International Conference ‘Wind Effects on Trees’
September 16-18, 2003, University of Karlsruhe, Germany

NUMERICAL ANALYSIS OF THE ANCHORAGE OF MARITIME PINE TREES IN CONNECTION WITH ROOT STRUCTURE

Fourcaud T. [1]**, Danjon F.**[2] **and Dupuy L.**[3]

[1]CIRAD-Amap, LRBB UMR CNRS/INRA/Univ. Bordeaux I, Domaine de l’hermitage, 69 route d’Arcachon, 33612 Cestas Cedex, France
[2]INRA, Unité de Recherche Forestière, Cestas, France
[3]IDF, LRBB UMR CNRS/INRA/Univ. Bordeaux I, France

Abstract

The mechanical structure of 24 root systems was studied in 50 year old Maritime pine (*Pinus pinaster* Ait) trees after the 1999 storm, which resulted in the loss of >4 million hectares of forest in south-west France. Half of the study trees had been uprooted during the storm and the other study trees were left standing. Topology and geometry of the root systems were measured using a 3D digitising device. The spatial distribution of roots was then analysed. The 3D representation of each root system was used to calculate the mechanical behaviour of the structure in different compass directions, using a finite element model. Results show that resistance to windthrow can be provided by four different structural adaptations of root systems, and that root architecture may explain half of the sensitivity to uprooting. There was no significant difference in uprooting resistance between trees that were damaged by the storm, and those which remained upright. However, all root systems were found to be highly asymmetric with regard to morphology. This asymmetry influenced strongly the mechanical behaviour of anchorage, depending on the direction of loading.

Introduction

The big storm that hit Western Europe in December 1999 destroyed millions of trees in the French Aquitaine Maritime pine (*Pinus pinaster*, Ait.) forest, resulting in huge economic losses. As this kind of catastrophic event is predicted to become more frequent in the future, it is essential to better understand the mechanisms that are involved when trees are damaged. Uprooting was the main mode of failure observed in the study region, which is close to Bordeaux (Cucchi et al 2003). This complex phenomenon has already been examined in many countries that are exposed to strong winds. Investigations have often been supported by field observations, as well as experiments. Early studies in Scotland were concerned with Sitka spruce, which develops shallow root systems (Coutts 1983). The role of anchorage components, i.e. resistance of roots in tension, resistance to bending, weight of root/soil plate and soil resistance were defined (Coutts 1986). It was shown that the root tensile strength is the most important factor for stability of Sitka spruce. However, there is a huge variability between trees, which can be explained by differences in root morphology. Subsequent research has addressed root anchorage in connection with an analysis of the root topology and geometry (Ennos 2000, Niklas et al 2002, Mickovski et al 2002), focusing on particular elements such as taproot, laterals or forks. Nevertheless, no studies have been carried out which integrate the full description of the whole root system of mature trees.

Root architecture is defined by the kinetics of branching which, in addition to the morphogenetic program, is very controlled by environmental factors. In particular it is suspected that mechanical stresses can play a fundamental role on the development of root structures, causing significant modification of allocation rules in order to optimize tree stability (Nicoll et al 1996, Stokes et al 1997). On a related issue, an interest in analyzing the biomechanical behavior of roots is found in investigations of root growth in addition to tree stability. Techniques have been developed to describe and record tree topology and geometry under a Multi Tree Graphs (MTG) format, in order to analyze and model tree architecture. This method has been recently adapted and used to digitalize root systems (Danjon et al 1999).

The aim of the current study was to describe and analyze the mechanical behavior of old Maritime pine tree root systems. Particular emphasis was placed on material that was available after the 1999 storm.

Material and methods

Studies were carried out on 24 root systems of 50 year old Maritime pine trees. These trees had been growing in the same stand at Bilos in the French Aquitaine region, where 10% of the trees were damaged during the 1999 storm. All of the trees fell in the eastward direction, and the prevailing wind in this region is typically from the west. The soil is a sandy podzol, with some hard pan, and a high water table in winter. Twelve root systems were from trees that were already uprooted, and the remaining 12 were extracted using a mechanical digger. The direction with regard to north was marked. The root systems were cleaned with an air spade and transported to a site close to the Pierroton INRA station where they were weighed. The morphology of each root system was described using a 3D Fastrak Polhemus digitalizer, adapting the technique which has been already used by Danjon et al 1999 to larger structures. Diameter of each measured segment was also recorded. Major and minor axes were measured when the cross section was found elliptical. Morphological data were recorded under Multi Tree Graph (MTG) format files (Godin et al 1998). These files were then used to visualize the 3D root systems on a computer (fig. 1) and to analyse statistically morphological parameters with the software AMAPmod (Godin et al 1997).

Fig. 1: 3D representation of a digitized root system of a 50 year old Maritime pine tree.

In total, 150 000 root segments were measured. The spatial variability of the hard pan was high: in some places there was no hard pan, and in other places it was approximately located a depth of 80 to 130 cm. In places where the hard pan was absent, rooting depth was constrained by a high water table level. The trees had generally developed a dense windward root network, and a large chuck resting on the hard pan, which can be larger than the tap root. Large horizontal surface laterals were often highly tapered determining a "Zone of Rapid Taper" (ZRT) set to 80 cm radial distance from the main axis of the stump. About 150 summary variables per tree have been computed in order to perform a statistical analysis. They correspond to the branching characteristics, and to the distribution of volume or length of roots as a function of diameter, order, depth, azimuth, radial distance, inclination and type. Several types of roots were distinguished: (1) stump, (2) tap root, (3) & (4) horizontal and shallow roots [segments within the ZRT and outside the ZRT], (5) & (6) sinker roots [base within the ZRT and outside the ZRT], (7) deep roots, (8) other roots (oblique and at an intermediate depth). Fisher's parametric and Wilcoxon's non-parametric pair-wise tests were used to compare the pairs of uprooted and undamaged trees from the same diameter at breast height (dbh) class. The multivariate variability was assessed through a Principal Component Analysis (PCA) that has been carried out on the different root types considering geometric, topological and spatial variables.

A finite element model was developed under the Abaqus software (Hibbitt, Karlsson & Sorensen, Inc.) in order to calculate the mechanical behavior of root structures submitted to bending forces. Bernoulli 3D beam elements were used to discretize each structure. An interface was developed under the software MatLab that allows meshes to be generated from the MTG files, and Abaqus command files to be automatically generated. The model does not take into account the soil matrix, given the focus on behavior of the root structure itself. Embedded boundary conditions were applied at each branch extremity and a homogeneous elastic perfectly plastic material $E_L = 8000\text{MPa}$ was considered for all beam elements. This constitutive law allows failure to occur in the elements reaching a fixed stress threshold $\sigma_L = 28\text{MPa}$ (Stokes 2002). Displacement increments were imposed in two perpendicular directions, i.e. East-West and South-North, to a node at a fixed distance above the tree base. Increments of reaction force were calculated at the displaced node. They were used to trace the force vs. displacement curves that represent the mechanical behavior of the whole root structure.

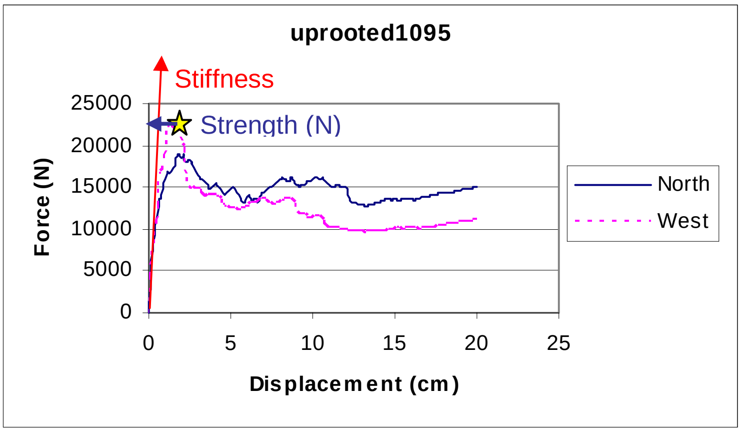

Fig. 2: force vs. displacement curves calculated in two different directions

Comparisons between the different root systems were used to determine a stiffness of the structure stiffness, which is defined by the slope of the tangent to the curve at its origin, and the strength which is the maximum force reached before the first failure (fig. 2).

Results and discussion

A paired comparison (parametric or non parametric) yielded few significant differences of the mean between the windthrown and the undamaged trees (Table 1). The stump corresponds to approximately 20% of the coarse root volume both for the windthrown and the undamaged trees, and is not taken into account in the root volume computations because it has a specific role in the root system. Undamaged trees had more sinkers in the ZRT (25% of root volume vs. 17%), and a larger East chuck (7% of root volume vs. 3.5%). In contrast, windthrown trees had more oblique roots and roots between 40 and 60 cm depth (18% of root volume vs. 9%). Undamaged trees had also less root volume south (20% vs. 29%), and therefore a higher proportion of roots leeward and windward.

Table 1: Percentage of root volume in winthrown vs. undamaged trees. Paired tests: Fisher and Wilcoxon.

Variable	winthrown	Undamaged	coef.variation	difference(%)	fischer	wilcoxon
vertical roots	19.1	27.3	0.432	-29.8	0.008**	0.009**
ZRT sinkers	16.7	25.3	0.471	-33.9	0.006**	0.009**
oblik and medium deep	17.9	9.52	0.767	88.5	0.047*	0.034*
East chock	3.4	7.1	0.779	-51.7	0.021*	0.034*
medium deep	26.4	20.1	0.323	31.6	0.032*	0.021*
South	28.8	20.1	0.289	43.2	0.004**	0.005**
North and South	48.2	41.5	0.174	16.2	0.003**	0.002**

The multivariate variability was assessed through a PCA with 18 variables. The two first components correspond to nearly half of the variability. Four windthrown trees (32, 663, 583 and 761) have high negative loadings for the first component (PC1) which corresponds to a high proportion of oblique and moderately deep roots but a small tap root and a low root volume in the leeward ZRT. Five undamaged trees (370, 685, 374, 100 and 114) had exceptionally high loadings for the second component (PC2) which correspond to a low proportion of root volume perpendicular to the wind direction and a high volume of sinker roots, including the east chuck. All these 9 trees had a high root volume / stem volume ratio.

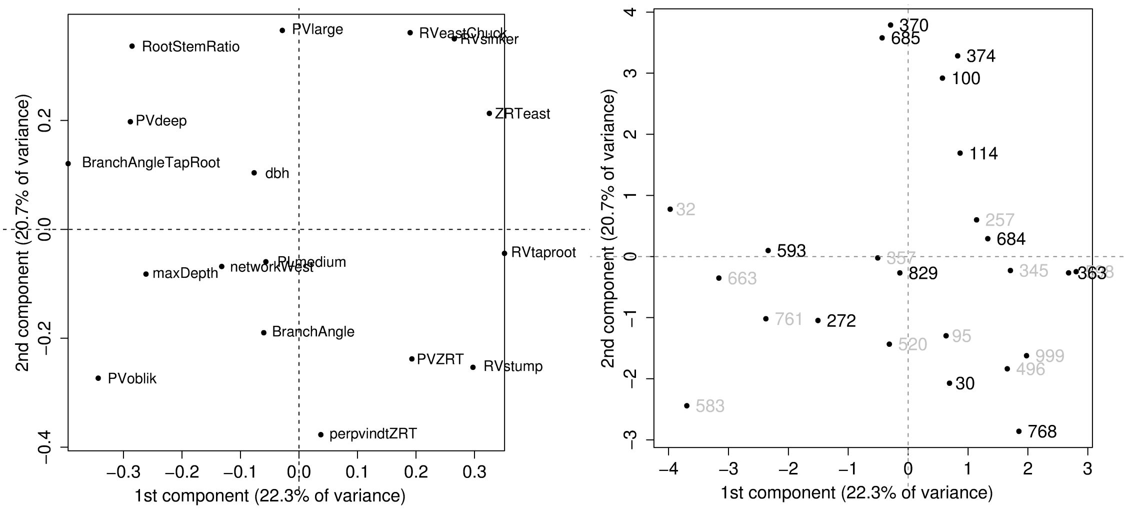

Fig. 4 : Principal component analysis of tree characteristics. Scores for PC1 and PC2 (a) loadings for the 18 original variables; (B) loadings for the 24 trees of the sample, P refers to the proportion, V to root volume, L to root length.

Only the uprooted tree 520 yielded a very high negative loading on PC3 (14% of variability). This tree has a very low proportion of root volume in the ZRT and a high length of medium diameter roots. Three trees (496 et 761 windthrown, 100 undamaged) had exceptionally high loading on PC4 (10% of variability): they had a low dbh and a low windward network. It should be noticed that the undamaged tree 100 has a high loading for PC2 which may have counterbalanced its low windward network.

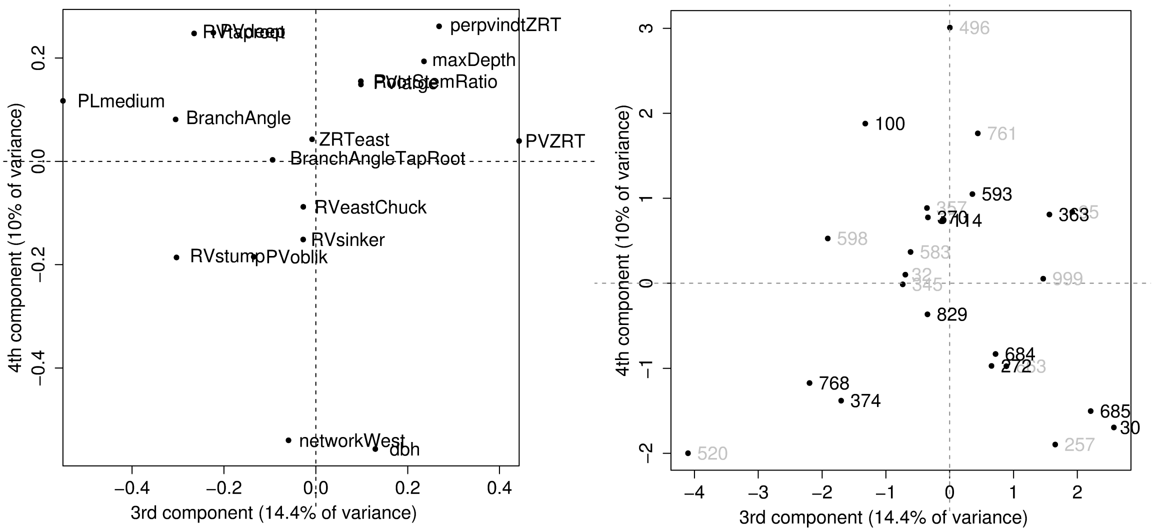

Fig. 5 : Principal component analysis of tree characteristics. Scores for PC3 and PC4 (a) loadings for the 18 original variables; (B) loadings for the 24 trees of the sample, P refers to the proportion, V to root volume, L to root length.

Resistance to uprooting depends on the four first principal components which together, originate in the four following structural features:

- a strong vertical rooting coming from various proportion of tap root, secondary sinkers and an east chuck;
- a high proportion of root volume in the ZRT, especially the leeward ZRT;
- a large windward network of roots;
- a larger proportion of root volume windward and leeward.

One or a combination of these structural elements were poorly developed on 6 windthrown trees and strongly developed on 5 undamaged trees. These characteristics were moderately developed on the 13 remaining samples. Structural adaptation of root systems may explain about half of the resistance to uprooting, even if the location of the trees in the stand and sizes of crown and stem remain important parameters that must also be taken into consideration. In this study, pairwise comparisons were poorly adapted to examine differences between root architectures due to the large number of adaptation strategies to resist windthrow.

Results of the mechanical analysis show very complex responses and a significant variability in behavior (Fig. 6). This is attributed to the huge variability of root morphology and size. Strength of the root systems varies from 20kN to 150kN. Some response curves show one or more hardening zones, i.e. increasing parts of the curves, which could be due to initially curved elements that straighten out during deformation of the root system and then hold under tension. This assumption must be examined more closely for each individual case, given consideration of root morphology.

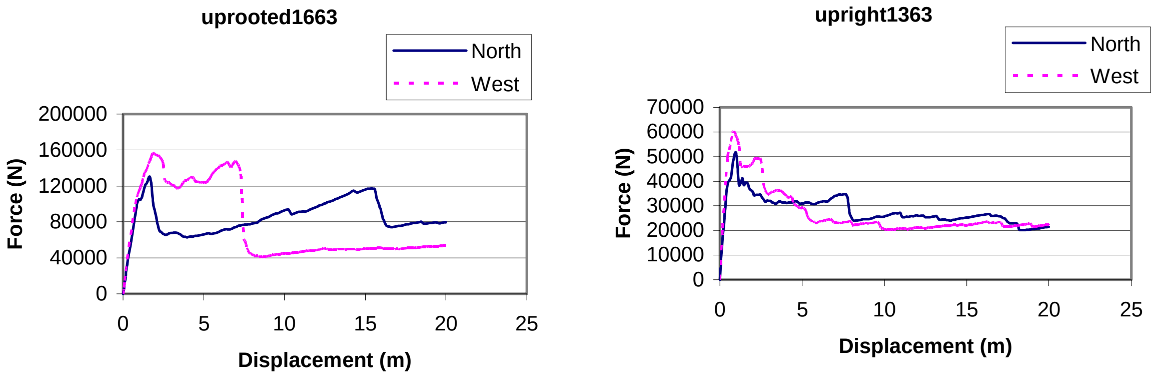

Fig. 6: two examples of force vs. displacement curves showing anisotropic responses and hardening.

Numerical calculations show significant differences between the mechanical behavior of a root system in the two directions of pulling, recognizing that the strength of uprooted trees is a highly variable resistance (Fig. 7). It is believed these anisotropic responses are related to the asymmetric growth that has been observed concerning both ramification ratio and root cross section areas. Nevertheless, strength and stiffness factors do not discriminate between uprooted and stable trees.

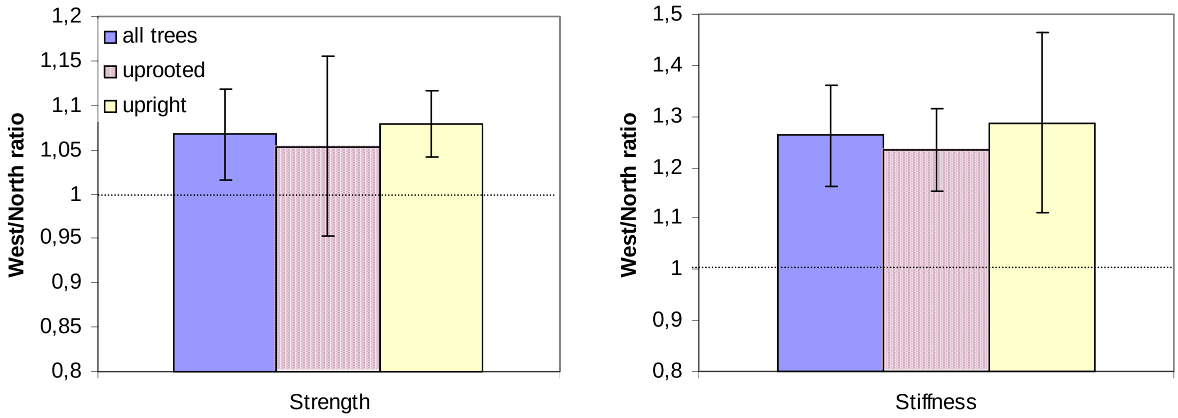

Fig. 7: root systems strength and stiffness ratio between West and North

Recognizing the prevailing winds are oriented in the West, North-West directions, the results appear to confirm the hypothesis of a biomechanical adaptation of trees in order to reinforce root anchorage (Stokes et al 1997, Coutts et al 1999). Such anisotropic development has been already observed, for example with more ramified roots windward and woody root structures leeward. Furthermore, I and T cross section shapes are often encountered (Nicoll et al 1996), which optimize bending stiffness for a given available quantity of carbon.

Concluding remarks

A structural mechanical model has been developed in order to calculate the mechanical state of Maritime pine tree root systems. This tool can be used for any root system that has been extensively measured and recorded in a MTG file, including either real or simulated architectures (Blaise et al 2000). Soil matrix was not taken into consideration, given the focus on the influence of the root structure only. Notwithstanding these simplifications, the results corroborate the idea that trees may adapt their root growth to achieved an improved their anchorage, as evident in the anisotropy of root structure that has been found.

It is possible to improve the model by taking into account MOE and MOR, which depend on root diameter. The model could also differentiate between the strength of roots in tension and in bending. These improvements would allow for a characterization of mechanical behavior of root systems in two opposite directions, i.e. windward and leeward. Companion analyses have also the soil component taken into consideration (Dupuy et al 2003).

In conclusion, linking models of root architecture to mechanical state is a great challenge which merits further development, given some attempts that have not considered the roots as a 3D branching system (Mattheck et al 1997). Similar developments have been already published for the aerial part, which link growth simulations to the biomechanical behavior of trees (Fourcaud et al 2003a, Fourcaud et al 2003b).

Acknowledgements

This work has been founded by the Région Aquitaine and the French government via GIP-ECOFOR. Thanks are due to T. Carnus, M. Curtet, C. Espagnet, B. Issenhuth, F. Lagane, M. M'Houdoir, P. Pougné for their full contribution to the root system digitalizing. Gratitude also is due to J. Fannin for his comments and corrections.

References

Blaise, F., Fourcaud, T., Stokes, A., de Reffye, P., 2000: "A model simulating interactions between plant shoot and root architecture in a non-homogeneous environment", A. Stokes (ed.) 2000, The supporting roots of trees and woody plants: form, function and physiology, Bordeaux, 20-24 July 1998, Kluwer Academic Publishers, pp. 195-207

Coutts, M.P., 1983: “Root architecture and tree stability", Tree root systems and their mycorrhizas, Nijhoff/Junk, The Hague, Netherlands, pp. 171-188

Coutts, M.P., 1986: "Components of tree stability in Sitka spruce on peaty gley soil", Forestry, 59, pp.173-197

Coutts, M.P., Nielsen, C.C.N., Nicoll, B.C., 1999: "The development of symmetry, rigidity and anchorage in the structural root system of conifers", Plant and Soil, 217, pp. 1-15

Cucchi, V., Bert, D., 2003: "Wind-firmness in Pinus pinaster Ait. stands in Southwest France: influence of stand density, fertilisation and breeding in two experimental stands damaged during the 1999 storm", Annals of Forest Science, pp. in press

Danjon, F., Sinoquet, H., Godin, C., Colin, F., Drexhage, M., 1999: "Characterisation of structural tree root architecture using 3D digitising and AMAPmod software", Plant and Soil, 211, pp. 241-258

Dupuy L., Fourcaud T., Lac P., Stokes A., 2003, “influence of morphological and mechanical properties on the anchorage of root systems”, proceedings Wind Effects on Trees, September 16-18, 2003, University of Karlsruhe, Germany, in the current proceedings

Ennos, A.R., 2000: "The mechanics of root anchorage", pp. 133-157 Advances in Botanical Research Incorporating Advances in Plant Pathology, Vol 33,33. ACADEMIC PRESS LTD, London

Fourcaud, T., Blaise, F., Lac, P., Castera, P., de Reffye, P., 2003a: "Numerical modelling of shape regulation and growth stresses in trees II. Implementation in the AMAPpara software and simulation of tree growth", Trees-Structure and Function, 17, pp. 31-39

Fourcaud, T., Lac, P., 2003b: "Numerical modelling of shape regulation and growth stresses in trees I. An incremental static finite element formulation", Trees-Structure and Function, 17, pp. 23-30

Godin, C., Caraglio, Y., 1998: “A multiscale model of plant topological structures”, Journal of Theoretical Biology, 191, pp.1-46

Godin, C., Costes, E., Caraglio, Y. 1997: “Exploring plant topological structure with the AMAPmod software: an outline”, Silva Fennica, 31, pp. 357-368

Mattheck, C., Teschner, M., Schafer, J., 1997: "Mechanical control of root growth: A computer simulation", Journal of Theoretical Biology, 184, pp. 261-269

Mickovski, S.B., Ennos, A.R., 2002: "A morphological and mechanical study of the root systems of suppressed crown Scots pine Pinus sylvestris", Trees-Structure and Function, 16, pp. 274-280

Nicoll, B.C., Ray, D., 1996: "Adaptive growth of tree root systems in response to wind action and site conditions", Tree Physiology, 16, pp. 891-898

Niklas, K.J., Molina-Freaner, F., Tinoco-Ojanguren, C., Paolillo, D.J., 2002: "The biomechanics of Pachycereus pringlei root systems", American Journal of Botany, 89, pp. 12-21

Stokes, A., 2002: "The biomechanics of tree root anchorage", pp. 175-186, *In* Y. Waisel, et al., eds. Plant Roots The Hidden Half. Plenum Publishing, NY.

Stokes, A., Nicoll, B.C., Coutts, M.P., Fitter, A.H., 1997: "Responses of young Sitka spruce clones to mechanical perturbation and nutrition: effects on biomass allocation, root development, and resistance to bending", Canadian Journal of Forest Research, 27, pp. 1049-1057