establishment.

Current UK (Moffat and McNeill, 1994) guidance for woodland establishment on restored sites recommends a rootable soil depth of at least 1 m. A 'rootable soil' is defined as having a bulk density of less than 1.5 g cm^{-3} to at least 0.5 m depth, and less than 1.7 g cm^{-3} to 1.0 m depth (Bending *et al.*, 1999). Similarly, a soil depth of 1.2 m is recommended for agricultural soils (Defra, 2005) with a bulk density of less than 1.3 g cm^{-3} to 0.25 m depth and less than 1.5 g cm^{-3} for the remaining profile (Bending *et al.*, 1999). To achieve this thickness of rootable soil, the recommended method for soil reinstatement in forestry is loose tipping (Moffat and McNeill, 1994). However, where soils have either been poorly restored, or already replaced but have suffered from subsequent compaction, 'complete cultivation' to 1 m depth is recommended. Complete cultivation uses an excavator to progressively remove and replace the soil without trafficking over the cultivated soil surface. However, this procedure is labour intensive, making it much more expensive than the industrial ripping technique normally favoured by developers. Industrial ripping uses a winged tine cultivator pulled by a prime mover to break up compacted soil. Previous studies have shown that ripping can achieve soil loosening to about 0.6 m, although the effects are reported to be short-lived with recompaction often taking place within the first year (Moffat and Boswell, 1997).

In recent years, research on ripping has improved the process, and evidence of relatively prolonged loosening has been published for soils restored to grassland and arable farming (Foot and Spoor, 2003). As part of these developments in ripping technology, a newly developed prototype ripper, the Mega-Lift, was developed by Tim Howard Engineering Services (www.maxi-lift.co.uk) to be tested for its applicability for land restoration primarily to a woodland end-use. The equipment design was based on the principles outlined in Spoor (1998) in order to loosen soil materials to a depth of 1 m in multiple passes. The design aimed to meet the bulk density standard required of soils used in land restoration to woodland and overcome recompaction problems associated with conventional industrial ripping techniques. If successful, the Mega-Lift could offer an improved ripping technology without significantly increasing the cost of the standard industrial ripping operation. However, although it has been demonstrated at different sites, including at Bramshill Forest in Hampshire in terms of practicability, handling and cost-effectiveness (Jones, 2001), no evaluation of its effect on ground conditions has previously been reported.

This paper presents the results of an investigation to compare the effectiveness of complete cultivation, standard industrial ripping and the Mega-Lift ripper at achieving sustained soil loosening on restored sand and gravel workings, based on a fully replicated field experiment.

SITE DETAILS

The study site is located at the Warren Heath Plantation in Bramshill Forest, Hampshire, UK (National Grid Reference SU783594, 51°19'N,0°52'W). The site is a working sand and gravel extraction quarry that has been subjected to phased excavation and restoration over the past forty years. A 2-4 m deep layer of flint gravel overlies the Tertiary (Eocene) Bagshot Formation (Curry *et al*., 1978; Sumbler, 1996) in extensive plateau deposits. These gravels are overlain by a stony sandy loam drift (Jarvis *et al.*, 1984). Prior to gravel extraction the regional slope was almost level at an altitude of 100 m above sea level (Moffat and Boswell, 1997). Average annual rainfall is 657 mm (Meteorological Office, 2005).

During sand and gravel extraction the soil material is removed and stored on site. The gravel is then removed to the top of the Bagshot Formation. During restoration, a series of ridges were constructed 30 m wide and 1.5 m high according to Forestry Commission recommendations (Wilson, 1985). The ridge and furrow landform was used at Bramshill to minimise the risk of waterlogging as the site has a relatively high watertable. The ridges were then cross ripped to 0.5 m at a tine spacing of approximately 1.1 m using a winged tine ripper during August 2000. No further operations had been carried out prior to this study. Signs of original ripping were still present with some subsequent soil erosion and resettlement. Natural regeneration of grasses, *Juncus* Spp., heather (*Calluna vulgaris*), gorse (*Ulex europeaus*) and Scots pine (*Pinus sylvestris*) had taken place across the site.

METHODS

Study area

To allow for soil heterogeneity across the study area, experimental treatment plots were grouped into blocks with similar soil properties. The study area was divided into three blocks (0.4 ha each) with each further divided into five plots of dimensions 55 m x 14 m.

The cultivation treatments took place in June 2001 following a dry period when soil conditions were suitable for cultivation. No further mechanical trafficking over the treatment plots occurred in the three years following cultivation. The soil is an anthropic Regosol (FAO, 1998) which has been created following sand and gravel extraction. The soil properties, sampled four years after cultivation, are shown in Table 1. The soil is relatively homogeneous across the site.

Cultivation treatments

The study consisted of five treatments:

- standard industrial ripping using one pass to 0.9 m measured in loosened soil;
- deep ripping using two passes of the Mega-lift ripper to 0.75 m measured in loosened soil;
- deep ripping using four passes of the Mega-lift ripper to 0.9 measured in loosened soil.
- complete cultivation to 1.1 m;
- an unloosened control;

Treatment type was randomised within each block giving three replicates of each cultivation method, including the control. As an additional experiment to study the long-term impacts of the different cultivation methods on tree rooting and growth, four tree species were planted in equal sized sub-plots within each plot.

Industrial ripper. The industrial ripping was achieved with a Mark 7 Simba™ rooter with a Mark 6 tool carrier. The rooter is a winged three tine ripper designed for alleviating compaction to 0.9 m on restored quarries and opencast coal sites (Simba Machinery Limited, 2005). The tines are positioned in a triangular formation with a central tine at the front with two tines set behind at a wider working width. The leg length is 0.95 m, the leg width 7.5 cm and the effective leg spacing 1.1 m. The tine point width is tapered from 6 cm (rounded) to 11 cm, the lift height of the wing is 15 cm and the wing starts 16 cm up the leg, reducing the effective breakout depth from 0.95 m to 0.79 m, with a total working width of 3.0 m. The crawler used was a 336 kW 45t Fiat Alliss FD31. The crawler made the first cultivating run, turning at the headland to make the second run, turning again to run three and so on until the desired area was cultivated. Only one pass was made.

Mega-Lift ripper. The Mega-Lift consists of a five tine ripper mounted onto a tractor / crawler by means of a trailed drawbar, with hydraulic rams to control the depth of the legs and transporting wheels. Tines are positioned in a triangular formation with a central tine at the front. A rear packer leaves the soil surface level and firm. The length of each of tine leg is 1.05 m, leg width is 2.5 cm and the effective leg spacing 0.7 m. The tine point width is 3 cm and the lift height of the wing 5 cm. The wing, with a width of 28.5 cm, starts at the base of the leg and 1 cm above the tine point, and the total working width is 3.5 m. The crawler used was a 336 kW 45 t Fiat Alliss FD31.

The effectiveness of the Mega-lift ripper at alleviating soil compaction was trialled in both two and four passes, aiming loosening to 1.0 m in both cases. Previous field trials (Jones, 2001) found that the Mega-Lift failed to achieve loosening to 1.0 m in two passes, but achieved this depth successfully after four passes. The crawler made the first cultivation run, turning at the headland to make the second run, turning again to run three and so on until the desired area was cultivated. At the end of the final run, the crawler turned back to the first run and started the second pass, running deeper than the first pass to ensure further loosening of the soil. This process was repeated for the third and fourth passes. During the two pass operation, the depths of loosening were aimed at 0.5 and 1.0 m in the first and second pass respectively. During the four pass operation the progressive depths of loosening were intended to reach 0.35, 0.50, 0.75 and 0.9 m from the unloosened soil surface.

Complete cultivation. A 99 kW 21 t Komatsu PC210 LC excavator, fitted with 700 mm tracks, was used for the complete cultivation treatment. The Komatsu PC210 LC has a boom length of 12.8 m. The bucket width is 0.95 m and the capacity 1 m^3, with teeth 4 x 10 cm spaced at 19 cm intervals. This loosening followed the Profiled Strip Method as shown in Figure 1.

Control. The control plots received no ground disturbance following the initial restoration in 2000.

Assessments

Penetration resistance. Unfortunately, no measurements of penetration resistance were taken at the time of cultivation. Penetration resistance was recorded three years after cultivation, using a modified Bush recording cone penetrometer (Anderson *et al.*, 1980). The assessments were carried out when the soil was at field capacity (November 2004) in an attempt to standardise the effects of soil moisture on penetration resistance values; soil samples were taken and analysed for moisture content and there was found to be no significant difference between the treatments. A board with holes at 0.1 m intervals was laid alongside two adjacent trees in each of the four species sub-plots. Twenty measurements were taken every 0.1 m along a 2 m transect from 0.2 m to the left of a planted tree 1 to 0.2 m to the right of planted tree 2, giving a profile size of 1.90 x 0.45 m (0.855 m^2). The penetrometer recorded the soil resistance at 0.03 m depth intervals down to a total depth of 0.45 m. It is possible that some soil loosening may have occurred following cultivation during the tree planting undertaken as part of the wider study into rooting, but this would have been localised to the immediate positions around each tree, and relatively uniform across the treatments.

All of the cultivation treatments used were designed to achieve soil loosening to a depth greater than the 0.45 m recorded by the penetrometer. A method using an ELE 'lifting driving tool' reported by Baker (1990) was therefore employed to ascertain the degree of soil loosening to a depth of 1.1 m. This work was carried out in February 2005, when the soil was at field capacity. This tool consists of a driving point 15 cm in length, with a maximum diameter of 2.6 cm tapering to 2.3 cm after 11.5 cm, the remaining 3.5 cm reducing to a cone with an angle of 30^{o}. This is screwed onto a cylindrical rod of 1.0 m length and 1.2 cm diameter. The point was driven into the ground using a 3 kg drop hammer which attaches to the top of the rod. The drop hammer was raised and allowed to drop repeatedly under gravity and the number of impacts required to drive the point into the soil to a depth of 0.1 m recorded. This was repeated for each 0.1 m increment down to a depth of 1.1 m. The board was again laid alongside two adjacent trees in two of the species sub-plots from 0.2 m to the left of tree 1 to 0.2 m to the right of tree 2. The 'lifting driving tool' was used at 0.2 m intervals along a 2 m transect.

Statistical analysis

The penetrometer measurements were averaged across each 2 m transect at each 3 cm depth increment. These mean values were then subjected to a square root transformation to equalise the variance. The 0 m, 0.03 m and 0.45 m penetrometer values were discarded as there were very small variations between them.

The 'lifting driving tool' measurements were averaged across the 2 m transect taken alongside each tree at each 10 cm increment. The mean values were then subjected to a log transformation to satisfy the analysis assumptions.

Repeated measures analysis using the method of residual maximum likelihood (REML) in Genstat version 8.1 (Genstat, 2005) was employed to analyse both the penetrometer and 'lifting driving tool' data. The layout factors (i.e. block, plot, sub-plot) were input as random effects with depth, cultivation treatment and species as fixed effects. A Wald statistic divided by its degrees of freedom was used to evaluate the significance of differences among cultivation methods, tree species and soil depths. This value has an approximate Fdistribution with m, n degrees of freedom, where m is the degrees of freedom for the fixed effect and n is the number of residual degrees of freedom for that effect. An approximate value for n was chosen by taking into account the size of the variance components of the random effects and the residual variation. The REML analysis was used to ascertain whether there was a significant difference in the soil penetration resistance between the different tree species. It was found that there was not and therefore the effect of species was removed from the analysis (P=0.91 for penetrometer and P=0.31 for 'lifting driving tool').

Several alternative REML Repeated Measures models were tested (Genstat, 2005). An auto-regressive order 1 model for the correlations between depths with heterogeneity of variance (to allow for unequal variances) was accepted for both the penetrometer and the 'lifting driving tool' measurements. T-tests were used to evaluate the depths at which the penetration resistances differed significantly among the cultivation treatments.

An auto-regressive Order 1 model was applied to the penetrometer data measured at the 0.03 m soil depth increments. This assumed that at adjacent depths penetration resistance values will be more highly correlated than those further away in the profile. An auto-regressive Order 1 model was also applied to the repeated measures (by depth) data obtained using the 'lifting driving tool'. This assumed that the number of impacts of the drop hammer at adjacent depths will be more highly correlated than depths further away in the profile.

RESULTS

Penetrometer

As expected the penetration resistance increased with increasing depth across all treatments (P<0.001). The penetration resistance was significantly different between the cultivation treatments (P=0.013) as was the interaction between depth and cultivation treatment (P<0.001). The depths at which significant differences were observed between treatments are shown in Table 2.

When averaged across depth the cultivation treatments all significantly reduced the penetration resistance of the soil compared to the control. There was no significant difference in the average penetration resistance between the soils treated with the two pass Mega-lift and either the industrial rip or the four pass Mega-lift. However, four pass Mega-lift treated soils had a significantly greater penetration resistance than those cultivated with the industrial ripper above 0.12 m, but below this there was no significant difference. The penetration resistance values for the industrial and Mega-Lift ripped soils were significantly higher than those subjected to the complete cultivation below 0.18 and 0.21 m respectively. Table 3 and Figure 2 show the mean penetration resistance values that were recorded for each cultivation treatment at each depth.

Lifting Driving Tool

As expected, soil resistance increased with increasing depth across all treatments ($P<0.001$). Soil resistance was also significantly different between the cultivation treatments ($P<0.001$) as was the interaction between depth and cultivation treatment ($p<0.001$). The depths at which significant differences were observed between treatments are shown in Table 5.

Soil penetration resistance values in the control plots were significantly larger than those for the treated plots at relatively shallow depths (between 0.10 and 0.30 m), although these differences were not apparent below 0.70 m and 0.80 m in the industrial rip and Mega-Lift plots. This suggests that these methods of soil loosening are not effective below these depths. Penetration resistance of the soils treated with the two pass Mega-Lift were not significantly different from those for the industrially ripped plots. Contrary to the results presented using the penetrometer there was a significant difference between two and four pass Mega-lift treatment; the penetration resistance for the two pass treated soil being significantly larger between 0.20 and 0.50 m soil depth. The penetration resistance values for the industrial and Mega-Lift ripped soils were significantly greater than those under complete cultivation below 0.20 and 0.50 m respectively.

Table 6 and Figure 3 show the mean number of impacts taken to force the ‘lifting driving tool’ each 0.1 m depth increment for each cultivation treatment at each depth. These values demonstrate the large treatment differences in the number of impacts required to drive the point into the soil. The control plot required approximately 20 impacts to penetrate one 0.10 m increment at a relatively shallow depth (0.20 – 0.30 m) compared to the other treatments (0.60 – 0.8 m).

DISCUSSION

Comparison of the different cultivation treatments at Bramshill suggests that complete cultivation is the most technically effective method for alleviating soil compaction. All of the tested cultivation treatments resulted in some degree of soil loosening compared to the control. Previous studies have reported that both tree and crop root growth is significantly impeded in soils with penetration resistance values in excess of 1.3 MPa and

1.5 MPa (Zou *et al.*, 2001 and Boone and Veen, 1994, respectively) and effectively ceases in those with values above 2 MPa (Taylor and Ratcliff, 1969) or 3 MPa (Greacen and Sands, 1980; Boone and Veen, 1994). On the basis of previous studies, a value of 2 MPa was selected as likely to indicate a significant reduction in root growth. Using such a threshold allows a comparison of potential rooting across the treatments, although it is recognised that its use assumes that there are no continuous pores or fissures present within the profile that would allow root growth. The data from both the penetrometer and the 'lifting driving tool' suggests that the control plots reached the 2 MPa threshold value at an average depth of 0.20 m. This has important implications when it is considered that this was not a true control plot, as it had been subjected to industrial cross-ripping to 0.50 m in 2000 prior to this study. It infers that either a significant amount of recompaction has taken place on the site following its restoration or that the original cross-ripping had been ineffective at reaching depths greater than 0.20 m. Moffat and Boswell (1997) also found that after four years there was very little difference in the depth at which a penetration resistance of 2 MPa was attained between ripped and unripped soils.

The industrial and Mega-Lift rippers both achieved sustained soil loosening at Bramshill compared to the control. However, these treatments only achieved a penetration resistance value of less than 2 MPa to a depth of approximately 0.23 under industrial rip, and 0.24 and 0.33 m under the two and four pass Mega-Lift ripper respectively. This suggests that rooting may be impeded below these depths and well above the 1.2 m rootable depth currently recommended by UK guidance (Bending *et al.*, 1999, Defra, 2005). The degree of rooting suggested by the penetration resistance data is not sufficient for sustainable tree growth as mature trees are expected to draw water from a depth of 1.5 to 2.0 m during summer months at this Bramshill site (Fourt and Hinson, 1970). Similarly, minimum soil depths for woodland establishment on this site are estimated as between 1.5 and 2.0 m (Moffat, 1995). Whilst the results suggest that successful woodland establishment may not be achieved using these treatments, the soil loosening observed here may be adequate for amenity grassland, which may only require a soil depth of 0.5 m (Bending *et al*., 1999). The industrial and Mega-lift rippers may also provide sufficient soil loosening for shallow rooting crops such as potatoes. However, the planting of shallow rooting crops, those that require late harvesting or that would result in bare soil over winter months is not recommended for newly restored mineral sites as they do little to improve soil structure in the long-term (Defra, 2005).

The soil penetration resistance values achieved on the industrial ripped plots were significantly less than the control to a depth of 0.45 m. The data from the 'lifting driving tool' suggest that industrial ripper achieved significantly greater soil loosening compared to the control to a depth of 0.70 m, which is shallower than the target 0.9 m depth of loosening. The high penetration resistance values recorded in this treatment are probably the result of recompaction over the three years following cultivation that has previously been reported for this site under industrial ripping (Moffat and Boswell, 1997). The results support the suggestion by Moffat and Boswell (1997) that the industrial ripper may not be the most appropriate choice of method for achieving sustainable soil loosening on sites suffering from severe compaction.

The soil penetration resistance values recorded following the Mega-Lift ripper are significantly less than the control to a depth of 0.42 m. The values obtained using the 'lifting driving tool' demonstrated that this greater loosening is maintained to a depth of 0.80 m. This depth is comparable with the target loosening depth of 0.75 m in two passes, but shallower than the 0.9 m target for four passes. Qualitative work carried out on the soil profile immediately following cultivation suggested that the use of the Mega-Lift ripper had resulted in relatively uniform soil loosening to a depth of 1.0 m, from the loosened soil surface, under the four pass treatment (Jones, 2001). It is therefore likely that the soils treated with the Mega-Lift ripper also suffered from recompaction in the three years following cultivation. Depending on growth rate, it is possible that tree roots could have developed sufficiently before recompaction occurred. However, data on early rooting from this site suggest that this is not the case as the mean maximum rooting depth in the plots treated by complete cultivation were 0.53 and 0.74 m after 1 and 3 years growth respectively (Sinnett, unpublished data). On similar sites it may prove beneficial to plant deep rooting crops such as lucerne or winter cereals following restoration as they can contribute to the longevity of loosening operations if planted prior to recompaction taking place (Greacen and Sands, 1980; Defra, 2005). In addition, the soils at Bramshill have a high sand content which may have resulted in a greater degree of recompaction taking place following cultivation using either the industrial or Mega-lift rippers than would be expected on heavier textured soils (Greacen and Sands, 1980). It is also possible that in the future recompaction may occur on plots treated with complete cultivation.

The greater penetration resistance observed at depths above 0.12 m in the four pass Mega-Lift treated plots compared with those treated with the industrial ripper may be explained by the presence of the rear packer on the Mega-Lift that firms the upper surface of the soil (Jones, 2001). When assessing penetration resistance using the 'lifting driving tool' the four pass Mega-lift ripper gave greater soil loosening than the industrial ripper between 0.20 and 0.70 m. Similarly, the soil treated using the four pass Mega-lift had a smaller penetration resistance than the two pass alternative between 0.20 and 0.50 m. This suggests that whilst the Mega-Lift may have failed to maintain a ‘rootable’ profile to 1.0 m depth it still resulted in significantly more soil loosening than the industrial ripper when the four pass method was employed.

It may be more appropriate to compare the Mega-lift ripper with complete cultivation, as this is the current best practice methodology where soil material has already been placed. The penetrometer data for the complete cultivation suggests that on average the soil depth at which 2 MPa is exceeded is not reached at the maximum depth of 0.42 m. Complete cultivation resulted in significantly smaller penetration resistance values than any of the other cultivation treatments tested, although the penetrometer readings suggest that this difference is not apparent below 0.36 m and 0.39 m when compared to the Mega-lift or industrial ripper treatments respectively. When the ‘lifting driving tool’ was used to assess penetration resistance the soils subjected to complete cultivation appeared significantly looser than control soils below 0.30 m. These results suggest that complete cultivation is capable of providing a suitable ‘rootable’ medium to a depth of at least 0.42 m. Unfortunately, it is not possible to give penetration resistance values in MPa below the reach of the penetrometer. However, complete cultivation resulted in soils that were significantly looser than either control soils or those cultivated using the alternative treatments to a depth of 1.10 m. This maintains the premise that complete cultivation is currently the most effective method of alleviating compaction where soil or soil-forming materials are already present on the site in their final position.

The Mega-lift ripper was not as effective at alleviating soil compaction as complete cultivation. The differences between these treatments are apparent below 0.21 m using the penetrometer and 0.50 m using the ‘lifting driving tool’. The operational cost of the Mega-lift ripper is comparable to that of an industrial ripper (£744 per ha and £700 per ha respectively), making it substantially cheaper than complete cultivation (£1500 per ha) (Jones, 2001). However, in these trials the Mega-lift ripper performed relatively poorly compared to complete cultivation, failing to achieve equivalent soil loosening below, at best, 0.50 m regardless of the number of passes used. This may have been due to the lift height of the wing; the greater the lift height the greater the degree of soil disturbance (Spoor, 2006). The Mega-lift has a lift wing height of 5 cm which is less than the 10-12 cm recommended by Spoor (1998) for deep ripping. A further limitation to the use of this equipment is that trials conducted on a clay soil by Forest Research Technical Development Branch on the handling of the machinery found that when a 316 kW 23 t John Deere 9400T and 250 kW 37 t D8 Caterpillar were used as the prime mover, they struggled to pull the Mega-Lift (Jones, 2001), although they may be adequate in soils with a lower clay content. These tractors are often more readily available to site developers than the powerful Fiat Alliss FD31 (or equivalent) used in this study.

The higher standard deviations at depths below 0.70 m suggest that there is considerable variation between the soil loosening achieved by the industrial and Mega-Lift rippers at depth. This may be explained by the presence of undisturbed soil between the tines of both rippers, and a greater degree of soil loosening at the tine locations. However, this is likely to have been minimised during the Mega-lift treatments by the use of multiple passes, and the breakout profiles carried out after cultivation on the Mega-lift treatments showed that the loosening was relatively uniform. The high degree of variability in these profiles is likely to result in some areas of soil that can be penetrated by roots, even though the mean penetration resistance measurements suggest that the soil is too compact. Additionally, where subsoil compaction exists, it is possible that crop roots may grow laterally or restrict themselves to the lower density areas of soil without a significant reduction in productivity (Hamza and Anderson, 2005). It has been reported that penetrometers may overestimate the soil resistance by two to eight times compared to that which may be the encountered by the root (Bengough and Mullins, 1991; Whiteley *et al.*, 1981). This is primarily due to the increased frictional resistance on the metal probe of the penetrometer. In addition, the metal probe is forced vertically into the soil profile, whereas roots will develop around compacted areas (Bengough and Mullins, 1990). A study is currently underway to assess the effects of these cultivation treatments on tree rooting and this will provide further information on the reliability of the penetrometer and 'lifting driving tool' to estimate the rooting potential of restored soil materials.

Our study suggests that when restoring soils following mineral extraction the risk of compaction can be significantly minimised by following current best practice. Loose tipping of replaced soil materials can prevent compaction from occurring, thus avoiding the need for any additional cultivation treatments (Moffat and McNeill, 1994; Bending *et al*. 1999).

CONCLUSION

The study at the former sand and gravel pit at Bramshill Forest has demonstrated that new ripping technologies using the Mega-lift ripper are effective at alleviating a degree of soil compaction to a depth of approximately 0.80 m using either two or four passes. However, the soil penetration resistance was greater than 2 MPa at relatively shallow depths, indicating that the level of alleviation may be insufficient,to avoid restriction in depth of tree root penetration. Three years after treatment, complete cultivation remains the most effective method of alleviating soil compaction. The relative failure of ripping to produce a soil profile which met satisfactory conditions for tree development, combined with the comparatively high cost of complete cultivation emphasises that prevention of soil compaction is better than cure. In order to eliminate the need for cultivation, soil should be replaced using loose tipping at the restoration stage.

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Table 1: Mean physical soil properties at the Warren Heath Plantation

Table 2: Depths below which there was significant difference (*P*<0.05) between two cultivation treatments (n=56)

Table 3: Mean penetration resistance values recorded for each cultivation treatment determined by a penetrometer (n=56)

Table 4: Predicted mean area of the profile where the penetration resistance was less than 2 MPa for each cultivation treatment (n=56)

Table 5: Depths below which there was significant difference (*P*<0.05) between two cultivation treatments using the 'lifting driving tool' (n=37)

Table 6: Mean number of impacts recorded for each cultivation treatment (n=37)

Table 1: Mean physical soil properties at Warren Heath Plantation (n=56). Values in parenthesis indicate standard deviation.

Depth (cm)	Organic matter content[a] (%)	Sand[a] (%)	Silt[a] (%)	Clay[a] (%)	Stoniness[b] (%)	Textural class[c]
0 – 20	7.8 (2.0)	73.5 (2.7)	20.3 (2.8)	6.3 (1.2)	10.5 (3.8)	Sandy loam
20 – 40	6.7 (2.0)	74.4 (2.5)	17.7 (3.4)	7.9 (1.7)	8.2 (3.1)	Sandy loam
60 – 80	6.4 (1.5)	73.8 (3.1)	18.8 (2.9)	7.4 (1.7)	10.0 (2.5)	Sandy loam
80 – 100	5.7 (1.5)	74.7 (2.2)	16.5 (2.7)	8.8 (1.3)	12.0 (2.8)	Sandy loam

[a] as a percentage of <2 mm fraction; [b] as a percentage of total soil, n=80; [c] USDA system

Table 2: Depths below which there was significant difference (*P*<0.05) between two cultivation treatments using the penetrometer (n=56)

Treatment	Significant differences between treatments (depths at which *P*<0.05)
2 pass Mega-Lift	a (below 0.15 m)
Complete cultivation	a (below 0.18 m); b, c (between 0.21 and 0.36 m); d (between 0.18 and 0.39 m)
4 pass Mega-Lift	a (below 0.18 m)
Industrial ripper	a (below 0.18 m); c (above 0.12 m)

Letters indicate where penetration resistance is significantly less than control (a), 2 pass Mega-Lift (b), 4 pass Mega-Lift (c) and industrial ripper (d)

Table 3: Mean penetration resistance values recorded for each cultivation treatment (n=56)

		Mean penetration resistance values at each depth of measurement (MPa)														
	Depth (m)	0.03	0.06	0.09	0.12	0.15	0.18	0.21	0.24	0.27	0.30	0.33	0.36	0.39	0.42	0.45
Control	Mean	0.04	0.23	0.68	1.20	1.58	1.90	**2.10**	**2.40**	**2.83**	**3.38**	**3.77**	**3.90**	**4.27**	**4.27**	**5.09**
	SD	0.04	0.08	0.20	0.55	0.72	0.61	0.68	0.69	0.86	0.96	1.12	0.92	0.96	0.60	1.35
2 pass	Mean	0.07	0.38	0.79	1.12	1.40	1.56	1.79	**2.00**	**2.25**	**2.45**	**2.58**	**2.74**	**2.97**	**2.84**	**2.85**
Mega-Lift	SD	0.07	0.21	0.31	0.34	0.35	0.31	0.34	0.32	0.30	0.29	0.26	0.32	0.53	0.51	1.14
Complete	Mean	0.05	0.25	0.66	0.92	1.14	1.23	1.33	1.43	1.55	1.63	1.71	1.82	1.78	1.87	1.97
cultivation	SD	0.05	0.12	0.19	0.21	0.32	0.34	0.41	0.45	0.43	0.45	0.40	0.51	0.41	0.33	0.96
4 pass	Mean	0.12	0.48	0.94	1.20	1.26	1.43	1.69	1.79	1.86	1.99	**2.18**	**2.37**	**2.37**	**2.36**	**2.31**
Mega-Lift	SD	0.14	0.26	0.24	0.29	0.32	0.30	0.37	0.40	0.43	0.40	0.39	0.54	0.54	0.35	0.66
Industrial	Mean	0.06	0.24	0.62	0.95	1.29	1.64	1.85	**2.07**	**2.23**	**2.38**	**2.50**	**2.51**	**2.63**	**2.76**	**3.47**
ripper	SD	0.08	0.18	0.26	0.36	0.39	0.50	0.55	0.58	0.60	0.64	0.58	0.69	0.60	0.87	1.26

Values in bold indicate where the critical rooting value of 2 MPa is exceeded.

Table 4: Predicted mean area of the profile where the penetration resistance was less than 2 MPa for each cultivation treatment (n=56)

	Control	2 pass Mega-Lift	Complete cult.	4 pass Mega-Lift	Industrial ripper
Mean area (m^2)	0.45	0.54	0.69	0.59	0.55
Mean area (%)	53.0	63.0	80.8	69.3	64.6

Mean area calculated from the depth at which 2 MPa value was not exceeded across the 1.90 m profile. The percentage area calculated from the mean area available for rooting in the 1.90 x 0.45 m (0.855 m^2) profile.

Table 5: Depths below which there was significant difference (*P*<0.05) between two cultivation treatments using the 'lifting driving tool' (n=37)

Treatment	Significant differences between treatments (depths at which *P*<0.05)
2 pass Mega-Lift	a (between 0.20 and 0.80 m)
Complete cultivation	a (below 0.30 m); b, c (below 0.50 m); d (between 0.20 and 0.80 m)
4 pass Mega-Lift`	a (between 0.10 and 0.80 m); b (between 0.20 and 0.50 m); d (between 0.20 and 0.70 m)
Industrial ripper	a (between 0.10 and 0.80 m)

Letters indicate where penetration resistance is significantly lower than control (a), 2 pass Mega-Lift (b), 4 pass Mega-Lift (c) and industrial ripper (d)

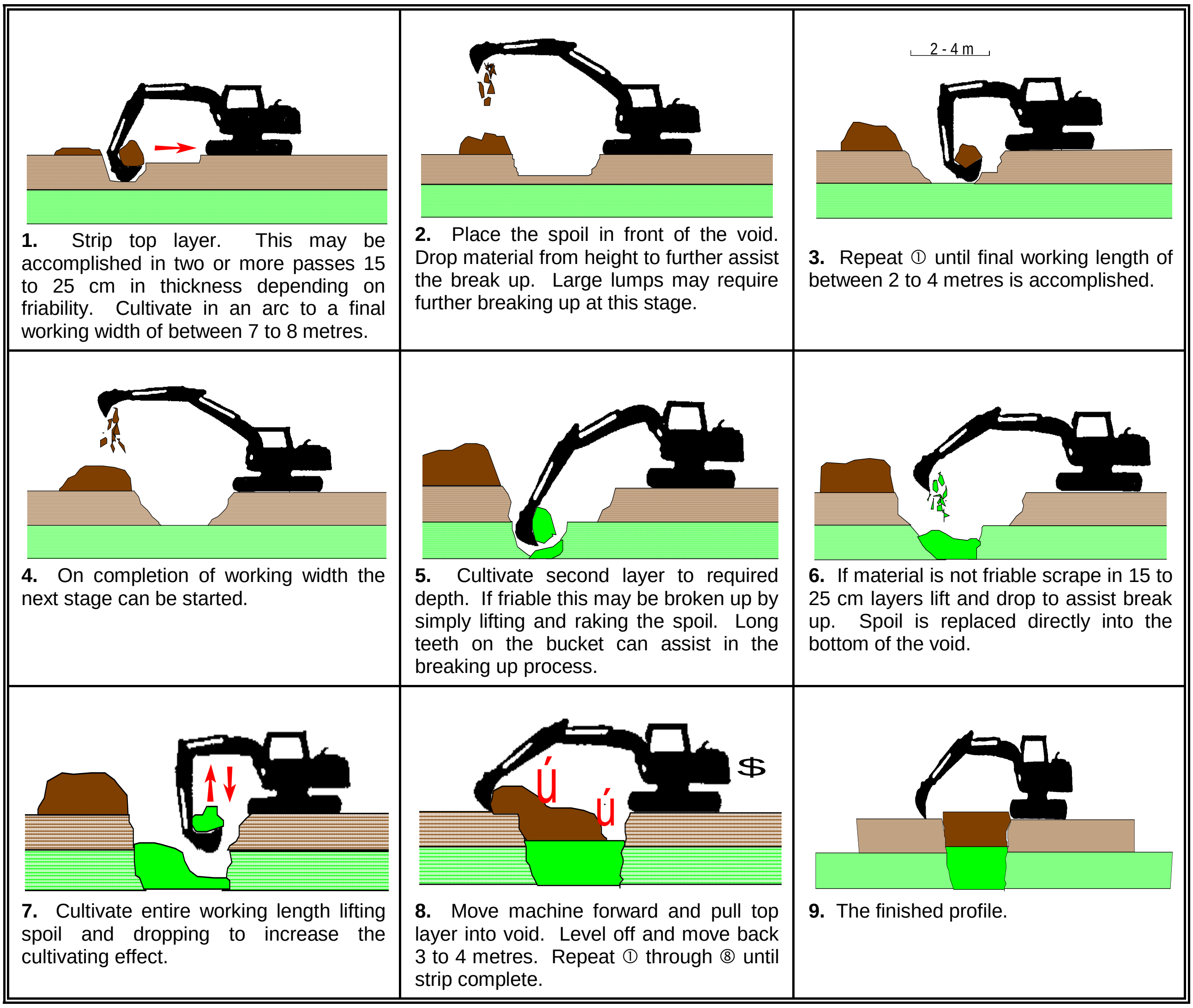
Table 6: Mean number of impacts recorded for each cultivation treatment (n=37)

		Mean number of impacts each depth increment (Number of impacts)										
	Depth (m)	0.0-0.1	0.1-0.2	0.2-0.3	0.3-0.4	0.4-0.5	0.5-0.6	0.6-0.7	0.7-0.8	0.8-0.9	0.9-1.0	1.0-1.1
Control	Mean	5.26	9.87	21.13	35.55	60.13	59.97	58.65	59.14	66.33	85.87	74.02
	SD	1.26	4.28	7.88	10.67	12.51	25.46	27.02	27.19	24.85	33.87	36.23
2 pass	Mean	4.66	6.80	11.54	11.74	13.99	13.53	13.69	23.31	43.85	65.49	57.55
Mega-Lift	SD	0.61	1.18	3.00	4.04	4.98	6.99	8.74	13.79	17.87	14.49	14.59
Complete	Mean	3.55	4.56	5.95	6.15	7.87	9.57	11.37	18.31	23.35	32.76	35.78
cultivation	SD	0.65	0.49	0.87	1.02	1.64	2.62	3.82	11.05	11.92	17.55	17.96
4 pass	Mean	4.72	5.39	7.64	7.98	8.87	9.75	12.39	27.37	49.85	68.82	55.62
Mega-Lift	SD	1.00	0.99	1.25	1.58	2.33	2.31	4.24	23.96	22.58	26.34	26.91
Industrial	Mean	4.33	6.17	10.01	13.40	24.51	32.70	31.24	32.99	45.58	61.73	61.29
ripper	SD	0.71	2.10	3.64	9.31	16.29	16.12	9.34	16.89	25.22	31.91	32.25

Figure 1: Profiled Strip Method (Reynolds, 1999)

Figure 2: Mean penetration resistance of soil under different cultivation treatments (n=56)

Figure 3: Mean number of impacts taken to penetrate soil under different cultivation treatments (n=37)



1. Strip top layer. This may be accomplished in two or more passes 15 to 25 cm in thickness depending on friability. Cultivate in an arc to a final working width of between 7 to 8 metres.

2. Place the spoil in front of the void. Drop material from height to further assist the break up. Large lumps may require further breaking up at this stage.

3. Repeat ① until final working length of between 2 to 4 metres is accomplished.

4. On completion of working width the next stage can be started.

5. Cultivate second layer to required depth. If friable this may be broken up by simply lifting and raking the spoil. Long teeth on the bucket can assist in the breaking up process.

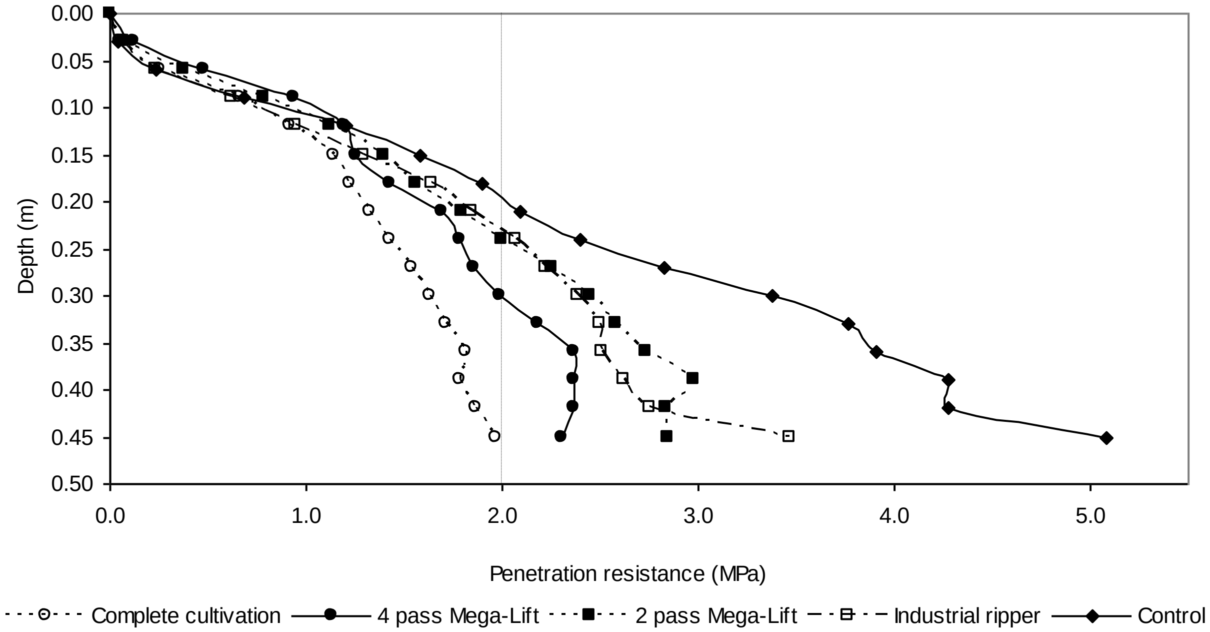
6. If material is not friable scrape in 15 to 25 cm layers lift and drop to assist break up. Spoil is replaced directly into the bottom of the void.

7. Cultivate entire working length lifting spoil and dropping to increase the cultivating effect.

8. Move machine forward and pull top layer into void. Level off and move back 3 to 4 metres. Repeat ① through ⑧ until strip complete.

9. The finished profile.

Figure 1: Profiled Strip Method (from Reynolds, 1999)



473 **Figure 2: Mean penetration resistance of soil under different cultivation treatments (n=56)**

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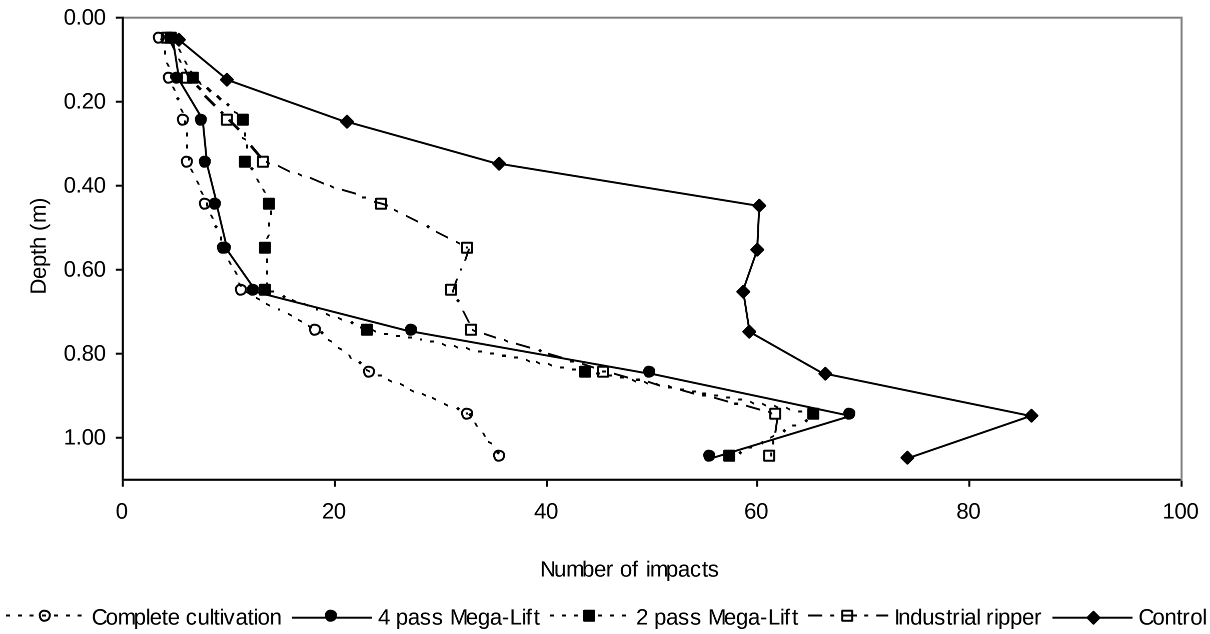

475 **Figure 3: Mean number of impacts taken to penetrate soil under different cultivation treatments**
476 **(n=37)**