An Experimental Investigation of the Resistance of Model Root Systems to Uprooting

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The architecture of a tree root system may influence its ability to withstand uprooting by wind loading. To determine how the root branching pattern may alter the anchorage efficiency of a tree, artificial model root systems with different topologies and branching angles were built. The root systems were embedded at various depths in wet sand and the pull-out resistance measured. A model to predict the uprooting resistance from the data collected was designed, allowing predictions of anchorage strength with regards to architecture. The dominant factors influencing pull-out resistance were the depth and length of roots in the soil. The most efficient type of branching pattern predicted by the program was one with an increased number of roots deep in the soil. The optimum branching angle most likely to resist pull-out is a vertical angle of 90° between a lateral and the main axis. The predicted mechanically optimal radial angle between a lateral branch and its daughter is between 0 and 20°. Values of branching angle are compared with those measured in real woody root systems of European larch and Sitka spruce.

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Key words: Root architecture, root anchorage, pull-out resistance, windthrow, Picea sitchensis, Larix decidua.

INTRODUCTION

The type of branching pattern found in the root systems of plants influences their efficiency at exploiting the soil for water and nutrients (Fitter, 1987). Herringbone root systems (where laterals arise off one main axis) are the most effective at resource capture. The nutrient depletion zones around the lateral branches do not overlap to the same extent as would occur in a root system with a more random branching pattern (i.e. with second and third order lateral roots). The architecture of a root system also influences its ability to withstand uprooting. A vertical force is best resisted by a large number of thin fibrous roots which have a large surface area over which tension can be quickly transferred to the soil (Ennos, 1990). Rotational forces transmitted by a tree stem to the roots, e.g. when the stem is loaded under wind, would need to be resisted by a rigid element in the root system such as a tap root with horizontal laterals (Fitter and Ennos, 1989). However, as a tree with a plate system, e.g. Sitka spruce [Picea sitchensis (Bong) Carr.], overturns due to wind loading, the windward roots are held in tension and provide the greatest resistance to uprooting (Coutts, 1983, 1986). Tension is transferred to the soil via friction, therefore a large root surface area on the windward side, over which the load can be distributed, is beneficial for tree anchorage.

Root form is the dominant influence on uprooting resistance (Ennos, 1993). However it is unknown exactly what characteristics best promote tree stability. A symmetric distribution of woody lateral roots around the main axis will make the tree less vulnerable to windthrow (Coutts, 1983). Recent studies on young Sitka spruce grown in a wind tunnel, or mechanically flexed in two directions have shown that there is an increase in the number, size, branching and hence surface area, of windward roots per unit volume of soil (Stokes, 1994; Stokes, Fitter and Coutts, 1995a, b). Tests of anchorage strength showed that resistance of the plants to overturning was also increased. This enhanced stability may have been a function of increased root size, a change in the architecture, or a combination of both.

Another unstudied component which may affect anchorage strength of root systems is the angle of branching between the tap root and primary laterals and between lateral roots. For stems, theoretical branch angles which result in exposure of maximum effective leaf area to sunlight, were close to the values observed in trees of Terminalia catappa (Honda and Fisher, 1978), suggesting that angles can be adaptive. Information regarding root branching angles is scant however, due to the difficulties in quantifying non-woody roots (Fitter, 1987, 1991).

It is important to identify characteristics contributing to tree stability, e.g. whether changes in branching pattern can indeed affect the pull-out resistance of roots. If so, such knowledge can be incorporated into breeding techniques and the development of clones with an increased mechanical
stability, which will be of great economic value on exposed sites with poor soils.

This paper describes experiments on models which simulate the uprooting of a root system with different branching patterns and angles. The relationship between architectural characteristics and anchorage efficiency will be investigated. Predictions of anchorage abilities are made with regard to root architecture.

MATERIALS AND METHODS

Development of the physical model

A series of mechanical tests were carried out on artificial root systems made out of copper coated steel wire, embedded in sand (0.05–2.00 mm in diameter). Steel wire was used because of its strength and stiffness. The lateral roots could also easily be soldered into holes drilled in the main axis. Anchorage was quantified by measuring the maximum pull-out resistance before failure in the sand, thus simulating the behaviour of roots in soil. The tap root was represented by 3 mm thick wire and the laterals by 1.5 mm thick wire, which are typical of roots found in young trees. Three basic types of root systems were developed to determine the pull-out resistance of the following components:

Type of root system: ‘1’ Main axis alone (30 cm long) (Fig. 1A). ‘2a,b’ First order lateral (1° L) roots; one main axis (30 cm long) with two 1° L roots (each 10 cm long), at 90° angles off the base of the main axis (Fig. 1B). ‘3a,b,c’ Second order lateral (2° L) roots; one main axis (30 cm long) with two 1° L roots as above, and one 2° L root (5 cm long) positioned 5 cm along a 1° L root, at one of three angles: (a) 30°, (b) 60° and (c) 90° in the horizontal plane (Fig. 1C).

There were three models of root system type 1, nine of root system type 2 and two of type 3. There were more replicates of types 1 and 2 because variation in the tests of these two types was large compared with that in type 3. The number of tests carried out are given below in the description of root system type. Each root system was tested by putting it into a cylindrical container 30 cm high and 20 cm wide and manually packing damp sand around it, leaving the top 5 cm of the axis exposed. The sand was saturated with water and allowed to drain for 1 h before being sealed in a plastic bag and used as required. The sand in the container was replaced with fresh sand after each series of tests. An Instron tensile testing machine was used to pull each type of model root system vertically out of the sand and measure the force required. The jaws of the Instron were clamped

![Diagram](image_url)

Fig. 1. Artificial model root systems with different branching patterns were pulled out of sand at different depths. Numbers refer to the length of each component of the root system. A, Type 1 is main axis alone; B, types 2 a & b are a main axis with 1° Ls; C, type 3 is a main axis with 1° and 2° Ls at different branching angles (θ).
onto the top 2 cm of exposed axis. The root systems were pulled out of the sand at a speed of 10 mm min⁻¹.

**Root system type 1**

The main axis was buried to a depth of 25 cm and the maximum pull-out resistance measured. Wire cutters were then used to prune the root by 1 cm, and the test was repeated with only 24 cm of the main axis buried. This procedure was carried out until all the main axis had been removed. The test was repeated three times for every length of the main axis, with three model replicates, therefore a total of 225 tests were made.

**Root systems type 2**

In an initial series of tests, a type 2 was buried at a depth of 25 cm and the pull-out resistance measured. Wire cutters were then used to prune the root by 1 cm, and the test was repeated with only 24 cm of the main axis buried. This procedure was carried out until all the main axis had been removed. The test was repeated three times for every depth of the main axis, with three model replicates, therefore a total of 225 tests were made.

**Root systems type 3**

These were buried at a depth of 25 cm and after each test, the depth was decreased by 5 cm intervals until 10 cm below the surface when the intervals were 2 cm. The test was repeated three times at every depth, with two replicates, therefore a total of 78 tests were made per model.

**Herringbone and random branching root systems (types 4 and 5)**

Two more elaborate artificial root systems were developed in order to test whether the amount of force required to pull up a basic root system was linearly related to the depth of that root system in the sand and the number of lateral branches present. The two new model root systems were designed so that they had different branching patterns but a similar surface area. To prevent the sand above a lateral root being broken up by a lateral root higher up the main axis, both models had lateral roots positioned so that there was no root above any other. One model had a typical herringbone pattern (type 4) (Fig. 2) and the other an approximately random branching pattern (type 5) (Fig. 3). Two replicates of each model were made and the root systems were pulled three times out of sand in a container 60 cm high and 20 cm wide. When the complete herringbone root system had been tested, four branches were removed, or ‘pruned’ and the model re-tested with five branches at the top and then with the five branches at the bottom. The randomly branching model was first tested with the 2° Ls at the top of the system and then with them at the bottom.

**Measurement of real branching angles**

Branching angles of woody root systems were examined so that the mean angle could be compared with the branching angles tested with the artificial models. Non-woody roots were ignored as they may have altered their shape on uprooting. One-year-old larch trees were used to measure the angle between the tap root and primary lateral
root (Fig. 4). The remainder of the root system was not woody enough to measure branching angles between lateral roots, so four, 20-year-old, washed Sitka spruce root systems were examined. Sixty branching angles, between the 1° and 2° L roots within 50 cm distance of the stump were measured. Roots which had branched as a result of damage to the apex were ignored, as these form ‘forks,’ i.e. when a third lateral root grows between the first and second order laterals (Wilson, 1970) and the branching angles are therefore very small.

RESULTS

The physical model

Linear relationships were fitted for each experiment. The variance was proportional to the mean, so a square root transformation was used to stabilize the variance. All regressions used a weighting variate, \( W \), defined by:

\[
W = \text{number of replicates/force required to uproot models}
\]

Root system type 1

The main axis slid out of the sand when pulled vertically, and the surface of the sand did not crack as the root was pulled up. The maximum force (N) required to extract the main axis from the sand was 3.65 N at a depth of 23 cm. The longer the main axis, the greater was its pull-out resistance. The regression of mean force against length of the main axis was highly significant (Table 1). However the \( x \)-intercept calculated from the regression equation was 4.0 cm depth in the soil, therefore it can be assumed that the force acting on a model root < 4.0 cm was negligible.

Root system type 2

As the main axis and two lateral roots emerged from the sand, the sand cracked around the lateral roots and some sand was also lifted up with them before dropping off after the lateral roots were clear of the surface. The maximum force required to uproot the root system in the first series of tests, at different depths in the sand, was 30 N at 25 cm below the surface. The regression of mean force against the depth of the lateral roots below the sand surface was highly significant (Table 1). In the second series of tests, where the lateral roots were cut before each uprooting, the maximum force needed to pull the system vertically out of the sand was 16.5 N. The regression of mean force against length of lateral roots was highly significant (Table 1).

Root system type 3

When the roots with 2° Ls were pulled vertically out of the sand, a plate of sand was also lifted up, between the primary and secondaries. This plate was approximately 1–2 cm² when lifted up by roots with branching angles of 30° or 60°. When the lateral roots had a branching angle of 90°, the plate was only 0.5–1 cm². Due to the pressure of the sand acting on the root system, it was very difficult to pull the root systems out of the sand below a depth of 20 cm. Below this point, the wire roots bent downwards and slid out of the sand diagonally, as they were not rigid enough to counteract the resistance of the sand. Consequently, the results below 20 cm deep for roots with 30° and 60° angles, showed a decrease in the force needed to pull the system up and were ignored. The maximum force required to pull each system up was 26 N at 30° and 60°, both at 19 cm depth and 25 N at 90°, 24 cm below the surface. The regression of the mean uprooting force against depth below the surface was significant for each of the three types of root system (Table 1). Further analysis showed that the regression equations were not significantly different between types 3a and b, but that both were significantly different to type 3c (\( F_{1,17} = 52.5, P < 0.001 \)). Therefore, showing that the branching angles experimentally tested, pull-out resistance was enhanced at an angle less than 90°.

Development of the model

A single, simple model which could describe the data from all the experiments was sought. The requirement was that this model used inputs that could be justified on physical grounds. Initially it was considered that there were two independent inputs affecting the uprooting resistance: a depth component (consisting of the total vertical component of root length), and a horizontal component (consisting of the total horizontal component of root length). By simple trigonometry, it can be shown that the total vertical component of root length, \( V \), is the length of the main axis, \( (D_1) \), plus the vertical projection of the 2° L, \([ L_2 \sin(\theta) \])\), so that \( V = D_1 + L_2 \sin(\theta) \). Similarly the total horizontal component, \( H \), is the length of the 1° L (\( L_1 \)) plus the horizontal projection of the 2° L \([ L_2 \cos(\theta) \]), so that \( H = L_1 + L_2 \cos(\theta) \). An initial assumption was that these two inputs acted independently and additively, with an additive constant, \( a \) and appropriate scaling parameters \( b \) and \( c \), so that:

\[
F = a + bV + cH \tag{1}
\]

where \( D_1 \) is the length of the main axis, \( L_1 \) the length of the 1° L, \( L_2 \) the length of the 2° L, \( \theta \) the angle between the 1° and 2° Ls and \( V = D_1 + L_2 \sin(\theta) \) and \( H = L_1 + L_2 \cos(\theta) \).
Table 1. Linear regression equations of force required to uproot artificial root models against their depth in sand compared with linear regression equations predicted by the model. Regressions were fitted with weighting for replicates

<table>
<thead>
<tr>
<th>Root system type</th>
<th>Equation fitted</th>
<th>Intercept A ± s.e. fitted from the uprooting tests</th>
<th>Intercept A ± s.e. predicted by the model</th>
<th>Slope B ± s.e. on 51 d.f. fitted from the uprooting tests</th>
<th>Intercept B ± s.e. predicted by the model</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Main axis (1)</td>
<td>A + B × Depth</td>
<td>−0.591 ± 0.141</td>
<td>−0.653</td>
<td>0.122 ± 0.013</td>
<td>&lt; 0.001</td>
<td>0.118</td>
</tr>
<tr>
<td>Axis with 1° Ls (2a)</td>
<td>A + B × Depth</td>
<td>3.161 ± 0.487</td>
<td>3.351</td>
<td>0.840 ± 0.042</td>
<td>0.004</td>
<td>0.890</td>
</tr>
<tr>
<td>Axis with 1° Ls (2b)</td>
<td>A + B × Length of 1° L</td>
<td>0.216 ± 0.110</td>
<td>0.532</td>
<td>0.696 ± 0.026</td>
<td>0.093</td>
<td>0.586</td>
</tr>
<tr>
<td>Axis with 1° &amp; 2° Ls at 30° (3a)</td>
<td>A + B × Depth</td>
<td>3.140 ± 1.040</td>
<td>4.510</td>
<td>1.196 ± 0.129</td>
<td>&lt; 0.001</td>
<td>1.057</td>
</tr>
<tr>
<td>Axis with 1° &amp; 2° Ls at 60° (3b)</td>
<td>A + B × Depth</td>
<td>3.010 ± 1.050</td>
<td>4.360</td>
<td>1.238 ± 0.130</td>
<td>0.029</td>
<td>0.987</td>
</tr>
<tr>
<td>Axis with 1° &amp; 2° Ls at 90° (3c)</td>
<td>A + B × Depth</td>
<td>4.740 ± 1.040</td>
<td>3.940</td>
<td>0.799 ± 0.119</td>
<td>0.007</td>
<td>0.890</td>
</tr>
</tbody>
</table>

Table 2. Results of the model when eqn (2) is fitted

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Estimate ± s.e. on 59 d.f.</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>−0.653 ± 0.165</td>
</tr>
<tr>
<td>b</td>
<td>0.119 ± 0.0159</td>
</tr>
<tr>
<td>c</td>
<td>0.200 ± 0.0219</td>
</tr>
<tr>
<td>d</td>
<td>0.0386 ± 0.0022</td>
</tr>
</tbody>
</table>

However, this model does not take into account the depth of the lateral roots, as these roots would be supporting a ‘slice’ soil of height $D_1$ and width dependent on the length of the laterals [$L_x + L_y \cos(\theta)$]. This ‘slice’ would have a weight proportional to the total area of the slice, $D_1 \cdot H$.

Again it is assumed that the force is linearly dependent on this weight, with an appropriate scaling parameter, $d$. This gives the following equation:

$$F = a + bV + cH + dD_1 \cdot H$$

(2)

Parameter $a$ has a dimension of force; the scaling parameters $b$ and $c$ have dimensions force/unit length, and scaling parameter $d$ has dimension force/unit area. The parameters of the model were estimated (Table 2) using weighted multiple regression vs. variables $V, H$ and $(D_1 \cdot H)$, using the same weights used to fit the regression lines to the separate experiments (Table 3). The model predictions are generally in agreement with the actual regression lines (Table 1). However, there was significant evidence of lack of fit of eqn (2) as compared with the separate regression lines ($P < 0.001$). This lack of fit was entirely caused by the results from root system 2b, which behaved differently from the other root systems (a direct comparison could be made between root system 2a and root system 2b at $D_1 = 10$ and $L_1 = 20$; the observed values are 12.6 and 14.6, respectively; the corresponding fitted values using separate regression lines are 11.6 and 14.1); when root system 2b was removed from the analysis there was no evidence of lack of fit of eqn (2). There is no obvious reason for the different behaviour of root system 2b so the results from it were included in the model parameter estimation for the sake of completeness. As the model has inputs that can be justified on physical grounds, it could reasonably be considered to have a wider applicability and can be used to explore branching systems of this type in more detail. One immediate prediction is that root systems 2a and 3c will behave identically, except that the forces for type 3c are increased by an amount 5b ($= 60$ N).

Table 3. Values of intercept and slope predicted by eqn (2)

<table>
<thead>
<tr>
<th>Root system type</th>
<th>Intercept A</th>
<th>Slope B</th>
<th>Values of fixed measurements</th>
</tr>
</thead>
<tbody>
<tr>
<td>Main axis (1)</td>
<td>a</td>
<td>b</td>
<td>$1° L = 0$; $2° L = 0$</td>
</tr>
<tr>
<td>Axis with 1° Ls (2a)</td>
<td>a + 20 × c</td>
<td>b + 20 × d</td>
<td>$1° L = 20$; $2° L = 0$</td>
</tr>
<tr>
<td>Axis with 1° Ls (2b)</td>
<td>a + 10 × b</td>
<td>c + 10 × d</td>
<td>$D = 10$; $2° L = 0$</td>
</tr>
<tr>
<td>Axis with 1° &amp; 2° Ls at 30° (3a)</td>
<td>a + 5 × sin (30) × b + [20 + 5 × cos (30)] × c</td>
<td>b + [20 + 5 × cos (30)] × d</td>
<td>$1° L = 20$; $2° L = 5$</td>
</tr>
<tr>
<td>Axis with 1° &amp; 2° Ls at 60° (3b)</td>
<td>a + 5 × sin (60) × b + [20 + 5 × cos (60)] × c</td>
<td>b + [20 + 5 × cos (60)] × d</td>
<td>$1° L = 20$; $2° L = 5$</td>
</tr>
<tr>
<td>Axis with 1° &amp; 2° Ls at 90° (3c)</td>
<td>a + 5 × b + 20 × c</td>
<td>b + 20 × d</td>
<td>$1° L = 20$; $2° L = 5$</td>
</tr>
</tbody>
</table>
Maximum resistance occurs at a radial angle of $\theta = 20^\circ$ between 1° and 2° L roots. The mean root branching angle calculated from the 60 1° and 2° Ls of mature Sitka spruce measured, was $58 \pm 13.6^\circ$.

**DISCUSSION**

In all the tests with the artificial root systems, resistance to uprooting increased with depth in the sand. The graphs of uprooting curves were all linear for the first 20 cm below the sand surface except for that of the main axis. One resisting force acting on the main axis alone was friction between the wire and the sand. This force may have been weaker in the top 4 cm of sand because of differences in the strength of the root-sand bond, as the sand was more difficult to pack around the small amount of buried axis. The root-soil bond is an important factor in resisting uprooting (Waldron and Dakessian, 1981). However, a more important factor contributing to the root pull-out resistance was the shear strength of the soil. According to Mohr–Coulomb’s law of soil mechanics, soil shear strength increases with the pressure which the shear surfaces exert on one another. Therefore, the sand strength would increase with depth, due to the increase in friction and hence cohesion, between the sand particles (Mattheck, 1993).

The optimal radial branching angle between daughter laterals, predicted from the computer program was less than 30°. As the root systems were pulled upwards, a bending moment was set up at the junction of a 1° L and the main axis, causing the 1° Ls to be placed in tension along with 2° Ls with small branching angles. Roots held in tension play a major role in resisting the uprooting of trees (Coutts, 1983, 1986). Daughter laterals with larger branching angles, i.e. > 45°, would be placed in torsion and therefore offer less resistance to uprooting.

The length of a lateral branch is a key component of anchorage. The vertical branching angle between the main axis and the 1° L will alter the projected length of that branch. Consequently, a lateral at 90° to the tap root which is the same length as a lateral at 45° will be better anchored because the surface area of the soil above the latter be reduced. Mechanically, therefore, the optimum vertical branching angle for primary lateral roots would be 90° to the tap root. When the strength of the sand above the 1° L exceeded the strength of the root, the artificial roots to began to bend and the joints broke. Steel is four times stronger in tension than dry Sitka spruce wood and fifteen times stiffer (Gordon, 1968). Woody roots of the same diameter would therefore bend sooner than steel wire, reducing the vertical branching angle to the main axis.

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**Table 4. A comparison of predicted and mean observed values of pull-out resistance for different types of branching pattern**

<table>
<thead>
<tr>
<th>Type of branching</th>
<th>Predicted value (N)</th>
<th>Observed value (N)</th>
<th>± Standard deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Complete herringbone</td>
<td>68.9</td>
<td>72.3</td>
<td>2.0</td>
</tr>
<tr>
<td>Herringbone with lower four branches removed</td>
<td>31.1</td>
<td>31.5</td>
<td>2.5</td>
</tr>
<tr>
<td>Herringbone with upper four branches removed</td>
<td>49.0</td>
<td>48.5</td>
<td>6.5</td>
</tr>
<tr>
<td>Complete random, with 2° Ls at the top</td>
<td>55.3</td>
<td>61.0</td>
<td>—</td>
</tr>
<tr>
<td>Complete random with 2° Ls at the bottom</td>
<td>61.0</td>
<td>61.0</td>
<td>—</td>
</tr>
</tbody>
</table>

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**Fig. 6.** The mechanically ‘optimal’ branching angle, predicted by the computer program. Maximum resistance occurs at a radial angle of $0^\circ$–$20^\circ$ between 1° and 2° L roots.

**Fig. 7.** The branching angle between the main axis and 1° L roots decreases with depth below the soil surface. $r^2 = 0.08$, $P < 0.001$, $y = -0.49 + 98.16$.
The results of the tests carried out show that whilst an increase in root surface area influences uprooting resistance, the depth of the root system in the soil is more important in determining its anchorage. The longer the root, the greater the shear resistance of the soil (Waldron and Dakessian, 1981). A large root surface area will also transfer tension more rapidly to the soil. However if there are too many roots in a small space (as with 2° and 3° Ls), the soil surrounding the roots may fail and the roots will come up surrounded by a block of soil (Broms, 1964). The branched structures were more difficult to uproot at greater depths than those without branches. A main axis at a depth of 10 cm, with two branches, each 10 cm long was approximately six times more resistant to uprooting than the same structure at a depth of 2 cm. However, a main axis without branches at a depth of 10 cm was only 0.6 times more resistant than at a depth of 2 cm. Broms (1964) calculated that soil will resist the lateral movement of vertically positioned piles up to 9 cu, where cu is the cohesive strength of the soil. At low load levels, the deflections of laterally loaded piles increase linearly with the applied load. However, as the ultimate capacity is increased (9 cu), deflection or failure of the pile can occur very rapidly.

The mean vertical branching angle for European larch primary laterals in the top 4 cm of tap root was 89°, which is close to the optimum predicted by the model, i.e. 90° for vertical pull-out resistance. Although trees are seldom, if ever, pulled vertically, a tree with horizontal laterals at 90° to the tap root will probably also resist rotational movement best because the horizontal laterals resist tension and keep the tap root vertical (Fitter and Ennos, 1989).

The lateral roots further down the tap root grew at a more acute angle to the main axis (66±20°). Fitter (1987, 1991) has predicted that the optimum branching angle, in terms of nutrient capture, after emergence of a daughter root from the epidermis is the one which allows it to reach the outer shell of the parent root’s depletion zone the fastest. In the case of an actively growing root system, this would mean roots with branching angles greater than 75°. The actual optimum angle depends on the age and growth rate of the parent root and the diffusivity of a local limiting resource. Therefore the mean radial angle of 58° found in mature root systems of Sitka spruce and the lower vertical angle found when laterals emerge further down the tap root, suggest that the depletion zone, growth rate and resource diffusivity may have altered so that more acute angles are required to escape the depletion zone.

The models can be criticized for their artificiality. Steel wire is very unlike woody material; the type of sand used is not typical of most soils; and a more sophisticated control of compaction and moisture content could be achieved. The model could be extended by using different artificial materials to simulate roots, but also by investigating the processes of failure in real roots, which have a different strength and stiffness to steel wire. Real root systems could be treated in a similar way to the wire roots, pruning them to test different branching patterns. The horizontal movement of root systems through soil could also be investigated, where tension and compression forces interact to provide resistance to overturning.

The model which describes the interaction between the force applied and the root structure has been developed to be, as far as possible, a sensible description of the relationship. The model parameters have, of necessity, been estimated using the measured results from the different root systems, and the model predictions for this set of data are reasonably close to the observed ones. Therefore, confidence can be had in the model, as an inappropriate model would not be capable of producing sensible predictions of the observed results. Obviously, the parameters of the model will change for different soil types and densities but, hopefully, the general form of the relationship will be widely applicable.

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LITERATURE CITED


