A COMPARISON OF CULTIVATION TECHNIQUES FOR SUCCESSFUL TREE ESTABLISHMENT ON COMPACTED SOIL

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Summary

Soil compaction is often responsible for the poor establishment of trees on restored brownfield sites. This paper examines the root development, survival and growth of *Alnus cordata*, *Larix kaempferi*, *Pinus nigra* and *Betula pendula* after cultivation with complete cultivation, a standard industrial ripper and a prototype ripper. The industrial ripper was used in one pass across the experimental plots and the prototype ripper in both two and four passes. Whilst the maximum root depths, after five growing seasons, attained by trees were similar to the target soil loosening depths for the cultivation techniques, the total number of roots suggests that root development was not uniform across the soil profile. All treatments significantly increased both the maximum root depth and total number of roots compared to the untreated control; the complete cultivation had approximately double the number of roots compared with the other treatments. Larger average root diameters and a higher percentage of coarse roots also suggest that roots experienced physical restriction in the control, 2 pass prototype and industrial ripper plots. Similarly, whilst all species had attained significantly greater height growth on the treated soils compared with the control, the height of *Alnus cordata*, *Larix kaempferi* and *Betula pendula* was greatest after complete cultivation. The results demonstrate that complete cultivation is the most effective method of alleviating soil compaction for tree establishment.

Introduction

Soil compaction is often responsible for the poor performance or failure of trees planted as part of the restoration of brownfield sites (Moffat and McNeill, 1994; Moffat and Boswell, 1997). Brownfield sites are areas of land that have undergone some form of development in the past, including mineral extraction, waste disposal, industrial activity and commercial or residential development. Soil compaction alters the moisture regime of the soil, often resulting in drought conditions during summer months and waterlogging during wetter periods. It can also impede the growth of roots so that trees are unable to draw water or nutrients at depth, which in turn may have adverse effects of the growth of trees (Greacen and Sands, 1980). Soil compaction and resulting poor root development can also make mature trees more susceptible to wind-throw (Dobson and Moffat, 1993). It is therefore essential that any compaction present at a restored site must be effectively alleviated prior to tree establishment.

Current UK guidance recommends that a soil suitable for tree establishment should be 'rootable' to a depth of at least 1 m and have 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). A friable topsoil depth of at least 0.5 m is recommended for vegetation establishment in Australia (DITR, 2006), whilst bulk densities ranging from less than 1.4 g cm^{-3} in clay soils to less than 1.7 g cm^{-3} in loamy sands are recommended for crop production in the US (Soil Quality Institute, 2003).

Compaction may occur during all stages of the restoration process: during soil stripping, storage and reinstatement. Best practice for soil placement is loose tipping which uses a 360 ^{o} excavator to spread soil, without trafficking over the surface and should, therefore, prevent significant soil compaction from occurring, and although terminology may vary it is generally recognised that the soil handling and the trafficking over placed soil should be kept to a minimum. Where soil compaction is already present it is normally alleviated by cultivation. Complete cultivation is recommended in the UK as the most suitable cultivation method when restoring sites for tree planting. Complete cultivation uses an excavator to progressively remove and replace the soil without trafficking over the cultivated soil surface. This method is expensive and, for this reason, the cheaper industrial rip method is often favoured by site developers in the UK and is recommended for compaction alleviation following mining operations (WHO and UNEP, 1998; DITR, 2006). Industrial or deep ripping uses a winged tine cultivator pulled by a prime mover to break up compacted soil. This can have significant implications for the success of tree establishment on restored sites, as soils cultivated by industrial ripping often suffer from recompaction, where wetting-drying cycles result in precipitation of fine clay and colloids (Hamza and Anderson, 2005), before the roots have penetrated deep into the soil profile (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, the 'Mega-Lift', was developed by Tim Howard Engineering Services, Cambridgeshire, UK for land restoration primarily to a woodland end-use. The ripper was designed to loosen soil materials to a depth of 1 m in multiple passes based on the principles outlined in Spoor (1998). The design aimed to meet the bulk density standards required for soils 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 even though it did not achieve the same level of soil loosening as a complete cultivation (Sinnett *et al.*, 2006).

Previous studies have shown that the cultivation treatment employed at restored sites has a significant effect on the survival and growth of planted trees (Bending and Moffat, 1997; Moffat and Bending, 2000). Moffat and Bending (2000) found that loose tipping and complete cultivation significantly improved the survival and growth of a range of tree species on three sites compared with conventional industrial ripping techniques. This paper presents the results of a fully replicated field experiment to compare root development after soil loosening using the prototype Mega-Lift ripper, complete cultivation and a standard industrial ripper at a restored sand and gravel quarry. The second objective was to relate root development to tree survival and growth as the basis for recommendations on the use of cultivation techniques for tree establishment.

Materials and methods

Site details

The site is at Warren Heath Plantation in Bramshill Forest, Hampshire, UK (National Grid Reference SU783594, 51°19'N, 0°52'W). The site is still 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) Middle and Upper Bagshot Beds (Sumbler, 1996; Daley and Balson, 1999) in extensive plateau deposits. These gravels are overlain by a stony sandy loam drift (Jarvis *et al.*, 1984). Prior to gravel extraction, the site 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 down to the top of the Bagshot Beds. When the soil was returned, a series of ridges were constructed 30 m wide and 1.5 m high according to Forestry Commission (GB) recommendations (Wilson, 1985) 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* L. (Hull)), gorse (*Ulex europaeus* L.) and Scots pine (*Pinus sylvestris* L.) had taken place across the site.

Study area

The soil is an anthropic regosol (FAO, 1998) which has been created from sand and gravel extraction. Four years after cultivation (i.e. in 2005), soil samples were collected from four depths in each plot in Experiment 1; the soil properties are shown in Table 1. The data suggest that the soil is relatively homogeneous across the site.

Due to the destructive nature of root development assessments, two separate experiments were concurrently set up to examine the effects of the cultivation treatments on tree survival, growth and root development. Experiment 1 was used for the invasive assessments of penetration resistance and root development. Experiment 2 was left undisturbed following the cultivation treatment to allow for assessment of tree survival and growth. The cultivation treatments (see below) took place in June 2001 following a dry period when soil conditions were suitable. No further mechanical trafficking over the treatment plots occurred in the five years following cultivation. Following cultivation treatments, the entire site was enclosed with standard forestry fencing to protect trees against rabbit and deer damage (Trout and Pepper, 2006). The site was also subject to a pre-planting herbicide application and subsequent weed control was then carried every year by mechanical weeding and with the herbicide glyphosate at a rate of 5 l ha^{-1}.

Cultivation treatments

The study consisted of five treatments:

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

Industrial ripper

The industrial ripper was 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 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 cultivated 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 completed on any given area using the industrial ripper.

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, with the aim of 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 cultivated 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 a further loosening of the soil. This process was repeated for the third and fourth passes of the four-pass treatment. 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 (Sinnett *et al.*, 2006).

Control

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

Experimental design

Treatment type was randomised within each of three blocks for each experiment giving three replicates of each cultivation method, including the control. The study area for Experiment 1 was divided into three homogeneous blocks with each further divided into five plots of dimensions 8 m x 47 m; one for each treatment. Each treatment plot was then divided again into four sub-plots of equal size (8 m x 11.75 m). The study area for Experiment 2 was again divided into three homogeneous blocks with each further divided into five plots of 12 m x 42 m; one for each treatment. The treatment plots were then divided again into three sub-plots of equal size (12 m x 14 m). Enough space was left between each plot to allow the movement of an excavator without the need to traffic over the surface of the plots.

Tree establishment

Trees were notch planted as bare rooted stock during January 2002 in a rhomboidal pattern with 1.5 m spacing between each tree. Table 2 shows the trees species planted in both experiments, along with their age and mean height at planting. Tree species were selected to represent those that are suitable to the site as well as those used in both a community woodland and forestry context.

The planting design in Experiment 1 was uniform within each sub-plot so that there was one species in each sub-plot. There were 5 x 5 samples trees in each sub-plot, plus a guard row of trees around each sub-plot, giving 100 sample trees, 25 of each species, in each plot. The locations of the four species were randomised between blocks but not within them.

Tree planting position within Experiment 2 was mixed, with two species planted alternately in one row and the other two species planted alternately in the next row, returning back to the first two species in the next row and so on to give one species on each corner of the rhomboidal design. The order of planting was changed in each sub-plot so that the surrounding trees were rotated 120^o around the central tree in each sub-plot. There were 6 x 8 trees in each sub-plot, plus a guard row of trees around each sub-plot, giving 144 sample trees, 36 of each species, in each plot. The pattern of tree species was randomised between blocks but not within.

Assessments

Tree root development

Root development of two adjacent trees in each sub-plot of Experiment 1 was assessed during 2002, 2004 and 2006 i.e. during the first, third and fifth growing seasons, respectively. The rooting assessment methodology was based on that used by Yeatman (1955) and Böhm (1979). A trench was dug alongside the two trees within 0.10 m of the tree stem using an excavator. The trench ran from at least 0.5 m to the left of tree 1 to at least 0.5 m to the right of tree 2 and was approximately 1 m wide and 1.1 m deep. The face of the trench was 'cleaned' with a trowel and a palette knife was used to expose the roots and remove soil smearing caused by the excavator bucket. A 'cocktail stick' was placed into the soil profile wherever a root was protruding from the face of the trench, immediately following exposure to minimise the risk of desiccation reducing the visibility of fine roots. Root positions were then recorded for two 1 m sections of the trench, with each tree stem at the 0.5 m position on the horizontal axis and the depth from the soil surface as the vertical axis. Immediately after the placement of the 'cocktail sticks' the co-ordinates of each root and its diameter were measured at the point at which it protruded from the soil using callipers down to a root size of 0.1 mm.

Tree survival and growth

The heights of all trees in Experiment 2 were measured after planting and at the end of each growing season, between November and February, resulting in tree height data after 1, 2, 3 and 4 growing seasons. The height was measured from the base of the tree to the base of the apical bud. A record of the survival of each tree was also made at the same time. Dead trees were replaced during the spring of 2003 and 2004.

Statistical analysis

Replacement trees, those in guard rows, and those previously assessed for root development were not included in the analysis. All statistical analysis was carried out in Genstat version 8.1 (Genstat, 2005).

The root development data were used to calculate the average root diameter, maximum root depth and total root number for each tree. The percentages of roots in the root diameter classes used by the Soil Survey (Hodgson, 1976) were also calculated for the fifth growing season (very fine < 1 mm, fine 1-2 mm, medium 2-5 mm and coarse > 5 mm).

Maximum root depth, total root number and root diameter, data from Experiment 1 were analysed using the method of residual maximum likelihood (REML). The hierarchical design structure factors (i.e. block, plot, sub-plot) were input as random effects with cultivation methods, species and the cultivation x species interaction as fixed effects. A Wald statistic divided by its degrees of freedom was used to evaluate the significance of cultivation methods, species and the cultivation x species interaction. This value has an approximate F-distribution with m, n degrees of freedom, where m is the degrees of freedom for the fixed effect and n is the 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. Where the fixed effect was significant ($P<0.05$) T-tests were used to make specific comparisons between species and cultivation methods.

Tree survival data in year 4 from Experiment 2 were analysed using generalised linear models with a binomial distribution and a logit link function to assess the significance of changes in survival under different cultivation techniques. The tree height data from Experiment 2 were analysed using analysis of variance (ANOVA). The incremental increase in tree height between planting and year 4 were also calculated and analysed using ANOVA. Percentage cumulative growth was calculated for Experiment 2, being calculated as the percentage increase on year 0 height in year 1, years 1+2, years 1+2+3 and years 1+2+3+4. These data were also analysed using ANOVA. T-tests were used to make specific comparisons between species and cultivation methods.

Results

Tree root development

Maximum root depth, total number of roots and mean average root diameter data for the cultivation treatments are presented in Figure1a-c. Generally, the root development data suggested that cultivation treatment had a significant affect on all three measurements, although the maximum root depth and total number of roots were influenced earlier than the average root diameter. Species also had a significant affect on the root development in the early years of tree growth, but by the fifth growing season these differences were no longer apparent (Table 3). The interaction between treatment and species was not significant in any growing season for any measurement.

Maximum root depth

During the first and third growing seasons the species had a strong influence on maximum root depth ($P<0.001$), but again, by the fifth year this effect was no longer evident. The species x cultivation interaction was not significant in any sampling year. Cultivation treatment significantly affected maximum root depth in all sampling years ($P<0.001$) with trees in the cultivated treatments having significantly greater maximum root depths compared with the control treatments; 2 pass Mega-Lift (*P*=0.005, *P*=0.005 and *P*<0.001 respectively), complete cultivation (*P*=0.009, *P*<0.001 and *P*<0.001 respectively), 4 pass Mega-Lift (*P*=0.002, *P*<0.001 and *P*<0.001 respectively) and industrial rip (*P*=0.004, *P*<0.001 and *P*<0.001 respectively). By the fifth growing season the complete cultivation also gave a significantly greater maximum root depth than the 2 pass Mega-Lift (*P*=0.022).

Total number of roots

Species had a significant effect on the total number of roots (*P*<0.001), until the fifth year. The species x cultivation interaction was not significant in any year. The effect of cultivation treatments was not significant during the first year. Within the third growing season cultivation treatment began to have a significant effect on the total number of tree roots (*P*=0.015), with the complete cultivation, 4 pass Mega-Lift and industrial ripper treatments all resulting in a greater number of roots when compared with the control (*P*=0.006, *P*=0.021 and *P*=0.027 respectively). By the fifth year cultivation treatment had significantly affected the total number of roots (*P*<0.001) with all treatments having a significantly greater number of roots compared to the control; 2 pass Mega-Lift (*P*=0.007), complete cultivation (*P*<0.001), 4 pass Mega-Lift (*P*=0.009) and industrial ripper (*P*=0.011). Complete cultivation also resulted in a significantly greater number of roots than the 2 pass Mega-Lift (*P*=0.006), 4 pass Mega-Lift (*P*=0.005) and industrial ripper (*P*=0.004), with an average of 151 roots compared to 80, 76 and 73 roots per tree within the 1 m^2 section of the trench face for the 2- and 4- pass Mega-Lift and industrial ripper treatments respectively.

Average root diameter

During the first and third growing seasons there was no significant effect of cultivation treatment or species x cultivation interaction on the average diameter of the tree roots. During the first year of growth the different species had significantly different average root diameters (*P*=0.031), but this standardised with time and by the third and fifth years was no longer significant. During the fifth growing season cultivation had a significant effect on average root diameter (*P*<0.001) but there was no species x cultivation interaction. Trees grown in soils treated by complete cultivation had a smaller average root diameter than those on all of the other treatments, but this was only statistically significant when compared with the control (*P*=0.004), 2 pass Mega-Lift (*P*=0.026) and industrial ripper (*P*=0.007) treatments. The average root diameter of sample trees planted on the control plots were also significantly larger than those on than the 4 pass Mega-Lift plots (*P*=0.037).

Figure 2 shows the percentage of roots in each root diameter size class during the fifth growing season. There was no significant difference between species or the cultivation x species interaction in any size class. There was a significant difference between cultivation treatments for the very fine (*P*=0.003) and coarse (*P*=0.003) roots, but not between the fine or medium root diameters. Complete cultivation significantly increased the percentage of very fine roots compared with the control, 2 pass Mega-Lift and industrial ripper treatments (*P*=0.007, *P*=0.002 and *P*=0.014 respectively). The trees grown on the control plots had a higher proportion of roots in the coarse diameter class than the complete cultivation (*P*=0.006) and 4 pass Mega-Lift plots (*P*=0.028). In addition, the trees grown on the 2 pass Mega-Lift and industrial ripper plots had a higher percentage in the coarse diameter class than those on the complete cultivation plots (*P*=0.032 and P=0.029 respectively).

Tree survival and growth

Survival

Table 4 shows the mean percentage survival between the different species and cultivation treatments four years after planting. Tree survival was significantly affected by cultivation treatment (*P*=0.007), species (*P*<0.001) and there was a significant species x cultivation interaction (*P*<0.001). The significant relationships are summarised in Table 5. Survival after four growing seasons across all treatments was generally high; with Italian alder, Japanese larch, Corsican pine and birch exceeding 75 %, 80 %, 60 % and 95 % respectively. All forms of soil treatment resulted in larger survival rates than the control for at least one species. Complete cultivation resulted in greater survival of Italian alder compared to all other treatments, Japanese larch compared with the control and Corsican pine compared with the 4 pass Mega-Lift.

Tree height

Figure 3 shows the mean tree height increment after each growing season for each species and cultivation treatment combination. As expected there was a significant effect of species on tree height in all years (P<0.001). At planting and after one year of growth, there was no significant effect of cultivation or species x cultivation interaction. After two, three and four growing seasons there was a significant effect of cultivation treatment (P=0.049, P=0.041 and P=0.023 respectively) and species x cultivation interaction (P<0.001, P=0.003 and P=0.001 respectively) on tree height. The significant relationships between cultivation treatments and the interactions between species and cultivation for each year are summarised in Table 5.

All of the cultivation treatments had a significant positive effect on tree growth of most species compared with their growth in the control plots (Table 5). There were no significant differences between the 2 and 4 pass Mega-Lift and the industrial ripper in the heights of Japanese larch, Corsican pine and birch. The 4 pass Mega-Lift treatment resulted in greater growth of Italian alder than those of either the 2 pass Mega-Lift or industrial ripper. The growth of Italian alder was not significantly different between the 2 pass Mega-Lift, industrial ripper or control plots. Complete cultivation resulted in significantly greater growth of Italian alder, Japanese larch and birch than all other cultivation treatments. Only the complete cultivation resulted in a significant increase in the growth of Corsican pine, and this was not evident until the fourth growing season.

Cumulative percentage growth

Figure 4 shows the cumulative percentage growth for each cultivation and species combination. There was a significant effect of species on the cumulative growth after each growing season (P<0.001). There was no significant effect of cultivation treatment after one and two growing seasons, but this effect was significant after three and four growing seasons (P=0.043 and P=0.022 respectively). Again, the industrial ripper, 2 pass and 4 pass Mega-

Lift resulted in significantly greater growth than the control for Japanese larch and birch. The growth of Italian alder was also significantly greater after treatment with the 4 pass Mega-Lift compared with the control, 2 pass Mega-Lift and industrial ripper. The complete cultivation resulted in significantly greater growth of the Italian alder, Japanese larch and birch compared with all other treatments and of the Corsican pine compared with the control. The cumulative percentage growth rates in Figure 3 show that the difference between complete cultivation and the other treatments increased between the second and fourth growing seasons, for example in the case of Italian alder: control 54 to 109 %, 2 pass Mega-lift 33 to 73 %, 4 pass Mega-Lift 18 to 42 % and industrial rip 47 to 98 %. A similar pattern was found for Japanese larch, whilst for Corsican pine the differences were only larger when complete cultivation is compared with the control and industrial ripper treatments and in birch, only when complete cultivation is compared with the control.

Discussion

Comparison of tree root development, survival and growth on the soils treated with different cultivation techniques demonstrate that complete cultivation consistently produced significant improvements in tree performance compared with the other techniques tested. Whilst all the other treatments resulted in significant improvements on tree performance compared with the control plots there were very few significant differences between them.

Maximum root depths, measured during the fifth growing season, of the sample trees grown in all treatment plots were significantly greater than those in the control plots. Soil compaction has a detrimental effect on the root development of vegetation; roots are often reported to be severely restricted at penetration resistance values of 1.3 MPa and 1.5 MPa (Boone and Veen, 1994; Zou *et al.*, 2001) with a complete cessation at between 2 and 3 MPa (Boone and Veen, 1994; Greacen and Sands, 1980; Taylor and Ratcliff, 1969). The maximum root depths for the 2 and 4 pass Mega-Lift and industrial ripper treatments suggest that the roots were able to penetrate deeper into the soil profile than the penetration resistance values reported by Sinnett *et al.* (2006) would have suggested based on a restrictive penetration resistance value of 2 MPa. This study, carried out as part of the same experiment at Bramshill, found that a penetration resistance of 2 MPa was reached at 0.21 m, 0.24 m, 0.33 m and 0.24 m in the control, 2 pass Mega-Lift, 4 pass Mega-Lift and industrial ripper plots respectively. However, these penetration resistance values were the average values across a soil profile, whilst the maximum root depths reported here may only include a few roots that have penetrated deeper into the soil through cracks and fissures and therefore may not be suggestive of a uniform root distribution throughout the soil profile. The substantial difference in the total number of roots recorded in the trees between the treatments during the fifth growing season suggests that the discrepancy between the maximum rooting depths and the depth at which the penetration resistance is likely to restrict rooting is, in fact, caused by a small number of roots penetrating deeper into the profile through cracks and fissures rather than a uniform increase in rooting depth. Nambiar and Sands (1992) and Sheriff and Nambiar (1995) found that the roots of radiata pine were able to penetrate to a greater depth in a compacted soil by exploiting simulated root channels occupying only 0.2 % of the soil volume. Again, whilst all the treatments resulted in a significant increase of total root numbers in all treatments compared to the control and there was no significant difference between the 2 and 4 pass Mega-Lift and industrial ripper treatments. In contrast, the complete cultivation had significantly greater numbers of roots compared with all the other treatments.

The larger average root diameters in the 2 pass Mega-Lift, industrial ripper and, particularly, control plots suggest that the roots were suffering from physical restriction. The roots of trees grown in the 4 pass Mega-Lift treated soils had both significantly smaller average diameters and a smaller percentage of coarse (> 5 mm) roots than those in the control plots. Moreover, those in the complete cultivation plots had both significantly smaller average diameters and percentage of coarse roots than those in the control, 2 pass Mega-Lift and industrial ripper plots. It has been reported that an increase in root diameter occurs during root elongation in compacted soils, through increases in both the diameter of the outer cells and the number of cells per unit length of the root causing an increase in the thickness of the cortex (Bengough and Mullins, 1990). Increases in tree root diameter have also been reported following addition of N, P and K (Coutts and Philipson, 1976); however the increase in root diameters observed here are unlikely to be due to differences in soil nutrient status as the soil is relatively homogenous across the treatments. In addition, the complete cultivation produced significantly higher percentages of very fine roots than the control, 2 pass Mega-Lift and industrial ripper plots.

Whilst the differences between treatments in root distribution, maximum root depth and, to a certain extent, the total number of roots were evident since the first growing season this was mainly confined to differences between the treatments and the control plots. It was not until the fifth growing season that differences among the cultivation treatments, particularly for root diameter, became apparent. This suggests that the root development of trees is relatively slow and it is unlikely that the roots had begun to reach the compacted parts of the soil profile until at least the third growing season and that this was not having a significant effect until the fifth. It has been suggested that although roots may not be able to develop into compact subsoils, they may develop laterally or restrict themselves to less compact areas without any significant effect on productivity (Hamza and Anderson, 2005). Nambiar and Sands (1992) found that the above-ground growth of radiata pine, although significantly reduced by soil compaction, was equivalent to that observed on uncompacted soils when the roots were able to exploit simulated root channels, occupying only 0.2 % of the soil volume, in an otherwise compacted soil. However, in a similar study, Sherriff and Nambiar (1995) found that, although a deeper penetration of roots was observed in simulated root channels, this did not equate to an increase in growth compared to a uniformly compacted soil unless it was coupled with fertiliser addition, suggesting that the presence of channels alone is not necessarily enough to overcome the adverse effects of compaction. This study also suggests that the availability of cracks and fissures was not enough to compensate for the overall compaction with the species studied here.

All treatments provided some improvement on the tree growth and root development compared to the control, but there were very few little consistent differences between the 2 and 4 pass Mega-Lift and industrial ripper treatments. Although the maximum root depth data suggest that roots are able to penetrate to the target depths of loosening for each cultivation treatment, the data on tree growth, total number of roots and root diameter all suggest that the performance of the trees is significantly better on the soils treated with complete cultivation compared to any other technique tested in this study. There is also a general pattern of tree performance against treatment; complete cultivation > 4 pass Mega-Lift = industrial ripper = 2 pass Mega-Lift > control. This pattern was also observed when considering potential tree performance based on soil penetration resistance using both a penetrometer and a 'lifting driving tool' at this site (Sinnett *et al.*, 2006).

The differences in survival rates between the treatments builds on Moffat and Bending's (2000) work which found that the cultivation technique used had a significant effect of the survival of common alder, grey alder, Corsican pine and Japanese larch at restored sites. In their study, complete cultivation produced higher survival in common alder and Japanese larch compared with ripping after three growing seasons. They reported differences in survival between the two treatments that were more dramatic than those observed in this study; ripping resulted in a reduction of between 10 and 20 % depending on the species. Survival of Corsican pine was lower than for the other species across all treatments, with the literature suggesting that this is commonly the case as Corsican pine is difficult to establish and often suffers from high mortality rates (Jinks and Kerr, 1999).

Differences in tree height and growth observed between treatments were more pronounced and consistent than those for survival, suggesting that cultivation had a more significant impact on tree growth than mortality. These data also have the same pattern between treatments as the root development work, demonstrating the importance of root development to above-ground biomass production. The current study at Bramshill found Italian alder heights of 134 cm, 79 cm and 70 cm after three growing seasons on plots treated with complete cultivation, industrial ripper and the control respectively. Moffat and Bending (2000) also found a significant improvement in Italian alder and Japanese larch height, measuring approximately 240 cm and 160 cm respectively after three growing seasons, on the Streets Lane restored colliery following complete cultivation compared with ripping. The differences in Italian alder height are likely to be due to the different soil conditions between the Bramshill and Streets Lane sites; the heights at Bramshill are comparable to the height of Italian alder found after three growing seasons at the Shaw landfill site of 104 cm (Bending and Moffat, 1997).

This study recorded heights of Japanese larch of 156 cm, 118 cm and 80 cm for the complete cultivation, industrial ripper and control treatments respectively. Again, Moffat and Bending (2000) also found a significant improvement in Japanese larch height at the Maesgwyn colliery following complete cultivation compared with ripping recording heights of approximately 125 cm and 50 cm respectively.

The height of birch trees after four growing seasons ranged from 158 cm in the control plots to 299 cm on the plots treated with complete cultivation. These are smaller than the control trees in studies conducted by van Hees and Clerkx (2003) and Rey and Jarvis (1997) who found heights of four-year-old birch trees to be 320 and 375 cm on natural soils. This may be due to the limiting factors imposed on restored sites compared to their controls in natural soils.

The height of Corsican pine was generally similar across all treatments, with the only significant difference occurring between the complete cultivation and the control. When growth was considered as cumulative growth rates the other treatments suggested an improvement of the growth of Corsican pine compared to the control. The height of Corsican pine in this study is comparable with those found by Jinks and Kerr (1999) on natural soils at around 100 cm compared with their 90 cm and, after three growing seasons were substantially greater than those reported by Bending and Moffat (1997) on three landfill sites. Corsican pine is a slow growing species in the early years, and, as has been stated earlier, is often difficult to establish (Jinks and Kerr, 1999), so that any differences between treatments are small and the significance of them masked by the variation within the treatments. Moffat and Bending (2000) also reported no significant differences between the height of Corsican pine following loose tipping compared to ripping after five growing seasons. In order to overcome these problems with the assessment of treatment effects on Corsican pine it may prove beneficial to carry out height assessments after a longer period of time than this study allowed.

The differences in the rate of growth between cultivation treatments provides further evidence that the complete cultivation is the most effective treatment and suggests that the trees in this study are not recovering from the initial differences in growth, in fact the differences in tree heights between the treatments appear to be increasing with time.

The tree performance data reported here support the findings presented in Sinnett *et al.* (2006) that the Mega-Lift ripper is not as effective at alleviating soil compaction as the complete cultivation. The Mega-Lift ripper is significantly cheaper than the complete cultivation method at £744 per ha using four passes compared with £1500 per ha (Jones, 2001). However, its comparable cost with the standard industrial ripper, at £700 per ha, together with the reported limitations concerning its handling with more widely available tractors than the Fiat Alliss FD31 used in this study (Jones, 2001) mean that it is unlikely to provide any added benefit to the greening of restored sites over the standard industrial ripper.

Whilst it is recognised that the use of the complete cultivation method has significant cost implications for any restoration project the results presented in this paper would suggest that it has greatly improves the performance of trees. The height data after four growing seasons suggests that this method increases the height of Italian alder, Japanese larch, Corsican pine and birch by 100, 40, 12 and 22 % respectively, over the industrial ripper and by 27, 28, 3 and 24 % respectively, over the 4 pass Mega-Lift. This has important implications for both commercial forestry and community woodland development in terms of increased timber production and quick aesthetic improvements on restored sites.

The experiments of tree performance on the former sand and gravel quarry at Bramshill Forest demonstrate that whilst the Mega-Lift ripper provided benefits over the control, it did not perform well compared with the complete cultivation and was generally no better than the standard industrial ripper. After four growing seasons complete cultivation remains the most effective method of alleviating compaction in terms of both root development and tree growth. Although equivalent tree performance can be achieved with complete cultivation to that for loose tipping, its large cost underlines the importance of preventing soil compaction from occurring at the soil placement stage of the restoration process.

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

Table 2: Species, age and mean height at planting of tree.

Table 3: Mean total number of roots, average root diameter and maximum rooting depths of each species in Experiment 1 (Year 1 n=48, Year 3 n=50, Year 5 n=49).

Table 4: Percentage survival of four year old trees in Experiment 2 after different cultivation treatments (n=180).

Table 5: Significant relationships in tree survival and growth ($P<0.05$) between species x cultivation treatment interactions in Experiment 2 four years after planting (n=180).

Figure 1: Mean (a) maximum root depth, (b) total number of roots and (c) average root diameter per tree within the 1 m^2 section of the trench face in Experiment 1 after different cultivation treatments (Year 1 n=48, Year 3 n=50, Year 5 n=49; error bars indicate standard error of differences). Letters indicate where measure is significantly more than (a) control, (b) 2 pass Mega-Lift, (c) complete cultivation, (d) 4 pass Mega-Lift and (e) industrial ripper.

Figure 2: Mean percentage of roots in each root diameter class in the fifth growing season in Experiment 1 after different cultivation treatments (n=49; error bars indicate standard error of differences).

Figure 3: Mean tree heights over four years in Experiment 2 after different cultivation treatments (n=180).

Figure 4: Mean cumulative tree growth over four years in Experiment 2 after different cultivation treatments (n=180; error bars indicate standard error of differences).

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

Depth (cm)	Organic matter[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: Species, age and mean height at planting of tree.

Common name	Latin name	Age	Mean height at planting in cm Experiment 1 (n=2160)	Experiment 2 (n=1500)
Italian alder	*Alnus cordata* Desf.	1/0	34.8 (0.5)	33.0 (0.7)
Silver birch	*Betula pendula* Roth	½u½	47.4 (0.4)	47.3 (0.6)
Corsican pine	*Pinus nigra* subsp. *laricio* (Poir.) Maire	1u1	12.1 (0.3)	13.5 (0.7)
Japanese larch	*Larix kaempferi* (Lamb.) Carr.	1+1	26.9 (0.4)	25.9 (0.5)

1/0 = 1 year old (1 year seedling), ½u½ = 1 year old (undercut in situ in the first growing season), 1+1 = 2 years old (1 year seedling, 1 year transplant), 1u1 = 2 years old (undercut in situ in the second growing season). Values in parenthesis indicate standard error

Table 3: Mean total number of roots, average root diameter and maximum rooting depths of each species in Experiment 1 (Year 1 n=48, Year 3 n=50, Year 5 n=49).

	Year 1	Year 3	Year 5
Total number of roots			
Alder	32.8 (3.1)^{a}	30.9 (8.6)^{ab}	92.8 (17.6)
Birch	27.9 (3.1)^{a}	49.9 (8.6)^{b}	95.7 (17.6)
Corsican pine	18.6 (3.1)^{b}	11.9 (8.6)^{a}	58.5 (17.6)
Japanese larch	17.1 (3.1)^{b}	19.2 (8.6)^{a}	65.4 (17.6)
Average root diameter			
Alder	0.8 (0.1)^{ab}	1.2 (0.2)^{a}	1.3 (0.2)
Birch	0.9 (0.1)^{ab}	1.1 (0.2)^{a}	1.4 (0.2)
Corsican pine	0.9 (0.1)^{a}	1.0 (0.2)^{a}	1.5 (0.2)
Japanese larch	0.7 (0.1)^{b}	1.2 (0.2)^{a}	1.4 (0.2)
Maximum rooting depth			
Alder	59.4 (5.0)^{a}	57.7 (5.7)^{ab}	75.9 (5.3)
Birch	54.1 (5.0)^{ab}	71.1 (5.7)^{b}	79.7 (5.3)
Corsican pine	42.7 (5.0)^{bc}	43.9 (5.7)^{a}	86.2 (5.3)
Japanese larch	37.8 (5.0)^{c}	50.1 (5.7)^{a}	76.7 (5.3)

Subscript letters indicate significant differences ($P<0.05$) between species. Values in parenthesis indicate standard error.

Table 4: Percentage survival of four year old trees in Experiment 2 after different cultivation treatments (n=180).

Treatment	Mean survival (%) Italian alder	Japanese larch	Corsican pine	Birch
Industrial ripper	93.5 (2.94)	92.6 (3.13)	75.0 (5.14)	99.1 (1.13)
2 pass Mega-Lift	92.6 (3.07)	94.4 (2.70)	69.4 (5.19)	96.3 (2.24)
4 pass Mega-Lift	95.4 (2.51)	98.1 (1.61)	63.9 (5.74)	98.1 (1.61)
Complete cultivation	100.0 (0.0)	99.1 (1.13)	79.6 (4.77)	99.1 (1.13)
Control	75.0 (5.03)	84.3 (4.28)	73.1 (5.14)	95.4 (2.50)

Values in parenthesis indicate standard error

Table 5: Significant relationships in tree survival and growth (*P*<0.05) between species x cultivation treatment interactions in Experiment 2 four years after planting (n=180).

			Significant differences between treatments (*P*<0.05)			
Treatment	Species	Measure	Year 2	Year 3	Year 4	Years 0-4
Industrial ripper	Italian alder	Survival				a
		Height				
		Cumulative growth				
	Japanese larch	Survival				
		Height	a	a	a	a
		Cumulative growth	a	a	a	
	Corsican pine	Survival				
		Height				
		Cumulative growth		a	a	
	Birch	Survival				
		Height	a	a	a	a
		Cumulative growth	a	a	a	
2 pass Mega-Lift	Italian alder	Survival				a
		Height				
		Cumulative growth			a	
	Japanese larch	Survival				a
		Height	a	a	a	a
		Cumulative growth	a	a	a	
	Corsican pine	Survival				
		Height				
		Cumulative growth	a	a	a	
	Birch	Survival				
		Height	a	a	a	a
		Cumulative growth	a	a	a	
4 pass Mega-Lift	Italian alder	Survival				a
		Height	a e	a e	a b e	a b e
		Cumulative growth	a e	a e	a e	
	Japanese larch	Survival				a
		Height	a	a	a	a
		Cumulative growth	a	a	a	
	Corsican pine	Survival				
		Height				
		Cumulative growth	a	a	a	
	Birch	Survival				
		Height	a	a	a	a
		Cumulative growth	a	a	a	
Complete cultivation	Italian alder	Survival				a b d e
		Height	a b e	a b d e	a b d e	a b d e
		Cumulative growth	a b e	a b d e	a b d e	
	Japanese larch	Survival				a
		Height	a b d e	a b d e	a b d e	a b d e
		Cumulative growth	a b d e	a b d e	a b d e	
	Corsican pine	Survival				d
		Height			a	a
		Cumulative growth		a	a	
	Birch	Survival				
		Height	a b d e	a b d e	a b d e	a b d e
		Cumulative growth	a b d e	a d e	a b d e	

Letters indicate where measure is significantly more than (a) control, (b) 2 pass Mega-Lift, (c) complete cultivation, (d) 4 pass Mega-Lift and (e) industrial ripper