General paper

The influence of wind on forestry in Ireland

Áine Ní Dhubháin

Forestry Section, Department of Crop Science, Horticulture and Forestry, University College Dublin, Belfield, Dublin 4.

Paper presented at the Annual Symposium of the Society of Irish Foresters, entitled 'The Impact of Climate Change on Tree Growth', Tullamore, Co. Offaly, 1 May 1998.

Summary
Wind is the major abiotic factor influencing Irish forestry. The most obvious manifestations of the impact of wind are windblow and windsnap. Every year, an average of 85,000 m^3 of timber are blown over. Wind can influence trees in other ways. It can alter some physiological processes within the tree, and contribute to the formation of reaction wood. Not all impacts of wind upon trees are harmful. Air movement plays a vital role in the reproductive process of many species, spreading seed and pollen. This paper outlines the influence of wind upon forestry in Ireland. It also attempts to predict the future impacts of wind in light of both probable climate change and changes in afforestation trends and practices.

Introduction – impacts of wind
Windblow and windsnap are the most obvious impacts of wind on forests in Ireland. Wind also has a major impact on tree growth and development.

Windblow and windsnap
Ireland has a severe wind climate compared to most other European countries. The country is situated in the path of Atlantic depressions which bring high rainfall and gusts, particularly along the west coast. Many of these depressions pass over the country each year, invariably resulting in the overturning of trees in forest stands. At less frequent intervals, severe storms hit the country, such as that experienced in most parts of Ireland during Christmas 1997. The gusting winds of over 40 m/sec associated with this storm were responsible for overturning or breaking trees in many forest sites, particularly in the south-west. Table 1 details the total volume of timber windblown in Irish State (and latterly Coillte) forests since 1980.

Much research, particularly in Britain, has focused on how and when wind will cause trees to overturn. In their work on the topic, Quine *et al.* (1995) show that windblow occurs when the overturning forces of the wind exceed the resistive forces of the tree. They argue that the resistance a tree within a stand offers to wind is a function of how well rooted it is and how much support it gets from its neighbours. The main determinants of rooting are soils and ground preparation techniques. Soils determine root depth. In free draining soils such as brown earths, greater depth of rooting is achieved, while in heavy textured soils such as gleys, root depth is restricted. Root spread is largely influenced by ground preparation methods. Savill (1983) highlights that attempts to reduce waterlogging in gley and

Table 1. *Volume of timber windblown within State forests from 1980-88, and Coillte forests from 1989-97. Source: Anon. (1980-88) and Anon. (1989-97a).*

Year	*Windblown volume ('000 m^3)*	*Year*	*Windblown volume ('000 m^3)*
1980	7	1989	111
1981	10	1990	167
1982	61	1991	80
1983	53	1992	125
1984	141	1993	92
1985	95	1994	155
1986	74	1995	42
1987	84	1996	not available
1988	101	1997	500

peat soils through intensive drainage by plough furrows introduced a new problem of restricted root spread.

When wind passes over a forest canopy, the behaviour of a tree within that stand is a function of the tree's height relative to stand height, stem stiffness, effective canopy drag area (Quine *et al.*, 1995) and taper (Petty and Worrell, 1981). The taller and less tapered the tree is, the more vulnerable it is to windblow (Savill, 1983). This is because the overturning moment exerted by wind of a given velocity on a crown is greater in a tall tree than in a short one. In contrast, the overturning moment is reduced with increased stem stiffness. The greater the effective drag area, the greater the risk of windblow. Trees with stiff foliage such as Sitka spruce (*Picea sitchensis* (Bong.) Carr.) have a higher drag factor than species with more flexible foliage. In addition, any operation which breaks the canopy, such as thinning or roading, will increase the size of the crown and hence, the drag area. Thinning also influences the resistance of stems to overturning by reducing crown contact. As previously mentioned, trees within stands gain much resistance to overturning through crown contact with their neighbours. This contact results in a damping effect and allows trees to dissipate the energy of the wind. Thinning reduces crown contact and renders the crop more susceptible to damage during the 2-5 year period when the canopy is re-closing (Savill, 1983). Thinning systems which cause major disruption to the canopy, namely systematic systems, have the greatest negative impact on crop stability (Hamilton, 1980). Delayed or heavy thinning also lead to windblow on vulnerable sites (Lynch, 1985). Damage to residual stems and compaction of soils during the extraction of thinnings compound the impact of thinning on stability.

It is clear that stand and site characteristics play a crucial role in determining the vulnerability of a stand to windblow. If rooting is restricted or the canopy disturbed, trees may overturn during the course of normal winter gales. If stands are well rooted, stem snap can occur during storms. Both types of damage have considerable financial implications for forest managers. Not only is wood damaged during windblow, but the cost of harvesting windblown material is high. Most significantly, rotation lengths are shortened as stands have to be prematurely clearfelled. The financial implications of shortened rotations are substantial.

Wood quality

Wind can lead to a change in wood properties within the tree. The formation of reaction wood within trees is attributed to the displacement of the stem from its normal vertical position (Haygreen and Bowyer, 1996). One of the common elements causing the tree stem to be displaced is wind, although poor root development, soil creep and phototropism play a part (Walker, 1993). If displaced for a period of time known as the presentation time, a gravitropic response is stimulated which leads to the development of reaction wood. Presentation time has been shown to range from 0.6-76 minutes by Westing (1965). In conifers, the reaction wood which forms is known as compression wood, and it develops on the lower side of leaning stems and branches. In hardwoods, reaction wood forms on the upper side of the leaning stem, and is called tension wood. Both types of reaction wood act to correct the lean of the stem (Walker, 1993). During the formation of compression wood, the tracheids on the underside of the leaning stem expand longitudinally, pushing the stem up. In the formation of tension wood, the fibres shrink, effectively pulling the stem up. Both forms of reaction wood have undesirable qualities. For example, compression wood will exhibit much greater longitudinal shrinkage than normal wood and is also less stiff (Desch and Dinwoodie, 1981). Tension wood has a tendency to warp upon drying and may collapse.

Reaction wood forms in an effort to return the displaced stem to the vertical position. The tree is, however, rarely returned to the vertical position (Timell, 1986). Instead, the stem may produce a distinctive sweep in the bole which effectively returns the apical meristem, and not the entire tree, to the vertical orientation (Telewski, 1995). The resulting curved stem proves difficult to saw and conversion rates are low (Williston, 1981). Reaction wood may also be found in vertical stems. This occurs when the displacement is small and the formation of reaction wood returns the stem to the vertical position with negligible sweep (Timell, 1986).

Tree growth

It has been shown that exposure to wind can lead to a reduction in height growth in a range of tree species. For example, Rees and Grace (1980) found that windspeeds of 8.5 m/sec resulted in a 22% reduction in height growth in lodgepole pine (*Pinus contorta* Dougl.). This reduction in height growth was attributed to a reduction in cell length within the tree arising from the mechanical impacts of wind, such as flexing and shaking. On the other hand, increases in diameter growth have been noted in trees exposed to wind. The swaying motion induced by wind leads to an expansion in diameter growth by stimulating an increase in production of the growth regulator ethylene, particularly on the leeward side. Consequently, the increase in radial growth tends to be asymmetrical, as the number of tracheids in the direction of flexure, or on the leeward side, increases (Larson, 1965).

The combined effect of increased diameter growth and reduced height growth is particularly evident in trees exposed for long periods to high winds, such as those growing on the edge of plantations as well as individual trees growing in exposed areas. Long term exposure tends to result in a more compact tree form with greater stem taper, shorter branches and smaller leaves (Telewski, 1995). These trees are more stable as the drag area is reduced. Many of these exposed trees can lack branches on the windward side where buds have been killed (Kozlowski *et al.*, 1991). With increasing altitudes and exposure, trees become progressively more deformed and stunted, with branches nearest to the ground tending to proliferate.

Much research has focused on the above-ground physiological and mechanical impacts of wind. Less effort has been expended specifically on the impact on tree roots. In much the same way that mechanical impacts of wind stimulate increased diameter growth in the stem, Fayle (1968) noted an increase in root growth where trees were subjected to the mechanical impacts of wind. He attached guy ropes to Scots pine (*P. sylvestris* L.) saplings which allowed only the tops of the plant to sway. Fayle found the annual ring widths of the lateral roots of the free-standing trees to be 75% greater than those of the guyed trees. This increase in diameter growth is greater on the tops and bottoms of lateral roots, leading to an increasingly eccentric cross-sectional appearance (Quine *et al.*, 1995). This can make the root three times more resistant to bending in the vertical direction than a root with the same cross-sectional area but circular in section.

Other impacts of wind

Wind has complex effects on photosynthesis (Kozlowski *et al.*, 1991). Leaves can became more clustered in response to exposure to wind. This effectively reduces the leaf display to irradiation and results in a reduction in the photosynthetic rate (Caldwell, 1970). Shorter needles have been observed on lodgepole pine trees exposed to high wind speeds (Rees and Grace, 1980), thereby reducing the photosynthetic area. Leaves and needles can also be torn and abraded as a result of wind. Rushton and Toner (1989) noted wind damage on sycamore (*Acer pseudoplatanus* L.) leaves. Some leaves had up to 46% of their leaf area damaged, while the majority had less than 10%.

The influence of wind on transpiration rates can vary according to species and wind speed. Kozlowski *et al.* (1991) describe a typical pattern of an initial increase in transpiration as wind speeds increase above 1.0 m/sec, followed by an eventual decrease. Stomata will eventually close in response to increasing wind speed for a combination of reasons, including leaf dehydration and leaf shaking (Kozlowski *et al.*, 1991), as well as a response to increased CO_2 levels at leaf surface when wind speeds are high (Mansfield and Davies, 1985).

Future impacts of wind in light of climate change and afforestation trends

This section examines how probable changes in climate, and changes in afforestation trends, will influence the impact of wind on forests in Ireland in the future.

Climate change

Some global climate change models predict an increase in both the frequency and intensity of storm events which give rise to catastrophic windblow (Emanuel, 1987). Conversely, Fitzgerald (pers. comm., 1990) quoted in Keane *et al.* (1991) suggested that wind speeds may decrease in the long term. Therefore, the implications of climate change on catastrophic wind events, such as that which occurred in Ireland in late 1997, is unclear. Predicting the occurrence of storms is quite difficult, although return periods for various wind speeds in Ireland have been estimated (Lowe, 1993). These return periods indicate the frequency of occurrence of certain wind speeds, based on historical records.

Afforestation trends

As a consequence of the current grant structure, afforestation is occurring and is likely to continue to take place on more lowland, sheltered sites than before. The predominant soil types on these afforestation sites are gleys and the majority will be planted with mixtures. In farm forestry sites, the afforested areas are likely to be small, as has been the case to date. There may also be a change to the silvicultural systems practised, as pressure to move away from the clearcutting system is exerted. These afforestation trends will have consequences for stand stability, as well as for stand growth and development.

Stability

The decrease in site elevation, as well as the increase in shelter, will result in lower wind speeds. Assuming that the mean altitude of forested sites was to fall from 350 m to 250 m, it is possible to estimate the reduction in mean wind speed. Tatter flags have been used in Britain and, to a lesser extent, in Ireland, to provide a cheap but effective means of estimating site windiness. Using tatter flag data from Scotland (Miller *et al.*, 1987), it is possible to show that the reduction of 100 m in elevation outlined above will result in a 13% reduction in windspeed. Mean wind speed is not a strong predictor of windblow risk. However, the strength of gusts or turbulence, which do influence windblow risk, is related to mean wind speed. Therefore, a reduction in mean wind speed should result in a reduction in the strength of gusts. Turbulence is also influenced by topography. If afforestation takes place on more sheltered areas than before, such as in valleys, a reduction in turbulence may follow. Much will, however, depend on the degree of wind funnelling in these areas.

Much of the recent afforestation has been with mixtures or with monocultures of broadleaves. It is quite extraordinary how little is known about crown and root development - both key components of stability - of the different species in a mixture, and how they relate to one another. Apart from the generalised view of differential rooting and stability, major differences have been demonstrated between the root systems of different broadleaf species, especially in their fine root density (Table 2). Little is known about the rooting behaviour of these species when grown in mixture. Mixtures also exhibit many complex activities in reaction to competition within the crown and proximity to neighbouring trees (Schütz, 1998). For example, crown development in larch (*Larix* spp.) trees is impaired when their crowns come close together. Therefore, one would expect less intertwining in larch stands (pure or mixed) than in mixed stands of beech (*Fagus* spp.) or spruce (*Picea* spp.), where the crowns intrude considerably before crown regression occurs (Pretzsch, 1992). This response to competition within mixed species stands will have implications for crown contact and hence, stability.

Table 2. *The rooting characteristics of some broadleaf species (Schütz, 1998).*

Species	*Depth*	*Rooting characteristics*
Beech (*Fagus* spp.)	Deep	Very fine and very dense near the soil surface
Oak (*Quercus* spp.)	Moderately deep and spreading	Fine
Ash (*Fraxinus* spp.)	Superficial	Coarse
Maple (*Acer* spp.)	Moderately deep	Dense fine root structure
Birch (*Betula* spp.)	Very deep	Coarse

The experience to date in Britain regarding conifer and broadleaf mixtures is that the broadleaf component remains stable and the conifer component, usually *Picea* spp., is at least as vulnerable as before. Savill *et al.* (1997) claim that such mixtures are possibly more vulnerable, as the deciduous trees are usually leafless at the times of major storms. This can cause pockets in the stand which lead to turbulence. These pockets in the canopy can also be quite wet during vulnerable periods.

There is increasing pressure in many countries to re-examine the silvicultural systems being used within forests. Large scale clear-cutting is becoming increasingly unacceptable for environmental, landscape and aesthetic reasons. Moving from the even-aged, clearfell systems currently used in Irish forests will have implications for stability. Quine and Miller (1990) recommend that if windblow risk is high (i.e. Hazard Class 5 or 6 using the British Forestry Commission model (Booth, 1977)), the clearfell system, with no thinning, is appropriate. They also consider the selection system to be appropriate in these sites, although it is unlikely to be widely applicable. In less vulnerable sites (Hazard Class 3 or 4), some of the shelterwood systems, such as the strip or the wedge, could be considered. However, any shelterwood system which creates irregular gaps in the canopy, such as the group shelterwood system, is unsuitable. This latter system should only be used in more sheltered areas (Hazard Class 1 or 2). While no objective assessment of windblow risk in Irish forests has yet been carried out, it has been estimated that over 75% of Coillte stands have at least a moderate windblow risk (Spaan, 1993). Therefore, any move to introduce alternative silvicultural systems, especially some of the shelterwood systems, could result in a decline in stability, particularly in Sitka spruce crops.

Growth and yield

In general terms, the decline in exposure associated with lowland sheltered sites will have a positive impact on yield classes. Worrell and Malcolm (1990) show that the general yield class (GYC) of Sitka spruce in Scotland increased by about 3-4 m^3/ha/year for every 100 m decrease in elevation. In addition, they showed that GYC values at any specific elevation were higher on inland and southern sites than on coastal and northern sites. This increase in yield class was attributed to the combined effect of increasing temperature and declining wind speeds. Worrell (1987) also quantified the impact of increased shelter on yield class. He showed that on hilltop sites with topex values of 0, GYC values were 2.5 m^3/ha/year lower than on sites of topex values of 30. Therefore, a reduction in altitude of 100 m and a move to more sheltered sites could result in an increase in yield class of at least 4 m^3/ha/year in the case of Sitka spruce stands.

Wood quality

A decline in wind speeds experienced at lower elevations may have consequences for wood quality. A reduction in taper may result in a consequent increase in conversion rates at the sawmill. In addition, the amount of reaction wood in planks sawn from trees growing on these lower elevation sites should be lower. One factor which counteracts these predictions regarding wood quality is the high number of edge trees in farm forests. Many farm forests are small. For example, almost 50% of private forests planted in 1995 were less than 6.0 hectares (Anon., 1995b). Consequently, the proportion of edge trees within these stands is high. If the areas afforested remain as low, the large taper of edge trees will lead to much greater wastage when sawn.

Future impacts of wind on existing stands

Aside from the changes afforestation trends might bring to bear on the occurrence of windblow, the situation on existing sites might be somewhat easier to predict. In the very short term, one might expect that damage due to endemic windblow (i.e. windblow arising from regular wind events) will increase. This is due to that fact that many Irish forests, planted 15-20 years ago, are reaching critical heights in relation to windblow. Many of these were established on relatively exposed sites which had been ploughed prior to establishment. In the longer term, however, the occurrence of endemic windblow should decrease as a result of the changes in silvicultural practices implemented in the mid-80s. For example, the majority of sites have not been ploughed prior to afforestation since that time. Instead, alternative techniques such as mechanical mounding or ripping are used. It is anticipated that trees established on mounded sites will be more wind-firm than those on ploughed sites, although there has been no scientific evidence to support this to date. Similarly, since 1985, systematic thinnings have been replaced by rack and selective thinnings, which should also improve stability. However, as root anchorage is a key component of stability, further work is necessary on identifying means of improving anchorage. Furthermore, while well-rooted trees are less prone to windblow, their susceptibility to windsnap increases. Therefore, an undesirable consequence of improvements to rooting may be an increase in the number of broken stems.

Other means to improve stability, some quite easy to implement, are available to foresters. These refer to the treatment of edges as well as the whole issue of forest design. The structure of the forest edge influences the amount and location of turbulence within the stand. If unsuitable, the edges can cause the winds hitting the stand to be deflected, leading to turbulence within 10 to 15 times the height of the edge. Any operations which allow the edges to filter the wind through the canopy decrease vulnerability. It has been recommended that a depth of 30-50 m from edges should be treated as shelterbelts (Kramer, 1980). Another means of reducing windblow risk is to take this risk into account when planning fellings coupes. The most vulnerable stands should be felled first, with care taken to avoid exposing other vulnerable stands to the prevailing wind (Quine *et al.*, 1995).

Quantifying stand vulnerability to windblow and implementing appropriate preventative strategies will play an important role in reducing the occurrence of windblow. Models which predict windblow risk have already been developed in Ireland and Britain. A number of these aim to guide management by suggesting appropriate preventative strategies for windblow. The best known of these is the British Forestry Commission Windblow Hazard Classification (Booth, 1977), which has been revised a number of times since its development (Miller, 1985). The latest version of this model (Quine and White, 1993) predicts the onset of windblow based on an assessment of the following five factors: soil, location, exposure, elevation and aspect. While this latest version is an improvement on previous models in that it accounts for the funnelling effect of topography on wind, it is deterministic similar to previous versions (Quine *et al.*, 1995). Therefore, it gives no indication of the range of possible outcomes. For example, it does not indicate what percentage of high risk sites will actually experience windblow. Recent efforts in Britain are attempting to address this problem. A new model is being developed which estimates the probability of windblow occurring rather than stating a precise height at which damage will occur (Quine, 1996).

Currently in Ireland, estimates of stand vulnerability to windblow are made subjectively by forest managers, with thinning and clearfelling decisions made accordingly. While local knowledge is crucial in determining windblow risk, providing forest managers and forest developers with an accessible and objective means of assessing windblow risk is a priority. A more objective means of assessing windblow risk would result in greater consistency and would be a very useful decision support tool for foresters. Work commenced in 1997 on a project to develop a windblow model for Ireland. This project, funded by COFORD, involves researchers from the Forestry Section of the Department of Crop

Science, Horticulture and Forestry, UCD, Coillte, Teagasc and Trinity College Dublin. The aim is to integrate the model into databases in the Forest Service as well as in Coillte. In this way, a user-friendly model accessible to all potentials users will be developed.

Conclusion

Wind has a major impact on forests in Ireland. It causes trees to blow over, changes wood properties, and has a major influence on tree growth. It is known that the magnitude of this impact is influenced by the site on which the trees are growing, the species of tree and the silvicultural practices applied to the stand. However, limited research has been conducted to quantify how these factors interact with each other and with wind to influence tree growth and stability. It is hoped that the new model being developed for Irish conditions, described above, will quantify some of these interactions.

REFERENCES

Anon. 1980-88. Forest and Wildlife Service Annual Reports. Government Publications Sales Office, Dublin.

Anon. 1989-97a. Coillte Teoranta. Annual Report and Accounts. Coillte Teo., Dublin.

Anon. 1995b. Forest Service planting statistics. Unpublished.

Booth, T.C. 1977. Windblow Hazard Classification. Forestry Commission Research Note 22/77/SILN.

Caldwell, M.M. 1970. Plant gas exchange at high wind speeds. *Plant Physiology* 46:535-537.

Desch, H.E. and Dinwoodie, J.M. 1981. Timber: Its Structure, Properties and Utilisation. Sixth edition. The Macmillan Press.

Emanuel, K.A. 1987. The dependence of hurricane intensity on climate. *Nature* 326:483-485.

Fayle, D.C.F. 1968. Radial Growth in Tree Roots. Technical Report 9. Faculty of Forestry, University of Toronto.

Fitzgerald, D. 1990. Meteorological Service, Dublin. Personal communication.

Hamilton, G.J. 1980. Line Thinning. Forestry Commission Leaflet 77. HMSO, London.

Haygreen, J.G. and Bowyer, J.L. 1996. Forest Products and Wood Science: An Introduction. Third edition. Iowa State University Press.

Keane, M.G., McCarthy, R., Pfeifer, A. and Ward, D. 1991. Forestry. *In:* Climate Change - Studies on the Implications for Ireland. Edited by McWilliams, B.E. Environment Action Programme, Department of the Environment. Government Publications Sales Office, Dublin.

Kozlowski, T.T., Kramer, P.J. and Pallardy, S.G. 1991. The Physiological Ecology of Woody Plants. Academic Press Inc.

Kramer, H. 1980. Tending and stability of Norway spruce stands. *In:* Stability of Spruce Ecosystems. University of Agriculture, Brno, Czechoslovakia.

Larson, P.R. 1965. Stem form of young *Larix* as influenced by wind and pruning. *Forest Science* 11:212-242.

Lowe, R. 1993. Report of a Study Visit to the Forestry Commission's Northern Research Station, Scotland, March-June 1993. Unpublished Report. COFORD.

Lynch, T.J. 1985. Windblow damage in research plots. *In:* The Influence of Spacing and Selectivity in Thinning on Stand Development, Operations and Economy. Edited by Gallagher, G. Proceedings of the Meeting of IUFRO Project Group P.4.02.02, Dublin, Ireland.

Mansfield, T.A. and Davies, W.J. 1985. Mechanisms for leaf control of gas exchange. *BioScience* 46:158-164.

Miller, K.F. 1985. Windblow Hazard Classification. Forestry Commission Leaflet 85. HMSO, London.

Miller, K.F., Quine, C.P. and Hunt, J. 1987. The assessment of wind exposure for forestry in upland Britain. *Forestry* 60(2):179-192.

Petty, J.A. and Worrell, R. 1981. Stability of coniferous tree stems in relation to damage. *Forestry* 54(2):115-128.

Pretzsch, H. 1992. Modellierung der kronenkonkurrenz von fichte und buche in Rein und Mischbeständen. *Allg. Forest.-u.J.-Ztg.* 163:203-213.

Quine, C.P. 1996. The chance of a windfall? *Forestry and British Timber* August:17-19.

Quine, C.P. and Miller, K.F. 1990. Windblow – a factor influencing the choice of silvicultural systems. *In:* Silvicultural Systems. Edited by Gordon, P. Proceedings of a discussion meeting, University of York, 6-8 April 1990. Institute of Chartered Foresters, Edinburgh.

Quine, C.P. and White, I.M.S. 1993. Revised Windiness Scores for the Windblow Hazard Classification: The Revised Scoring Method. Forestry Commission Research Information Note 230. Forestry Commission, Edinburgh.

Quine, C.P., Coutts, M.P., Gardiner, B.A. and Pyatt, D.G. 1995. Forests and Wind: Management to Minimise Damage. Forestry Commission Bulletin 114. HMSO, London.

Rees, D.J. and Grace, J. 1980. The effects of wind on the extension growth of *Pinus contorta* Douglas. *Forestry* 53:145-153.

Rushton, B.S. and Toner, A.E. 1989. Wind damage to leaves of sycamore *(Acer pseudoplatanus* L.) in coastal and noncoastal stands. *Forestry* 62:67-88.

Savill, P.S. 1983. Silviculture in windy climates. *Forestry Abstracts* 44:473-488.

Savill, P., Evans, J., Auclair, D. and Falck, J. 1997. Plantation Silviculture in Europe. Oxford University Press.

Schütz, J. 1998. The principle of functioning of mixed forest stands. Experience of temperate Central European forest conditions. Paper to be published in a report of Concerted Action (AIR3-CT94-2149) entitled 'Management of Mixed-Species Forests: Silviculture and Economic'.

Spaan, E. 1993. A Study of the Main Site Factors affecting Forest Windblow in Ireland. Unpublished Final Year Project. Forestry Department, University College Dublin.

Telewski, F.W. 1995. Wind-induced physiological and developmental responses in trees. *In:* Wind and Trees. Edited by Coutts, M.P. and Grace, J. Cambridge University Press.

Timell, T.E. 1986. Compression Wood in Gymnosperms. Vol. II. Springer-verlag, Berlin.

Walker, J.C.F. 1993. Primary Wood Processing, Principles and Practice. Chapman and Hall, London.

Westing, A.H. 1965. Formation and function of compression wood in gymnosperms. *Botanical Review* 31:381-480.

Williston, E.M. 1981. Small Log Sawmills: Profitable Product Selection, Process Design and Operation. Miller Freeman Publications.

Worrell, R. 1987. Predicting the Productivity of Sitka spruce on Upland Sites in Northern Britain. Forestry Commission Bulletin 72. HMSO, London.

Worrell, R. and Malcolm, D.C. 1990. Productivity of Sitka spruce in Northern Britain 1. Effects of elevation and climate. *Forestry* 63(2):105-118.