Soil Penetration Resistance and Tree Root Development

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Abstract

Current UK guidance suggests that a ‘rootable’ soil profile of at least 1.0 m depth should be sufficient to allow adequate rooting of the majority of species in a range of soil types and climatic conditions (Moffat, 1995). However, there is some uncertainty as to what constitutes a loosened soil profile in terms of penetration resistance. In this study the root development of Italian alder, Japanese larch, Corsican pine and birch was assessed after five years of tree growth. These data were compared to penetration resistance measured using both a cone penetrometer and a ‘lifting driving tool’ (dropping weight penetrometer). Tree root number and percentage were significantly reduced by increasing soil penetration resistance measured with both the cone penetrometer ($P<0.050$) and the ‘lifting driving tool’ ($P=0.011$ and $P=0.008$ respectively). The vast majority of roots were recorded in soils with a penetration resistance of less than 3 MPa (90.7 %) with a significant amount in the less than 2 MPa class (70.2 %). Root development of Italian alder, Japanese larch and birch all showed a similar pattern, but Corsican pine appeared to be capable of rooting into more compact soils. The ‘lifting driving tool’ can be used as an alternative measure of soil penetration resistance. This equipment is more cost effective, easier to use and capable of measurements at a greater depth than the cone penetrometer. The majority of Japanese larch and birch roots (84.3 %) were recorded in soils where it took less than 15 impacts to penetrate one 10 cm soil depth increment. The modelled data also suggests that a penetration resistance of 2 and 2.5 MPa relates to 10 and 15 impacts respectively.

Keywords: soil compaction, penetration resistance, restored soils, tree root development

Introduction

Soil compaction is often responsible for the poor performance or failure of tree planting in both land regeneration projects and within existing woodlands. Compaction occurs as a result of soil stripping, storage and placement and from the trafficking of heavy machinery during restoration and timber harvesting. It alters the moisture regime of the soil and can impede the growth of roots so that the tree is not able to draw water or nutrients at depth; poor root development can also make mature trees more susceptible to wind-throw. Current UK best practice recommendations are that generally a 'rootable' soil depth of at least 1.0 m should be provided for successful woodland planting; this guidance covers the range of species, soil types and climatic conditions that would normally be expected within the UK (Moffat & McNeill, 1994; Moffat, 1995).

Penetration resistance, recorded using a penetrometer, is used to assess the degree of soil compaction, often to determine whether cultivation is required and, post-cultivation, whether sufficient soil loosening has been achieved. The penetrometer measures the force, expressed in MPa, required to drive a metal cone progressively deeper into the soil. It is essential that the values obtained using a penetrometer can be related to the potential root development both to save the costs involved in unnecessary cultivation and to ensure that cultivation has been successful. This is particularly important in the case of tree establishment where there is only one real opportunity for cultivation as the trees are likely to be present on the site for a considerable number of years and any adverse effects of compaction may not be observed until several years have passed.

This paper uses the data obtained during a deep cultivation trial to predict the penetration resistance value at which the root development is significantly impeded. In addition to the standard cone penetrometer the root development data are also related to the penetration resistance measured with the 'lifting driving tool' as this equipment offers the ability to assess compaction to a greater depth than the penetrometer.

Study site and methods

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) Middle and Upper Bagshot Beds (Daley and Balson, 1999; 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 & 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 Beds. 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.

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 two plots of dimensions 55 m x 14 m with enough space between them to allow the movement of an excavator.

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 five years following cultivation. The soil is an anthropic regosol (FAO, 1998) which has been created from sand and gravel extraction. The soil properties, sampled, as part of this trial, four years after cultivation, are shown in Table 1. The data suggest that the soil is relatively homogeneous across the site.

Cultivation treatments

The study consisted of two treatments; a complete cultivation to 1.1 m using an excavator and an unloosened control. Treatment type was randomised within each block giving three replicates of each. The complete cultivation method has not been expanded on here as this work does not compare the treatments; further details can be found in Sinnett *et al.* (2006).

Tree establishment

Trees were notch planted as bare rooted stock during January 2002 with a 1.5 m spacing between each tree. Tree species (Table 2) 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 site was also subject to a pre-planting herbicide application and subsequent weed control was then carried every year according to Willoughby and Dewar (1995).

Each plot was divided into four sub-plots with one species in each sub-plot; their locations were randomised between blocks but not within them. There were 7 x 7 trees in each sub-plot, including a guard row of trees around each sub-plot, giving 100 sample trees, 25 of each species, in each plot.

Assessments

Penetration resistance. Penetration resistance was recorded 4 yr 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 2005) in an attempt to standardise the effects of soil moisture on penetration resistance values; 5 soil samples were taken every 10 cm to a depth of 50 cm from near each tree and analysed for gravimetric moisture content and there was found to be no significant difference between the treatments (repeated measures analysis using the method of residual maximum likelihood in Genstat version 8.1: cultivation treatment x depth interaction $P>0.05$, d.f.=16, Wald statistic with a chi-squared distribution=23.91). A board with holes at 0.1 m intervals was then laid alongside two adjacent trees in each of the four species sub-plots. Using a penetrometer twenty measurements were taken every 0.1 m along a 2 m transect from 0.2 m to the left of the first tree to 0.2 m to the right of the adjacent tree, 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, but this would have been localised to the immediate positions around each tree, and relatively uniform across the treatments.

The recommended depth of loosened soil is 1.0 m (Moffat & McNeill, 1994) which is deeper 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 also carried out in November 2005. 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 the Japanese larch and birch sub-plots from 0.2 m to the left of tree 1 to 0.2 m to the right of tree 2. This assessment was carried out on the same trees as the penetrometer, although the board was laid alongside the other side of trees. The ‘lifting driving tool’ was used at 0.2 m intervals along a 2 m transect.

Tree root development. The root development of two trees in each sub-plot was assessed during 2006 after 5 years of growth. In order to relate this to soil compaction the same trees were used as for the penetration resistance. The rooting assessment 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 the first tree to at least 0.5 m to the right of the second and was approximately 1 m wide and 1.1 m deep. The face of the trench was ‘cleaned’ with a trowel and, if necessary, a palette knife to expose the roots and remove the 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, this was carried out immediately following exposure to minimise the risk of desiccation reducing the visibility of fine roots. The root positions were then recorded for a 1 m section of the trench, with the tree stem at the 0.5 m position on the horizontal axis and the depth from the soil surface as the vertical axis. The co-ordinates of the root and its diameter were measured, and the cocktail stick removed until all the roots within the section had been recorded. The diameter of each root was measured at the point at which it protruded from the soil using callipers down to a root size of 0.1 mm.

Statistical analysis

In order to compare the penetration resistance and rooting data, a programme was written in Genstat version 8.1 (Genstat, 2005) to calculate the number of roots within each penetration resistance class. Using a simple interpolation, this programme assigned a penetration resistance value, in either MPa or number of impacts, to the co-ordinates of each root in each trench. It then calculated the number of roots falling within each penetration resistance class. The classes assigned to the penetrometer data ranged from 0 to 8.0 MPa in 0.5 MPa increments, and those for the ‘lifting driving tool’ from 0 to 50 in increments of 5 impacts and from 50 to 100 in increments of 10 impacts. Where a root was recorded without a corresponding penetration resistance value, an arbitrary value was assigned for the penetration resistance; these values were then discounted from all further analysis. No roots were recorded where the penetration resistance was recorded above 6.0 MPa, so the classes above this value were also removed from the analysis. The final data were then used to calculate the percentage of roots present in each penetration resistance class. A binomial generalised linear model with logit link accounting for overdispersion was fitted to the number and percentage of roots in each resistance class. The back transformed predicted proportions and associated standard errors were then computed.

Models were developed to assess the relationship between the number and percentage of roots in each penetration resistance class. Linear models of the average number and percentage of roots in each penetration resistance class, using both the penetrometer and the ‘lifting driving tool’ were fitted using Genstat version 8.1 (Genstat, 2005). The ‘lifting driving tool’ data were highly skewed with large numbers of impacts for a small number of roots, the models for this tool were therefore developed by limiting the data to 25 impacts and these data were also subjected to a log transformation prior to analysis. Tree species had a significant effect on the number of roots related to the penetrometer data (linear regression analysis, $P<0.001$, d.f.=50), therefore models were fitted for each species. However, tree species did not have a significant effect on the ‘lifting driving tool’ data (linear regression analysis, $P>0.050$, d.f.=35), so models were fitted for the entire data set.

In order to ascertain the relationship between the values obtained using the penetrometer and those from the ‘lifting driving tool’ a model was developed from the two datasets. The measurements were averaged across the 2 m transect taken alongside each tree at each depth increment. Because the measurement depths were different between the methods the average penetration resistance across the 0.10 m increments were calculated from the penetrometer data (e.g. 0.03, 0.06 and 0.09 m penetration resistance averaged to give the 0 to 0.10 m increment) to a depth of 0.40 m. These data were again limited to 25 impacts using the ‘lifting driving tool’. Linear and exponential models of the penetration resistance values from the two methods were fitted using Genstat version 8.1 (Genstat, 2005). As the linear can be viewed as a limit of the exponential, the models were compared using the difference in residual sum of squares of alternative models relative to the smallest residual mean square to determine the more appropriate model. This comparison is compared to an F-distribution with 1, n degrees of freedom where n is the residual degrees of freedom from the exponential model.

Results

Root development

Figure 1 shows the percentage of roots within each of the penetration resistance classes measured using the penetrometer. Japanese larch had 32.4 % of its roots in soil with a penetration resistance of less than 1.0 MPa and 63.7 and 86.6 % in that with a penetration resistance of less than 2.0 and 3.0 MPa respectively.

Italian alder and birch followed similar patterns with 30.9 and 39.2 % of their roots in the less than 1.0 MPa class respectively, 73.7 and 73.8 % in the less than 2.0 MPa class respectively and 96.3 and 92.0 % in the less than 3.0 MPa class respectively. Corsican pine roots appeared more able to penetrate more compact soils, with only 13.7 % of the roots in the less than 1.0 MPa class, 62.9 % in the less than 2.0 MPa class and 83.9 % in the less than 3.0 MPa class. Of the remaining 16.1 %, 9.9 % were in soil with a penetration resistance of between 3.0 and 4.0 MPa. However, the Corsican pine data showed a much higher degree of variability than those for the other species making it difficult to draw any real conclusions about the ability of the roots of this species to penetrate into the different penetration resistance classes. Figure 2 shows the average rooting data for all species; an average of 70.2 % of roots was found in the less than 2 MPa class and 90.7 % in the less than 3 MPa class.

Figure 3 shows the number of roots in each penetration resistance class measured using the ‘lifting driving tool’. The only species subplots assessed using this method were those of Japanese larch and birch. When Japanese larch trees were assessed, 84.4 % and 92.6 % were found in the areas where it took less than fifteen or thirty impacts respectively to drive the point one 10 cm depth increment. The birch roots again followed a similar pattern with 84.3 and 94.7 % in the soil where less than fifteen and thirty impacts respectively were needed. Figure 4 shows the percentage of roots in each penetration resistance class averaged across both species. There were 84.3 % and 93.9 % of roots in the soil where it took less than fifteen and thirty impacts respectively.

Modelling

Tables 3 and 4 show the models for both the number of roots and the percentage of roots against each penetration resistance class measured with the penetrometer and ‘lifting driving tool’ respectively. All species showed a significant negative relationship between the number of their roots and the penetration resistance. When models were fitted to the number of roots against penetration resistance using the penetrometer there was a significant difference in the models between birch and the other three species; alder (P=0.032), Corsican pine (P<0.001) and Japanese larch (P=0.032). There were no significant differences in the models between the alder, Corsican pine and Japanese larch or between any species using the percentage of roots data. The relatively high P values presented for Corsican pine again demonstrate the variability in the root development for this species.

Equation 1 and Figure 5 describe the exponential model of the relationship between penetration resistance measured with the ‘lifting driving tool’ (I) and the penetrometer (MPa).

$\mathrm{MPa}=2.59-5.85(0.785^{l})$ Equation 1 ($n=34$, $P<0.001$, $R^2=0.43$)

Discussion

The data presented here show that tree root numbers are significantly reduced as penetration resistance increases. It also suggests that tree root development is significantly impeded at penetration resistance values of between 2 and 3 MPa. All species had between 63 and 74 % of their roots in soils with penetration resistance values of less than 2 MPa and between 84 and 96 % in soils of less than 3 MPa. The roots of Corsican pine appeared to be more able to penetrate soils with higher penetration resistance values with a smaller proportion of roots in less than 1 MPa class and a larger proportion of roots in the less than 4 MPa class. Observations made in the field during the root development assessment suggested the roots of this species are woodier than those of the other species.

Other workers have found that root development is significantly impeded at penetration resistance values in excess of 1.3 and 1.5 MPa (Zou *et al.*, 2001; Boone & Veen, 1994 respectively) and, effectively ceases when soil penetration resistance reaches 2 MPa (Taylor & Ratcliff, 1969) or 3 MPa (Greacen & Sands, 1990; Boone & Veen, 1994). These values have primarily been derived from agricultural crop root development, often based on laboratory studies that have used homogenised soil. However, *in situ* soils will often contain cracks or fissures that roots may exploit despite high penetration resistance readings. Penetrometers may overestimate the penetration resistance to which a root is subjected by between two and eight times (Whiteley *et al.*, 1981; Bengough & Mullins, 1991). This is mainly due to the increased frictional resistance on the metal probe of the penetrometer, but also because the probe is forced vertically into the soil profile, whereas roots will develop around compacted areas (Bengough & Mullins, 1990). Our study using trees at the Bramshill site supports previous work on agricultural crops; the model for the mean data shows that as a reduction of 50 % of maximum percentage of roots recorded in a class (~10 %) equates to a penetration resistance of approximately 2.5 MPa.

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 & Anderson, 2005). However, the extremely stony soil at the Bramshill site should provide opportunity for root development around stones but the clear decline in root numbers as penetration resistance increases indicates that this not the case. In addition, significant reductions in tree growth and total root number have been observed at the Bramshill site on plots with high penetration resistance (Sinnett *et al.*, submitted). Indeed, tree roots require different consideration from those of crop species; compaction in subsoils that prevents 90 % of roots from developing at depth may not allow the exploitation of sufficient water to sustain tree growth in the long term. In addition, poor vertical root development will also increase the risk of wind-throw which may not be of importance in arable systems.

The results obtained using the 'lifting driving tool' to measure penetration resistance demonstrate that this equipment may provide a useful alternative to the use of the cone penetrometer. Again, root number is significantly affected by the increasing penetration resistance. The modelled relationship between the data from the two methods of assessment show that at a penetration resistance of 2 and 2.5 MPa the number of impacts required to force the probe of the 'lifting driving tool' one 10 cm depth increment into the soil is approximately 10 and 15 respectively. The observed differences in the percentage of roots in each penetration resistance class show that 84.3 % of the roots occurred in soils taking less than 15 impacts to penetrate one 10 cm increment. This equipment should provide an effective alternative for those assessing the requirements for cultivation prior to vegetation establishment. The model shown in Equation 1 can be used relate the number of impacts recorded using the 'lifting driving tool' to MPa up to around 25 impacts per 10 cm depth increment (i.e. approximately 3 MPa). This suggests that the 'lifting driving tool' is not sensitive enough to determine differences in penetration resistance above 3 MPa, this, however, should not limit its use as this value is above that which would normally be considered to be suitable for sustainable tree growth. The 'lifting driving tool' is significantly cheaper than the cone penetrometer, costs approximately £100, requires no data manipulation to convert counts to MPa and is simple to use as the operator simply raises and drops the weight repeatedly and counts the number of times this must be repeated to drive the point progressively deeper into the soil. It also substantially reduces the operator effect that is a limitation in the use of the penetrometer (Herrick & Jones, 2002), where the comparison of results between different penetrometer readings assumes that the probe has been moved through the soil at a constant velocity which is difficult to achieve, particularly where different operators may have been used (Herrick & Jones, 2002); not the case in this study. In addition, because the 'lifting driving tool' relies on the force created by the dropping weight to drive the cone through the soil it is suitable for a range of soil conditions, whereas the penetrometer will be limited by the strength of the operator (Herrick & Jones, 2002). It can also be used to measure the penetration resistance to a depth of 1.1 m which is particularly important in tree crop systems because many cone penetrometers do not penetrate this far into the soil profile. However, the 'lifting driving tool' used in this study may be limited by its shape as the diameter of the probe after the 30^{o} cone does not reduce to the diameter of the rod for 11.5 cm which may result in increased resistance with depth (Herrick & Jones, 2002) after this the rod diameter is constant at 1.2 cm which should mean that the increased resistance is constant after the initial 15 cm penetration into the soil. Penetrometers also have standard methodologies associated with them and there is a substantial amount of information in the literature relating their outputs to soil properties which is not the case for the ‘lifting driving tool’ (Herrick & Jones, 2002).

Conclusion

Tree root development is significantly impeded when soil penetration resistance exceeds between 2 and 3 MPa at a restored sand and gravel quarry. Approximately 68 % of roots occur in soils with a penetration resistance of less than 2 MPa and 90 % in soils of less than 3 MPa. The ‘lifting driving tool’ can be used as an alternative to the cone penetrometer to assess the cultivation requirements of soils. This equipment can be used to measure the number of impacts of a dropping weight it takes to drive the probe 10 cm into the soil up to a depth of 1.1 m. Tree root development is significantly reduced when greater than between 10 and 15 impacts are required to drive the probe one 10 cm depth increment.

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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 Species and age at planting

Common name	Latin name	Age
Italian alder	*Alnus cordata* Desf.	1/0
Silver birch	*Betula pendula* Roth	½u½
Corsican pine	*Pinus nigra* var. *maritima (*Ait.) Melville	1u1
Japanese larch	*Larix kaempferi* (Lamb.) Carr.	1+1

1/0 = 1 year old (1 year seedling), ½u½ = 1 year old (½ year seedling, undercut in situ), 1+1 = 2 years old (1 year seedling, 1 year transplant), 1u1 = 2 years old (1 year seedling, undercut in situ).

Table 3 Relationships (Root=mMPa+c) between both the number and percentage of tree roots (Root) and the penetration resistance using the cone penetrometer (MPa).

Species	Measure	n	*P*	m	c
Italian alder	Number of roots	6	0.002	-1.701[a]	8.48
Japanese larch	Number of roots	7	<0.001	-1.493[a]	7.854
Birch	Number of roots	8	<0.001	-2.784[b]	13.693
Corsican pine	Number of roots	5	0.038	-0.724[a]	4.24
Italian alder	Percentage	6	<0.001	-4.403[c]	21.56
Japanese larch	Percentage	7	<0.001	-3.756[c]	19.61
Birch	Percentage	8	<0.001	-4.115[c]	20.69
Corsican pine	Percentage	5	0.044	-2.193[c]	14.91

n = number of samples, *P* = *P* value from regression analysis, [a,b,c] denotes significant differences ($P<0.05$) between species

Table 4 Relationships (Root=$10^{m(l+c)}$) between both the number and percentage of tree roots (Root) and the penetration resistance using the 'lifting driving tool' (l).

Species	Measure	n	*P*	m	c
Birch and Japanese larch	Number of roots	12	0.011	-0.0595	1.648
Birch and Japanese larch	Percentage	12	0.008	-0.0595	1.821

n = number of samples, *P* = *P* value from regression analysis

Figure 1 Mean percentage of roots in each penetration resistance class using the penetrometer (n=26; error bars indicate standard error of the mean)

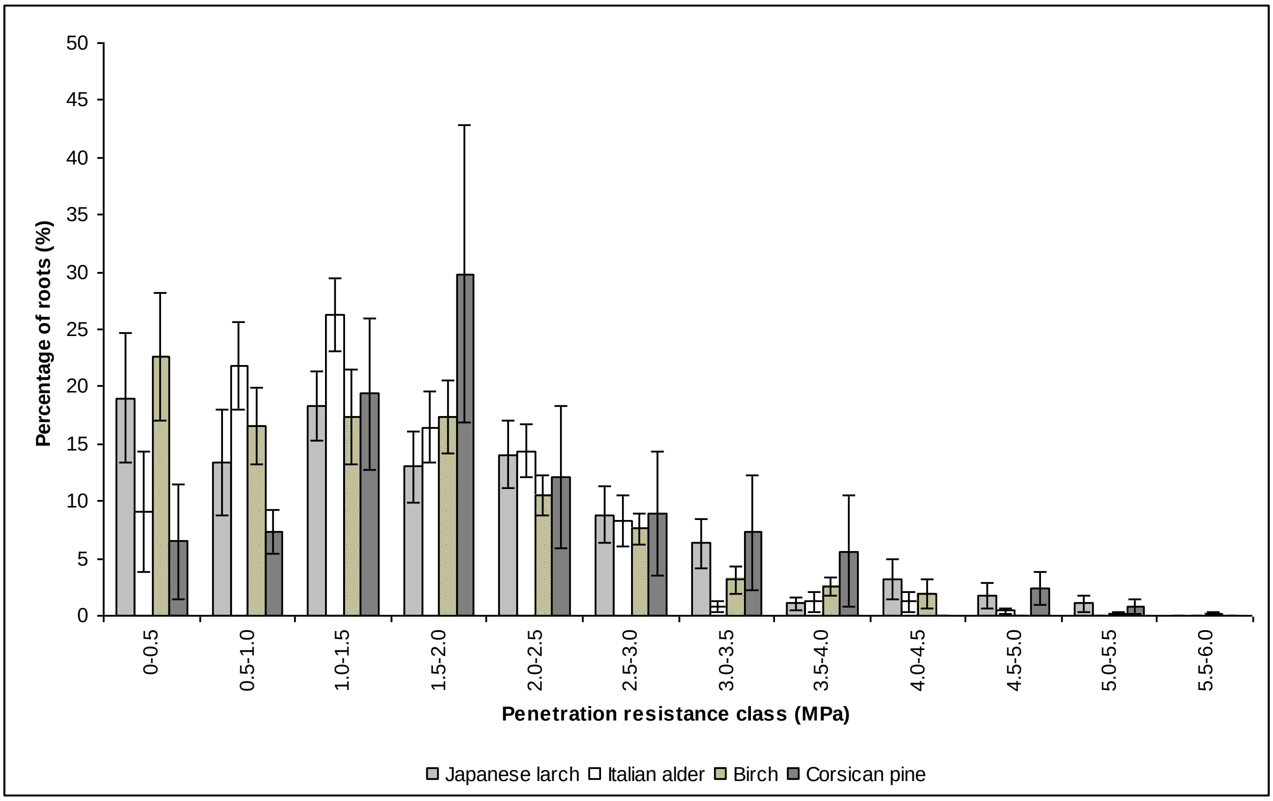

Figure 2 Mean percentage of roots in each penetration resistance class using the penetrometer (n=26; error bars indicate standard error of the mean)

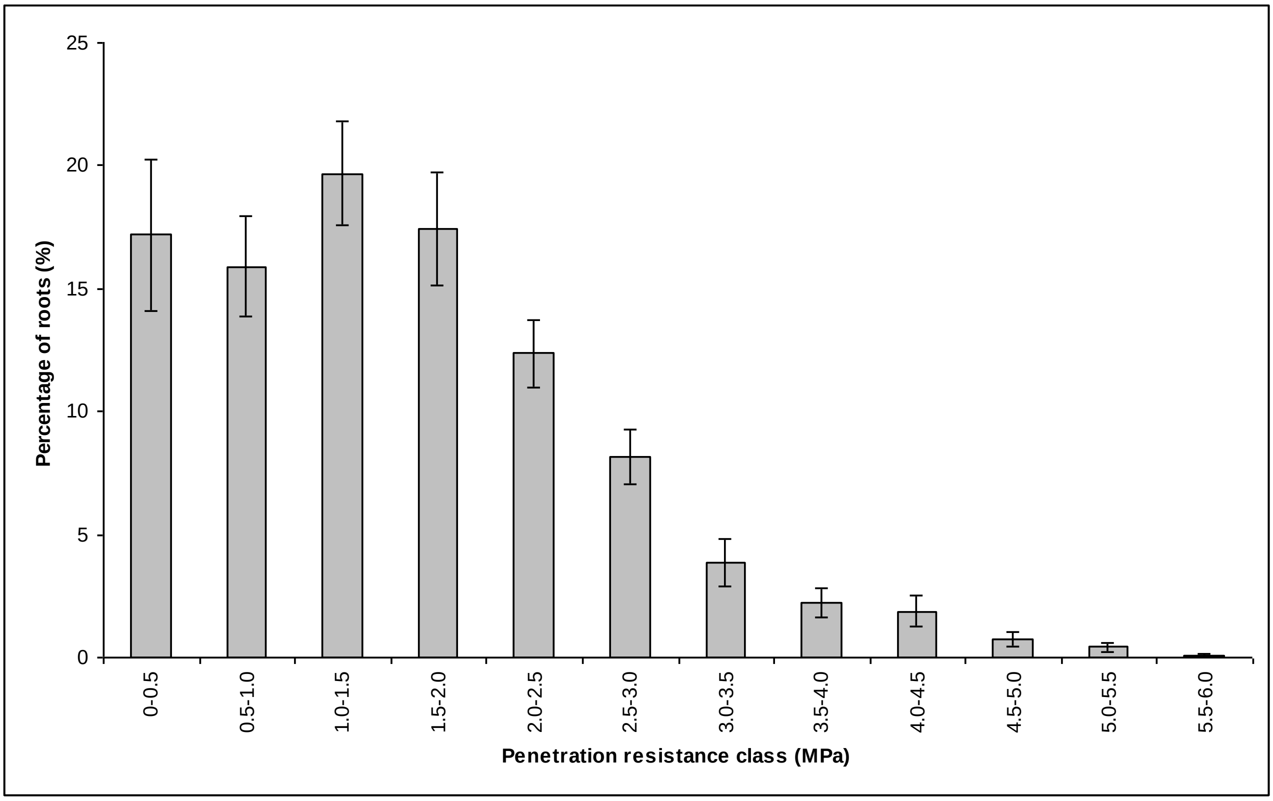

Figure 3 Mean percentage of roots in each penetration resistance class using the ‘lifting driving tool’ (n=12; error bars indicate standard error of the mean)

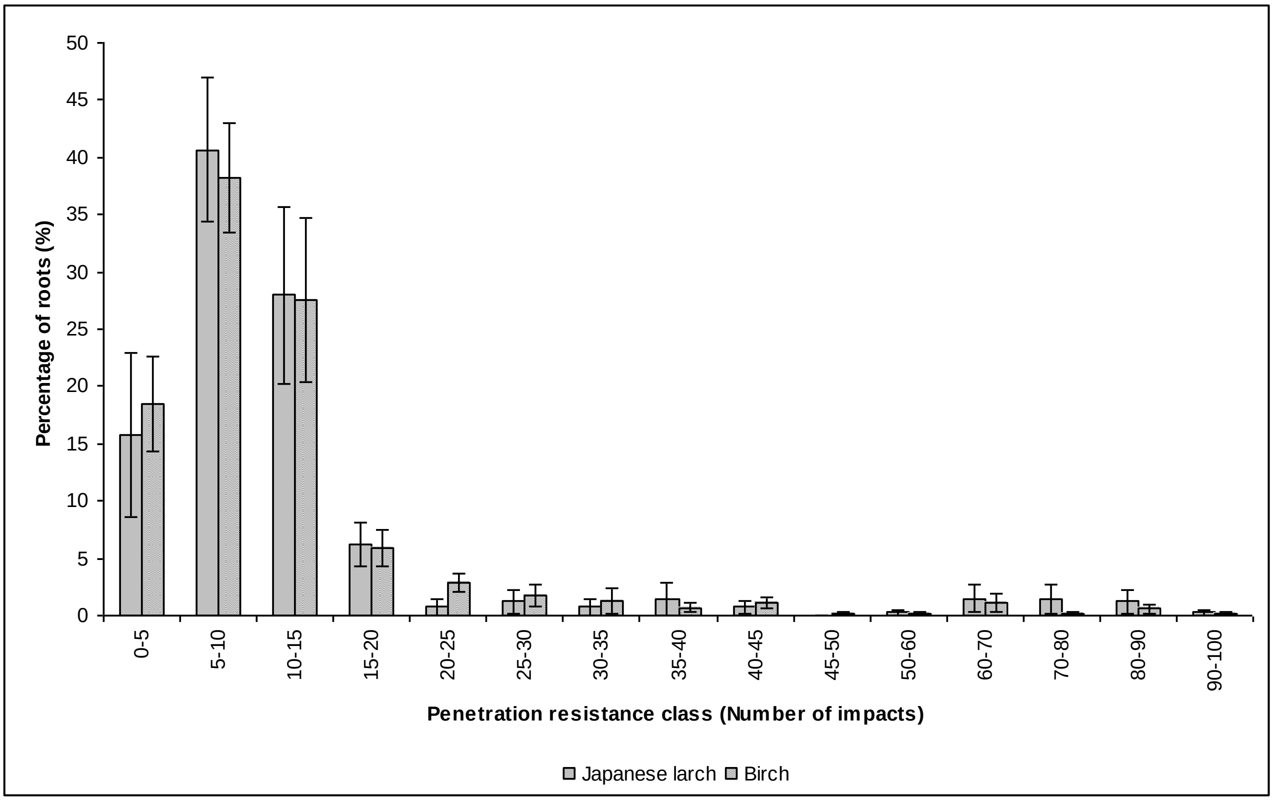

Figure 4 Mean percentage of roots in each penetration resistance class using the 'lifting driving tool' (n=12; error bars indicate standard error of the mean)

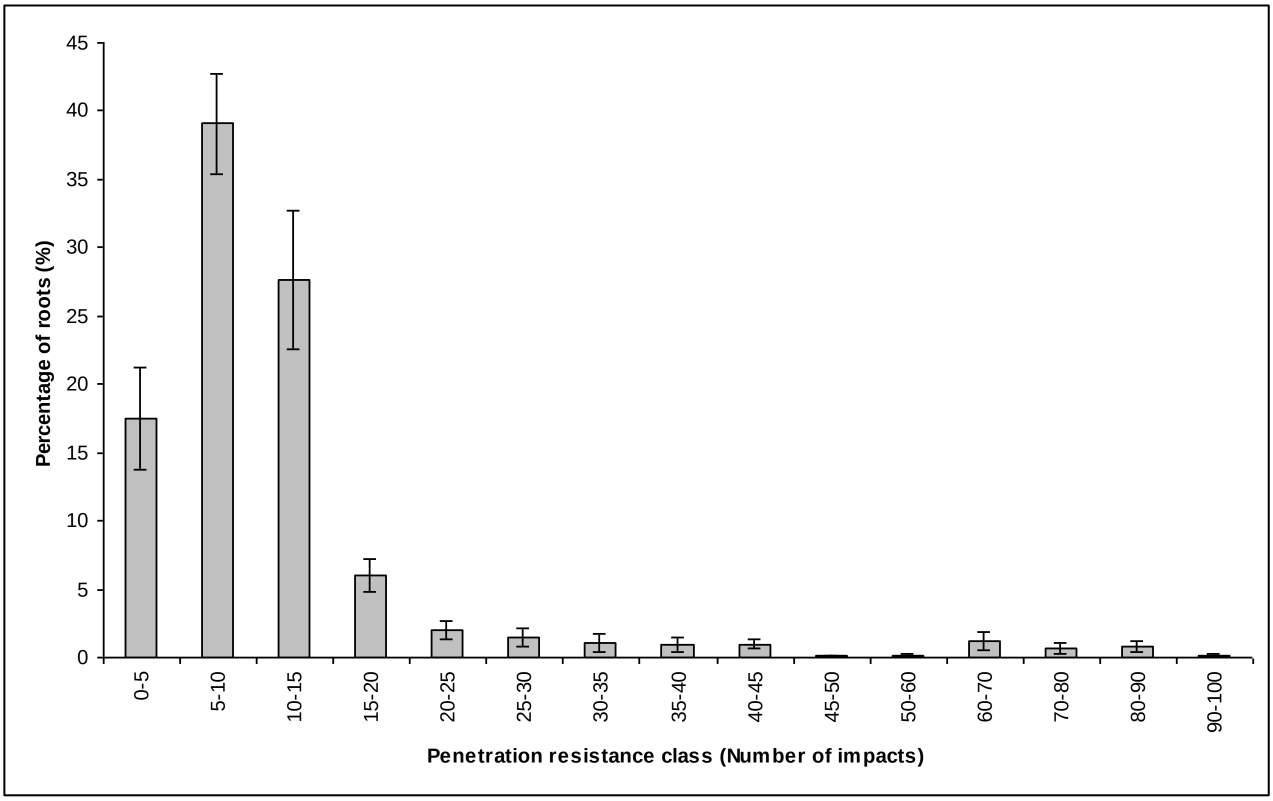

Figure 5 Data and model for penetration resistance measured using the penetrometer versus 'lifting driving tool' (n=34)