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Soil physical factors affecting the growth of sycamore (*Acer pseudoplatanus* L.) in a silvopastoral system on a stony upland soil in North-East Scotland

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Abstract. Tree growth and soil physical properties were compared on two grazed plots planted with sycamore at 5 and 10 m square spacing on an upland Scottish site. Both plots received fertilizer and stocking density of ewes and lambs was adjusted to maintain a constant sward height.

Mean tree height in 1990 and height increment (1988–90) were significantly greater in the 5 m spaced plot ($P < 0.05$). Although matric potential under the trees was generally greater than in the grassed rows between trees, mean penetration resistance (37–107 mm depth) was significantly greater ($P < 0.01$) under the trees. Even when the soil was close to field capacity, less than 10% of penetrometer readings were < 1 MPa under the trees, in comparison to 44% in grassed areas between trees. This demonstrates that surface compaction due to preferential treading by sheep near the base of trees was sufficient to have seriously reduced tree root growth. Penetration resistance under the 5 m spaced trees was significantly less ($P < 0.05$) than under the 10 m spaced trees. A technique for estimating the probability of root deflections by stones (in 35 mm depth intervals), Ps, from penetrometer readings was used. A significant relationship ($P < 0.1$) was found between tree height increment and depth to Ps $\geqslant$ 0.4 in the 10 m plot.

Introduction

Large-scale systems experiments are currently being used to evaluate the applicability of agroforestry systems such as silvopastoralism to UK conditions in a network of sites throughout the UK [Sibbald and Sinclair, 1990]. Preliminary data from one of these sites indicated that there were differences in survival and growth of sycamore (*Acer pseudoplatanus* L.) between treatments with different square spacing (5 and 10 m) [Sibbald et al., 1989]. Since the treatments had similar stocking rates there were four times as many sheep per tree in the widely spaced plots. Although browsing of the above ground parts of the tree was prevented by plastic tree-shelters supported by wooden stakes, shoot damage may have occurred when sheep rubbed against the shelters. Sheep were observed to shelter beside the trees in preference to open pasture and may have damaged tree roots by treading and have restricted rooting conditions by soil compaction. Pressure from grazing animals is known to compact soils and restrict infiltration after rainfall [Linnartz et al., 1966].

Soil compaction reduces porosity, especially macroporosity. For example on a compacted forest soil in southern Australia [Sands et al., 1979] penetration of radiata pine (*Pinus radiate* D. Don) roots was severely restricted above a critical penetration resistance of about 3 MPa. In general, where roots are unable to use soil structural features to bypass the bulk of the soil, soil with a penetration resistance of between 3 and 6 MPa is found to halt root growth and a penetration resistance of 1 MPa is likely to significantly reduce root growth rate [Bengough and Mullins, 1990]. As a result of compaction, soil aeration may be reduced and soil mechanical impedance to root growth is increased. Because of the sandy texture of the soil on the site and its freely draining profile, compaction was not expected to reduce aeration but it might well have significantly increased mechanical impedance.

This paper describes the difference in tree growth between the wide and narrow spaced trees and attempts to relate this to differences in the soil physical properties.

Study site

The site (National grid reference NO670783) is about 38 km south-west of Aberdeen, in north-east Scotland. The study was carried out from August 1990 to June 1991 on two plots, on which there were 4-year-old sycamore trees at either 5 or 10 m spacing (400 and 100 stems/ha) on a regular grid pattern. The site ranges in altitude from about 140 to 205 m. The soils belong to the Strichen Association and Fungarth Soil Series, being freely drained soils developed on glacial till derived from quartz-mica schists [Glentworth et al., 1963]. The soils have an indurated subsoil horizon in some areas, a common feature of free draining soils in north-east Scotland. The indurated layer is hard, dense and compact and is present at a depth of between 34 and 46 cm in the 5 m plot but is not found in the 10 m plot [Lilly, 1988]. Topsoil texture is sandy silt loam overlying fine sandy loam or sandy loam subsoil. The soils have low nutrient and water retention, and are generally moderately stony (15% coarse stones). Profile available water ranged between 54—67 mm and 113—135 mm in the 5 and 10 m plots, respectively [Lilly, 1988].

The trees were planted in early April 1988 as one year old seedlings in rows oriented north to south, east to west (Fig. 1). Trees were planted in pairs at each location (to the east and west of a stake). Each tree was protected by a 1.2 m high plastic tree-shelter (Tubex Ltd, Tannery House, Send, Woking, U.K.) fastened to a central 1.5 m high wooden stake. A second short key stake was used to prevent the shelter twisting. To protect the long term viability of the experiment, additional posts were added to the 10 m plots during the winter of 1989 to give an equivalent number of posts/

ha as in the 5 m plots. These posts allowed additional positions for the sheep to rub against.

The grass sward between the trees was maintained in both plots to a predetermined sward height by adjusting the number of sheep whilst maintaining a core group of 12.5 ewes plus lambs per ha [Maxwell and Treacher, 1987]. A grass-free circle (50 cm radius) of bare ground was maintained at the base of each tree by the use of herbicides. The plots were fertilized uniformly with a compound fertilizer (N:P:K 20:6:6) at 160 kg/ha/annum in four split dressings.

Methods

Tree growth was assessed by measuring tree height and stem diameter. Stem diameter was measured at 20 cm about the soil surface. Three annual height increments were recorded at the annual growth rings visible on the stem. The first growth ring represented the first year's growth after planting in Spring 1988. The second was the height the tree had grown to be the end of 1989 and the third height was the total height of the tree when measurements were carried out in March and April 1991. Tree survival and damage were assessed at the same time.

In the 5 m plot a 72 m transect was chosen and a total of 30 adjacent trees on either side of the transect were selected for penetrometer measurements (Fig. 1). The transect ran across the plot, near its centre, in order to cover a representative area. In the 10 m plot, an area covering about a third of the plot was selected encompassing 30 trees (Fig. 1). On each plot penetration resistance was measured using a hand-held Bush recording soil penetrometer with a cone semi-angle of 15° and base diameter of 12.83 mm [Anderson et al., 1980], at depths of 37, 54.5, 72, 89.5, 107, 142, 177, 212, 247, 282, 317, 352, 387 and 422 mm. Readings were not taken at < 37 mm depth because readings at depths of less than 3 times the probe diameter are unrepresentative [Bengough, 1991]. Penetration resistance was measured at regular intervals both at 30 cm from the base of the trees and in the grassed rows, midway between the lines of trees.

To test for compaction caused by sheep treading preferentially on the soil around the base of the trees, mean penetration resistance at the base of trees was compared to that in the grassed rows, both averaged over the depth range 37 to 107 mm.

To study the effect of surface compaction in more detail a frequency distribution of the proportion of penetrometer readings in 0.5 MPa increments from 0 to 4.5 MPs within the depth range 37 to 107 mm, was plotted for both the driest and wettest series of days. Driest and wettest days were determined from tensiometer data.

The probability of a stone encounter as a function of depth was deter-

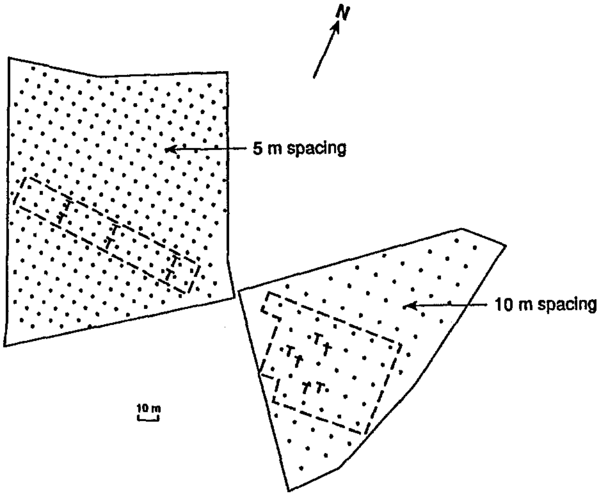

Fig. 1. Plan of the experimental plots showing the position of pairs of trees (•), the 30 trees selected (----) for the study and the position of the tensiometers (T).

mined from the same set of penetrometer readings for each plot. During each penetration stroke, whenever the cone hit a stone, the depth interval of the encounter (e.g. 142—177 mm) was recorded and the penetration was discontinued. There were 600 penetrations per plot but the number of penetrations actually reaching any given depth decreased with increasing depth. Thus the probability of encountering a stone in any 35 mm depth interval was calculated as the total number of stone encounters in that depth interval divided by the total number of penetrations which had reached that depth. The upper limit of the depth interval (e.g. 107, for the interval 107—142 mm) in which there was a probability of 0.4 or more of encountering a stone was calculated for each tree using the ten penetrations that were taken around it. Tree height increment and girth were then regressed against this depth. The value of 0.4 was chosen arbitrarily assuming that, if roots were deflected by stones with a greater frequency (i.e. more than about once every 92.5 mm), then the consequent contortions in their growth pattern would severely restrict the development of the root system.

The soil water regimes in both plots were monitored during the study period using puncture tensiometers. In each plot, three replicate tensiometers were installed at depths of 15 and 25 cm, at 30 cm distance from the base of three trees and at mid-tree spacing. Readings were taken once or twice weekly with a pressure sensor (DTE 1000) usually on the same occasions that penetrometer measurements were made. Results are expressed as hydraulic potential with the soil surface as a reference level. This allows the direction of water flow to be deduced from the difference between 15 and 25 cm tensiometer reading.

Results

Water regime

As expected, when the soil was close to field capacity (around −5KPa), replicate tensiometers always agreed to better than 2 kPa (usually better than 1 kPa). In drier soil the coefficient of variation for replicate tensiometers never exceeded 30%. The tensiometer data (Fig. 2) show that from 23 August 1990, the soil in both plots was drier than field capacity until 25 September 1990. However, it was wetter under the trees than in the rows and the gradient in hydraulic potential indicated that water movement was upwards.

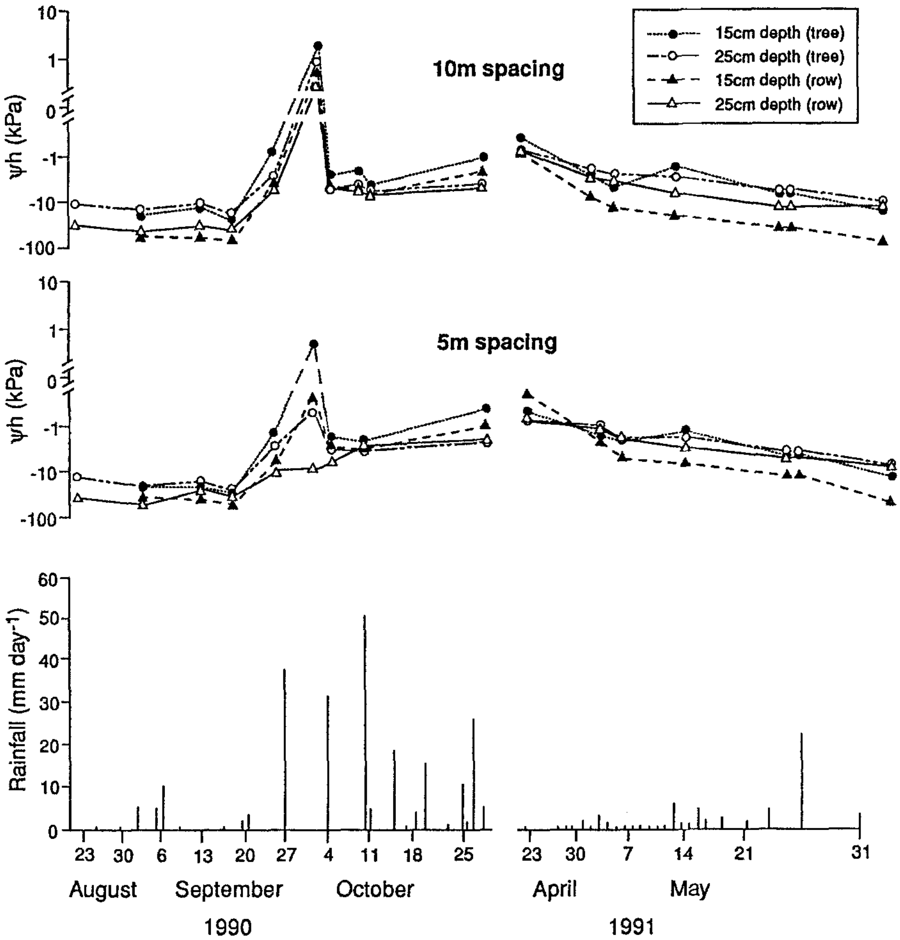

Fig. 2. Rainfall and average hydraulic potentials for the 5 and 10 m spacing plots.

The soil was wetted to around field capacity after rain on 25 September 1990 and it briefly became saturated at 15 and 25 cm depth on 4 October. During the subsequent measurements in October, the profile in both plots was draining as indicated by greater hydraulic potentials at 15 than at 25 cm depth.

During the period from April to June 1991, the soil in both plots was again generally wetter under the trees than in the rows at the same depth.

Tree growth

There was a significant difference between plots ($P < 0.05$) in mean total height of the trees in 1990 and height increment between 1988 and 1990 (Table 1). However, mean height of trees in the 5 m plot was only significantly greater than in the 10 m plot after the 1990/91 growing season and not during the two previous growing seasons.

There was no significant difference in tree girth between the plots.

Table 1. Sycamore growth at 5 and 10 m spacings.

	Spacing	Mean	St dev.	SEM
Height 88 (m)	5 m	0.377	0.066	0.012
	10 m	0.342	0.085	0.016
Height 89 (m)	5 m	0.780	0.186	0.034
	10 m	0.654	0.293	0.056
Height 90 (m)	5 m	1.574*	0.371	0.068
	10 m	1.254*	0.594	0.110
Height Increment	5 m	1.196*	0.345	0.063
(m) 1988–90	10 m	0.926*	0.532	0.100
Girth (mm)	5 m	9.6	0.22	0.040
	10 m	8.2	0.31	0.061

Significant differences ($P < 0.05$) between pairs of means are indicated by *.

Soil surface compaction

The mean penetration resistance was significantly greater ($P < 0.01$) at the base of the trees than in the intermediate rows in both plots. Penetration resistance under the 5 m spaced trees was significantly less ($P < 0.05$) than under 10 m spaced trees (Table 2).

Figure 3a shows that during the wettest days (ie. when the matric potential was close to −5 kPa), the rows had about 16 and 31% of penetration readings less than 1 MPa for the 5 and 10 m plots respectively. In contrast less than 5% of readings were less than 1 MPa under the trees in both plots. These readings represent the percentage of the soil that was relatively easily

Table 2. Penetration resistance at 37—107 mm depth under the trees and grass rows.

Penetration resistance		Spacing	Mean (Mpa)	St dev.	SEM
Trees vs rows	Trees	5 m	2.38**	0.44	0.06
	Rows		2.09**	0.64	0.09
	Trees	10 m	2.55*	0.42	0.06
	Rows		2.24**	0.74	0.10
Trees vs trees		5 m	2.38*	0.44	0.06
		10 m	2.55*	0.42	0.06
Rows vs rows		5 m	2.09	0.64	0.09
		10 m	2.24	0.74	0.10

Pairs of means significantly different $P < 0.05$ and $P < 0.01$ are followed by * and **, respectively.

penetrable by roots. A similar trend was found during the drier days (i.e. at a high potential). There were less than 2% of readings less than 1 MPa under the trees in both plots compared to 8 and 10% in the rows on the 5 and 10 m plots, respectively (Fig. 3b). This contrast is even more striking because the soil was wetter under the trees than in the grass rows (Fig. 2). For both locations and for both moisture ranges, the majority of the readings were within the 1.5 to 3.0 MPa range.

Overall there is strong evidence of increased soil surface compaction at the base of the trees in both plots.

Stone encounters

Figure 4 shows the probability of stone encounters in any 35 mm depth interval, Ps, in both plots as a function of depth. All penetrations that encountered stones within the top 54.5 mm were discarded so this figure is only a meaningful record below this depth.

For each plot, height increment and girth were regressed against the depth at which Ps $\geqslant$ 0.4. There was weak evidence of a relationship ($P < 0.1$) between tree growth and depth to Ps $\geqslant$ 0.4 for trees in the 10 m plot (Table 3).

Discussion

Water regime

During the whole of the measurement period the soil was wet enough to provide favourable conditions for root growth. There was only one brief

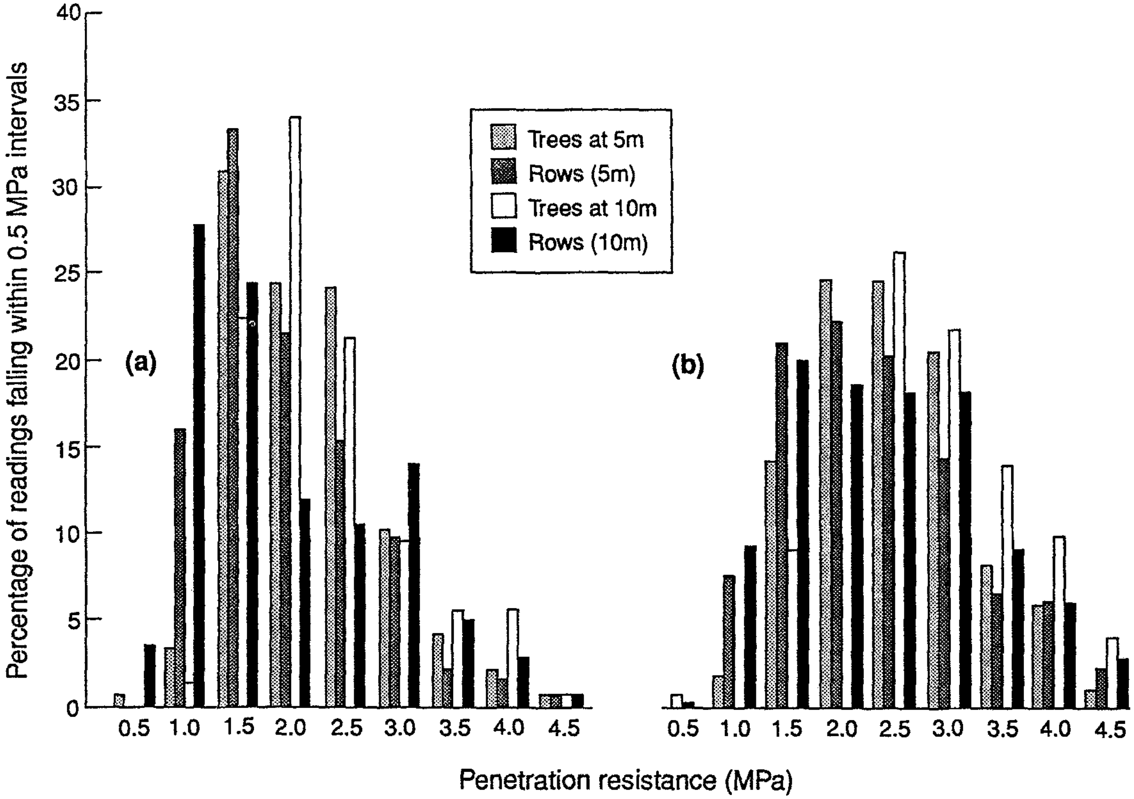

Fig. 3. Percentage of total penetrometer readings in the 37 to 107 mm depth range that lie in 0.5 MPs intervals from 0 to 0.5 up to 4.5 MPa for: (a) sets of readings obtained on the two wettest measurement occasions (matric potential close to −5kPa) and (b) sets of readings obtained on the four driest days (matric potentials between −20 and −50 kPa).

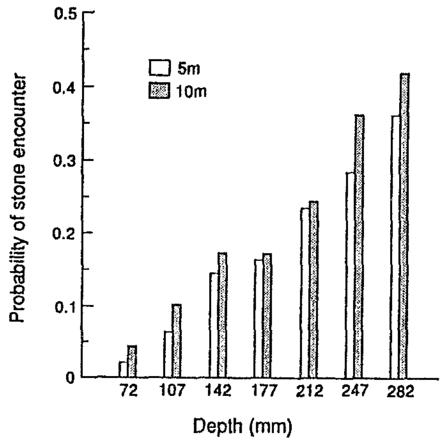

Fig. 4. Probability of a stone encounter in any 35 mm depth interval versus depth for the 5 and 10 m spaced plots deduced from the proportion of penetrations encountering stones at each depth.

Table 3. Sycamore growth (y) in relation to the depth (x) at which there was a probability of 0.4 or more of encountering a stone in any 35 mm depth interval.

	Tree spacing	Regression equation	Correlation coefficient (r)
Height increment vs depth	5 m	y = 0.833 + 0.0022x	0.223
	10 m	y = 0.054 + 0.0074x	0.374*
Girth vs depth	5 m	y = 0.009 + 0.000002x	0.046
	10 m	y = 0.011 − 0.000002x	0.215

Significant ($P < 0.1$) correlation coefficients are followed by *.

period of waterlogging observed, otherwise plots remained drier than −1 kPa even during October 1990 and it is highly likely that the soil was never sufficiently wet for one enough for roots to have suffered from reduced aeration. This is consistent with the soil profile morphology [Lilly, 1988].

Tree growth

On average trees grew taller in the 5 m plot than in the 10 m plot. Despite the difference in the observed mean height, the individual trees in the 10 m plot that grew well performed comparably with those at 5 m spacing.

There are a number of possible explanations for the smaller mean height increment of trees in the 10 m plot including bud damage, root damage and surface soil compaction.

More trees in the 10 m plot, a total of 12 out of 44 trees (27%), had their terminal bud damaged and one of the laterals had assumed dominance. This may have slowed down the normal growth of the tree as the lateral branch assumed dominance. Trees in the 5 m plot had only 7 out of 60 trees (12%) with terminal bud damage. The damage to the terminal bud may have been due to the frequency of sheep damage to the protective shelters which according to [Sibbald et al., 1989], was more severe in the 10 m than the 5 m plots.

Although surface root damage was not assessed, it is possible that the sheep kicked away more soil at the base of these trees and thus exposed their roots to damage by trampling. Roots exposed by sheep scraping at the base of trees has been observed on other sites and in this study, soil surface disturbance was more noticeable at the base of the 10 m spaced trees.

Surface soil compaction

If is often difficult to compare penetrometer results between treatments because the soils may be of different matric potentials. However, although soil at the based of the trees was generally wetter (higher matric potential) than in the grassed rows, the mean penetration resistance was greater under the trees. This demonstrates that significant surface compaction due to treading by the sheep has occurred. Because roots can exploit the pathways of lower resistance it is important to look at the frequency distribution of penetrometer results [Jamieson et al., 1988]. The greater proportion of penetrometer reading less than 1 MPa in the grassed rows (44%) compared to below the trees (10%) even when the soil was close to field capacity (Fig. 3a), is clear evidence that tree root growth is likely to have been quite seriously impeded. These results also suggest that the situation was worse under the 10 m spaced trees and this is supported by the significantly greater average penetration resistance under these trees. Grazing animals are known to use trees, for shelter, and bare ground areas when camping [Arnold and Dudzinski, 1978]. In young but established orchards in the U.K., herbicide use usually resulted in increased bulk density and reduced porosity, leading to lower infiltration rates, possibly as a result of reduced soil organic matter [Atkinson et al., 1985]. The influence of human and/or machinery pressure was not quantified in the latter study so it is not clear if herbicide use *per se* caused this effect.

Stone encounters

Obtaining the probability of stone encounters from penetrometer readings as described is a quick and simple technique which indicates how frequently roots are likely to be deflected. However, since it provides no information on stone size, it does not indicate how big a detour each encounter will force a root to make, nor can it be directly related to the volume fraction of stones in the soil. However if, as our observations suggest, the relative size distribution and orientation of stones did not vary much with depth or across the site, then the volume fraction of stones will be roughly proportional to Ps. There are two ways in which a high stone content may have impaired tree growth. Firstly, it will reduce the soil volume that can store and supply water. Since the soil is fairly coarse textured, the available water capacity was low and a horizon stoniness of say 50% would reduce this by half. Where rooting depth was also limited by an indurated layer then there may have been a variable and, in places, very low profile available water. Although our measurements of matric potential did not show any period when the trees or grass would have been water stressed, they covered only two half-growing seasons. The site has, at other times, experienced drought when the grass has wilted and so the trees may also have been affected at this early stage of growth. Secondly, stones may directly reduce the rate at which the root system can expand, and this could exacerbate any potential drought problems. As roots normally grow around stones, a high probability of stone encounters as found at this site should have a significant effect on root and tree growth. There was a positive correlation between depth to Ps $\geqslant$ 0.4 and height increment on one of the two plots but this was only significant at $P < 0.1$. It seems probable that stoniness was an important factor limiting the growth of trees but has not shown up more clearly both because of the limited nature of our measurements (a maximum of 10 penetrations per tree) and because the depth to Ps $\geqslant$ 0.4 was not sufficiently variable to cause much variation in tree growth.

Figure 3 shows that on both plots there was a clear tendency for the probability of stone encounters to increase with increasing depth. However, although stoniness is likely to have influenced root growth, the similar values of Ps in both plots mean that this cannot be used to explain the observed differences in growth between plots. In the 5 m plot the subsoil horizon had an indurated layer at 37 cm depth which would have further increased the penetration resistance of the soil and may have been completely impenetrable. The effects of this may become apparent in later years when the trees are larger.

Conclusions

In conclusion, both surface compaction by treading and site stoniness are likely to have had and continue to have a significant effect on tree root growth rate and morphology. It is not possible to clearly attribute the difference in tree growth to difference in surface compaction alone although it seems likely that this was an important contributory factor. Better tree survival and faster early tree growth may be best achieved by planting at initially high tree densities. The installation of extra rubbing posts to reduce sheep activity at the base of trees could therefore be a useful ameliorative measure.

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