

WIND STABILITY OF TREES ON SLOPES

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Abstract

Windthrow risk assessment models, such as ForestGALES used by the British forestry sector, have the ability to predict the occurrence of wind damage in a wide range of conditions. These predictions are based on good understandings of wind regimes, of the effects of topography on wind flow, and of the effects of soil type, drainage, and cultivation on tree anchorage. However, they do not take into account the possible effects of the slope of a terrain on tree anchorage and critical wind speeds.

Sitka spruce trees were pulled over with a winch on a 30-degree slope in Leanachan Forest, Scotland. Maximum resistive moments of trees pulled up, down, and across the slope and of trees from a control plot on flat ground were calculated and compared. There was no overall difference in anchorage between trees on slopes and on the horizontal, but trees pulled up slope required a greater overturning moment than equivalent trees pulled down slope.

A mechanistic model was constructed of tree anchorage on slopes adapted from the Blackwell, Rennolls and Coutts tree anchorage model. Results from the tree-pulling study were used as input for the model and the model was run to resolve the components of anchorage of trees on slopes. The model revealed that the turning moment due to root weight appeared to be more important for trees pulled down the slope than for the trees pulled up-slope. There was however a higher resistive moment attributable to the roots under tension for the trees pulled up-slope. The implications for windthrow prediction are discussed.

Introduction

Windthrow in forests located on complex terrain is notoriously difficult to predict (Quine 1995, Gardiner and Quine 2000). Patterns of wind flow can be modelled using sophisticated air flow models (Gardiner and Quine 2000), or recorded over extended periods of time using anemometers or tatter flags (Quine and White 1994). However, even though these methods can now be used to predict the return times of damaging winds in a particular topographic location, there is insufficient information about tree development and anchorage on slopes for us to make accurate windthrow predictions. In the absence of empirical data on tree development and anchorage on slopes, existing windthrow models such as ForestGALES (Gardiner and Quine 2000) assume that there is no difference between trees on the horizontal and on slopes. As windthrow is common in mountainous regions, it is important that we examine the effects of slope on tree development, anchorage and stability in order to refine our predictive models. In this paper we test the hypotheses that *anchorage of trees is reduced on slopes compared to those grown on horizontal sites* and that *the anchorage of trees is related to the direction of overturning*.

Coutts (1986) separated the mechanical components of tree anchorage into soil-root plate weight, resistance to bending of the root-soil plate at the hinge, pull-out resistance of windward roots, and strength of the soil under the plate. The moment of overturning resulting from these components is scaled by the position of the hinge point on the leeward side of the root-soil plate. However, the relative importance of these components has not been investigated for trees grown on slopes.

We present here results of an experiment where trees grown on a 30° slope were mechanically overturned and their resistance to overturning compared to that of nearby trees grown on a horizontal area with the same soil. A model was developed of the components of anchorage of trees on slopes, adapted from the Blackwell, Rennolls and Coutts (1990) tree anchorage model. The model was run using data from the field experiment to permit an investigation of the effects of slope on individual anchorage components.

Methods

Tree pulling experiment

Thirty-six Sitka spruce trees were pulled over in Leanachan Forest near Fort William, in the west of Scotland (Lat/Long: 56° 51.8' N 4° 57.7' W). The site was a uniform slope between 26° and 33°, 300 m long and 25 m deep with horizontal areas at top and bottom. The soil was a free draining brown earth. Trees were planted on this site in 1962. At the time of this investigation, tree heights were between 25 and 30 m, and mean diameter at breast height (dbh) was 23.4 cm.

In each of three slope plots we pulled over a total of nine trees; one dominant, one co-dominant and one sub-dominant tree in each of three directions, up-slope, down-slope and across-slope. In the horizontal control plot we also overturned nine trees; three dominant, three co-dominant, and three sub-dominant, in random directions.

Trees were selected, numbered labels fixed to each tree base on the up-slope side and digital inclinometers were fixed at the base and at half tree height. Neighbouring trees were felled where necessary to avoid obstruction. A chainsaw powered winch was attached to the anchor tree using a strop and a load-cell was positioned on a 8 mm steel cable between the anchor tree and the winch. The inclinometers and load cell were connected to a data logger. The pulling cable was fixed to the tree with a nylon sling placed on tree at approximately half tree height. The distance and angle of inclination were then recorded from the winch attachment point to the base of the pull tree. The tree was then pulled over using the winch and the maximum load and angles from both inclinometers was recorded at the time that the maximum load was reached. The height of the winch-cable attachment point, height of both inclinometers, lowest live branch whorl position, and tree height were then recorded on the stem. Stems were measured and a section weighed for stem density, volume, and mass calculations. Root-soil plate dimensions were then measured, i.e. width, depth (3 points), top to stem centre, and stem centre to root hinge.

Data analysis

For each tree, the positions (x,y coordinates in the vertical plane) of the anchor tree, the hinge, the attachment point, and the centre of gravity of the tree were all determined for the time when the maximum load was reached. From these, the complete lever arm (stem plus part of the root-soil plate) and an accurate measurement of the angle of the pull cable at maximum load were calculated. The stem and root-soil plate were considered to be rigid for the purpose of this calculation. Only the trees that were overturned were included in the analysis (i.e. snapped trees were excluded), and the hinge distance treatment average was used for three trees for which the hinge distance could not be measured on site.

A linear statistical model was developed in order to determine how the different treatments influenced tree anchorage. Orthogonal contrasts were used to compare:

1. The turning moment required to overturn trees on flat ground or on a slope.
2. The turning moment required to overturn trees up and down slope.

Because the strong relationship with critical overturning moment has been well established in other studies (Fraser and Gardiner 1967, Gardiner et al 1997, Meunier et al 2002), stem weight was also included in the statistical model.

Mechanistic model

A simplified static version of the tree anchorage model described by Blackwell et al (1990) was developed in order to investigate the results of the tree pulling experiment in more detail. The stem and root plate are represented as a rigid lever rotating around the hinge. Four turning moments (Nm) are considered to act at the hinge point during the overturning: the turning moments applied by the wind (M_{wind}), the weight of the leaning stem and crown (M_{sw}), the weight of the root-soil plate (M_{rw}), and the resistance of the soil and roots in tension (M_{spring}). The later is represented as acting like a single spring attached between the edge of the root-soil plate and the edge of the resulting crater. We assume that it is stretched inside its elastic deformation limit. The cable attached to the tree during the pulling test represents the static effect of the wind. We ignored the resistance of roots at the hinge as Coutts (1986) showed that this effect reached an insignificant level when the applied force was at a maximum.

As expressed by the following equation, M_{spring} and M_{rw} normally act in opposition to both M_{wind} and M_{sw} when the tree reaches a critical deflexion at which it overturns.

$$M_{wind} + M_{sw} = M_{rw} + M_{spring}$$

The following equations describe how each component of M_T were calculated:

$$M_{wind} = F_{horiz} [h_f \cos \alpha + l_h \sin(\alpha + \beta)] + F_{vert} [h_f \sin \alpha - l_h \cos(\alpha + \beta)]$$

where F_{horiz} and F_{vert} are the horizontal and vertical components of the force applied by the cable, h_f is the pull height, l_h (m) is the length of the hinge, α (degrees) is the angle of deflection of the root plate and β (degrees) is the slope angle.

$$M_{rw} = m_r g \frac{l_r}{2} \cos(\alpha + \beta)$$

where m_r (kg) is the mass of the root-soil plate, g (9.81) is the gravitational constant, and l_r is the total length of the root plate from the edge of the windward side to the hinge. It is assumed that the plate has no depth and is homogenous.

$$M_{springs} = kl_r^2 \sin \alpha$$

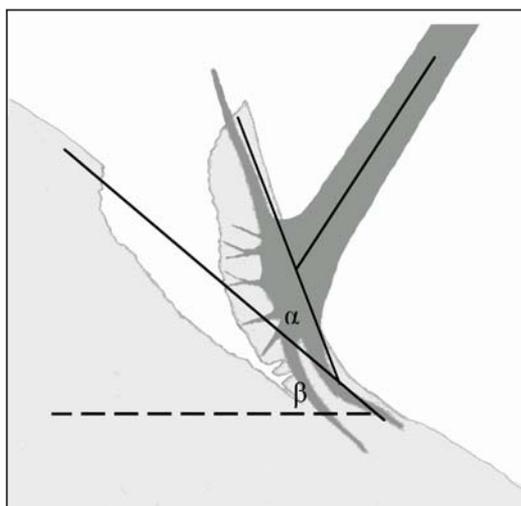
where k is the root and soil spring constant.

$$M_{sw} = m_s g [l_h \cos(\alpha + \beta) - h_c \sin(\alpha)]$$

where m_s is the tree weight and h_c is the height of the tree's gravity centre. Figure 1 illustrates the angles input in the model.

The model was run for each overturned tree from the Leanachan experiment. The equations were solved for k at the time at which the maximum turning moment was applied. All other variables needed to solve the equations were available from the measurements made on the site.

Fig. 1. Model input angles for tree overturning



Results

Tree pulling experiment

A strong relationship existed between the overturning moment and the stem weight of the tree. Ignoring the treatments and fitting a simple linear regression model gave a p-value <0.001 and a R^2 of 0.73. The intercept of the linear regression was not different from zero ($p=0.96$) and consequently this and subsequent treatment regressions were restricted to pass through the origin.

To examine if there was any effect of the slope treatments on the observed overturning moments, individual regression lines were fitted for each slope treatment; horizontal, across, down, and up slope (Figure 2).

For a given stem weight, the overturning moment was similar between trees growing on horizontal ground and those growing on slopes; average of across, down, and up slope ($p=0.98$). However, a smaller turning moment was required to overturn a tree pulled down the slope in comparison to an upward direction ($p<0.05$). The difference was in the order of 25%.

Mechanistic model

Figure 3 shows how the model separated the critical overturning moments into individual anchorage components, using all data. On average, the moment due to the overhanging

weight of the tree represented 14% of the moment applied by the wind whilst the resistive moment due to the weight of the root-soil plate represented 24% of the resistive moment due to the wind. There was a linear relationship between each turning moment and stem weight.

Fig. 2: Measured critical turning moments as functions of stem weight for each treatment

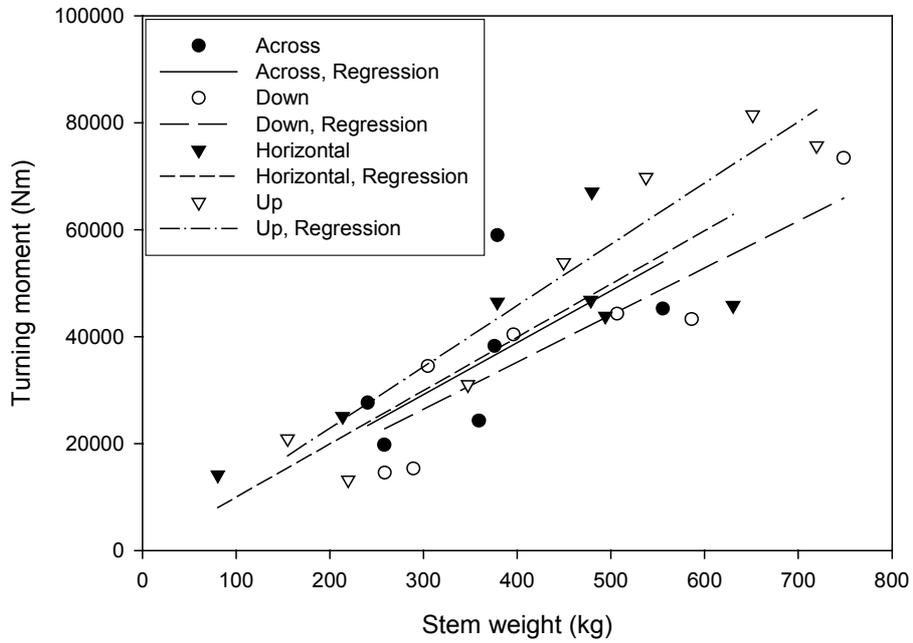


Fig. 3: Modelled turning moments as functions of stem weight

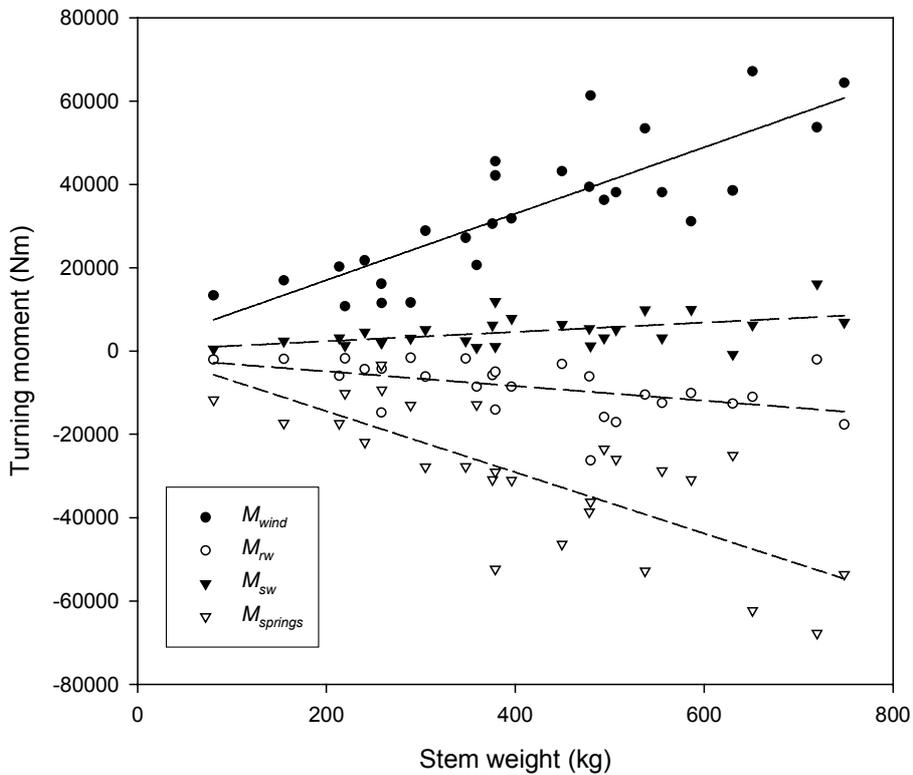
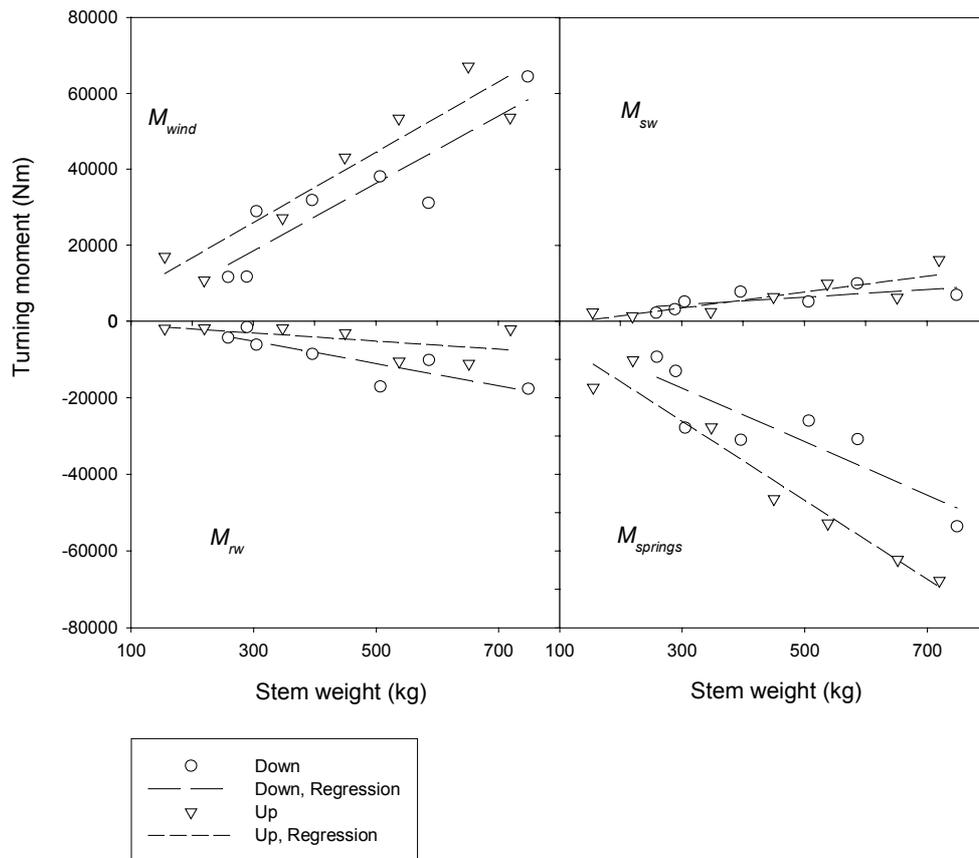


Figure 4 shows the modelled components of critical overturning moments for the two treatments that were significantly different from each other; the trees pulled up and down the slope. The turning moment due to root weight appeared to be more important for the trees pulled down the slope than for the trees pulled up. This effect was however overshadowed by a higher resistive moment attributable to the root springs of the trees pulled up the slope.

Important variation was observed between the values of k (the spring constant) calculated for each tree, and their values were not significantly related to the applied overturning moments from the empirical study ($p=0.08$). Deflection of the root plates were also not significantly related to the measured applied moments ($p=0.90$).

Fig. 4: Modelled turning moments as functions of stem weight for trees pulled up and down-slope



Discussion

Trees in this study were more resistant to overturning when pulled up-slope than down-slope. Analysis of these data using our mechanistic model suggested that the higher turning moment required to overturn trees up-slope was attributable to a better root anchorage. We suggest two possible explanations for this. Firstly, there may be more efficient root development down the slope, meaning that trees pulled up slope would benefit from better windward anchorage (Coutts 1986). Secondly, improved structural root development on the up-slope side would move the hinge point further from the tree and increase the resistive turning moment. Ongoing work by the Forestry Commission is investigating the effect of the slope on root architecture of the same trees.

The long-term objective behind the development of our model is to enable prediction of tree anchorage in conditions for which no empirical assessment has been made. For the model to be used in this manner, we would need to be able to predict how the input variables are affected by different rooting conditions or silvicultural practices. Whilst this may be possible for a number of the variables, evidence from this study suggests that predicting root spring constants could prove difficult. An important step will be to increase our understanding of how the windward roots behave when a turning moment is applied to the stem. Spring constants calculated by our model were not significantly related to measured applied moments. This may be attributable to a poor representation of root displacement by stem deflection (Coutts 1986), and also to our representation of root and soil strength as a single spring. In the next version of the model this will be separated into springs for windward roots and for soil and root resistance under the plate. The lee-side roots resistance to bending will be represented by a torsion force at the hinge.

The impact of the difference in anchorage between up-slope and down-slope overturning is hard to assess because slopes also affect wind flow. Trees exposed to strong down-slope winds, for example on the lee-side of a crest, may have a higher risk of windthrow. However, in most areas up-slope winds would be expected to be stronger than down-slope winds, and predictions of windthrow risk must take into account such differences. As tree roots are known to develop unevenly in response to wind action (Nicoll and Ray 1996), the differences we have observed in anchorage may result from such adaptive growth. Analysis of the root systems from this study will reveal if observed differences in up and down-slope anchorage result from uneven structural root development.

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References

- Blackwell, P.G., Rennolls, K., Coutts, M.P., 1990. A root anchorage model for shallowly rooted Sitka spruce. *Forestry* 63, 73-91.
- Coutts, M.P., 1986. Components of tree stability in Sitka spruce on peaty gley soil. *Forestry* 59, 173-197.
- Fraser, A.I., Gardiner, J.B.H., 1967. Rooting and stability in Sitka spruce. 40. 28 pp., Forestry Commission, London.
- Gardiner, B.A., Quine, C.P., 2000. Management of forests to reduce the risk of abiotic damage - a review with particular reference to the effects of strong winds. *For. Ecol. Manage.* 135, 261-277.
- Gardiner, B.A., Stacey, G.R., Belcher, R.E., Wood, C.J., 1997. Field and wind tunnel assessments of the implications of respacing and thinning for tree stability. *Forestry* 70, 233-252.
- Meunier, S., Ruel, J.-C., Laflamme, G., Achim, A., 2002. Résistance de l'épinette blanche et du sapin baumier au renversement. *Can. J. For. Res.* 32, 642-652.
- Nicoll, B.C., Ray, D., 1996. Adaptive growth of tree root systems in response to wind action and site conditions. *Tree Physiology* 16, 891-898.
- Quine, C.P., White, I.M.S., 1994. Using the relationship between rate of tatter and topographic variables to predict site windiness in upland Britain. *Forestry* 67, 245-256.
- Quine, C.P., P. Bell, A. Mackie, 1995. Use of geographic information systems in windthrow studies. Forestry Commission report on forest research 1995 37-38.