The role of wind in the ecology and naturalisation of Sitka spruce in upland Britain

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Abstract

Sitka spruce (*Picea sitchensis* (Bong)Carr) is a coniferous tree species from North Western America which has been used extensively in afforesting upland Britain. In its natural habitat, Sitka typically regenerates within wind-formed gaps in mature stands. These gaps are vital if the species is to maintain a presence in mixed stands with more shade tolerant competitors, such as western hemlock (*Tsuga heterophylla* Raf).

Wind damage in British forests of Sitka spruce has been considered a serious commercial constraint and research has sought to predict and prevent such losses. However, developments in forest policy have reduced the focus on timber production. Not all stands are to be managed to economic rotations. Some stands are to be left in perpetuity to provide structural and biological diversity; others are being given extended rotations or managed by silvicultural systems that do not involve clearfelling. I consider that wind could become the determinant of stand structure, rather than simply an agent of damage, and in some cases lead to self-perpetuating stands of Sitka spruce through spontaneous regeneration.

To examine the potential for self-perpetuation, I studied the frequency of strong winds in upland Britain, and examined the processes of gap formation, expansion and filling of Sitka spruce stands. Britain has an extreme wind climate, comparable with a few maritime locations in temperate areas of the World. This implies the need for caution in transference of results from elsewhere. Gaps of a range of size, including those apparently suitable for spruce regeneration, form during periods of very strong winds. In intervening periods, there is a slow expansion of gaps by attrition at the edges, but this does not produce the largest gaps found within stands. Gap filling is occurring through lateral closure of small gaps, and by seedling regeneration and epicormic sprouting within larger gaps. The mechanism of epicormic sprouting from fallen trees has not been emphasised in literature from the Pacific North West, and bears some resemblance to recovery of forests in hurricane-prone areas.

A case study of one of the oldest stands of Sitka spruce in upland Britain, Birkley Wood, showed that the components can come together to produce a self-perpetuating stand. Gap area has increased from 4 to 30% over 16 years. The tallest regeneration has now reached 8 m height, close to cone-bearing size, and meeting one of the accepted definitions of gap filling.

The results have practical application in the development of alternatives to clear-felling, the selection of spruce areas as 'natural reserves', and in the treatment of Britain's wind climate in models of windthrow risk.

Declaration

I hereby declare the work to be my own except where assistance is explicitly acknowledged.

Acknowledgements

This thesis is the culmination of a substantial educational journey, and it is impossible to acknowledge all those who have influenced me. Most directly, it has benefited from the input of my supervisors – particularly Douglas Malcolm, and also John Moncrieff and Derek Redfern. Many colleagues in Forest Research have helped in my development as a researcher. I would like to single out Barry Gardiner, and Jonathan Humphrey for their ongoing enthusiasm and friendship, Mike Coutts for his wisdom, and Calvin Booth for his interest. David Miller and Jean Palutikof have been valued associates over many years, and I have been stimulated by international links with John Moore and Jean-Claude Ruel. A large number of other colleagues and friends have, perhaps unwittingly, spurred me on by assorted questions to do with the progress of my PhD – and past students Paul Hannah and Robin Jackson have challenged me to follow their example. George Peterken and John Grace provided a stimulating critique of the thesis. I am also grateful to the Forestry Commission for granting me permission to undertake the study, and providing resources and some study leave.

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I have found a quote from the Open University book on how to get a PhD particularly reassuring – 'Anxiety is a permanent part of the process of getting a PhD'. Undertaking this study has been far more of a learning process than I envisaged. It has been very influential in giving me personal rather than team experience of research, and helping me develop from a forest officer to a forest ecologist!

The data used in this thesis have been gathered by myself and by colleagues in Forest Research with the co-operation of a large number of Forestry Commission staff involved in managing the sites. I am particularly grateful to the large number of staff in the fieldstations at Kielder, Mabie, Talybont, Cairnbaan, and Newton for their efforts in the monitoring areas; Dave Tracy and Elma Wilson at Cairnbaan have latterly looked after the wind data. Bryce Reynard and Angus Mackie provided invaluable support, and participated in some epic adventures, to gather wind data and take measurements in Birkley Wood; Jim Wright and Patrick Bell contributed to my understanding of GIS and the use of IDRISI. Paul Hannah, of National Wind Power, kindly provided wind data for sites near Cwm Berwyn. The wind measurements could not have been taken without Martin Hill's genius at developing cheap data loggers that could survive in upland Britain, and a suite of effective data summary programs.

I have been so fortunate to have a supportive family. I am profoundly grateful to my parents, David and Mary Quine, for the opportunities they have given me to become acquainted with, and fascinated by, the natural world and natural history. My (younger) brother, Tim Quine, started and finished his PhD many years ahead of me, and so I have benefited from his encouragement and interest. Similarly, my in-laws, Malcolm, Ruth and Jo Jeeves have been very supportive. But the occupants of 48 Oxgangs Road have had to bear the brunt of this enterprise – and so with deep thanks I dedicate this thesis to -

Sarah,

and

Hannah Miriam Alistair

Le Fin!

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"The practical woodsman thinks he can see a lot of things in the woods that will tell him a lot about what can't be seen there."

Norman Maclean, Young Men and Fire, p128.

1.1 Planted forests in upland Britain

1.1.1 Recent forest development in Britain

The long history of settlement in the British Isles, with associated development of agricultural, and then industrial, practices has led to the loss of all natural woodland. The extent of the deforestation was so severe that Britain nearly ran out of timber during the First World War and by 1919 only 5% of the land area remained wooded. To construct a strategic reserve, an ambitious programme of reforestation was pursued on land regarded as marginal for agriculture and which, in places, had not carried trees for hundreds or thousands of years. Exotic tree species were used in preference to native, because of desirable properties of exposure tolerance, rate of growth, and utilisable timber. The predominant species planted was Sitka spruce (*Picea sitchensis* (Bong)Carr), a conifer which occurs naturally in a narrow coastal belt of the Pacific North West of America stretching from Alaska to California (Roche and Haddock 1987).

The silviculture developed to manage these new forests differed substantially from classical European methods of tending high forest. Afforestation was achieved through planting, fertilisers were applied to improve growth, thinnings were neglected due to cost and risk of wind damage, and rotations were kept short to maximise economic return and stimulate the development of timber-using industries. An extreme form of 'tree-farming', with rotations of less than 40 years, was advocated by the most enthusiastic proponents of production forestry (Davies 1978). However, the consequential changes to the landscapes of upland Britain, and loss of open habitat, were not met with universal approval. In addition, the concept of single-objective forestry to create a strategic reserve of timber became outmoded in a society no longer facing a conventional World War and which expected forestry to deliver more than just cheap timber. As a result, there was substantial pressure to change forestry practice in Britain. Changes have occurred since the late 1980's in both policy and practice, and are observable in governing what can be supported by public grant, and the methods deemed acceptable in the management of the public forest. Similar trends are also evident in other developed countries in Europe, North America and Australasia.

Forest managers have sought to diversify the composition and structure of the planted forests, to incorporate more natural processes, and to reduce the scale and rate at which change occurs. As a consequence, there are limits to the permitted size of clearfells, an increased use of natural regeneration, and an encouragement to develop alternative silvicultural systems to clearfelling. Many stands are being given extended rotations and some stands are to be left in perpetuity to provide structural and biological diversity (Peterken et al. 1992, Ratcliffe and Peterken 1995) (Figure 1.1). Under the United Kingdom Woodland Assurance Scheme (Anon 2000) it is intended that 1% of the forest area be designated as minimum intervention reserves (natural reserve), at least 1% be identified as long-term retention, and a larger proportion than at present be managed by extended rotation. This reflects a tacit acceptance by conservationists that the forests of exotic species are here to stay, and that with some modification may provide substantial ecological benefit. Sitka spruce may be regarded as naturalised, or 'long-established', that is forming part of a food web where the majority of species are native (Usher 2000), as well as forming part of an accepted type of cultural landscape (Peterken 2000). However, there remains substantial pressure for forest enterprises to be cost effective and profitable. As a result, the management of some stands on the most exposed sites may be abandoned on economic grounds; some managers are interested in ascribing ecological benefits to such abandonment.

The pace of change has been such that both the forest managers and the researchers have struggled to acquire the knowledge base required for successful implementation of policy. The youthfulness of the forests limits our experience of the consequences of many practices and the complete destruction of Britain's natural forest has removed a comparative source of information.

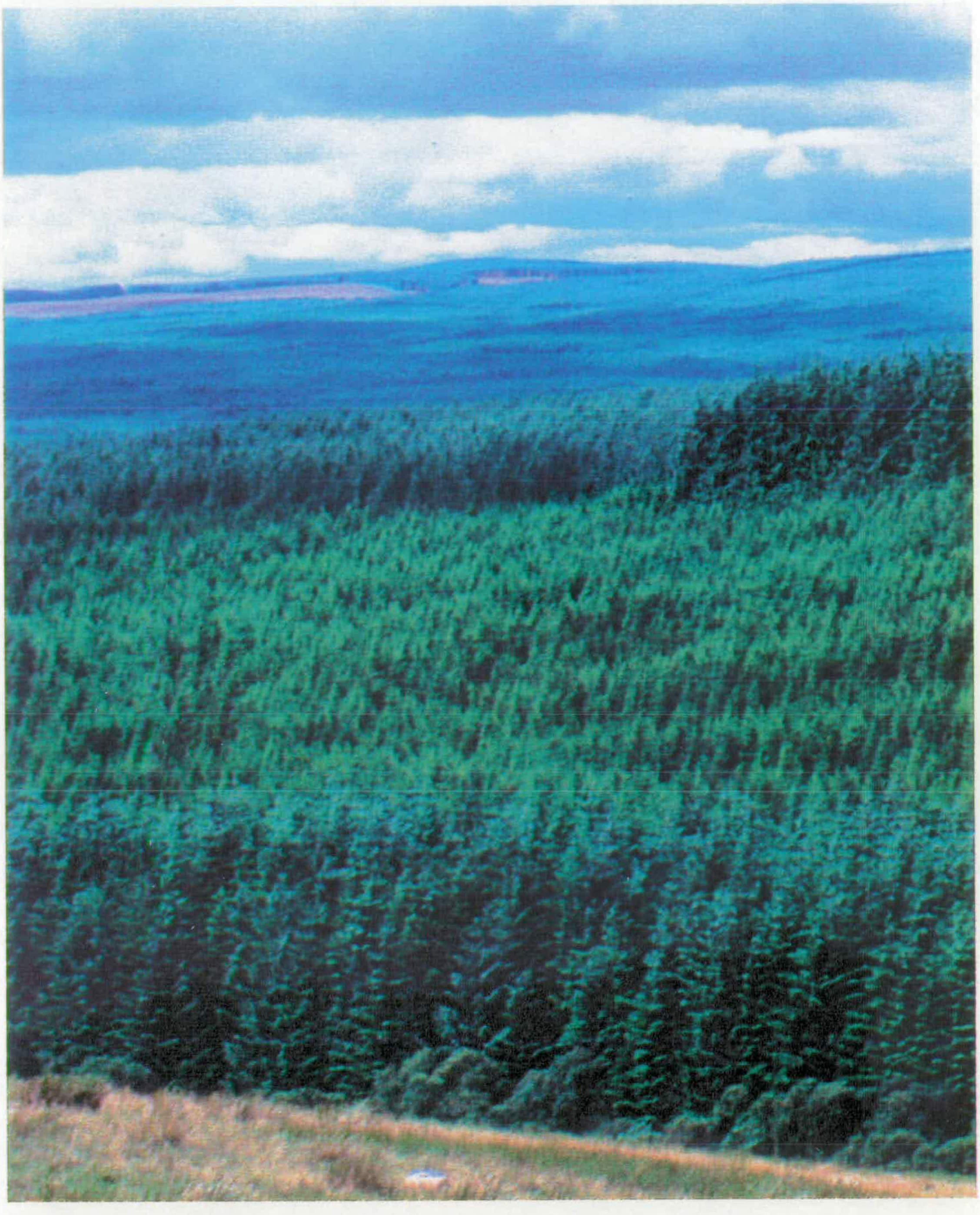


Figure 1.1 Photograph of a Sitka spruce forest in the British uplands showing a mosaic of age classes; Kielder forest, Northumberland. The tallest trees visible, in the middle right of the picture are in Birkley Wood, an example of a stand retained beyond economic maturity, and the subject of the study reported in Chapter 7.

1.1.2 Windthrow as a constraint on management

Fire, whether from muirburn, arson or steam train, was regarded as the greatest threat to the establishment of the upland forests. However, as the forests matured, it became clear that wind was the major abiotic hazard to their development and to silvicultural practice (Petrie 1951). Although substantial progress has been made in both prediction and prevention (Quine et al. 1995, Dunham et al. 2000), wind remains a serious constraint to the planned diversification of forests required by policy. Little is known about the structure that might develop in areas where natural processes are to be encouraged – or in those areas where commercial forest practice is to be abandoned. The ecology of future naturalised forests has rarely been considered.

1.2 Disturbance in forest ecosystems

Ecological thinking has undergone a substantial shift during the period in which Britain's forests have been planted. Ecosystems are no longer considered to develop along an orderly course to a dominant, 'climax' state but rather are recognised as following multiple pathways with no prevalent, single, end-point. This has been summarised as a shift from a paradigm of the 'balance of nature' to one of the 'flux of nature' (Wu and Loucks 1995, Landres et al. 1999). The concept of 'disturbance' plays a key role in this new understanding.

1.2.1 Definitions of disturbance

Pickett and White (1985) have proposed the definition "A disturbance is any relatively discrete event in time that disrupts ecosystem, community, or population structure and changes resources, substrate availability, or the physical environment". Some authors have distinguished endogenous or autogenic (within the community) (Barden 1981) from exogenous or allogenic (outside the community) disturbance (White 1979), but the distinction is often imprecise. Similarly, forest ecologists distinguish between fine-grained disturbance (gap-phase, or chronic disturbance), and stand-replacement disturbance (acute disturbance).

Three types of knowledge are needed to predict the effects of disturbance (Pickett and White 1985). Firstly, an understanding of the disturbance variables and their spatial and temporal distribution; for example an understanding of the relationship between the magnitude of strong winds, their frequency, and the intensity of the resulting disturbance. Secondly, an understanding of the ecosystem response; for example whether it is the composition or the structure of the ecosystem that is affected. Finally, an understanding of the context and constraints to the disturbance; for example, the life history of dominant organisms in the ecosystem or the influence of their distribution within the landscape.

Disturbance regimes are characterised by size, frequency and magnitude (Glenn-Lewin and van der Maarel 1992). Size is usually expressed as area affected by a disturbance event. Frequency may be expressed as *recurrence interval or return period* (the mean time between disturbance events), or as *rotation (or turnover) period* (the mean time interval between successive disturbances of a particular forest stand or patch). The latter incorporates the time taken to recover from a previous disturbance and become vulnerable again. *Predictability* is a measure of variance in return interval. Magnitude is divided into *intensity* (a physical measure of the force of the event, e.g. wind speed) and *severity* (a measure of the impact on the community, e.g. biomass of trees blown down). Disturbance severity is not always a direct function of disturbance intensity, due to the interaction between disturbance, the successional state of the vegetation, and the physical characteristics of the land. For example, susceptibility to disturbance may increase with successional age through *biotic feedback* (White 1987), as when fire fuels build up during post-fire succession, or trees become vulnerable to overturning with increased height or snap with increasing fungal rot.

Disturbance has become widely recognised as an important determinant of forest ecosystem structure in boreal, temperate and tropical regions (Engelmark et al. 1993, Johnson 1993, Attiwill 1994). A wide variety of biotic, abiotic, and anthropogenic disturbance agents have been identified (Oliver and Larson 1990) (Table 1.1).

Table 1.1 Categories and types of disturbance relevant to forests.

Category	Agent
Abiotic	flood, wind, drought, fire, snow, frost, mass movements, vulcanism, glaciation
Biotic	insect and fungal pathogens, herbivores
Anthropogenic	fire, harvesting, roading, planting, cultivation, drainage, fertilisation

The important abiotic agents vary regionally due to climate, but wind is identified as a major harbinger of change in a number of natural forest types. The gaps or patches formed by the disturbance agent, and the subsequent dynamics of the ecological processes determine the forest structure (Pickett and White 1985).

Forest dynamics are determined both by the frequency and scale of disturbance and by the rate of subsequent recovery. A general model of stand development is observable after disturbance (Oliver 1981, Oliver and Larson 1990, 1996):

(1) Stand initiation stage. After a disturbance new individuals and species continue to appear for several years.

(2) Stem exclusion stage. After several years new individuals do not appear and some of the existing ones die. The surviving ones grow larger and express differences in height and diameter; first one species and then another may appear to dominate the stand.

(3) Understorey reinitiation stage. Forest floor herbs and shrubs and advance regeneration appear and survive in the understorey, although they may grow very little.

(4) Old growth stage. Much later, overstorey trees die in an irregular fashion, and some of the understorey trees begin growing to the overstorey.

The length of time that any stand spends in each stage, and hence the relative proportion of the different stand stages within the forest will depend upon the interaction of forest character (e.g. growth rate and life expectancy of tree species) and the scale and frequency of disturbance.

There has been particular interest in the scope for a shifting mosaic ecosystem to develop at a landscape scale. The patch (gap) birth and death rates are in balance and the landscape thereby achieves a form of steady state (Pickett and White 1985, Clark 1991). In such a system the change at any one site becomes cyclic and is mediated by recurrent disturbance. A steady state, or shifting mosaic, is most likely in ecosystems where disturbance is frequent and small in scale relative to a homogenous area of habitat. A feedback mechanism that affects disturbance frequency, such as increased vulnerability with age, will also encourage their development. Turner *et al* (1993) have suggested that apparent steady state landscapes occur when the disturbance interval is long compared to the post-disturbance recovery period and when the scale of disturbance is small compared to the landscape. Landscapes may also appear stable when the disturbance scale increases – but an increasing proportion of the landscape will be occupied by seral rather than mature stages. A form of shifting mosaic has been identified in western European deciduous forests (Emborg et al. 2000).

1.2.2 Sitka spruce in the Pacific North West

Wind is an important disturbance agent in perpetuating Sitka spruce in the coastal forests of Northwest America, both at the landscape scale through patch production by catastrophic disturbance (Harris 1989), and within mixed stands of Sitka spruce/western hemlock (*Tsuga heterophylla*) through gap phase dynamics (Taylor 1990). Sitka spruce can outlive western hemlock in mixed stands but in order to regenerate requires disturbance to provide gaps (Harmon and Franklin 1989, Taylor 1990). Regenerating Sitka spruce faces competition in gaps from advance regeneration of shade tolerant western hemlock and from mosses and herbs which occupy the forest floor. Sitka spruce is favoured by large gaps (Taylor 1990), sudden disturbances, and mineral microsites (Deal et al. 1991) or fallen logs (Harmon and Franklin 1989, Taylor 1990).

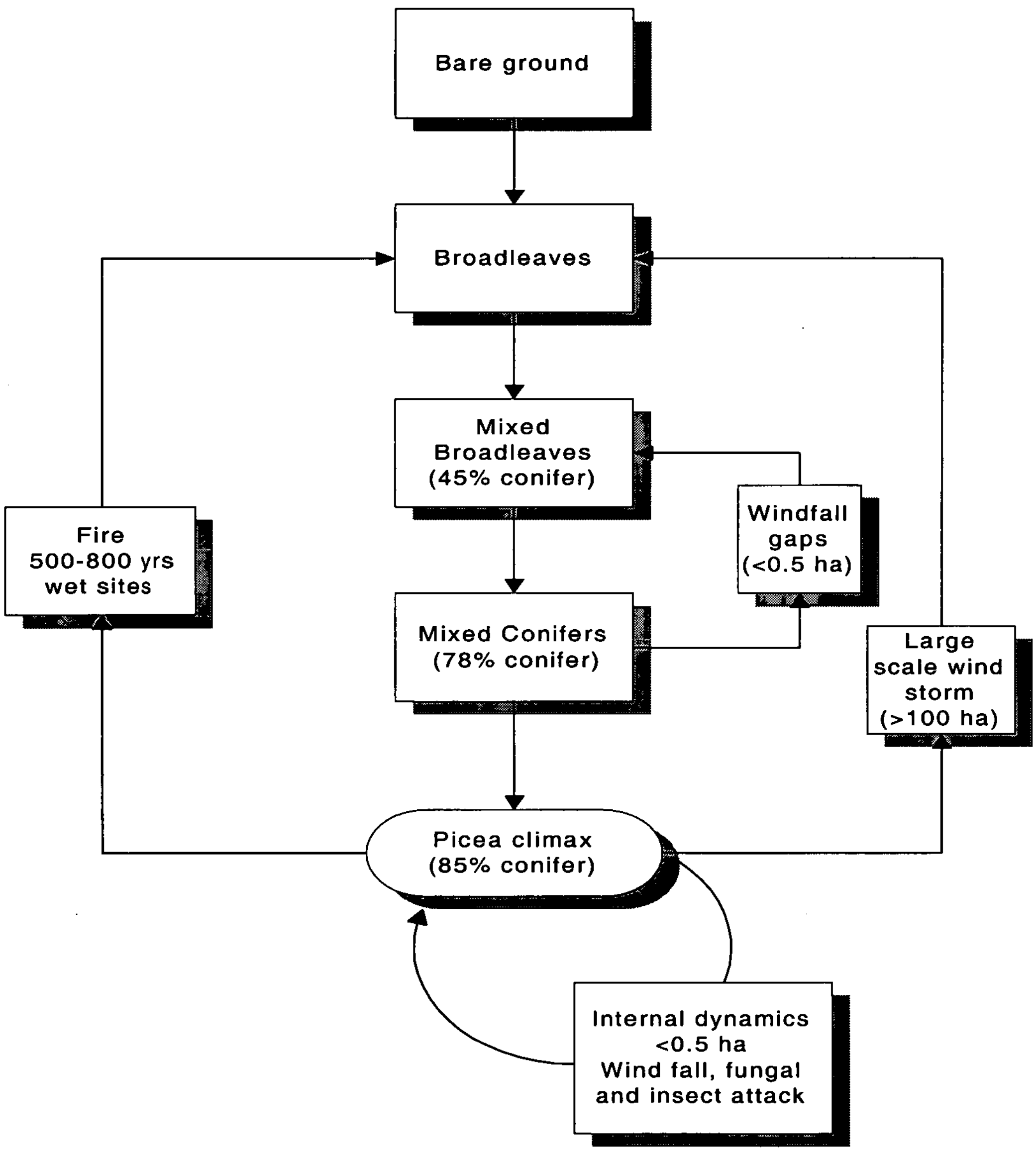
1.2.3 Norway spruce in the boreal forest of Northern Europe

On moist, fire refugia sites in the Northern European boreal forest, Norway spruce (*Picea abies*) regenerates in small gaps often formed by the fall of a single tree (Hornberg et al. 1995, Fries et al. 1997, Hornberg et al. 1997). A series of disturbance events may have to occur before the regenerated spruce can achieve a canopy position; up to 6 episodes have been recorded in the expansion of a single gap (Hytteborn et al. 1996). Despite the small size of many of the gaps, disturbance is nevertheless pervasive, and up to 40% of the forest may be composed of gaps. Many gaps are created by fall of dead trees, so that there is a high proportion of snapped rather than overturned trees. Rotten wood is an important site for regeneration as moss and herb competition limit establishment of seedlings on the forest floor (Leemans 1991, Liu and Hytteborn 1991, Esseen 1994). However, studies at larger spatial scales have identified occasional stand replacement events; for example, Syrjanen *et al.* (1994) used remote sensing to study the Russian boreal forest, and found evidence of both small scale and large scale wind damage on mesic sites (Figure 1.2).

1.2.4 Nothofagus in Patagonia

On the wind-exposed tip of South America, there are extensive Nothofagus forests, dominated by a few species, and showing a variety of structures related to disturbance (Veblen 1985b). Inland, many are characterised by small-scale gap phase disturbance, or by the predominance of other disturbance agents, such as insects or landslips. At the coast there are dwarf forests and wave forests (Tuhkanen 1992). However, in an intermediate zone, there is large patch disturbance, which appears to be repetitive at certain locations, such that the forest reflects a mosaic of relatively even-aged patches, with a very few all-age patches (Rebertus and Veblen 1993b, Rebertus et al. 1997).

Figure 1.2 The relationship between disturbance regime and dynamics of boreal *Picea abies* forests on mesic sites in sub-continental Russia, showing both gap-phase and stand replacement dynamics. After Syrjanen et al. 1994.



1.2.5 The special case of single species forests

In single species forests, disturbance cannot affect composition but can affect structure. There are few examples of such circumstances. Studies of natural lodgepole pine (*Pinus* *contorta*) in impoverished sites have shown the effect of fire and insect disturbance on age and size distributions (Stuart et al. 1989). Patch or catastrophic disturbance resulted in stands with unimodal or bimodal age and diameter distributions, whereas a predominance of smaller gaps resulted in age and diameter distributions that were negative exponential in form. Similar disturbance-mediated structural diversity has been observed in forests dominated by *Pinus uncinata* (Bosch et al. 1992). There are clear parallels between these observations and mensurational relationships derived from managed forests; unimodal or bimodal distributions characterise patch clearfell and shelterwood silvicultural systems whereas the 'inverse J-shaped curve' characterises a selection forest.

1.3 Application of disturbance ecology to silviculture

There is substantial interest in adapting forest management to produce more 'natural' outcomes. In central Europe, this takes the form of 'near-to-nature' forestry, which seeks to minimise anthropogenic disturbance and harness natural processes such as succession to produce the desired stand structures. The focus of this movement has been on individual stands, and on maintenance of high forest conditions. This may reflect the high human density and fragmented landscapes of these countries, and the moderate temperate climate in which fine-grained disturbance predominates. One motivation for the shift in management has been substantial disturbance to uniform coniferous stands during extreme wind storms.

In North America and Scandinavia, there has been more interest in combining knowledge of natural disturbance with desired objectives, to produce integrated management of whole landscapes and new forms of silviculture. This may reflect the survival of extensive natural forests, and the predominant use of native species in productive forestry. As well as making best use of all ecological knowledge, and not just that supported by formal silvicultural experimentation, this approach also has connotations of naturalness that appeal to the public. Thus, there has been the development of 'new forestry' and ecosystem/adaptive management.

The generality of this disturbance-related approach encompasses a number of sub-themes. A number of studies emphasise the development of technical understanding of ecophysiology by studying the species in its natural setting – for example in the development of a gap-based approach to silviculture (Coates and Burton 1997). Oliver and Larson (1990) suggest 'Most silvicultural manipulations are mimics of natural disturbances and other processes' and that silvicultural intervention should reflect the regeneration mechanisms of preferred species. Stand structures that mimic those of natural forests are also seen as desirable in enhancing biodiversity in managed forests. It has been suggested that selection forestry will improve biodiversity in managed forests of Norway spruce because it more closely mimics the natural gap phase forests than do clearcut and shelterwood systems (Fries et al. 1997). The most ambitious approach attempts to reflect a disturbance-dominated age class structure across an entire landscape through the deployment of a range of silvicultural methods (Bergeron and Harvey 1997, Bergeron et al. 1999). No one appears to have developed or implemented such thinking based on a natural disturbance regime for an exotic species. However, the desire to transform such plantations to something more natural may currently be restricted to countries such as Britain and Eire anyway.

1.4 Planted forests of Sitka spruce in Britain

1.4.1 The relevance of a new approach

Oliver (1992) advocates adaptive management of forests involving the transference of knowledge from one country to another or from natural ecosystem to managed forest. Clearly it is valuable to accept some transfer of knowledge from elsewhere, but such a process must assess the limitations of knowledge, and involve adjustment for climatic, soil, physiological, morphological and stand development differences.

The approach of combining disturbance and silviculture is relevant to the debate over the management (or non-management) of upland forests. It is difficult to anticipate what structure might develop in these forests as there are no valid comparisons available from natural stands within Britain.

1.4.2 Stand-based decision-making

Many management decisions are scale-dependent, involving prescriptions for a specific area of forest. Scale-less concepts such as ecosystems and populations are hard to capture in decisions and, as a consequence, the development of a more ecological approach to forestry has focussed on stands and landscapes (Seymour and Hunter 1999). In the past, most decisions in Britain's planted forests have been 'stand-based', that is referring to a reasonably homogenous patch of vegetation in terms of species composition, age and density. There is a trend toward decision-making at the 'landscape scale' (a mosaic of stands with open ground, water bodies), particularly following North American concepts of 'ecosystem management' (Ferris et al. 2000). However, designation of existing stands as biological retentions, to observe natural stand dynamics, is unlikely to occur over extensive areas implied by this approach.

Stands of Sitka spruce in Britain are typically of uniform age and species and contain no shade tolerant competitor. They occupy a wider range of site types than might be anticipated in natural conditions due to short-term technological dominance of the site and institutional reliance on a single species. Structural features of importance include the uniform stocking of stands and young age of trees when windthrow occurs. Of the 4 stages in the life of forest stands (stand initiation, stem exclusion, understorey reinitiation, old growth (Oliver and Larson 1990)) we have little evidence or experience of the latter 2 stages in planted spruce. Yet there is substantial evidence of disturbance, and the potential to develop a range of silvicultural practices.

1.4.3 Wind as the predominant natural disturbance agent

Where management is withdrawn, disturbance could become the determinant of forest and stand structure. Although there are a wide range of potential agents, it is assumed in this study that wind would be the main natural abiotic agent. There is substantial evidence that wind has shaped, and continues to shape stand and forest structure (see 2.5). In contrast, natural fire in the British uplands is very rare, due to the maritime climate, and lack of lightning unaccompanied by rain. The total area of forest burnt in the period 1970-1989 was 13500 ha (3000 ha less than the area windthrown in the storm of October 1987 alone), and of this only 3% had lightning as a possible cause (Aldhous and Scott 1993). It is also likely that fire suppression will continue to be practised across whole forests, whereas natural dynamics of wind distubance cannot be constrained (although possibly influenced by treatment of surrounding stands).

1.4.4 The potential for self-perpetuation

Sitka spruce maintains a presence in natural forests of the Pacific North-West because of disturbance and opening of the canopies. Could such stand dynamics develop in the British uplands? Self-perpetuating stands of Sitka spruce are likely to develop if a number of conditions are met. The principal conditions are that

- stands live to seed producing age;
- windthrown gaps provide appropriate substrates;
- dispersed seed reaches appropriate substrates;

- seedlings establish despite vegetation competition and herbivore pressure;
- growth of spruce saplings is sufficient to compete successfully with those of other tree species;
- gaps fill at least as fast as they are produced;
- the developing structure is not overwhelmed by occasional catastrophe.

Sitka spruce in Britain clearly fulfils some of these conditions. Seed production has been observed as early as 15 years and more reliably from age 20-25 (Malcolm 1987). Regeneration has successfully established on a range of microsites in felled areas and been observed in windthrow on the margins of these sites (Lees 1969). However, other characteristics are less favourable. Seed of Sitka spruce has short viability, there is no seed retention in cones, it is produced in large quantities infrequently (mast years every 7 years or so), and has a short dispersal distance (Philipson 1997). Seedlings are sensitive to competition from the ground flora and to browsing by deer and other herbivores. Sitka spruce is of intermediate shade tolerance, and would suffer competition from advanced regeneration or more rapid growth of saplings of other tree species.

There is little knowledge on the pattern and timing of gap development, subsequent gap expansion and the rate of gap filling; the rate of natural incursion of other tree species into planted spruce forests is not well known. There is clearly potential for wind to produce self-perpetuating stands but the extrapolation of existing knowledge is not straightforward and the type of structure that would develop is unknown. A stand-based investigation is therefore proposed.

The development of a naturalised and self-perpetuating Sitka spruce population within the upland landscape is of considerable interest but predicting the likelihood and the form of this is fraught with even more uncertainty than stand-level predictions. In particular, the development will be constrained by the proportion of stands selected for retention, their location relative to strong gradients in environmental conditions (eg wind speed and soil type) in upland Britain, and the proximity of seed sources of competing species. Results from stand-level investigations will be used to inform speculations on landscape development.

1.5 An investigation into the ecology of naturalised Sitka spruce

1.5.1 Aim of the investigation

The overall aim of this investigation is therefore to consider the ecology of naturalised Sitka spruce, and in particular the hypothesis that –

Self-perpetuating Sitka spruce stands will develop in upland Britain due to wind disturbance.

1.5.2 Objectives of the study

To consider the hypothesis that self-perpetuating stands will develop, the study pursues the following questions -

Is there evidence that the wind climate of the British uplands is likely to cause disturbance to naturalised forests (Ch 2)?
Do sufficiently strong winds occur at the study sites during the study period? (Ch4)
What are the characteristics of wind-formed gaps in the planted forests? (Ch 5)
Do the gaps fill by tree regeneration? (Ch 6)
What is the resultant stand structure? (Ch 7)

The sites and generic methods used to study these questions are introduced in Chapter 3, and other methods are detailed in the individual chapters. The findings are synthesised and management recommendations are summarised in Chapter 8.

1.5.3 Individual hypotheses addressed by the study

In addition to addressing the overall hypothesis, a number of individual hypotheses (in the sense of propositions), emerging from past research are considered. These are introduced here, but supported in the appropriate chapter.

In relation to gap formation and expansion, expectations were developed based on literature from both natural and managed forests (Ch 5). Based on the natural forests, the following were identified -:

- *Gap formation is likely to be infrequent*
- *Gap formation will result in a skewed gap size distribution.*

- *Individual gaps will expand, and the limited evidence suggests that this will occur largely in the direction of the wind.*
- *Temporal variation in both formation and expansion might be expected, assuming exogenous disturbance predominates.*
- *Gusts of 22-26 m s^{-1} (Hourly wind speeds of 14-16 m s^{-1}) will initiate damage.*

Based on the studies of managed forests, the following were proposed –:

- *Gap formation will be common but gap expansion will be more important subsequently*
- *Expansion will occur on the gap margins in the direction of the prevailing wind*
- *Gap size distribution is unknown but unlikely to be skewed to small gaps given the prevalence of gap expansion.*
- *Gusts in excess of 29 m s^{-1} (Hourly wind speeds in excess of 18 m s^{-1}) are required for windthrow of trees.*

With respect to gap filling (Ch 6), the following were proposed -

- *Gap filling will occur in the wind-created gaps.*
- *The dominant mechanism of gap-filling will vary with gap size.*
- *The rate of gap filling will depend upon filling mechanism and gap size.*

It was necessary to take measurements of the local wind climate to support the investigation of gap formation and expansion (Ch4). The specific objectives were –:

- *To take wind speed measurements in a locality relevant to the gap monitoring, thereby providing measures of magnitude of disturbance agent*
- *To produce a complete time-series, thereby permitting the identification of periods of change and no change*
- *To derive measures of recurrence, thereby indicating the frequency of disturbance*

Finally, a case study of an old stand of Sitka spruce was undertaken, with the following objectives -:

- *To observe the process of stand break-up and identify the forest structure that develops*
- *To consider whether the evidence supports the hypothesis that self-perpetuating stands of Sitka spruce will develop spontaneously through windthrow and subsequent regeneration.*

2 Wind climate of the British Uplands

'Vapours, and Clouds, and Storms. Be these my theme,
These! That exalt the soul to solemn thought,
And heavenly musing. Welcome, kindred glooms.'

James Thomson, 1726 – The Seasons: Winter.

2.1 Introduction

Disturbance by a variety of biotic and abiotic agents is ubiquitous in most forests world-wide and indeed defines their very character, and determines their composition and structure. In Britain, the lack of forest creates uncertainty as to which agents would be most influential in the ecology of naturalised Sitka spruce. However, there is evidence from a variety of sources that wind has been and continues to be extremely influential.

Documentary evidence of windthrow includes observations as early as the thirteenth century (Linnard 1982), with frequent references since, such as in the Statistical Accounts of Scotland (Anderson 1967). Even earlier evidence is provided by stems and stumps found in peat bogs, and those exposed in coastal areas (Allen 1992a, b), and tip up mounds in the vicinity of archaeological sites. Recently, with the reduction in coppicing and increased retention of woodland for conservation, it has been possible to observe storms influencing the development of woodland structure in semi-natural broadleaved woodlands in lowland Britain (Spencer and Feest 1994). Wind is acknowledged to be the major constraint on commercial woodlands, and there were at least five catastrophic storms in the 20th century (Grayson 1989, Quine 1991). However, for an understanding of the disturbance regime, rather than merely confirmation of the occurrence of windthrow, it is necessary to consider the disturbance agent in more detail. In addition, a comparison of the wind climate of Britain with the climatology of other countries provides a further means of assessing the relative importance of strong winds.

Damage to trees (windthrow or wind snap), leading to gap formation, occurs when the force applied by the wind exceeds either the resistive moment offered by root anchorage, or the stem strength. The vulnerability of the tree is influenced by a variety of features including the crown, stem and root architecture. There is little evidence of significant differences in the vulnerability of species, except due to snow loading in stands, and deciduous nature for individual trees. However, size and spacing of trees are particularly important. Severity of disturbance will depend upon the vulnerability of the population of trees and the intensity of the 'event'; in the case of damage by strong winds, the intensity (speed) varies significantly over space and time. It is the quantification of this that is of most concern at this juncture.

2.2 A note about measurements

An assessment of Britain's wind climate in a global context depends upon comparability of measurements. Unfortunately, there is considerable scope for confusion when comparing sources because of -

i) variable meteorological definitions of strong winds, for example the use of maximum gust (instantaneous wind speed), maximum hourly mean, maximum ten minute mean, or maximum one minute mean wind speed;

ii) Different specification of instrumentation, for example the height of anemometer above ground, the averaging period, and the sensitivity of anemometer to wind speed;

iii) confusion of terms describing the phenomena and the speed, for example the word 'hurricane' refers to a particular form of tropical cyclone and to a wind speed ie 'hurricane force' which is obtainable in storms that are not hurricanes (Table 2.1);

iv) inadequate coverage of instruments within variable topography, giving unrepresentative measurements, for example the predominance of measurement sites at low-lying air and sea ports;

v) the variable terminology of recurrence, for example, the occurrence of an event at a point (e.g. certain wind speed at a meteorological station); the occurrence within a region (e.g. for phenomena such as hurricanes); the recurrence of an ecological event (e.g. gap formation).

Wherever possible, the information presented here has been converted into m s^{-1}, and gusts measurements at 10m above ground have been cited. Roughness of the ground surface has less effect upon the gust speed than upon measures such as hourly mean, so the measure is more useful for comparisons across multiple sites. However, for circumstances where conversion is required, the ratio between gust and hourly mean is approximately 1.7 (range 1.4 – 2.1), and that between gust and 10 minute mean is 1.55 (Muir Wood, RQE, pers comm).

Table 2.1. Comparison of wind speed scales used to describe strong winds of any origin (Beaufort), Hurricanes (Saffir-Simpson) and Tornadoes (Fujita).

Beaufort Scale	**10min mean at 10m ($m\ s^{-1}$)**	**Saffir-Simpson Hurricane scale**	**Mean wind velocity ($m\ s^{-1}$)**	**Fujita tornado scale**	**Wind velocity ($m\ s^{-1}$)**
7 near gale	13.9-17.1	(tropical depression)	<17		
8 gale	17.2-20.7			0 Weak	17.2-32.6
9 strong gale	20.8-24.4				
10 storm	24.5-28.4	(tropical storm)	17-32		
11 violent storm	28.5-32.6				
12 hurricane	32.7 +	1 Weak hurricane	32.7-42.6	1 Moderate tornado	32.7-50.1
		2 Moderate hurricane	42.7-49.5		
		3 Strong hurricane	49.6 -58.5	2 Strong tornado	50.2-70.2
		4 Very strong hurricane	58.6-69.4		
		5 Devastating hurricane	69.5 +	3 Devastating tornado	70.3-92.1
				4 Annihilating tornado	92.2-116.2
				5 Disaster tornado	116.3 +

2.3 The climatology of strong winds

Wind arises from the existence of a pressure gradient across a volume of atmosphere, and the consequent flow of air from high pressure to low pressure areas. The flow of air is deflected by the rotation of the earth, and the resultant geostrophic wind blows parallel to notional lines of equal pressure (isobars) around the areas of high and low pressure. Where the gradient of pressure is intense, there is an additional rotational element known as vorticity, which deflects the geostrophic wind. The geostrophic wind is slowed by friction at the Earth's surface, but the effect is less significant when wind speeds are high.

Five types of strong winds have been identified (ESDU 1987, Hunt 1995, Wyatt 1995) and are outlined in more detail below. The mechanism by which strong winds originate can determine important features of the disturbance, and in particular the intensity, scale and frequency of the strong winds. Table 2.2 provides documented examples of forest disturbance due to winds originating from each of the mechanisms.

2.3.1 Extratropical cyclones

Extratropical cyclones, or depressions, are large scale air masses that form on the Polar front, the boundary between cold polar air and warm subtropical air. They follow a life cycle of deepening and filling, moving eastwards in the process, and as a consequence often affect the maritime fringes of continents in temperate regions, and less frequently penetrate into the main continental masses. In some cases there may be explosive deepening of depressions due to a local maxima in sea surface temperature giving particularly intense storms, such as those affecting Britain in 1987 and 1990 (Palutikof et al. 1997). In many temperate areas, extra-tropical storms are at their most intense during winter months. Particular features of strong winds produced from this mechanism, are the widespread area affected, and the relatively long duration. Whole regions may be affected by strong winds from systems with a diameter of the affected area up to 4000 km, and a single locality may be affected for three days. Such storms may also occur in families of events and the sequence of strong winds may have an important fatiguing effect on the soil/root interface.

Wind speeds up to hurricane force may be experienced in the most severe storms, but such storms represent a small fraction of the low-pressure systems that affect land areas. Locally, the most severe winds occur as down draughts along intense gust fronts and squall lines within the larger scale vortical motions and this can cause particularly strong winds, for example in narrow belts 30m by several hundred metres (Hunt 1995).

The frequent occurrence of these low pressure systems, means that a large population is available for measurement at any one site, and the recurrence of events of varying magnitude can be computed using a variety of statistical techniques (Cook 1985). The return period is very dependent upon location with respect to the typical storm tracks and to topography.

2.3.2 Thunderstorms

In this case, convective cells lead to the formation of gust and squall fronts (Gray and Marshall 1998). Winds associated with these cells can be very strong but are of short duration (five to thirty minutes) and limited extent. They are particularly prevalent in

Table 2.2. Documented examples of forest damage associated with different storm types. Examples from natural and managed forests combined.

Storm mechanism	Sources – examples of related forest damage
Extra-tropical cyclone	**Western Europe** - Britain (Andersen 1954, Quine 1991), Germany – (Mulder et al. 1973), Denmark - (Jakobsen 1986), France - (Pontailler et al. 1997; Doll 2000a) **Pacific Northwest of America** – (Harris and Farr 1974, Russell 1982, Taylor 1990) **South Island of New Zealand** – (Jane 1986); **Eastern Canada** - (Ruel and Benoit 1999) **South America** - Southern tip of Argentina, Chile - (Rebertus et al. 1997) Exacerbated by snow/ice especially in maritime areas – (Bruederle and Stearns 1985, Guild 1986, Boerner et al. 1988)
Thunderstorm	**Eastern Canada/USA** - Great Lakes of Canada/USA- (Flannigan et al. 1989, Frelich and Lorimer 1991); Wisconsin - (Dunn et al. 1982, Canham and Loucks 1984); Virginia – (Orwig and Abrams 1995); New York - (Kearsley and Jackson 1997). **Southern Germany** - Bavaria – (Fischer 1992). **Australia** - (Sheehan et al. 1982).
Tornado	**Eastern USA** – (Glitzenstein and Harcombe 1988, Peterson and Pickett 1991, Peterson and Pickett 1995, Peterson 2000, Peterson and Rebertus in prep); Texas - (Liu et al. 1997); Minnesota - (Dyer and Baird 1997). **Eastern Canada** - Ontario- (Harrington and Newark 1986); Quebec - (Lehmann and LaFlamme, 1975). **Russia** – (Lyakhov 1987, Syrjanen et al. 1994).
Tropical Cyclone	**Caribbean** – (Tanner et al. 1991); Puerto Rico – (Basnet et al. 1992). **Eastern USA** – (Foster 1988, Boose et al. 1994, Haymond et al. 1996, Clinton and Baker 2000) **Japan** – (Nakashizuka and Iida 1995, Ida and Nakagashi 1998, Ishizuka et al. 1998, Peters 1998, Chiba 2000). **North Island of New Zealand** – (Shaw 1983). **Northern Australia** – (Unwin et al. 1988).
Orographic and other local winds	**Britain** – Sheffield, (Aanenson 1965). **South Island of New Zealand** – Canterbury Plains – (Somerville 1980)

subtropical areas such as USA, Australia and continental regions, and are most likely to occur during summer months. Direction and strength are determined by the particular circumstances of the convective cell and not necessarily linked with topography and aspect. However; in temperate regions the winds from this mechanism are usually less strong than those associated with deep depressions. The frequency of this type of storm is known for some areas but little is known about the recurrence of the strong winds at a single location.

2.3.3 Tropical cyclones

Hurricanes, typhoons and cyclones are intense low-pressure systems that derive their energy from warm ocean waters (latitudes 5-20 degrees N and S). The systems lose strength as they travel inland and the wind speed may be reduced by 50% within 100 km of the coast (Cook 1985). They may also give rise to extratropical storms if they stray into cooler waters. These systems are of smaller scale than depressions, with a diameter of around 600km, but may have a long path up to 10,000km. In their fully developed form they are very intense so that the Saffir-Simpson scale extends beyond Beaufort force 12 (Table 2.1). In Hurricane Andrew, gusts in excess of 76 m s^{-1}, and sustained winds of 64 m s^{-1} were experienced in South-east Florida (Rappaport 1994). The passage of these systems is often associated with extreme precipitation (35cm in 24 hours). Tracks of individual storms are unpredictable, and the pattern of damage is often streaky and highly intermittent (Hunt 1995), with patches of complete destruction.

Unlike extra-tropical cyclones, hurricanes do not form a consistent population of events, and individual locations can go for many years without experiencing winds from this mechanism. Therefore, most calculations of hurricane recurrence are at the regional level because of the difficulty of constructing a statistically sound population at any one location. Thus, in Eastern USA there is a likelihood of one storm per 8 years (ESDU 1987), while for the South-east coastal plain the probability is approximately once in 14 years (Fredericksen et al. 1995).

2.3.4 Tornadoes

These are very small but powerful air movements which give rise to the strongest winds of any mechanism (Snow and Wyatt 1997); hence the Fujita scale extends beyond both the Beaufort and Saffir-Simpson scales (Table 3.1). The smallest form is short-lived and found on downdraft outflows or gust fronts from shallow convective clouds; tracks of these tornadoes may be typically 140m width and of 3km length. However, large tornadoes can also form beneath very large thunderstorms (supercells) and in extreme cases may be 2 km in width and 400km in length. Tornadoes are most common in moderate latitudes (20-60 degrees) where strongly contrasting air masses (e.g. polar and subtropical) meet. The greatest frequency has been recorded in the American mid-West. In Oklahoma the affected area is approximately 7km^2/per 100km^2/per year, giving a recurrence of 1 in 1500 years at any one place; in contrast in Central and Western Europe the recurrence is 1 in 10000 to 1 in 100000 years in any one place.

2.3.5 Orographic and other local winds

A variety of mechanisms are grouped in the category of local winds. These include strong winds often in the lee of mountains such as Föhn and gravity winds (Barry 1992). Such winds tend to affect discrete areas at frequent intervals, and may produce an adapted vegetation community with prostrate life-form.

2.3.6 Mixed wind climates

The mix of storm mechanisms will be represented in the disturbance regime. In general, in temperate maritime regions, extra-tropical storms dominate, but elsewhere, such as the sub-tropics, there may be mixed climates of tornadoes, thunderstorms and tropical cyclones. There are particular problems in assessing recurrence where there is a mixed wind climate.

2.4 Wind Climatology of Britain

2.4.1 Dominant mechanism of strong winds

Britain lies outwith tropical regions and is not affected by hurricanes. The relatively cool climate and distance from the intense sub-tropic temperature gradient means that tornadoes and thunderstorms are also rare; the dense human population nevertheless results in widespread reporting of tornadoes. Large thunderstorms, giving rise to strong down draughts and tornadoes, are rare – there has been only one example of a meso-scale convection cell in Scotland in 17 years (Gray and Marshall 1998). Downslope winds are locally of some significance – for example the helm wind of the Eden Valley, and the winds in the lee of the Pennines experienced around Sheffield. However, the vast majority of strong winds in Britain have their origin in extra-tropical low-pressure systems. These form on the polar front and travel eastwards, intensifying as they pass over the North-west Atlantic. On average Britain experiences approximately 160 such depressions per year. A fraction of these are particularly intense, and strong winds may be embedded within them due to frontal activity (Shaw et al. 1976) or downbursts (Hunt 1995).

2.4.2 Spatial variation

The wind climatology of Britain at the regional level is relatively well characterised, but is less understood at the local scale, particularly in regions of substantial topography. The countrywide pattern results from the main passage of low pressure systems to the north and west of the country, the drag (friction) exerted by the land, and the tendency for strong winds to be found on the south and west of the depression centre. As a result, there is an increase in strong winds from the south east to the north west of the country. This is apparent in maps of upper air pressure gradient, and surface wind speed measured by anemometer (Cook, 1985) or tatter flag (Quine and White 1994), and for both mean and extreme wind speeds. The prevailing wind and the highest wind speeds come from a south-westerly direction. However, the general wind flow is subject to very substantial modification due to topography, and near the ground, to surface roughness.

2.4.3 The role of topography

Gunn and Furmage (1976) provide evidence of the degree of topographic control through a study which compared geostrophic wind (>20 knots, no frontal systems) and surface wind for 4 valley sites in Scotland - Shin, Tummel Bridge, Fort Augustus, and Rannoch. In open level country, a directional backing of 20-25 degrees from the geostrophic wind direction is common. The measurement at Fort Augustus showed a backing of 80 to veer of 30 degrees, and that winds from directions of 180 to 320 degrees all funnel along the valley at 230 degrees. In open country a reduction in wind speed to 0.4 to 0.5 of geostrophic is typical, but at Fort Augustus the data showed a ratio of 0.2 to 0.35. Furthermore, gustiness (gust/mean) was found to be greater in cross-valley winds (1.65-2.3) than along-valley winds (1.52-2.07). The mean elevation of the horizon, was found to relate to speed ratio so that the deeper the valley, the greater the reduction in wind speed experienced. Price (2000) showed a three-fold increase in mean wind speed across a 500m elevation range between valley bottom and ridge top in Balquhidder, central Highlands.

Such extreme topographic effects have proved difficult to represent or to model. Although a number of meso-scale numerical models are available, the predictions of magnitude and direction of flow in complex terrain are poor (Hannah et al. 1995, Suárez et al. 1999). Relative windiness of sites in such terrain has been successfully represented by the DAMS system (Detailed aspect method of scoring) using geographic predictors to account for the effects of location, elevation, topographic shelter, aspect and funnelling (Quine and White 1993, Quine and White 1994). Although this system is suitable for comparison of sites, and for derivation of wind risk (Quine 2000), it does not provide predictions for the wind flow pattern in individual storms. Furthermore, individual storms may generate a pattern of affected area very different from that of the long-term averages; contrast, for example, the area affected in October 1987 against any map of the British Isles wind climate. There remains a need for local measurements of wind speed.

Measurements in forested and upland areas are rare. For example, Palutikof *et al.* (1997) showed that of 147 Meteorological Office anemometers listed in the 1991 Monthly Weather Report, only 24 were found at elevations between 100 and 200m and only 14 above 200m; the number of anemometers had only increased by 5 since 1978. Only very recently, due to advances in equipment, have measurements been possible for lengthy periods in remote locations.

2.4.4 Temporal variability

There is substantial temporal variability in the wind climate spanning seconds (gusts), hours (diurnal flows), days (movement of fronts) and greater (seasonal weather patterns, decadal shifts in location of polar front). These effects can be local, but may also be regional due to the shift in the track of depressions and, for extreme winds, the precise track of the individual intense storms. This variation cannot be anticipated, and so the climatology of strong winds depends upon probabilistic statements of frequency and magnitude. The Weibull distribution is commonly used to describe the parent wind distribution, and the extreme value distribution to represent the strong wind climatology (Cook 1985) (see 4.2.5).

A number of authors have identified notable storms for different purposes such as climate history (Harris 1970), context for debate over trends (Hammond 1990), or the needs of the insurance industry (Palutikof and Skellern 1991). The most comprehensive estimate of frequency gleaned from documentary evidence is the North Sea storm catalogue (Lamb 1991). The longest homogenous series using climate measurements is the Gale Index which measures of westerly and southerly flow and shear vorticity in the geostrophic wind; (Smith 1982, Holt and Kelly 1995, Palutikof et al. 1997) and gives number of gales, and maximum geostrophic wind speed. The range of values, and long 'tail' of extreme wind speeds is shown in Table 2.3.

Table 2.3 Frequency distribution of wind speeds over Northern England, calculated from the Gale Index; adapted from Table 11.3 (Palutikof et al. 1997).

Wind speed m s^{-1}	Frequency % 1881-1993
15-20	67.12
20-25	24.83
25-30	6.38
30-35	1.41
35-40	0.23
40-45	0.02
45-50	0.01
50-55	0.01

(Lamb 1991) suggested that there may be decadal or longer cycles of storminess, and that there was some evidence of increased storminess toward the end of the previous centuries. Recently, there has been the identification of the North Atlantic Oscillation, a phenomenon reflecting a decadal shift in the location of the Polar front along which the low-pressure systems form (Wilby 1997). This results in a change in location of storm initiation, so that the typical track of storms may vary by several hundred kilometres, and as a result bring changes to the regional pattern of windiness. In addition, the latest climate change predictions suggest an increase in storminess in Northern and Western Britain (Hulme and Jenkins 1998).

An understanding of the long-scale temporal variability is limited, by the short history of quantitative measurements of wind speed. For example surface pressure measurements only began in a systematic way in 1880, and in 1919 there were only 14 stations recording wind speed (Hunt 1995). There are additional problems with homogeneity of record, and in particular with changes to instruments, location and exposure, and method of data summary (Palutikof et al. 1997, Robinson 1999).

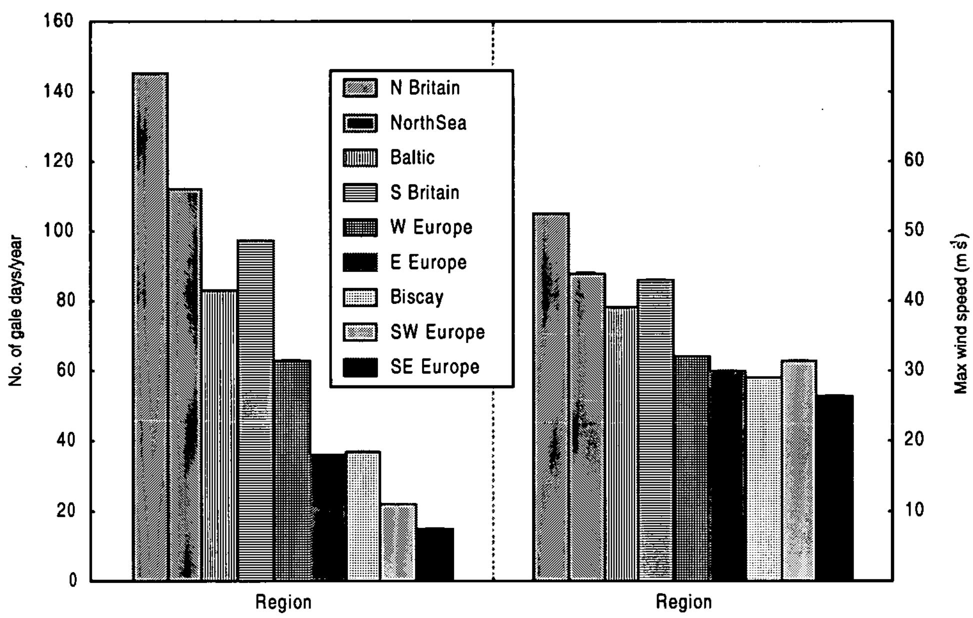
2.4.5 Comparisons with elsewhere

A number of sources indicate that Britain has the most severe wind climate of western Europe, consistent with its maritime position and the eastward movement of low pressure systems. For example, the European Wind Atlas (Troen and Petersen 1989) indicates that the mean wind speed experienced over Britain is approximately double that of southern

Germany. The trend is also visible in statistics derived from the geostrophic wind which shows a strong gradient in both number of gale days and maximum winds (Holt and Kelly 1995) (Figure 2.1). Note that such regional trends do not preclude local areas of strong winds, such as those of orographic origin.

Comparisons with other parts of the world are more problematic because of the difficulty of obtaining consistent wind statistics.

Figure 2.1 Statistics derived from the Gale index of geostrophic wind, indicating the windiness of Britain compared with the rest of Europe. Source (Holt and Kelly 1995).



The Pacific North-west of America appears to have a similar climatology to Britain. The polar front initiates a storm track across the eastern Pacific ending in South-east Alaska which as a result experiences numerous storms with a winter peak in occurrence. Both Wood (1955) and Day (1957) remarked on the similarities between Britain and parts of British Columbia with respect to rainfall and temperature. Day (1957) noted that strong winds were not so persistent in his study areas of central Graham Island (Queen Charlotte Islands) and the coastal Mountain Range near Terrace as in West Coast of Britain. Wind shaping of trees is confined to coastal margins and valley saddles, but stand-replacing storms are relatively frequent in the north of Vancouver Island (D Malcolm, pers comm). Peterson *et al* (1997) observe that the highest average wind speeds in North America occur on the southern part of the Queen Charlotte Islands and that all windward slopes of the archipelago are prone to extremely high winds.

Direct quantitative comparisons are difficult because of the scarcity of records and the predominant influence of locality e.g. surrounding topography, surface roughness, local obstacles; many anemometers are situated at low elevation in proximity to settlements. However, wind speeds in the coastal margin of Northern Washington, British Columbia and South-east Alaska are broadly comparable with those of mainland Britain (Quine et al. 1999). Table 2.4 provides a direct comparison of named sites. The records indicate that the mean wind speed varies from around 3 m s^{-1} to more than 8 m s^{-1} in the coastal margin which is comparable to that in Britain. The extreme wind speed, as characterised by the maximum gust occurring once in 50 years, varies from 36 to 49 m s^{-1} and is similar to that experienced at low elevations in Britain. However, there is a strong gradient between coast and inland, exacerbated by the high surface roughness of the forested land and the mountainous terrain (Anon 1991). As a consequence wind speeds in inland British Columbia and Washington and inland Oregon are substantially lower than those experienced over much of Britain (see Moses Lake data in Table 2.4); exceptions occur in gaps in the mountain chain such as the Columbia River valley. Wind speeds at the coast also decline south of Washington with a result that coastal Oregon is also less windy. In South-east Alaska there are also some local bora-type winds – that is strong downslope winds in the lee of high ground, similar to those occasionally experienced around Sheffield, England.

Tuhkanen (1992) drew attention to climatic and plant life-form similarities between Tierra del Fuego and the Scottish islands and mountains, Iceland, the North-west coast of Norway, the South coast of Alaska and Aleutians, the Southern Ocean islands, the mountains of New Zealand, and Patagonian Andes. Tierra del Fuego is in the path of eastward moving cyclones and as a consequence west winds prevail; at least 75% of winds were westerly in the Magellanic region. Annual average wind speeds range from 3.9-12 m s^{-1}; at one site, Isla de los Evangelistas, the minimum monthly average wind speed is 9 m s^{-1}, and winds of at least 30 m s^{-1} are experienced every month. There is a rapid decline in wind speed over land, and substantial shelter in the lee of cordillera.

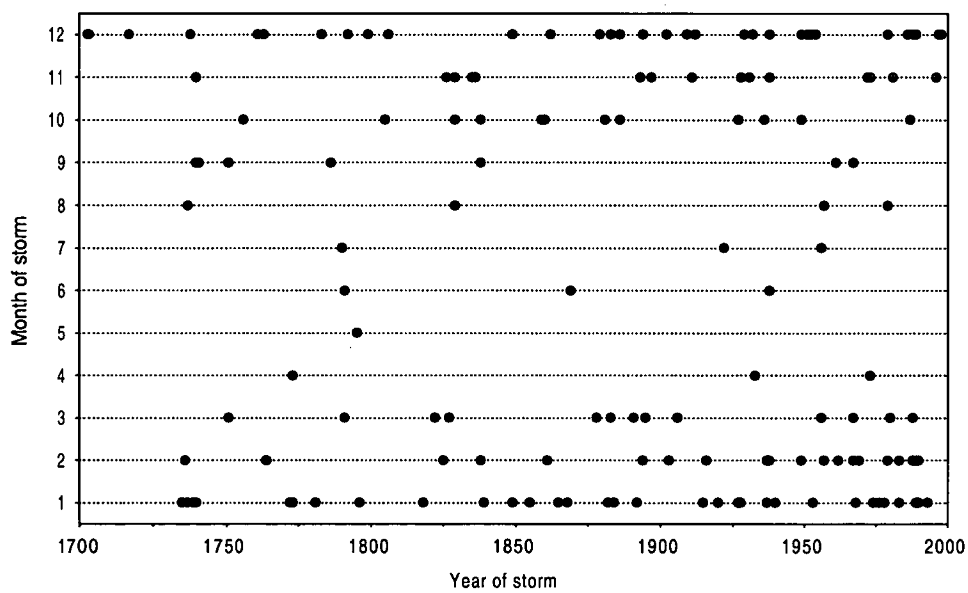
Table 2.4 Comparison of wind data for selected sites in the coastal margin of the Pacific North-West of America and for Britain. Sources of data - Met Office, AWEA, National Record Office. The gust wind speed required to cause catastrophic damage is approximately 45 – 50 m s^{-1} (Quine *et al*, 1996).

Site name, latitude and longitude	Geographic position	Elevation (m)	Annual mean wind speed (m s^{-1})	1:50 year maximum gust (m s^{-1})
ALASKA				
Kodiak 57.45 N, 152.3W	Western end of Sitka spruce range, Coastal Island	32	5.4	47
Juneau 58.22N, 134.35W	Inner coastal passage, SE Alaska	6	3.9	38
Gulkana 62.09N, 145.27W	Inland SE Alaska,	481	3.4	33
WASHINGTON				
Hoquiam 46.36N, 123.56W	Coastal South of Olympic Peninsula, Washington	8	5.5	45
Olympia 46.58N, 122.54W	100km inland from coast, south of Olympic Peninsula, Washington	66	3.2	38
Moses Lake 47.11N, 119.2W	400km inland from coast , Washington	361	2.8	33
BRITAIN				
Benbecula 57.28N 7.22W	Western Isles of Scotland	16	6.9	50
Abbotsinch 55.52N 4.26W	West coast of Scotland, close to Glasgow	16	4.5	46
Fort Augustus 57.08N 4.43W	Inland West Scotland, within glen, approx 100km from coast	58	2.7	37
Great Dun Fell 54.41N 2.27W	Ridge top of Pennines	858	11.5	64

2.5 Severe storms and frequency of disturbance to forests in Britain

A number of sources have been reviewed to identify those storms with observed tree and forest damage, and thereby estimate the frequency with which disturbance may occur within British forests. Commentaries on severe storms often mention damage to trees, and some reviews of forest history have highlighted when large areas of forest were damaged. However, it is difficult to obtain much about the intensity of damage because of the lack of consistency in sources and the substantial changes in area of woodland over the past three hundred years or so. The main sources for this review were (Andersen 1954, Anderson 1967, Lamb 1991). Table 2.5 provides summary details for the latter half of the twentieth century and Table 10.1 (Appendix) provides full details. In summary, between 1700 and 2000, there were at least 89 occasions of recorded forest damage somewhere in Britain, giving an approximate rate of once in every 3 years for disturbance. Damage is clearly most frequent in autumn and winter, and particularly January and December (Figure 2.2).

Figure 2.2 Occurrence of documented storms causing damage to trees and forests in Britain between 1700 and 2000.



Snow and glazed frost can be additional hazards (Nykänen et al, 1997; Dukes and Eden, 1997), and damaging snow storms seem particularly prevalent in some localities such as the North Yorks Moors (Wright and Quine, 1993).

Table 2.5: Storm Catalogue from 1945 - 2000 only for events known to have damaged forests/trees. Date gives first day if multiple day storms. See Appendix (Table 10.1) for further detail including sources.

Date of storm	Main area affected	Notes
26.12.1998	Central and West Scotland	Damage to many old trees; forests in Kintyre. Approx 850,000 m^3
24.12.1997	Ireland, Wales, NW England	Clocaenog; Eire – 360000 m^3
06.11.1996	Central and W Scotland	
08.12.1993	S W England, Midlands	
17.01.1993	S Scotland, N England	Kelso area
26.02.1990	England, Wales and S Scotland	
03.02.1990	England	
25.01.1990	S and W Britain	'Burn's Day' storm; 1.26mill m^3 (1-3% growing stock)
16.01.1990	N Scotland	
16.12.1989	SW England	
13.02.1989	NE Scotland	Black Isle (Record low-level gust of 123 knots at Fraserburgh)
14.01.1989	N Scotland	
21.12.1988	N Scotland	
03.03.1988	NE Britain	
09.02.1988	SW England, Wales, SW Scotland	
16.10.1987	SE England	3.91mill m^3 (13-24% of growing stock)
25.08.1986	Ireland	Hurricane Charley, Flooding and tree damage – especially old deciduous
13.01.1984	SW Scotland	
02.03.1982	Central Scotland	
02.01.1976	Midlands, mid Wales, E England	0.96mill m^3 (<5% growing stock)
12.01.1974	S Scotland	
02.04.1973	E England	
12.11.1972	Midlands and E England	
14.01.1968	Central Scotland	1 – 1.64mill m^3 (15-30% of growing stock)
21.07.1965	S England	Tornado RHS garden at Wisley – 179 trees uprooted
16.02.1962	NE England	'Sheffield' storm
16.09.1961	N Ireland	Hurricane Debbie
04.02.1957	Scotland	215000 m^3
01.03.1956	NE England	Pennine foothills Barnsley/Barnard Castle 28000 m^3
31.01.1953	NE Scotland	1.8mill m^3 (9.7-25.3% of growing stock)
30.12.1951	N/NW Scotl	FC - Borgie, Culloden, Alltcailleach. 8500 m^3. Private estates esp Alvie, Fyvie, Kiethhall, Dunkeld, Doune; 113,000 m^3
18.12.1949	Argyll	

2.5.1.1 Storm catalogue from other areas

Other maritime areas experience frequent storm damage from extra-tropical cyclones. The following table (Table 2.6) provides details of 36 notable storms of Western Europe, 25 of which have occurred since 1945, and 32 in the twentieth century.

Table 2.6: Notable European storms causing forest damage. Sources (Champs et al. 1983, Jakobsen 1986, Rottman 1986, Laiho 1987, Lohmander and Helles 1987, Reure 1987, Quine 1988, Poeppel 1994, Deram 1996, Doll 2000b)

Date	Region affected	Volume of timber (million m^3)	Notes
26-28.12.1999	France	140	2 separate storms
7.2.1996	France	1	Aquitaine, Les Landes
25.1.1990	NW Europe	100-115	Sequence through to 1.3.90
16.10.1987	France	7-8	NW France
26.10.1985	Finland	4.0	Whole country 'Manta'
11.8.1985	Finland	0.5	SE and W Finland, storm'Sanna'
**.11.1984	Germany	16	
25.6.1984	Finland	0.4	SE Finland, storm 'Jeremias'
6.11.1982	France	12	Massif Central
22.9.1982	Finland	3.0	North, storm 'Mauri'
24/25.11.1981	Denmark	3.0	2-3 years production for country
16.11.1978	Finland	2.5	South, storm 'Aarno'
7.9.1977	Finland	0.8	South
3.1.1976	Germany	2.0	Bundesrepublik
4.12.1975	Finland	1	West Finland
2.4.1973	Netherlands		150,000 trees
13.11.1972	Germany	17.4	Bundesrepublik; also 7.3 mill in DDR; 0.8 mill in Netherlands
1969	Sweden	37	Especially in S Sweden
17.10.1967	Denmark, Sweden	1.0 conifer 1.4 broadleaves	Waterlogging, trees in leaf and area rich in blvs
1967	Sweden	10	Especially in S Sweden
Nov '66-Feb'67	Osterreich	2	
**.03.1967	Germany		
4.11.1966	Germany	0.8	Obersteiermark
Feb-July 1962	Germany	2.5	Niedersachsen
16/17.1.1955	Germany	2.5	Baden-Württemberg
1954	Sweden	18	Especially in S Sweden
1943	Sweden	5	Especially in S Sweden
4.7.1929	Germany	0.9	Oberösterreich
11-15.1.1920	Germany	0.5	Nordschwarzwald
18-23.4.1903	Germany	4.5	Schlesien und Pommern
31.1-1.2.1902	Germany	1.96	Schwarzwald und Vogesen
1902	Sweden		Especially in S Sweden
10-12.2.1894	NE Germany	10	4 times annual cut; Mittel- u Norddtschld
12-13.3.1876	Germany	4.4	Hessen, Sachsen, Schlesien
26-27.10.1870	Germany	11.1	Süddeutschland davon Württemberg
7.11-29.12.1868	Germany	16	Süddeutschland, Schlesien, Sachsen, Böhmen, Mähren

At least 5 major blowdown events were experienced in the Pacific North West of America in the 20th Century (Ruth and Harris 1979). The following table (Table 2.7) provides notable storms of the Pacific North-west.

Table 2.7: Storms in Pacific North-west of America causing forest damage. Sources (Grier 1978, Ruth and Harris 1979, Russell 1982, Maser et al. 1988, Taylor 1990, Bormann et al. 1995)

Date	Region	Volume of timber (million m^3)	Notes
12.2.1979	Olympic Peninsula and Puget sound	1.4	Lincoln Day storm
11.1968	S E Alaska	35	gusts to 34-42 $m\ s^{-1}$
12.10.1962	Wn Oregon and Wn Washington	78	(Decker et al 1962) (Columbus Day storm)
4.12.1951	Wn Oregon	26	(lee flow common – see Ruth and Yoder 1953)
Also 1950, 1953, 1957, 1958, 1963, 1971, 1981, 1983	Oregon coast		Other high velocity wind storms since 1950
1942	Cascade Head		ice storm
29.1.1921	Olympic Peninsula	56	('Big Olympic blowdown')
9.1.1880	N Oregon and Sn Washington		
1830	SE Alaska		Evidence of region wide wind storm, also pre 1700, and 1930

2.6 Discussion

2.6.1 The severity of Britain's wind climate

There are five mechanisms for the delivery of strong winds, and many regions of the world experience a mixture of types. Thus, the eastern United States, where there have been many gap-related structure studies, experiences hurricanes, tornadoes, and extreme thunderstorms. However, Britain has a strong and simple wind climate, dominated by extra-tropical depressions. In contrast to many more continental areas, this means that there is regular stress on the forest and wind is likely to be a major disturbance agent both as chronic disturbance, and occasional acute, stand-replacement disturbance. Evidence from documentary sources confirm that wind-induced change to forest structure occurs somewhere within Britain at a frequency of approximately once every three years. Substantial change occurs at a regional scale once every 10-50 years.

Detailed quantitative comparisons with other parts of the world are difficult due to lack of meteorological data. However, strong winds are much more prevalent in Britain than in the central Europe, most of Scandinavia and central North America. For example, wind speeds that are experienced every year in the British uplands on sites such as Eskdalemuir (Quine 1995), are experienced only every few decades in Ontario (Smith et al. 1987) and Alberta (Flesch and Wilson 1993). Comparable frequencies of strong winds are seen in the extreme coastal fringe of the Pacific North-west (especially SE Alaska), and in Tierra del Fuego.

2.6.2 Potential climate change

Instruments capable of measuring wind (or as pressure measurements, deriving wind) have only been available for approximately 120 years. Measurements at individual sites show substantial variability between years and between decades, and regional differences in the year of highest wind speed. As a consequence of this variability, it is not possible to observe the signal of climate change yet in wind speed records. The change in area and character of forest also makes this impossible to observe through trends in amount of damage.

Global warming will introduce more energy into the atmosphere, leading to accentuated pressure differences and increased windiness (O'Brien et al. 1992). However, it is difficult to predict which regions of the world will experience this enhanced windiness. Changes that would have a significant impact on forests in Britain include those to the delivery mechanism (e.g. increased thunderstorm activity), the frequency, timing or magnitude of storms, the direction of strongest winds, or the coincidence with other significant events (e.g. periods of heavy rain or wet snow). However, the current predictions to 2080 for Britain propose modest changes in wind speed and seasonality, with an increase in autumnal windiness, a decline in winter windiness and a tentative suggestion of more very intense winter storms (Table 2.8). There are modest differences between the regions. The magnitude of predicted changes are less than the variability from one year to another experienced in the recent past. This suggests that there is unlikely to be a major change in wind-related disturbance.

Table 2.8 Predicted frequency of very severe gales per year for Medium-High climate change scenario. Source – (Hulme and Jenkins 1998)

	1961-90	**2020s**	**2050s**	**2080s**
Winter storms	1.4	1.5	1.3	1.6
Summer storms	0.10	0.12	0.08	0.11

2.7 Conclusions concerning Britain's wind climate

The review of literature confirms the severity of Britain's wind climate. Wind is therefore likely to be a significant disturbance agent, and this is reflected in the use of tree and forest destruction as a means of identifying storms in historical times. Macro-fossils indicate that the phenomena has occurred earlier in the Holocene. There is no suggestion that the wind climate will moderate in the future, and some climate predictions suggest that parts of Britain may become marginally more windy. Thus, it seems highly likely that the structure of forest stands in the British uplands will continue to be influenced by strong winds in the future.

3 Methods and sites used in the investigation

"...little do inland dwellers in the south know of the difficulties which beset woodcraftsmen on the exposed hill-sides of the north."

Herbert Eustace Maxwell, 'Woods and Forests', May 7th 1884

3.1 Introduction

The previous chapters identified the need to investigate elements of wind climate, gap formation and gap filling. This chapter provides a description of the sites studied, the main methods used to collect and summarise data, and the major datasets produced. Methods of detailed analysis are provided in the individual chapters as appropriate.

The study has been the stand scale, as many of the management decisions, and therefore application of results, are taken at this scale. Wider issues of the landscape pattern resulting from wholesale abandonment of forest management, and subsequent natural disturbance, are outside the scope of this study. The study also requires the exploration of a wide range of interacting processes, across a broad time-scale. As a result, many of the elements of the study were investigative, and the scope for formal experimentation was limited by the lack of knowledge and available time.

3.2 Windthrow monitoring areas

Most of the work has taken place within a series of eight monitoring areas established in upland Britain to provide data for wind risk model development and validation (Quine and Reynard 1990, Quine and Bell 1998). Each is an area of 400-1200 ha representing varied topography, soils and wind climate but predominantly planted with Sitka spruce (Table 3.1). Annual aerial photography was obtained from 1988 to 1998, and basic soil and stand survey carried out. As part of the initial characterisation of the monitoring areas, transects were installed at 100m spacing, with start point and bearing dictated by access to the compartment. At every 100m along the transect, basal area plots were located and site and stand conditions described (see Table 3.2).

Table 3.1. Windthrow Monitoring areas - Site characteristics and windthrow hazard classification. After Quine and Bell 1998.

Monitoring Site and region	Area (ha)	Elevation range (m)	Pure Sitka spruce (% of area)	Top Height in 1990 (m)	Imperfectly drained soils (% of area)	Mean windthrow hazard class (revised scoring system – Quine and White, 1993)
Rosarie (RO) NE Scotland	360	190-355	34	3.0-26.7	75	4.0
Skye (SK) NW Scotland	561	0-274	42	6.0-31.5	19	3.4
Leanachan (LN) W Scotland	655	50-380	59	3.0-25.8	65	3.6
Cowal (CO) W Scotland	812	30-430	75	2.9-31.1	90	4.1
Kintyre (KN) SW Scotland	527	60-355	61	3.0-25.9	94	4.5
Glentrool (GT) SW Scotland	338	155-550	61	10.7-17.4	93	4.9
Kielder (KD) NE England	1098	210-460	72	7.6-21.3	93	4.7
Tywi (TY) Mid Wales	491	300-484	77	8.4-20.9	67	4.4

3.2.1 Measurements of wind climate

Measurements of wind speed and direction have been recorded at a well-exposed reference site in each monitoring area from 1988 to the present, and for shorter intervals at a number of other sites to explore topographic variability. These data are supplemented with that from a number of Meteorological Office and wind energy company sites and used in Chapter 3 to characterise the extreme wind climate.

An anemometer and a wind vane were placed on a 10m mast at each site (Figure 3.1). The equipment comprised a Vector Instruments A100R 3 cup anemometer, and W200R wind

Figure 3.1 Photograph of wind measuring equipment installed at Cwm Berwyn, a hill top site in mid Wales. View south-westwards on an exceptionally calm day, with the monitoring forest visible on the hilltop in the middle distance.

vane, together with a Holtech HAL10 datalogger. Wind speed (in 2 m s^{-1} bins) and wind direction (in 16 bins) was sampled every 8 seconds and a histogram of 225 values per half hour, stored on to a removable memory card. Under this logging regime, a gust constitutes an instantaneous reading every 8 seconds. The Holtech logging system does not record wind direction for wind speeds of 2 m s^{-1} or less to avoid spurious direction data when becalmed. Cards and batteries were changed every month, as close to the start of the month as possible, and as close to the start of an hour as possible. Holtech programmes were used to compute hourly averages from the half-hour records and to extract data for periods of interest.

3.2.2 Measurements of gap occurrence - Single visit transects

For this study, the transects used to locate the basal area plots were revisited in 1992/93 in 5 areas [Kielder (Bellingburn), Kintyre (Carradale), Moray (Rosarie), Glentrool (Drumjohn), and Tywi (Cwm Berwyn)]. Measurements were taken of every gap intersected by the transect (defined as a band 1.5m either side of a centre line, equating to a 3% sample of the area); this involved measurements of more than 600 gaps. These data are used to record the occurrence of gaps and derive estimates of gap formation (see Chapter 5). For each gap the position (as distance to adjacent plots), size (as number of trees and as long and short axis), and shape (coding) were recorded. The gap size is a measure of expanded gap rather than canopy gap (sensu Runkle) – see below. Areas of thinned stands were excluded from subsequent calculations; a sixth area (Tywi - Cefn Fannog) was therefore excluded from the analysis because of the prevalence of thinning.

A small number of the largest gaps were unmeasurable using the specified ground-based method. Estimates for these gaps were obtained from aerial photography interpretation and examination of the resultant digitised images in IDRISI Geographic Information System (GIS) (Eastman 1992). The resolution of the images and pixel size of the raster coverage meant that the minimum gap size identifiable was $100m^2$. The correct gap was selected by overlaying the location of the ground survey points onto the mapped windthrow. Individual polygon area estimates were obtained by applying the 'group' command to the windthrow image, performing the area calculation and accessing the area table for the correct group ID. This method provides areas of canopy gaps (between branch tips of edge trees) rather than expanded gaps (between stems of edge trees) but the mismatch is likely to be insignificant given the large gap sizes, and small distance of lateral crown extension into such large gaps.

3.2.3 Measurements of gap occurrence, expansion and filling - Return period transects

A subset of the transects in the 5 areas were selected for repeat visits to record changes to the existing 104 gaps and any creation of new gaps; selection was made subjectively on the basis of apparent typicality of aspect and stand type, and ease of access during winter. Table 3.2 provides a summary of the site and stand details for the areas sampled. Transects were visited at approximately monthly intervals over the winters 93/94 – 98/99 and gaps re-measured when change occurred; the stand at Kielder was felled prior to winter 98/99. At each gap, measures were taken of gap opening and gap cover (see below). These data are used to derive estimates of gap formation and expansion (Chapter 5).

Table 3.2 Summary details of stands traversed by return period transects, obtained from basal area plots located at 100m intervals along transects.

Site and Compartment numbers	Species and planting date	Elevation range (m)	Main Soil Type	Site preparation	Top Height (m) Mean of plots and range
Carradale 4020, 4021	Sitka spruce, some in mixture with Scots and lodgepole pine, planted 1951-1953	130-205	Peaty gley, surface water gley, deep peat	Spread turves	17.2 in 2/90 *(11.0 – 22.4)* 22.9 in 3/00 *(13.8 – 31.0)*
Cwm Berwyn 3271	Sitka spruce, planted 1962	440-485	Peaty gley, Deep peat, Peaty ironpan	Double mouldboard ploughing	16.4 in 11/99 *(11.4-21.1)*
Glentrool 682, 690, 691, 694-696	Sitka spruce, some in mixture with lodgepole pine planted 1963	150-170	Peaty gley, deep peat, upland brown earth	Single mouldboard ploughing	14.6 in 12/89 *(9.9-17.5)* 22.5 in 12/99 *(19.3-26.3)*
Kielder 3509, 3514	Sitka spruce, some in mixture with Scots pine, planted 1948-1949	245-300	Peaty Gley, deep peat	Spread turves	18.2 in 11/90 *(12.8-28.2)*
Rosarie 4264, 4265, 4271	Sitka spruce, some in mixture with Scots pine, planted 1951 - 1952	290-340	Peaty gley, surface water gley	Single mouldboard ploughing	15.3 in 8/89 *(10-21.5)* 21.0 in 10/99 *(14.6-27.3)*

Observations of the mode of gap filling, such as the presence/absence of regeneration were recorded each Autumn between 1996 and 1998 (1997 for Kielder) to provide evidence of the consequences of gap presence (Chapter 6).

3.2.4 Measurement of the rate of gap-filling - Destructive sampling on transects

One transect in Kielder was selected for destructive sampling of seedlings to confirm whether gap filling was occurring and to obtain an estimate of rate of gap-filling relative to areas of the stand without gaps. The presence of germinants, seedling and epicormic shoots were recorded and samples taken for dating. Further samples were obtained from three compartments in Rosarie forest. These data are used to provide estimates of the success of and rate of gap filling (Chapter 6).

3.3 Study sites for stand development - Birkley Wood and Archie's Rigg

Birkley Wood is a 1.9 ha wood close to the Kielder windthrow monitoring area, planted in 1923, and renowned for its size and apparent stability. As one of the oldest stands of Sitka spruce on an upland gley soil, it provides a preview that is pertinent to speculations on the future structural development of stands. The position of approximately 800 individual trees has been recorded, and their status (standing/leaning/fallen) assessed at approximately 80 intervals between 1987 and 2000. Wind climate data have been collected at 2 nearby sites. Fieldwork was undertaken to quantify presence/absence of regeneration. These data are used to provide estimates of gap expansion and filling integrated to explore the prospects for stand structure development (Chapter 7).

Archie's Rigg is another old spruce stand on an exposed site in Kielder, which has been designated by the Forest District Manager as a biological retention with the aim of observing the development of stand structure. Although no formal monitoring has been carried out, observations are used to develop the discussion in Chapter 7. The stand is largely growing on deep peat, whereas Birkley Wood is a gley site.

3.4 Gap definition and measurement

3.4.1 Definition of gaps and patches

Openings in the canopy of a forest stand due to the death or destruction of trees are variously described as gaps or patches. The smallest openings result from branch loss, but 'gaps' are more usually identified as resulting from impacts on a whole or several trees. This fine-grained stand dynamics is often referred to as 'gap phase disturbance'. The term 'patch' is more commonly used when large numbers of trees are affected. In extreme cases, whole stands may be damaged, so that the canopy opening is within a forest not confined within a stand – these are termed 'stand replacement disturbances'.

Many studies are reputedly gap-based, but the definition of what constitutes a gap is rarely stated precisely. Runkle (1992) has proposed that a gap is a group of less than ten trees, or alternatively an area of 1 tree height in diameter – or approximately 0.1ha. He suggests that where the ratio of gap diameter/height of edge trees is greater than 2, there is full light available. Gaps beyond these limits reflect 'large scale disturbance' to which the term 'patch' is sometimes applied. A similar theme is apparent in forester's attempts to define silvicultural systems, with use of the words 'openings', 'patch clearfelling', and definitions of maximum opening size to constitute continuous cover forestry. I do not attempt to adhere to the strict definition of a gap, but use gap as shorthand for gap and patch.

3.4.2 Quantification of gap cover and opening

Quantification of gap dimensions is required to define the change in forest structure brought about by phenomena such as strong winds, and as context for investigations of the ecological consequences of this change. Many studies describe the size of gaps by giving their spatial extent, and this can be tackled from above the canopy (aerial photography and remote-sensing) or from the ground.

Researchers have taken simple ground-based measures of gap size in 4 ways -

- by determining the lateral extent of a gap to a boundary defined by the boles of the standing trees; expanded gap of Runkle (Runkle 1985, 1992); note this term does not imply physical expansion/change in the gap since formation;
- by determining the lateral extent of a gap to a boundary defined by the vertical projection of the canopy of the edge trees; canopy gap of Runkle (Runkle 1985, 1992);

- by determining for a chosen point the angle to the vertical tips of the standing edge trees – for example, for the gap centre to the ends of the long and short axis of the gap thereby giving gap aperture (Lawton and Putz 1988).
- by determining the vertical extent of the canopy at a fixed grid of points and establishing where the lack of vertical canopy height distribution constitutes a gap (Hubbell and Foster 1986).

The first two are essentially measures of ***gap cover*** (cf canopy cover – (Jennings et al. 1999)) whilst the latter two are measures of ***gap opening*** (complement of canopy closure). More sophisticated measures of gap opening can be obtained using hemispherical photographs (Canham et al. 1990, Valverde and Silvertown 1997) and spherical densiometers (Jennings et al. 1999) and be used to derive indices such as the gap fraction and skyview factor (Groot and Carlson 1996). Other indices of gap opening include a ratio of gap diameter to border tree height that gives relative gap size (Liu and Hytteborn 1991), and Relative Light Index (RLI) (Messier and Puttonen 1995). However, many of the methods give comparable results – for example, there is a strong correlation between gap aperture and direct measures of photosynthetically active radiation (PAR) (Lawton and Putz 1988), and between RLI and measures from hemispherical photographs (Mailly and Kimmins 1997).

No single method is ideal, and consideration has to be given to the balance of precision and practicality. Measurements of gap cover are useful as descriptions of the physical structure of the stand and the effects of disturbance, and can provide a system for recording expansion of gaps caused by loss of further trees, and for comparisons within a locality of similar forest type. However, measurements of gap opening are more useful for investigations of the ecological consequences of the disturbance or for comparison between sites of differing character. For example, when comparisons were made between previous results there was a striking difference between gap areas found to be suitable for regeneration of Sitka spruce in Oregon (Taylor 1990) (ie 800-1000m^2), and that found acceptable in Britain (400m^2) (Lees 1969). However, Taylor's studies were made in stands with tree height in excess of 45m (Harmon 1989), whereas the British stands were 15 to 20m in height. A gap of the same area will result in a very different gap opening (and therefore light environment) in the two types of stand assuming common slope, latitude and aspect (Table 3.3).

Table 3.3: Measures of gap opening as influenced by border tree height for 2 sizes of gap cover.

Tree height at border of gap (m)	Gap diameter: tree height ratio (D/H) for circular gap of 400 m^2	Gap diameter: tree height ratio (D/H) for circular gap of 1000 m^2
15	1.5	2.4
45	0.5	0.8

3.4.3 Measurements of gaps in this study

In this study it was necessary to use measures of gap cover and gap opening, and for these measures to be applied to a large number of gaps, by a number of different observers. Sophisticated measures were felt to be inappropriate given the extensive nature of the study, and the lack of sidelight penetrating through unthinned, closely spaced stands. Two methods of measuring the gaps were developed –

- A measure of ***gap opening*** was developed by taking the angle to the gap outline (horizon formed by the edge trees) using a clinometer at the 8 principal points of the compass. *Mean skyview* was calculated as the mean of (90-i) where i is the angle of inclination to the canopy top for a given azimuth; *mean gap aperture* is given by (2 x mean skyview). *Skyview fraction* ie the proportion of the hemisphere represented by the gap opening was obtained by dividing mean gap aperture by 180 (degrees). A gap aperture of zero was obtained where a fallen tree indicated the presence of a gap, but no gap in the canopy was visible. The skyview measure provides a simple identification of the spherical co-ordinates of the outline of the gap with a co-ordinate system centred at a specified point in the understorey, proposed by Canham to derive Gap Light Index using hemispherical photographs or clinometer measurements (Canham 1988, Canham et al. 1990). This measure is used in Chapter 6. [Further readings, in addition to those at the principal compass points, were taken to define the shape of complex gaps and were used in IDRISI to calculate an 'area' of gap aperture akin to the skyview fraction of Groot (1996). Initially the number of measurements or the bearings used were not fixed, and the instruction was to take sufficient measurements to capture the gap shape. Repeated measurements were not always taken to the same bearings, and different observers used different numbers of measurements to capture the gap shape. This confounded estimates of change in gap size. Therefore, this measure was not developed further, but may have potential where repeat measurements will be taken by the same observer.]

- A simple estimate of ***gap cover*** was obtained by measurement of the expanded gap. In the single visit transects (see 3.2.2), this was achieved by measurement of the long and short axes of the gap between the edge trees, with area subsequently calculated using the appropriate formulae for the gap shape. Many gap studies assume an elliptical shape for area calculations; however, this was felt to be an inappropriate assumption following initial observations, and the shape of the gap was recorded (circle, ellipse, square, rectangle, linear, other). For the return transects, the area measurement of the 'expanded' gap was obtained by measuring the boundary of the gap (distance and bearing around perimeter between edge trees). The measurements were plotted and digitised (or latterly entered as co-ordinates) into the IDRISI GIS and the perimeter and area calculated assuming a pixel size of 1 m^2. Edge trees were painted to permit identification at the next visit.

Note that with growth of edge trees, the measure of gap opening will contract but there will be no change in the measure of gap cover. Annual measurements of gap opening were not sufficiently sensitive to observe the slow rate of such closure.

3.5 Definition of gap-filling and seedling establishment

Deciding when a gap ceases to exist can be important in determining the rate of turnover of the forest, and the proportion of the forest held to be in gap. Liu and Hytteborn (1991) considered that a gap has filled when the regeneration reaches two-thirds of the average canopy height, but Runkle (1982) suggests one-third to one-half. Runkle (1992), summarising the results of a workshop, proposed a definition of 'closed' for a gap when regeneration was dominated by stems greater than 5cm dbh. Similarly, establishment of a seedling can be judged to be successful, according to a variety of criteria. For example, Nixon and Worrell (1999) considered that 50cm – 1m marked the establishment of seedlings by natural regeneration.

3.6 Calculation of Turnover time

The concept of turnover rate or time has been found to be a useful summary of stand dynamics, particularly in studies of gap disturbance. Turnover time reflects the mean time between disturbances at any point in the forest (Pickett and White 1985), and has been derived in a number of ways. For example, Runkle (1992) suggests that it is calculated as the inverse of the mean rate of gap formation, whilst Lertzman and Krebs (1992) calculate it from the cumulative amount of gaps present in the forest. In the latter formulation, turnover time is taken to be the sum of the time to fill gaps plus the residence time of trees in the canopy after gap-filling. Turnover can thence be calculated as time to fill divided by the proportion of the forest in gap (or conversely, the residence time divided by the proportion of the forest intact). Time to fill is variously estimated by ageing of the oldest gap, and studies of seedling growth rates. Calculations are very sensitive to estimates of rate and proportion, and the concept requires an assumption that the forest, and particularly the gap formation and filling, is in some form of steady state.

4 Wind climate measurements

"...Where are the winds of yesteryear? And that poetic question soon turns up the equally poetic answer, Gone with the winds." Norman Maclean, Young Men and Fire

4.1 Introduction

The review of the literature in Chapter 2 confirms that strong winds are likely to be highly influential in shaping the structure of forests in Britain. There is a substantial documentary record of instances of damage at frequent occasions over the past 300 years. Comparison with the wind climate of other countries indicates that the wind climate, particularly of the uplands and of northern and western Britain, has few parallels elsewhere in the world. Areas of equivalent, persistent windiness include South-east Alaska and southern Chile/Argentina and in maritime areas of both these regions, there is substantial evidence for wind disturbance to natural forests (Rebertus et al. 1997, Nowacki and Kramer 1998). However, there is a very strong gradient in windiness at margins of continents, particularly where these coincide with mountain chains, so the area of comparability is small.

The review has also highlighted the importance of both temporal and spatial variability in wind speeds. Despite numerous storms, there are large differences between years and even between decades, in the incidence and magnitude of strong winds. As a result, contemporary measurements are required for disturbance monitoring, and long-term averages are unlikely to be representative of a particular period. The spatial variability, resulting from national location and local topography, is also great and this necessitates the acquisition of local measurements.

4.1.1 The objectives of measuring wind climatee

In order to support the wider investigation into disturbance in the planted spruce forests, it was necessary to carry out field measurements of wind speed. The aim was to provide a thorough temporal record at a relevant spatial location for the monitoring of changes within the study stands.

The specific objectives were therefore –

- *To take wind speed measurements in a locality relevant to the gap monitoring, thereby providing measures of magnitude of disturbance agent*
- *To produce a complete time-series, thereby permitting the identification of periods of change and no change*
- *To derive measures of recurrence, thereby indicating the frequency of disturbance*

4.2 Methods

4.2.1 Choice of statistic

Gap formation, through windthrow or wind snap, occurs in the instant when the applied force within a gust overcomes the anchorage of a tree, or the strength of its stem. However, the process leading to this event may take a much longer period and include fatiguing or rupturing of the soil/root interface in the preceding hours, days or weeks. There is a mismatch between the temporal resolution possible to obtain for wind speed measurements using modern logging equipment, and that possible to achieve for observations of windthrow. It was considered desirable that the record should be as continuous as possible for the studies of gap formation, that extremes should be captured, that the measurements should be comparable with other sources, and that some measure of power (cf fatiguing) should be included.

To achieve these requirements, I chose the following statistics –

- a continuous daily time series of maximum gust per 24 hours (representing the extreme); and mean daily wind speed within 24 hours (representing power), to identify wind strength associated with gap formation and expansion. Note that a daily time-series was preferable to monthly because the return visits to gap sites did not conform to precise calendar months.
- A summary of available hourly measurements maximum gust, and mean wind speed, to develop estimates of frequency of wind disturbance.

Comparison of the daily mean and daily maximum gust showed them to be highly correlated and there were insufficient observations of windthrow to explore the effect of storm sequences and fatiguing. As a consequence, only the daily maximum gust is reported further.

4.2.2 Measurements at the study sites

As part of the wider monitoring programme, data were collected at 29 sites ranging in elevation from 90 m to 580 m. (Table 4.1). Sites for wind measurements were established in accordance with general practice in open areas of low surface roughness, and at a distance of at least ten times the height of the nearest obstacle (Figure 3.1).

Table 4.1: Site details for wind measurement sites within Monitoring areas - Rosarie(RO)*, Skye(SK), Leanachan(LN), Cowal(CO), Kintyre(KN)*, Glentrool(GT)*, Kielder(KD)*, Tywi(TY)*. * = sites for which daily reconstruction necessary. # reference site for which time-series reconstruction not attempted.

Windthrow Monitoring Area	Site	Elevation (m)	DAMS score	National Grid Reference
Master				
RO	Rosarie	330	17.1	NJ335448
KN	Meall Buidhe	374	23.0	NR735325
GT	Mid Hill	411	22.5	NX288895
KD	Caplestone	479	21.7	NY590875
TY	Cwm Berwyn	448	21.8	SN771595
Other – FC				
SK	Ben Staic #	411	26.5	NG299237
SK	GlenMore	340	26.0	NG441418
SK	River Brittle	10	14.4	NG406229
RO	Rosarie RS	235	13.3	NJ340474
RO	Ben Aigan	470	20.6	NJ310481
LN	Leanachan Moor #	140	15.1	NN187786
LN	Aonach Mor	150	12.8	NN171771
KN	Deucheran	329	22.9	NR762442
CO	Strathlachlan #	317	20.4	NS052962
CO	Bernice #	370	19.3	NS116922
CO	Glenshellish RS	270	16.4	NS117935
CO	Glenshellish Lower	90	12.4	NS109944
CO	Cruach Buidhe	568	26.6	NS125947
CO	Garrachra	275	16.2	NS100926
GT	Drumjohn	265	19.1	NX329845
KD	Bellingburn	360	17.3	NY676937
KD	Birkley Wood	180	13.5	NY766906
KD	Birkley RS	250	15.8	NY775918
KD	Crookburn	217	15.3	NY493789
KD	Plashetts	260	14.1	NY676909
TY	Dalarwen	250	11.5	SN788494
TY	Cefn Fannog	448	19.4	SN824505
TY	Nant-y-Maen	510	21.1	SN769592
TY	Ochr Fawr	520	19.0	SN733567

At nine of the sites (reference sites) measurements were carried out for the duration of the monitoring (November 1988 – December 1998) (Quine and Bell 1998). The five reference sites closest to the transect stands were chosen as 'master' sites for time-series production. Other sites were established for shorter periods (1-4 years) to sample a variety of topographic types, and to provide duplication of measurement in an area thereby aiding reconstruction of the time-series.

4.2.3 Supplementary data from other sites

Measurements at the monitoring sites were supplemented by data from the Meteorological Office to provide information for missing periods and a time-series of greater length. The data sets acquired included monthly maximum gust for approximately 20 sites for the period 1965-1994; annual maximum gust for a smaller set of sites back to 1940 (and in the case of Eskdalemuir to 1914); daily gust charts for winter periods 1989 to present; limited hourly wind speed and direction data for a small number of sites in close proximity to study areas. Further hourly data for sites close to Cwm Berwyn (Tywi) were obtained from a wind energy company.

Table 4.2 Site details for Meteorological Office and Wind Energy sites

Meteorological Office/ Wind energy	Site	Elevation (m)	DAMS score	National Grid Reference
Met Office (hourly)	Aberporth	144	16.4	SN 242521
	Abbotsinch	16	13.3	NS 480667
	Tiree	21	21.7	NL 999446
	Machrihanish	10	15.8	NR 663226
	Eskdalemuir	259	13.7	NT 235026
	Charterhall	112	13.2	NT 590875
	Boulmer	33	13.3	NU 253142
	Burnhope	244	17.0	NZ 183475
Wind energy company (hourly)	Cellan	310	17.6	SN 619471
	Garn Gron	500	20.0	SN 766608
	Bryn Titli	470	20.1	SN 931471

4.2.4 Analysis to provide time-series reconstruction

The hostile environment and relatively long intervals between visits to the equipment led to data losses from equipment failure, lightning strikes, and occasional periods of instrument seizure due to icing. While such losses do not lead to serious errors in the estimation of the overall wind climate of the site, they can be problematic for gap studies if they coincide with periods of particularly strong winds.

A technique that has been used by Wind Energy prospectors is the MCP method (Measure-Correlate-Predict) (Bardsley and Manly 1983). Correlations are formed between measurements taken at the candidate site and at a long-term (e.g. Meteorological Office) site using relatively short periods (e.g. 6 months) of synchronous hourly data. The regressions are then used to predict the wind speeds that would have been experienced at the candidate site over a substantial retrospective period using frequency table data from the long-term site. (Palutikof et al. 1997) suggests that if the distance between the candidate and predictor sites exceeds 100km then it is unlikely that a strong relationship will be obtained (to get >50% variance (r=0.7)) particularly in areas of complex terrain.

The preferred version of this method is to use sectoral regressions (30-45 degree sectors) and thereby account for particular site factors (e.g. topographic funnelling) that might influence the relationship between the two measurement points. However, this places heavy demands on data availability. Wind energy developers are most interested in establishing the best estimate of the long-term mean windiness of the site, rather than the occurrence of any single storm event.

The method was adapted to provide a complete time-series for the master sites, rather than every site to minimise reliance on reconstruction. The following steps were followed –

- assemble available data;
- remove erroneous data by using scatterplots of hour/gust or site/site to highlight logging/equipment problems;
- establish a correlation matrix to identify the most related pairs of sites for the periods of interest;
- form linear regression between master and other predictor site and use this to synthesise a time-series;
- fill missing data only with the synthesised values; where multiple predictor sites were available to provide synthesised values, the sites with the highest correlation (>0.7) were used.

A longer time-series for the key sites in the period before monitoring was achieved by using the gust regressions, and the database of monthly maximum gusts from January 1958 – December 1988.

4.2.5 Extreme value/frequency analysis

Meteorologists and engineers have used a number of methods based on the Fisher-Tippett Type 1 extreme value distribution to calculate the probability of a particular wind speed, or the speed likely to occur within a given period of time (Cook 1985). Most methods are site specific and require measurements on-site – even if only to allow formation of ratios with other sites. Three broad approaches have been developed (ETSU, 1997). The most straightforward is by direct measurement and statistical manipulation of the data, but this obviously limits the number of sites for which the calculation can be performed. Data for at least 10 years, and preferably 20 years, are required if annual extremes are used, and other techniques, such as Peak-Over-Threshold require 3-5 years data. A number of simulation methods have been derived (e.g. Monte Carlo methods) but these are computer intensive. Finally, there is the derivation of the extreme value distribution parameters from the parent wind speed distribution. The latter is arguably the most robust, particularly if there are missing periods in data from year to year and therefore a chance that the annual maximum has been missed. This method is therefore followed.

4.2.5.1 Derivation of extreme value distribution from Weibull parameters

The wind climate of a site is commonly summarised using the Weibull distribution,

$P_v = 1\text{-}\exp[-(V/c)^k]$ [Equation 4.1]

Where P_v is the probability of a value less than V occurring, c is a constant and k an exponent. The parameters c and k can be used to derive extreme value distribution mode and dispersion (see below). The parameters were derived from a graphical fit method in the software package Statistica after confirmation that these gave similar values to those provided by the specialist wind energy software (WASP).

The method of ETSU 1997 (ETSU 1997), which is itself based on a re-working of ESDU 1988 (ESDU 1988b, a), was followed to derive extreme value mode and dispersion from estimates of Weibull c and k. The extreme value distribution is represented as a Fisher-Tippett type 1 distribution of the form -:

P_x=exp[-exp(-y)]   [Equation 4.2]

where

$y=a(x-U)$ [Equation 4.3]

and P_x is the probability of an extreme value less that value x in one year; U is the mode (the most likely value of x), and the parameter a is the inverse of the dispersion and represents a measure of the variability of x. It has been found that equating x to the square of the wind speed (V^2) rather than wind speed (V) gives a better fit to wind speed maxima.

The extreme wind speed (V_T) corresponding to a return period, T (in years) is obtained from

$V_T^2=U-(1/a)(\ln[-\ln(1-1/T)])$ [Equation 4.4]

Where
$U=[c(U^{0.5}/c)]^2$ [Equation 4.5]

And

$V_T = \text{sqrt}\ (V_T^2)$ [Equation 4.6]

The value of ($U^{0.5}/c$) in eqn 4.5 is derived graphically by ESDU, but approximated well by a third order polynomial (ETSU 1997)

$(U^{0.5}/c) = (-0.5903k^3 + 4.4345k^2 - 11.8633k + 13.569)$ [Equation 4.7]

The parameter $1/a$ in eqn 4.4 can be obtained from

$1/a=U/Ua$ [Equation 4.8]

where the product Ua is known as the characteristic value and is usually approximately constant for an area which is comparatively small compared to the dominant storm mechanism (ESDU 1987). ESDU suggest a value of 5 for *Ua* as typical for climates with predominantly extratropical storm systems.

By way of comparison the FT 1 method was also used, for 10 years worth of data (Quine, 2000).

4.2.5.2 Treatment of topography

The anemometer locations tended to be more exposed than the study stands. To represent this difference in exposure, and in particular the effects of topography, the ratio between the DAMS score of the anemometer site, and the DAMS score of the study site, can be used to scale the wind speed. This could provide an estimate of the wind speed experienced at the stands. This approach is justified because there is a linear relationship between Weibull and NUDAMS (Quine 2000). However, the speeds at the reference sites were considered acceptable for identification of frequency, and for between-period comparison, and local measurements were available for Birkley Wood (Chapter 7).

4.3 Results

4.3.1 Basic wind speed data

Prior to any reconstruction, summary daily (Table 4.3) and hourly data (Table 4.4) were prepared for the 5 key sites of the monitoring areas. The data confirm the severity of the climate, with wind speeds similar to those recorded in coastal South-east Alaska and by the Meteorological Office along the western sea-board of Britain (Table 2.4). The daily data are subsequently used to derive a full time-series, and the hourly to formulate Weibull and extreme value statistics.

Table 4.3: Summary of unsynthesised daily data – daily maximum gust 1989-98

Site	Sample Numbers	Mean Daily Gust $m\ s^{-1}$ *(Standard error)*	Mean –/+95% confidence limits	Maximum daily gust $m\ s^{-1}$
Kintyre	3231	16.39 *0.105*	16.18 - 16.59	47.0
Glentrool	3067	16.99 *0.118*	16.75 - 17.22	47.0
Rosarie	3279	12.59 *0.093*	12.41 - 12.77	37.0
Kielder	3222	14.59 *0.101*	14.39 - 14.79	41.0
Cwm Berwyn	1615	14.36 *0.133*	14.10 - 14.62	37.0

Table 4.4: Summary of unsynthesised hourly data– hourly mean and maximum gust 1989-98, the maximum number of possible samples is 87648.

Site	Sample Numbers	Mean $m\ s^{-1}$ *(Standard error)*	Mean –/+95% confidence limits	Maximum $m\ s^{-1}$
Hourly Mean				
Kintyre	75433	8.02 *0.0146*	7.99 - 8.05	32.78
Glentrool	71466	8.46 *0.0166*	8.43 - 8.50	36.83
Rosarie	77092	4.91 *0.0108*	4.89 - 4.93	26.36
Kielder	76063	7.07 *0.0133*	7.04 - 7.10	26.80
Cwm Berwyn	38310	6.83 *0.0179*	6.79 - 6.86	24.72
Maximum gust				
Kintyre	75433	11.47 *0.0201*	11.43 - 11.51	47.0
Glentrool	71466	11.58 *0.0217*	11.54 - 11.63	47.0
Rosarie	77092	8.37 *0.0163*	8.33 - 8.40	37.0
Kielder	76063	10.20 *0.0185*	10.16 - 10.23	41.0
Cwm Berwyn	38310	10.04 *0.0252*	9.99 - 10.09	37.0

4.3.2 Inter-site correlations

Full tables of between site correlations are presented in the Appendix for maximum daily gust (Table 10.2). Highest correlations were apparent within local clusters, with correlations declining with distance. Linear regressions were formed for sites showing correlations greater that 0.7. The site comparisons are summarised in Table 4.5, and the detailed regressions are listed in the Appendix (Table 10.3).

Table 4.5: Sites used to reconstruct time series for the 5 key sites. Marked * where used for Maximum gust only; marked # where used for long-term reconstruction. Note that recording at W Freugh commenced in January 1962, and Kinloss in January 1965.

Master site	Local Site	Acceptable distant monitoring sites	Meteorological Office and wind energy sites
Kintyre – Meall Buidhe	Deucheran	Mid Hill Strathlachlan	Machrihanish* Tiree*#
Glentrool – Mid Hill	Drumjohn	Meall Buidhe Strathlachlan	W Freugh*# Machrihanish*
Rosarie	Ben Aigan Rosarie Restock	Leanachan Moor* Beinn Staic*	Kinloss*#
Kielder - Caplestone	Bellingburn Birkley Birkley Restock Crookburn Plashetts	Leanachan Moor Strathlachlan*	Eskdalemuir#
Cwm Berwyn	Nant-y-maen Cefn Fannog Dalarwen Ochr fawr	Mid Hill	Aberporth# Cellan Bryn Titli Garn Gron

4.3.3 Daily time-series reconstruction

4.3.3.1 Maximum gust

The time-series of daily maximum gust was reconstructed for the period 1.1.1989 to 31.12.98 for each of the 5 master sites. A data summary is provided in Table 4.6. Note that there is very little change in the summary statistics, but a substantial increase in the available sample numbers. The time-series for Kintyre is shown in Figure 4.1.

Table 4.6: Summary of synthesised data 1989-1998 inclusive – daily maximum gust

Site	Sample Numbers	Mean $m\ s^{-1}$ *(Standard error)*	Mean –/+95% confidence limits	Maximum $m\ s^{-1}$
Kintyre	3736	16.47 *0.0974*	16.28 - 16.66	45.0
Glentrool	3726	17.01 *0.1054*	16.80 - 17.21	47.0
Rosarie	3727	12.46 *0.0842*	12.29 - 12.62	37.0
Kielder	3723	14.73 *0.0925*	14.55 - 14.91	37.0
Cwm Berwyn	3695	14.17 *0.0801*	14.01 - 14.33	37.0

The top 10 wind speeds were identified and are displayed by winter (Table 4.7). Note that if they were evenly distributed, then one occurrence would be observed per winter. These data will subsequently be related to the monitoring periods.

Figure 4.1: Reconstructed time series of maximum gust ($m\ s^{-1}$) for Meall Buidhe, the Kintyre key site for the return transect monitoring period 1994-1998.

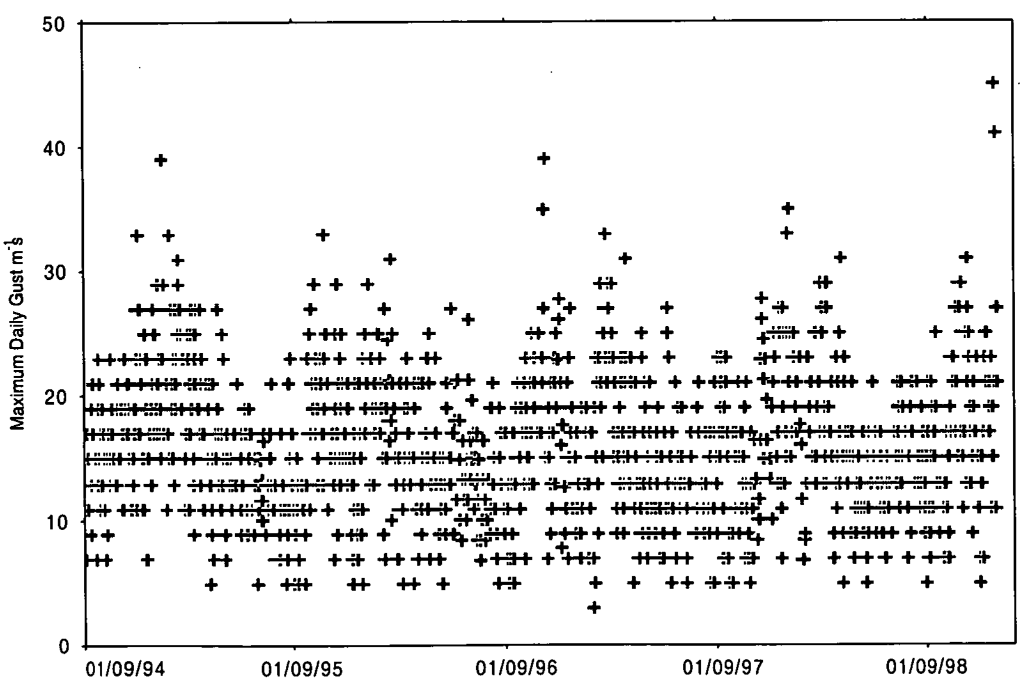


Table 4.7 Summary Occurrence of top 10 maximum daily gust wind speeds by winter (> 10 days shown where multiple occurrences of 10th ranked wind speed). ** = includes top ranked speed. # return transect studies commenced.

Winter	Cwm Berwyn (14 dates)	Kintyre (12 dates)	Glentrool (10 dates)	Kielder (16 dates)	Rosarie (15 dates)
88/89		1	1**	1	
89/90	1	2	3	3	3
90/91				2	1
91/92	3		2	2	2
92/93	3**	4		4**	2**
93/94#	6	1	2		3
94/95	1	1			3
95/96					1
96/97		1		2	
97/98					
98/99		2**	2	2	

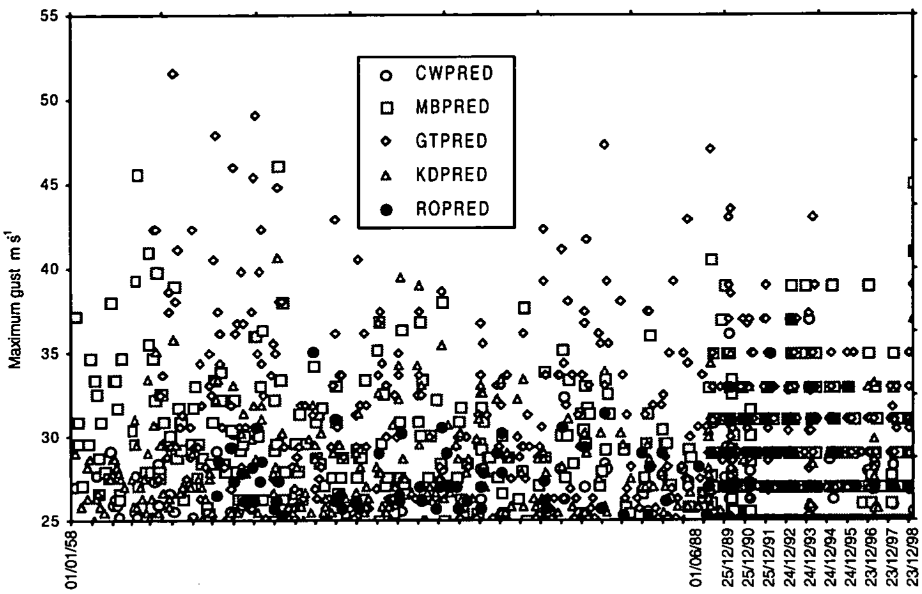
4.3.4 Construction of an extended time-series using monthly data

The longer-term, coarser resolution time-series is shown as Figure 4.2 and summary statistics provided in Table 4.8.

Table 4.8: Summary statistics of monthly data of maximum gust 1958-1988 predicted for master sites

Site	Sample Numbers	Mean $m\ s^{-1}$ *(Standard error)*	Mean -/+95% confidence limits	Maximum $m\ s^{-1}$
Kintyre	372	26.34 *0.2748*	25.80 - 26.88	46.11
Glentrool	319	29.21 *0.3596*	28.51 - 29.92	51.59
Rosarie	288	21.77 *0.2322*	21.32 - 22.23	35.09
Kielder	372	25.49 *0.2053*	25.09 - 25.89	40.63
Cwm Berwyn	364	21.04 *0.1837*	20.68 - 21.40	32.31

Figure 4.2 Monthly maximum gust time-series for each main site 1958-1998. Note that recording at West Freugh commenced in 1962, and Kinloss in 1965.



The reconstructed wind speeds experienced in the period prior to monitoring are compared with those experienced during windthrow monitoring in Table 4.9.

Table 4.9: Comparison of extreme gust wind speeds within and prior to overall monitoring period

Site	Maximum gust in monitoring period m s^{-1}	Maximum gust in pre-monitoring period m s^{-1}	Date of maximum in pre-monitoring period month/year	Dates of other maxima exceeding that of monitoring period month/year
Kintyre	45	46	1/68	2/61
Glentrool	47	52	12/62	12/66, 1/65, 1/84
Kielder	37	41	1/68	1/74, 12/74
Rosarie	37	35	9/69	None
Cwm Berwyn	37	32	12/81	None

The results indicate that the gusts experienced at Kintyre, Glentrool and Kielder during the monitoring period were exceeded within the extended time period, but those experienced at Rosarie and Cwm Berwyn were not.

For the period of the return transect studies, the wind speeds experienced were compared with previous events and the time of last exceedance was identified (Table 4.10). At the end of the monitoring period, 3 sites experienced the most powerful winds for 5 to 30 years.

Table 4.10 Summary of number of years since wind speed experienced during the monitoring period was last equalled/exceeded.

Winter	Cwm Berwyn	Kintyre	Glentrool	Kielder	Rosarie
93/94	< 5	< 1	< 4	< 2	< 1
94/95	< 1	< 2	< 1	< 1	< 1
95/96	< 1	< 1	< 1	< 1	< 2
96/96	< 2	< 2	< 1	< 4	< 1
97/98	< 3	< 2	< 2	< 2	< 1
98/99	< 1	< 30	< 5	< 6	< 1

4.3.5 Derivation of extreme value distribution from Weibull parameters

The hourly data were summarised to give Weibull parameters c and k for gust speed, and calculations performed to predict the mode and dispersion of the Fisher Tippett Type 1 distribution. This permits the analysis of the probability of wind speeds experienced in each monitoring area, and as a summary figure the 1:50 year return period hourly wind speed (V_{50}) was calculated using equation 4.5 (Table 4.11).

Table 4.11: Weibull distribution parameters for maximum hourly gust

Master site – gust	Weibull c Gust	Weibull k Gust	Mode	Dispersion	VT50 $m\ s^{-1}$
Kintyre	13.0	2.21	1172.55	234.51	45.7
Glentrool	13.1	2.11	1281.85	256.37	47.8
Rosarie	9.5	1.95	761.31	152.26	36.8
Kielder	11.5	2.12	991.26	198.25	42.0
Cwm Berwyn	11.4	2.16	930.30	186.06	40.7

The rarity of the wind speeds that occurred during the return period transect studies was assessed, and results are summarised in Table 4.12. This indicates the average interval between wind speeds of the magnitude experienced, and can be compared with Table 4.10 which indicates the actual interval in the time series.

Table 4.12 Summary of frequency estimation of gust wind speed experienced during the monitoring period of the return plots. Return period (years) of maximum gust experienced during the winter period.

Winter	Cwm Berwyn	Kintyre	Glentrool	Kielder	Rosarie
58-88	3	>50	>50	29	23
89-93	8	5	38	8	>50
93/94	12	5	10	2	10
94/95	3	5	1	1	5
95/96	1	1	1	1	10
96/96	1	5	1	3	1
97/98	1	2	1	2	1
98/99	1	39	6	8	1

4.4 Discussion

4.4.1 Reconstruction and representativeness of monitoring periods

Time-series were successfully reconstructed for each of the monitoring sites. The reconstruction made little difference to the summary statistics, but provided the necessary comprehensive temporal record. The data show considerable inter- and intra-annual variability at a site, and confirm that a 'family' effect does occur with groups of storms being experienced by the country or region over relatively short periods. This is most marked in the distribution between winters of the top-ranked storms (Table 4.7). The winter with highest winds differs between the sites, indicating that there is likely to be regional variation in timing of disturbance to stands in the British uplands.

There are some potential sources of error in the reconstruction, including the possibility of equipment malfunction not being identified. However, more problematic is the strong gradient in wind speed that may be present at the edge of severe storms. This means that two sites that are generally well correlated, may not be so in particular synoptic conditions. A consequence of this, if coincidental with a period requiring reconstruction, is that erroneous data will be produced, resulting in over- or under-prediction of significant winds.

The complete period of wind monitoring contains a number of extreme events, likely to have been influential in affecting stand development and gap formation. However, in the subset of years for which transects were revisited to study gap formation and expansion (see Chapter 5), the wind speeds were less remarkable at 3 of the five sites. There are complex interactions between absolute magnitude, and time since last exceeded, which are liable to have a role in determining the amount of damage in any one event. There is a surprising variety of experience with regard to prior exceedance, with sites separated by short distances (e.g. Kintyre and Glentrool) having different records of past severe storms.

4.5 Conclusions concerning wind speed measurements

Wind measurements have confirmed the severity of the wind climate in the uplands of Britain, and characterised the temporal, and some of the spatial, variability. Reconstruction of a complete time-series provides a dataset that can be used to calibrate periods of monitoring of gap formation and expansion. Calculation of probability of recurrence permits the assessment of likely frequency of any change related to the incidence of strong winds.

5 Gap Formation and Expansion

Alien they seemed to be:
No mortal eye could see
The intimate wedding of their later history
Or sign that they were bent
By paths coincident
On being anon twin halves of one august event
Till the Spinner of the Years said "Now"
Thomas Hardy, 'The convergence of the Twain'

5.1 Introduction

Openings in the canopy of a forest stand due to the death or destruction of trees are variously described as gaps or patches (see 3.4.1). Gap-phase and stand replacement represent descriptive end-points of a continuum of disturbance, both in terms of spatial and temporal scale, resulting from the interaction of dominant disturbance type, and forest type. At the regional or global scale, climate patterns determine whether wind is the dominant abiotic disturbance agent (see Chapter 2). At the regional or forest scale, disturbance may be affected by topography, geology, soil and forest type.

The mode, scale and frequency of gap formation can determine the structure and composition of the forest. In particular, disturbance can influence the longevity of the canopy trees, properties of the forest floor and the microclimate within which regenerating trees may develop. Only if suitable gaps form can regeneration and thereby self-perpetuation be possible. The concept of turnover rate summarises this influence by combining the fraction of the forest made up of gaps and the rate at which the gaps fill. Calculations of turnover rate are highly sensitive to estimates of gap formation and gap filling, but such estimates are lacking for upland forests of Sitka spruce in Britain. As a consequence, it is important to establish the occurrence and rate of formation (this chapter) and filling (next chapter).

5.1.1 Gap occurrence in natural forests

Canopy openings may be formed by a variety of abiotic or biotic disturbance agents, acting singly or together. For example, fungi and insect attack may lead to mortality of trees and subsequent canopy thinning, or 'snag' production; such gaps have been termed 'gradual' canopy gaps (Krasny and Whitmore 1992). In contrast, strong winds, and snow or ice loading of trees, may lead to rapid physical damage (uprooting or stem snap), and the creation of 'sudden' gaps (Krasny and Whitmore 1992). Gaps may result from a combination of abiotic (exogenous) and biotic (endogenous) agents such as when stem decay pre-disposes trees to stem snap (Barden 1981), and excessive epiphytic growth pre-disposes trees to over-turning in strong winds.

There is a very large literature on the contribution of gaps to forest structure and stand dynamics. Much of it concentrates on the consequences of the openings and does not address their formation or expansion. Many studies have been organised in response to an event such as a tornado or hurricane affecting a forest area (Putz and Sharitz 1991, Boucher and Mallona 1997, Pascarella 1997, Greenberg and McNab 1998, Battaglia et al. 1999). Others have sought to unravel past disturbance from the current structure of the forest/stand (Harcombe 1986, Veblen et al. 1989, Kneeshaw and Burton 1997); the selection of uniform (old growth) stands may accentuate the apparent predominance of gap-phase processes.

Gap dimensions are constrained by study method, by area studied, and by time monitored or represented by current stand structure (Everham III and Brokaw 1996). Nevertheless, studies in a wide variety of forest types, and subject to a range of disturbance agents have found that gap size distribution is highly skewed, with a predominance of small gaps and very few large gaps (Table 5.1). This skewed form of distribution has been found at a variety of scales, from studies along transects of a few hundred meters (Taylor 1990), to aerial photography covering thousands of hectares (Nowacki and Kramer 1998) (Table 5.2).

The rate and scale of gap formation has been found to vary between regions due to large-scale climate patterns. Thus in relatively wind-free regions, the fine-grained processes predominate and stand replacement is very rare; for example, studies in the northern hardwoods of the Eastern USA have indicated a very slow turnover, with a predominance of single tree gaps (Runkle 1998). In windier climates, there is a greater frequency of stand replacement and a tendency toward larger gap size. In some studies, the rate of gap formation has been found to vary from year to year due to climatic variability, and to vary with stand stage; there were more gaps but of smaller size in younger stages of hemlock-hardwood forest than in older stages (Dahir and Lorimer 1996).

Table 5.1 Summary of gap dimensions and occurrence from stand-level investigations (largely transect surveys); expanded gap sensu Runkle.

Forest types and source	Range in gap size (m^2)	Mean / median (m^2)	Gap fraction (%) and turnover (years)
Old-growth subalpine spruce-fir, NE USA (Battles and Fahey 1996)	12-1135	-/25-93	15-42%
Temperate deciduous (Nothofagus) Tierra del Fuego, Argentina (Rebertus, 1993)	55-1665	-/208	15.6% 320-448 yrs
Temperate coniferous forest, Oregon, USA (Taylor 1990)	111-1360	-/532	29% 206-248 yrs
Hardwood-hemlock, Michigan, USA (Dahir and Lorimer 1996)	-	28-115/-	- 128-192 yrs
Northern Hardwoods, New York, USA (Krasny and Whitmore 1992)	-	209/-	20.7%
Sub alpine old growth, British Columbia (Lertzman and Krebs 1991)	25-1127	286/203	52% 694 yrs
Primeval boreal forest, E-Central Sweden (Liu and Hytteborn 1991)	9-360	84/63	30.7% 195-228 yrs
Subalpine spruce-fir, Vermont, USA (Perkins et al. 1992)	48-319	170/-	40%
Old-growth beech forest, New Zealand (Stewart 1986)	91-939	-/295	22%
Temperate deciduous forest, Japan (Tanaka and Nakashizuka 1997)	-	104-190/-	8.8-20.2%

Many studies make no mention of gap expansion or enlargement following initial formation. However, this may not necessarily represent the lack of the phenomena but reflect the coarse temporal resolution in the data, or the rarity of the disturbance. Gap expansion appears rare where disturbance tends to be 'endogenous'. In the North-east United States, mortality of gap edge trees does occur but at a rate that is not enhanced compared to the mortality in the intact stand. For example, 46% of gaps showed some expansion but in only a quarter of cases was this due to blowdown and the remainder was due to standing death of edge trees (Runkle 1990, 1998). As a result, gap contraction due to lateral growth of the crown of edge trees is more commonly observed (see 6.2.3).

In situations where exogenous disturbance dominates, there is more frequent reference to gap expansion. However, this depends upon the repeatability of the damaging phenomena. In the case of tornadoes, the discrete and rare nature of severe wind speeds makes further enlargement by a repeat episode highly unlikely; even in the most prone areas, the recurrence is of the order of once in 1500 years (Ch 3).

Table 5.2 Summary of gap dimensions and occurrence from forest-level investigations (largely aerial photographs).

Forest types	Study area, event	Range in gap size (ha) * minimum measurable	Mean / median (ha)	Gap fraction (%) and turnover (years)
Hemlock-northern hardwood pre-settlement forest, NE USA (Canham and Loucks 1984)	>5mill ha Thunderstorm	1.0* – 3785ha	93.2 /	17-25% (in developing stages pre old-growth)
Second-growth hardwood-conifer, Massachusetts, USA (Foster and Boose 1992)	340ha Hurricane	0.04-37ha	< 2 /	-
Temperate coniferous forest (Harris 1989).	0.5mill ha Extra-tropical cyclones	0.81* - 70.8ha	7.5 /	1.6% overall; 10.6% of hemlock/spruce
Temperate coniferous forest, Oregon, USA (Taylor 1990)	<1000ha Extra-tropical cyclones	0.1* – 2.25	0.37	1.6-4.2% 279 yrs
Temperate coniferous forest, Kulu island, S E Alaska, USA (Nowacki and Kramer 1998)	129500ha Extra-tropical cyclones	0.8 – 405	15.8/5.7	-
Temperate southern beech forest, Argentina (Rebertus et al. 1997)	1040ha Extra-tropical cyclones	0.1 – 150	-	-/ 145yrs
Virgin Sub alpine spruce-fir forest, N Appalachians, USA (Foster and Reiners 1986)	667ha Hurricane and Extra-tropical cyclones	0.01 – 12.2ha	-	- 303 yrs

Where repeat disturbance occurs (e.g. through temperate storms) many gaps are found to be the result of multiple episodes. For example, 65% of gaps in a boreal forest reflected multiple episodes (Liu and Hytteborn 1991), 75% in temperate coniferous forest (Taylor 1990), and 53% in temperate deciduous forest (Rebertus and Veblen 1993b). In subalpine coniferous forest Perkins *et al.* (1992) found that half of all gaps expanded within a single year. Frequency of expansion is more commonly given than either rate or direction. However, Taylor (1990) identified 10 out of 73 patches expanded over a period of 26 years, with average annual rate of expansion of 7.1% (2.2-20.5%). The relative contribution to increase in gap area from new gaps and gap expansion is rarely distinguished.

Gap expansion results in an evolution of site and microclimate conditions that may have a significant effect upon the gap filling. Frequency of gap expansion is often established by the presence of multiple cohorts of regenerating trees that are spatially discrete. Taylor

(1990) found a 36 year age range in a complex growth pattern, Foster and Reiners (1983) found 5-7 episodes of 'stepwise' expansion, and Rebertus and Veblen (1993a) found at least 8 'releases' in the regeneration of a gap. Both Rebertus and Veblen (1993a), and Perkins *et al.* (1992) indicate that gap expansion was directional, and the latter found that 75% of the expansion was on the upwind margin. They suggested that this could lead to a form of 'unorganized fir wave', or partial wave. This type of spread is consistent with observations of reduction of growth, and enhancement of root and crown damage (Rizzo and Harrington 1988) at gap edges. However, other authors have observed enhanced development of lateral branches which in extreme cases can lead to overturning of trees into the gap – thereby suppressing regeneration (Young and Hubbell 1991, Young and Perkocha 1994).

Temporal variation in both the initial gap formation and in the subsequent expansion is observed, but few studies relate this to aspects of the wind climate. Tanaka and Nakashizuka (1997) observed decadal variation and attributed this to variability in typhoon frequency. Ogden *et al.* (1991) found that one half of all gaps created in a three year period was due to a single cyclone. Jonsson and Dynessius (1993) found substantial variation in rate of windthrow around a mean of 0-0.4 trees/year.

Very few studies have indicated wind speeds that cause damage or any form of wind speed/amount of damage relationship (see also Ch 2). Studies in the boreal forest have linked treefall with hourly mean wind speeds in excess of 14 m s^{-1} (approximate gust 22 m s^{-1}; with a frequency of 1.4/year) (Liu and Hytteborn 1991), or hourly mean in excess of 11 m s^{-1} (approx gust 18 m s^{-1}) (Jonsson and Dynesius 1993). Gusts of 26-32 m s^{-1} were sufficient for small scale disturbance of temperate deciduous forest and 32-39 m s^{-1} for catastrophic events which occurred approximately 3 times per century (Pontailler et al. 1997). A gust of 54 m s^{-1} was identified as damaging in sub-alpine conifer forest (Perkins et al. 1992). Peterson (Peterson 2000) recorded the passage of two tornadoes – one (F1 tornado) causing 1.5ha, the second (of F4 magnitude) causing 386ha of forest destruction.
Applying the evidence from the study of natural forests to upland British spruce forests (with an emphasis on exogenous wind disturbance), results in some interim hypotheses -:

- *Gap formation is likely to be infrequent*
- *Gap formation will result in a skewed gap size distribution.*
- *Individual gaps will expand, and the limited evidence suggests that this will largely in the direction of the wind.*

- *Temporal variation in both formation and expansion might be expected, assuming exogenous disturbance predominates.*
- *Gusts of 22-26 m s^{-1} (Hourly wind speeds of 14-16 m s^{-1}) will initiate damage.*

5.1.2 Gap occurrence in planted or managed forests

Studies of wind-induced gap formation in managed forests have differed in emphasis from those in natural forests reviewed in the preceding section. In particular, there has been little attention to the characteristics of individual gaps, but a focus on the proportion within the stand or management unit (compartment). Monitoring has commonly recorded the percentage of canopy trees blown over or snapped with little attention to the spatial disaggregation of this within the stand. Research has concentrated on causation, for prevention and latterly prediction, rather than the consequences of the damage (except in volume or economic terms).

In common with the ecological literature, many of the investigations of managed forests have been in response to discrete (economically catastrophic) events. However, in certain regions such as Britain, wind damage has been so frequent as to merit more continuous effort. In general, the monitoring has been at the forest scale (Pyatt 1968) and undertaken by aerial photography rather than by stand investigations. Studies of catastrophic events have shown that 4-30% of the mature forest area may be blown over (Holtam 1971, Grayson 1989, Quine 1991), with some stands being almost completely damaged (akin to widespread stand replacement disturbance). Other monitoring indicated 'endemic' damage of 2-8% area per year, and such increments were incorporated into a British hazard classification with an implicit assumption that they would occur annually (Miller 1986, Insley et al. 1987, Quine 1995). Early work (1960's) did not take account of temporal variation – and the resultant hazard model assumed similar damage in most years (Booth 1977, Miller 1985). Latterly, the importance of temporal variation in wind climate has been recognised (Quine 1995, Quine and Bell 1998), and represented by the development of a risk rather than hazard model (Quine and Gardiner 1998). Expansion of existing gaps was held to be a particularly important component of this increase in gap area (Neustein 1972). In recent work, the imprecision of geo-referencing in the photographic interpretation process used for the windthrow monitoring areas has prevented the proportion of formation and expansion of gaps being resolved (Quine and Bell 1998).

There have been few observations of damage with simultaneous measurements of wind speed. A study in a pine forest in East Anglia recorded gust wind speeds at the canopy top of 17.5 m s^{-1} (28 m s^{-1} at 31m above ground – 16 m above canopy) on a day when there was damage to the surrounding stand (Oliver and Mayhead 1974). There was also general damage elsewhere in the region and inspection of Meteorological Office records for the day suggest maximum gust speeds of 30-32 m s^{-1} at stations in the region.

The winds recorded at conventional Meteorological Office sites during catastrophic storms in the twentieth century have been reviewed (Quine 1991). In broad terms these indicate that gusts of 35 m s^{-1} experienced at low-lying sites are associated with low percentages of damage (ie less than 5% of vulnerable growing stock). Gusts of > 40 m s^{-1} result in widespread damage (10-30%); damage is rarely noted when gusts less than 30 m $s^{-1}$are recorded (Quine 1991, Mason and Quine, 1995). A recently derived risk model proposes hourly wind speeds of 25 to 29 m s^{-1} (gusts 40 – 46 m s^{-1}) are sufficient to cause damage to the mean tree in mature unthinned stands of Sitka spruce on gley soils (Gardiner and Quine 2000).

Research at the stand level has investigated the processes causing damage. Factors found to be important include root anchorage (root architecture and soil type) (Coutts 1983, 1986), stem and crown dimensions (Gardiner et al. 2000), and stand density (Gardiner et al. 1997). The bio-mechanical response of trees to reduction in stem numbers by thinning, windthrow or edge creation has been shown to be slow and involve an initial increased allocation to root growth, followed by stem and crown adaptation (Valinger 1992, Lundqvist, 1996, Urban et al. 1994). Openings in the canopy allow the penetration of strong winds, and generate turbulence (Gardiner 1995), leading to increased crown damage, rocking of trees and fatiguing of the root/soil interface. Monitoring of damage at the edge of artificially created circular gaps at Ae and Redesdale showed that gap size (and in particular perimeter) was an important factor in determining rate of spread (Neustein 1964, Neustein, 1968). Trees blew away from the gap in the direction of the wind, rather than fell into them. At least 9 separate events caused damage on the margins of the gaps in the Ae experiment during the winter 1962/63, each having a mean speed of at least 18 m s^{-1} (approximate gust 29m s^{-1}) 50 km distant at Eskdalemuir. Studies with model trees in a wind tunnel have shown that loading of trees on the downwind edge is substantially greater than that on the upwind edge which does not differ from the mid forest values. Loading increases very rapidly with increasing size of opening up to a gap diameter of twice the height of the edge trees. Trees on the downwind side of gaps of one tree height in diameter have double the loading of trees in mid forest (Stacey et al. 1994).

Based on the studies of managed forests, the following hypotheses are proposed –

Gap formation will be common but gap expansion will be more important subsequently
Expansion will occur on the gap margins in the direction of the prevailing wind
Gap size distribution is unknown but unlikely to be skewed to small gaps given the prevalence of gap expansion.
Gusts in excess of 29 m s^{-1} (hourly wind speeds in excess of 18 m s^{-1}) are required for windthrow of trees.

5.1.3 Objective of proposed study of gaps in planted spruce forests

The review of literature has highlighted the lack of knowledge on gap occurrence and expansion in British spruce forests. Evidence from both natural and managed forests has suggested some likely characteristics, but the predictions from the two forest types are not always consistent. An improved understanding is needed to provide the link between the occurrence of the disturbance agent, and the likelihood of gap filling following disturbance. A stand-based survey of gap formation and expansion was therefore proposed to establish a basic understanding of gap occurrence in planted forests, and address the hypotheses outlined above.

5.2 Methods

5.2.1 Single transect surveys of gap presence

Transects in five areas of upland, predominantly spruce forest were sampled at Kielder (Bellingburn), Kintyre (Carradale), Moray (Rosarie), Glentrool (Drumjohn), and Tywi (Cwm Berwyn). The presence, size and shape of each intersected gap was recorded (see 3.2.2); note that this will reflect both formation and subsequent expansion.

Gap area was calculated from the long and short axis measurements using the formula appropriate to the gap shape identified. After basic summary by area and shape, three calculations were performed –

- Transformation of the area data to account for increased chance of intersecting large gaps, thereby giving an amended size distribution (Runkle 1982, 1985, Foster and Reiners 1986).
- Calculation of fraction of area in gaps (De Vries 1974, Runkle 1985).
- Calculation of the turnover time implied by these figures (Lertzman and Krebs 1991).

De Vries (1974) developed the method of line intersect sampling to estimate the quantity of elements within an area traversed by the line (e.g. the volume of logs on a felling site). Runkle (1982) adapted the method to calculate the fraction of forest in gaps. When sampling the gaps intersected by a transect, there is a greater likelihood of intersecting a larger gap than a smaller gap. Runkle proposed that to obtain an unbiased size distribution the area of each gap is divided by the square root of the area (term proportional to the radius) to correct for the increased probability of large gaps being intersected. When a straight line, ***L***, goes through a population of gaps and intersects ***n*** of them, an unbiased estimate of the true mean quantity per unit area can be obtained by

$$e(x) = \left(\frac{1}{L}\right)\sum_{j=1}^{n}\left(\frac{x_j}{d_j}\right)$$ **Equation 5.1**

where ***xj*** is the gap area of the *j*th gap, ***dj*** is the diameter of the circular element, ***L*** is length of transect. (Runkle 1985 equation 1). The variance (Runkle '85 equation 3) can be calculated as

$$vare(x) = \left(\frac{1}{L}\right)^2\sum_{j=1}^{n}\left(\frac{x_j}{d_j}\right)^2$$ **Equation 5.2**

Runkle assumed an elliptical shape for the purpose of calculating gap area. Battles *et al.* (1996) have suggested that the assumption of an elliptical shape is likely to overestimate gap area as many are 'non convex polygons'; the use of the diameter of the circle when correcting for the probability of intersection is likely to lead to overestimates of the gap fraction. They identified a method of deriving alternative perimeter values through the use of area/perimeter regressions derived from intensive measurements of a subsample of gaps; such a subsample was not available from the single visit survey.

5.2.2 Return transects – gap formation and expansion

Selected transects within monitoring areas were established as 'return transects' in Autumn 1993 (see 3.2.3). The transects have been revisited at approximately monthly intervals throughout the succeeding winters to observe changes to existing gaps or formation of new gaps. After a change occurred the gap was re-measured and the boundary trees revised and marked.

Measurements of gap cover were plotted to scale, digitised, imported into IDRISI GIS and area, perimeter and gap centre (location in x and y relative to a fixed measurement post; standard radius and coefficient of dispersion) were computed. Change in gap shape was considered by calculating the fractal dimension D (twice the slope of the regression line of *log* area against *log* perimeter) for the gaps prior to and after expansion.

Changes identified during the surveys have also been qualitatively recorded as a visit summary. A change categorisation was developed to identify periods of change/no change for calculations of frequency of disturbance (Table 5.3).

Table 5.3 Summary classification of types of change to gap area

Type of change	Variants
No Change	-
New Gap formation	-
Increase in gap area	Extension to existing gap Coalescence of existing gap with pre-existing neighbouring gap Loss of internal trees (applies to islands of standing trees in large gaps)
Reduction in gap area	Gap closure (identified by skyview measurements no longer possible due to branch interlock). (Loss of gap due to felling of compartment.)

5.3 Results

5.3.1 Single period transect survey - Summary statistics

614 gaps were recorded on 56200 m of transect. Each monitoring area had a substantial number of gaps, but the frequency of occurrence varied between sites (Table 5.4). An example gap is illustrated in Figure 5.1.

Table 5.4 Gap numbers and density by monitoring area

Site	Total Number of gaps	Mean distance between gaps along transect (metres)	Gap abundance Numbers per ha	Mean gap size (m^2) *SE*	Median gap size (m^2)	Range in gap size (m^2)	Largest gap as % of total wind-thrown area
Carradale	48	146	3.3	140 *(48.7)*	12	2-1600	23.8
Cwm Berwyn	121	121	2.4	317 *(62.7)*	57	9-4398	11.5
Glentrool	133	57	7.3	211 *(59.3)*	38	3-6225	22.2
Kielder	245	71	3.4	361 *(97.5)*	18	3-16000	18.1
Rosarie	70	131	3.2	154 *(93.4)*	23	5-6534	60.7

The classification of gaps by size class indicated that most were small (less than 5 trees) and were circular, elliptical or rectangular in shape (Table 5.5). This preponderance of small gaps was confirmed by gap size distributions obtained from the area calculations. Mean gap size varied from 140 to 361 m^2, and maximum gap size ranged to 16000 m^2. At each site there was a highly skewed frequency distribution with a very large number of small gaps and a considerable tail of small numbers of large gaps (Table 5.5), (Figure 5.2). At one site, the single largest gap represented 60% of the total gap area.

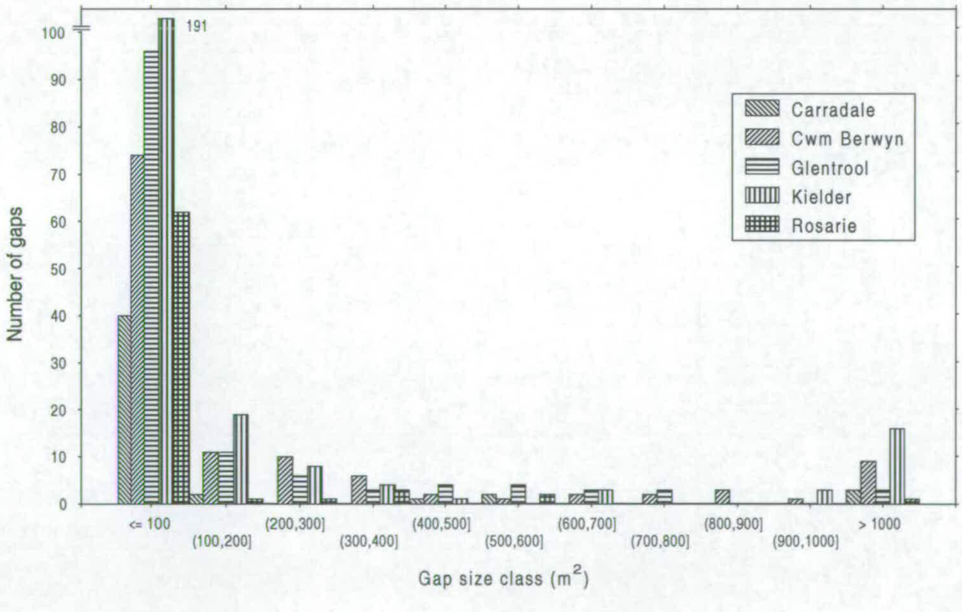
A log-normal distribution was fitted to the individual area data, and to all sites combined. Tests with the Chi-squared and Kolmogorov-Smirnov tests gave non-significant results; only if the test is significant is the hypothesis that the observed data follow the chosen distribution rejected.

Figure 5.1 Photograph of a gap intersected by a transect in Rosarie forest. The snow fall has occurred after gap formation.

Table 5.5 Summary of gap size (number of trees) and shape for all areas combined.

Shape	1-4 trees	5-10 trees	11-20 trees	21-50 trees	>50 trees	*Total number of gaps*
Circle	146	4	2	2	13	*167*
Ellipse	67	17	16	16	22	*118*
Square	19	2	3	1	0	*25*
Rectangle	86	33	23	11	14	*167*
Linear	51	11	3	0	0	*65*
Other	6	6	9	9	19	*49*
Total number of gaps	*375*	*73*	*56*	*39*	*68*	*614*

Figure 5.2 Summary histogram of gap size class frequency from the single transect survey.



5.3.2 Single period transect survey - Gap fraction and turnover time

Table 5.6 gives the estimated gap fraction and turnover time assuming a gap fill time of 10 years.

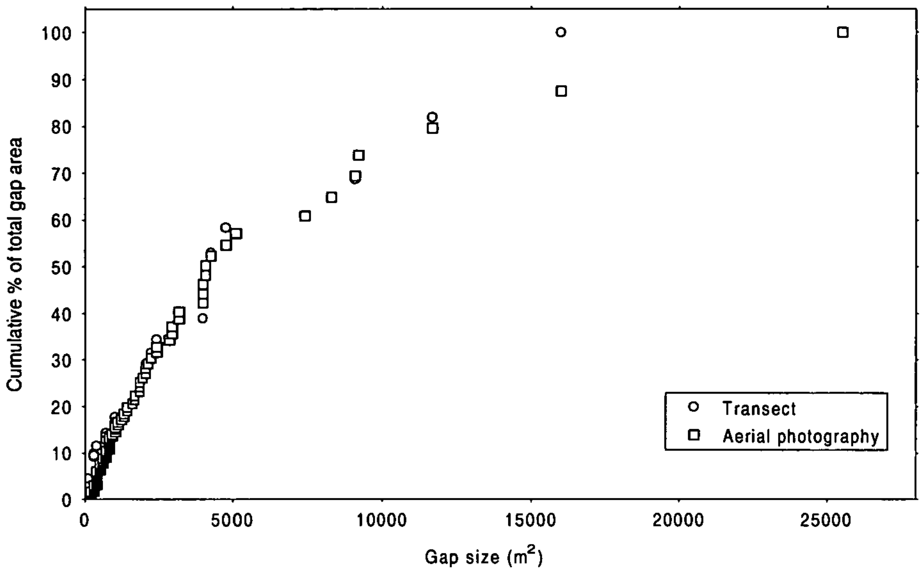
Table 5.6 Calculation of fraction of area in gaps and turnover time using 10 years to fill.

Site	Fraction of forest in gap *(Standard Error)*	Turnover time if fill time is 10 years
Carradale	0.046 *(0.104)*	219
Cwm Berwyn	0.076 *(0.011)*	133
Glentrool	0.154 *(0.195)*	65
Kielder	0.122 *(0.151)*	82
Rosarie	0.050 *(0.099)*	201

5.3.3 Single period transect survey - Comparison with previous estimates

More small gaps were identified than in the previous aerial photography interpretation because of the constraints of photo resolution. For example, in Kielder, in the subset of compartments sampled by transects there were 245 gaps; 78% of these were less than 100 m^2 (the approximate limit of aerial photography), but these only accounted for 4% of total windthrown area. In contrast the aerial photography interpretation for the whole of Bellingburn identified 115 gaps or patches (range of gap size 100-25500, mean 1772). However, the cumulative gap area curves were similar (Figure 5.3)

Figure 5.3 Comparison of cumulative area in gaps/patches estimated from transect and aerial photography for Kielder (Bellingburn) monitoring area.



5.3.4 Return period transect surveys - Change in gap numbers and area

12300 m of transect was visited and checked for changes to existing gaps.

Results summarising change in gap numbers, gap size and area in gaps are summarised by monitoring site in Table 5.7 to Table 5.9.

Data of the 5 sites are summarised in Table 5.10 which shows substantial differences between sites in the proportion of increase in gap area due to new gap formation or existing gap expansion, and in the numbers of gaps that form or remained unchanged.

Table 5.7 Change in gap numbers over monitoring period

Site	Total number of gaps at start	Gaps lost by coalescence	New gaps formed	Gaps expanding	Gaps showing no change
Carradale	16	1	7	7	8
Cwm Berwyn	19	0	2	4	15
Glentrool	23	3	23	13	14
Kielder	28	0	1	2	26
Rosarie	18	1	2	8	9

Table 5.8 Change in gap size over monitoring period

Site	Mean gap size at start (m²) *standard error*	Mean gap size at end (m²) *standard error*	Range in gap size at start (m²)	Range in gap size at end (m²)	Range in size of new gaps (m²)
Carradale	403.3 *308.5*	497.5 *252.2*	10.7 – 4998.5	10.7 – 5200.0	9 – 214
Cwm Berwyn	337 *110.6*	370 *109.6*	10.7 – 1545.9	6.9 – 1545.9	7
Glentrool	53 *16.6*	340 *100.5*	6.2 – 359.4	6.2 – 3450.2	14 – 1493
Kielder	133.3 *49.3*	139.0 *55.4*	4.3 – 1235.1	4.3 – 1494.5	31
Rosarie	109 *42.1*	259 *130.7*	15.5 – 695.5	21.1 – 2528.0	26 – 45

Table 5.9 Change in total amount of windthrow; percentage area windthrown calculated from intersection statistics

Site	% area wind-thrown start *standard error*	% area wind-thrown end *standard error*	Total gap area start (m²)	Total gap area end (m²)	Area of new gaps (m²)	Area of expansion (m²)	Area of coalescence with existing gaps (m²)
Carradale	9.9 *(0.418)*	16.5 *(0.545)*	6453	1094 4	325	763	3616
Cwm Berwyn	6.3 *(0.186)*	7.3 *(0.206)*	6405	7777	14	287	1072
Glentrool	5.7 *(0.141)*	23.0 *(0.487)*	1219	1461 4	4839	1758	6027
Kielder	8.6 *(0.208)*	8.9 *(0.216)*	3732	4031	31	268	0
Rosarie	6.9 *(0.059)*	9.5 *(0.196)*	1955	5190	71	274	2890

Table 5.10 Summary of change between the 5 sites over period 1993-1999

Site	Ratio of new:expansion	% number of new gaps	% number of gaps with no change	Increase in % area windthrown
Carradale	0.43	44	50	6.6
Cwm Berwyn	0.05	10	79	1.0
Glentrool	2.75	100	61	17.3
Kielder*	0.12	4	93	0.3
Rosarie	0.26	11	50	2.6

* shorter monitoring period

At all sites there was an increase in gap area and gap numbers over the period of monitoring. Gaps that expanded were significantly larger than those which remained unchanged (Kolmogorov-Smirnov test, Mean starting gap area for no change gaps 98.07 [n=72, SD 214.7], Mean starting gap area for changing gaps 434.12 [n=29, SD = 957.2], $p<0.025$)

(Figure 5.4). Furthermore, at least half of the gaps remained unchanged, and in the case of Kielder, over 90% of the gaps showed no expansion. However, the magnitude of change varied substantially between sites.

For three sites (Cwm Berwyn, Kielder and Rosarie) the change in gap area and numbers was modest (Figure 5.5), ranging from 4-10% over the study period. Expansion of gap area occurred largely by small-scale extensions to a small proportion of the gaps. New gaps were small, with sizes of 31 m^2 at Kielder, 7 m^2 at Cwm Berwyn, and 26-45 m^2 at Rosarie. Coalescence with pre-existing gaps, not previously intersected by the transect, created some apparently larger shift in gaps.

For two sites (Glentrool and Carradale) there was substantial change in both gap numbers and gap area – although, the majority of gaps still showed no change. Expansion in total gap area occurred via extension, coalescence and formation of moderately sized new gaps (range in size of 9-214 at Carradale, and 14-1493 at Glentrool). The magnitude of change was particularly marked at Glentrool (Figure 5.5).

Figure 5.4 Comparison of gap size distribution for gaps that expanded and those that did not change during the monitoring period

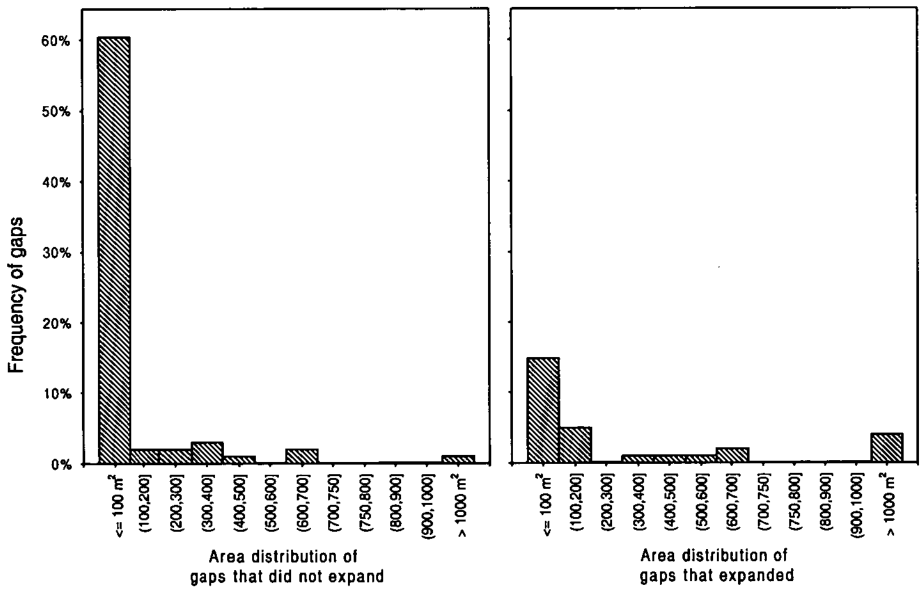


Figure 5.5 An example of small scale of change in gap numbers and area - Kielder

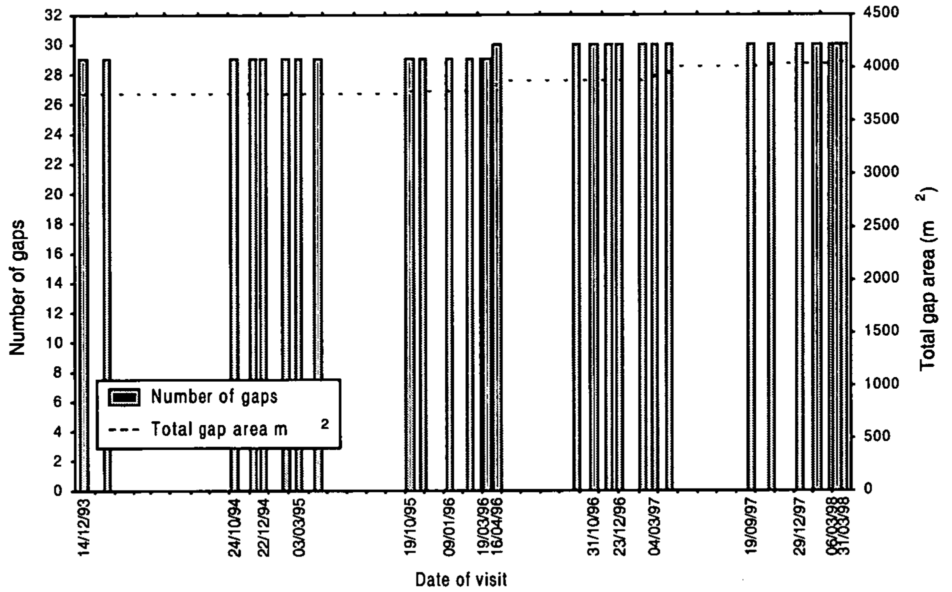
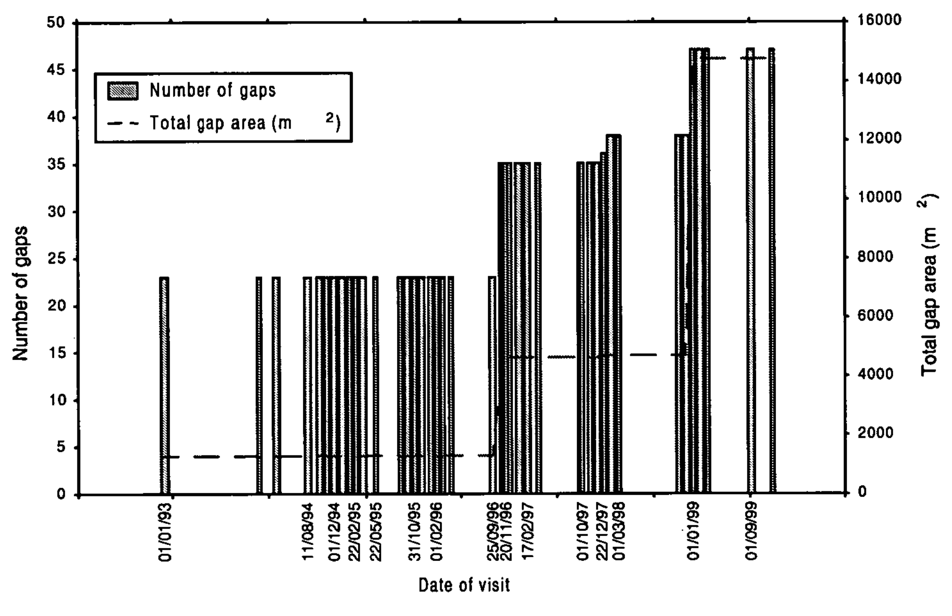


Figure 5.6 An example of large scale change in gap numbers and area - Glentrool



5.3.5 Return period transect surveys - Change in gap shape and location of gap centre

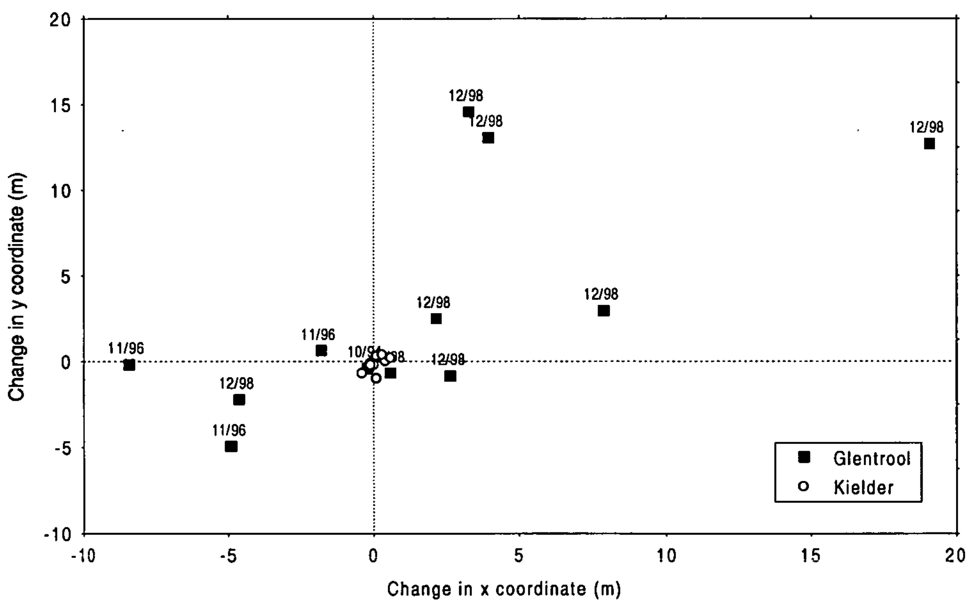
The change in gap shape was considered by calculating the fractal dimension *D* (logarea/logperim – twice the slope of the regression line) for the gaps prior to and after expansion. Results (Table 5.11) indicate increasing complexity at most sites.

Table 5.11 Summary of changes in fractal dimension (D) for gaps before and after expansion by monitoring site. A value of D of 1 would indicate gaps are circular. *shorter monitoring period

Site	Number of expanding gaps	Fractal D at start	Fractal D at end
Carradale	6	1.24	1.41
Cwm Berwyn	3	1.29	1.14
Glentrool	12	1.12	1.26
Kielder*	2	1.24	1.48
Rosarie	8	1.19	1.26

The change in location of the gap centre was also calculated using the IDRISI module 'Centre'. The results indicate little change at 3 sites, confirming the small scale of expansion relative to the size of the existing gap. At two sites, and where there was coalescence, larger shifts in gap centre were found. These shifts were not unidirectional, and indicate that the gap did not migrate solely in an easterly direction. The results are illustrated in Figure 5.7 for two contrasting sites.

Figure 5.7 Change in location of gap centre for two monitoring sites – Glentrool (major change) and Kielder (minor change)



5.3.6 Return period transect surveys - Periods of change

Data were processed for the period 1993-1999, (except for Kielder, where the monitoring was truncated by felling in 1998) to indicate the proportion of change periods and these are summarised in Table 5.12.

Table 5.12 Summary results of change periods for each site. * shorter monitoring period

Site	Total number of periods	Number with no change (%)	Number with new gaps	Number with expanding gaps only
Carradale	45	38 *(84%)*	1	6
Cwm Berwyn	49	45 *(92%)*	2	2
Glentrool	44	39 *(89%)*	4	1
Kielder*	29	18 *(62%)*	1	7 *(10 with changes to internal gap trees)*
Rosarie	48	38 *(79%)*	2	8

The results confirm the low level of change in 3 sites and greater change in two sites. The change that has occurred has been concentrated into a very few episodes, and there were more periods with expansion than with new gap formation. The period of greatest change appears to vary between sites indicating regional differences in timing of gap formation and expansion.

The relationship between the periods of change and the wind speeds recorded (see 4.3.3) was examined. For three of the sites, where change was extremely infrequent, there was not a strong dose/magnitude response. However, for the two sites that showed more substantial changes, there was a suggestion of a non-linear relationship between maximum wind speed and increment of gap area (Figure 5.8). Note that the wind speeds are those at the reference sites and no adjustment has been made for topographic differences.

However, tests of the difference in magnitude of wind speed between periods with and without new gap formation showed no significant differences (Table 5.13), although the mean was consistently higher for periods with new gaps. Similar results were found when comparing a three-class division of periods (no change, expansion, new gaps) using the Kruskal-Wallis ANOVA by ranks test (Table 5.14), although for two of the sites the differences were almost significant. A similar lack of discrimination was apparent when wind speeds were converted to return periods. However, at Carradale, periods with new gaps had wind speeds of 8 to 39 years return period, whereas periods with no change or expansion were had wind speeds with return periods of 1 to 5 years.

Figure 5.8 Relationship between period increment of gap area, and maximum wind speed recorded. Fitted lines are polynomials fitted to individual site data.

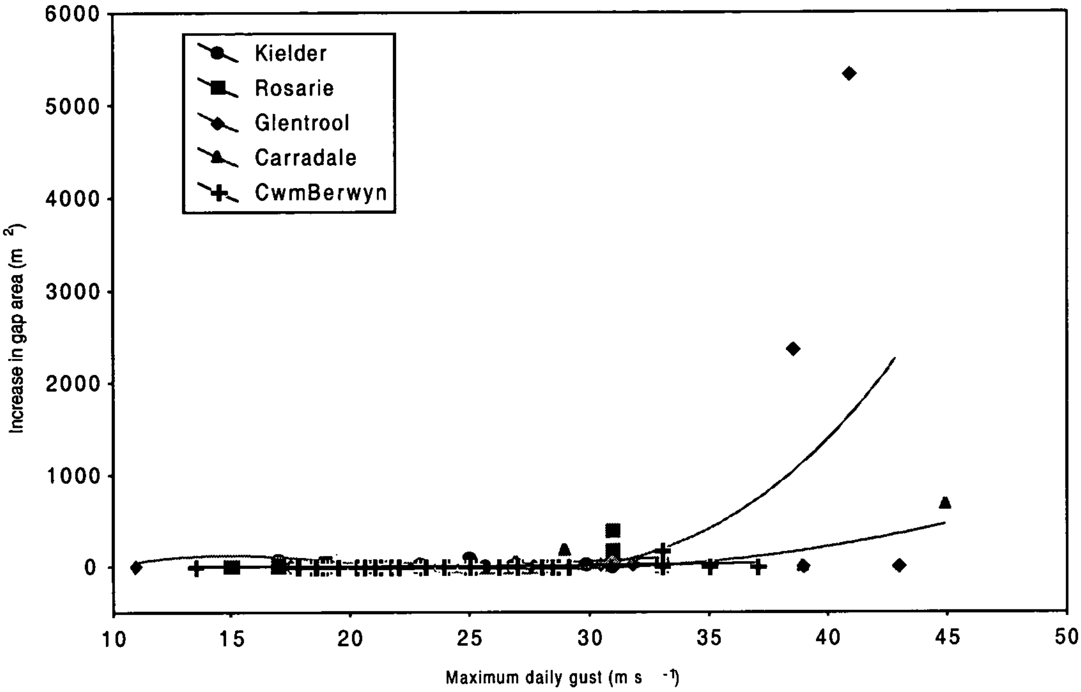


Table 5.13 Change period summary for 1993-1999 for the 5 sites – results of test of significance in wind speed recorded during periods of no new gaps and periods of new gap formation.

Site	Mean of Maximum Gust (m s^{-1}), Periods of no change *Standard error*	Mean of Maximum Gust (m s^{-1}) Periods with new gaps *Standard error*	Significance test p level for Maximum Gust *Sample numbers* *No change:change*
Carradale	28.9 *4.8*	32.2 *7.4*	p>0.1 *33:8*
Cwm Berwyn	24.1 *5.3*	25.8 *6.4*	p>0.1 *40:3*
Glentrool	29.1 *5.9*	33.6 *7.9*	p>0.1 *33:7*
Kielder	26.3 *4.5*	27.4 *4.7*	p>0.1 *18:11*
Rosarie	23.1 *4.1*	27.0 *6.0*	p>0.1 *32:11*

Table 5.14 Change period summary for 1993-1999 for the 5 sites, test of significance of wind speeds recorded in periods of no change: expansion: new gap formation.

Site	Daily Maximum Median test	Daily maximum ANOVA by ranks
Carradale	p=0.218	**p=0.051**
Cwm Berwyn	p=0.583	p=0.895
Glentrool	p=0.167	**p=0.051**
Kielder	p=0.377	p=0.100
Rosarie	**p=0.047**	p=0.076

5.4 Discussion

5.4.1 Formation of gaps

The single survey confirmed that gaps were prevalent in stands at all sites despite the comparative youth of the forests. The contrasting hypotheses generated from natural forests (that gap formation would be rare), and from the planted forests (that gap formation would be common) were tested using the data from the return transects. At 3 of the sites only 1 or 2 new gaps formed in the whole monitoring (equivalent to a 4-11% change by number) and adding only 0.2 – 3.6% to the total area windthrown. The formation was restricted to 1 or 2 of the sampling periods. This rate of gap formation could be described as infrequent.

At 2 of the sites (Glentrool and Carradale), there was a more substantial increase in the number of gaps – by 7 and 23 respectively (equivalent to a 43-100% increase by number), and a 5-396% increase in total windthrown area. However, at these sites the change was also restricted to 1 and 4 periods (2 to 9% of the observation periods), so was not common; nor was it common in comparison to periods of expansion (see below).

The low rate of gap formation appears to conflict with the actual presence of gaps within the monitoring areas. These results indicate that the gap formation is neither rare nor common – but infrequent, and event-related. In particular, at Glentrool and Carradale, the Boxing Day storm of 1998 was responsible for a major increase in gap numbers (and November 1996 in Glentrool also). The pre-existing large number of gaps e.g. at Cwm Berwyn, Kielder and Rosarie may reflect earlier extreme storms; results from monitoring the whole of these sites between 1988 to 1994 showed a windthrown increment of between 1.5 and 2.5 % of the area (Quine and Bell 1998).

5.4.2 Expanding gaps or static gaps

At the four sites other than Glentrool, more gaps expanded than formed during the monitoring, and expansion (alone) happened in more periods than new gap formation (with expansion). However, at all sites, at least 50% of the gaps remained unchanged in size. This result contrasts with the hypothesis based on previous work in planted forests that gap expansion would be common.

Gap expansion tended to be by small-scale attrition at edges of the larger gaps. The gaps that expanded were larger than those that did not, but the groups could not be distinguished by size alone. The direction of gap spread was variable, particularly where the degree of change was slight. At Glentrool, where there was substantial gap expansion, the movement of the gap centre indicated that expansion occurred both upwind and downwind; this does not reflect evidence in natural forests.

That expansion at gap edges should occur more than new gap formation, could be anticipated due to a variety of processes – including enhanced wind forces acting at gap edges, and waterlogging due to disrupted drainage. These processes may appear more important in young planted forests, than older natural forests, where individual tree senescense and mortality may have a significant role in contributing to tree vulnerability. In some studies of old growth forests, the proportion of snapped trees acting as gap-makers substantially exceed that of overturned trees.

5.4.3 Gap size distribution for planted forests

On the basis of results from natural forests, I hypothesised that the gap size distribution would be skewed, with many small gaps, and few large gaps. There was little evidence on which to base a hypothesis for planted forests alone; note that indication from aerial photography interpretation from the monitoring areas has subsequently shown this to be likely (Quine and Bell 1998).

The gap size distribution recorded in the single transect survey, was similar in form to that derived in studies of natural forests e.g. (Runkle 1982, Foster and Reiners 1986). This result is surprising given the relative uniformity in structure and the brief existence of these planted forests. Runkle (1982) used the lognormal distribution to summarise his results, and interpreted the lognormal as reflecting gap size as a result of many essentially random processes whose effects are multiplicative. Foster and Reiners (1986) used a negative exponential distribution, reflecting small single treefall gaps forming more often than large multiple treefall gaps. Many subsequent authors have used this distribution to summarise their data.

The results of the return transects confirmed the skewed nature of the distribution; the preponderance of gaps less than 100 m^2, indicates that the distribution is more markedly skewed than previous indications based on study of aerial photographs. However, the predominance of expansion over new gap formation (at least in 4 of the sites), raises questions over the randomness of the processes leading to a given gap size distribution. Furthermore, the evidence from Glentrool is that large gaps can form in a single event and not just by expansion leading to a slow increase in gap size. This suggests that there may be separate processes acting, and this might be reflected in the apparently discontinuous size distribution, with an apparent lack of mid-sized gaps. There are parallels in the literature on fire, where negative exponential patch size distributions are commonly used as descriptors. Li *et al* (1996) have criticised the application of this continuous distribution to discontinuous fire classes, and have highlighted that it may not be able to satisfactorily 'simulate' infrequent large fires. Many gap studies may inadvertently preclude the identification of large gaps or patches by the selection of uniform (e.g. old growth) sample sites and limited spatial and temporal scale of study.

Nevertheless, the confirmation of a skewed gap size distribution indirectly supports the ideas of careful transference of knowledge (adaptive management) from natural forests to managed forests. There is a substantial range of gap sizes present, some of which exceed the thresholds identified as being required by Sitka spruce for regeneration. Whether this knowledge is also transferable is explored in chapter 6.

5.4.4 Wind strength and recurrence

The major changes in gap occurrence at Glentrool and Carradale were caused by notable storms that were responsible for significant regional damage to forests. These storms (December 1998; November 1996) were relatively rare events, with return periods of 5 to 40 years, and which had not been exceeded for 6-30 years. However, the derivation of clear relationships between gap formation, expansion and wind speed was unsuccessful.

Although in each case, the mean of the wind speed statistics was higher for periods of change than no change, the differences were rarely significant. This may be due to a number of reasons – including the relative lack of samples of periods of change (particularly new gap formation), representativeness and accuracy of the wind measurements, the importance of storm sequences, pre-existing site conditions, additional abiotic factors e.g. wet snow. The wind speeds associated with new gap formation and expansion were consistent with those previously identified in the literature for natural forests and planted forests. The relationship between wind speed and amount of change appears to be non-linear, but more data is required to confirm this finding; this is further considered in 7.5.2.2.

5.4.5 Implications for forest structure

At the start of the monitoring, the area of forest that had been windthrown ranged from 5.7 to 9.9%. Assuming a stand age of 40, this would approximate to a gap formation rate of 0.14 to 0.25% area per year. If we assume that the stands are not vulnerable for the first 20 years, then the rate becomes 0.28 – 0.49, implying periods of 350 – 202 years for an equivalent area to the total to be windthrown. The monitoring period (six year) increment was 1 – 17% (excluding Kielder) – giving an annual rate of 0.17 – 2.88%, implying periods of 600 to 35 years turnover. The cumulative windthrow to the end of the period ranged from 7.3 to 23%, giving an annual rate of 0.16-0.5 (to assumed age of 46), or 0.28 to 0.88% (to assumed period of age 20 to 46).

The implied turnover rate for Glentrool would vary from 350 to 35 years depending upon whether you take the starting or monitoring period increment as representative. Alternatively, if the computations are based on the cumulative end of period increment (23% by 46 years = 0.5% annual rate; or 23% in 26years (post 20 years) = 0.88 annual rate), a range of 114-200 years is suggested. However, given the event-specific drive to the gap formation and expansion, a better understanding of the wind speed/gap area increment/frequency of occurrence is needed.

Are these forests governed by gap-phase or stand replacement disturbance regime? It may be appropriate to propose some intermediate regime between these limits. That is to say neither an intimate small gap regime, or a whole stand regime, but rather more a mosaic of gaps and patches governed by particular circumstances of the storm series, and site and forest growth heterogeneity. Even this mosaic does not rule out the occasional complete stand replacement, as this has happened to equivalent forests in the past – for example, patches of 100ha formed in spruce forests in Argyll as a result of the 1968 storm (Holtam 1971, Quine et al. 1999).

5.5 Conclusions concerning gap formation and expansion

The investigation has identified the gap structure of windthrow in planted forests for the first time. The skewed size distribution is similar to that of many natural forests, with a predominance of small gaps, and a few very large gaps. However, it appears that the gap size distribution may be the result of a number of different processes, and thus not be a continuous form. In particular, there appear to be different mechanisms in periods of relatively modest wind speeds, when the most vulnerable trees on the edge of the large gaps are likely to fall, and periods of extreme wind speeds when substantial new gaps will form. The rate of gap area increment is highly variable, and values obtained from short periods of monitoring may be misleading in calculations of turnover time.

6 Mechanisms of Gap Filling

"There were straight rows of trees – colonnades – growing out of the seedbed of trees that had fallen two hundred years before and sunk and become the earth itself. The forest floor was a map of fallen trees that had lived half a thousand years before collapsing – a rise here, a dip there, a mound or moldering hillock somewhere – the woods held the bones of trees so old no one living had ever seen them." David Gutterson, 1994, Snow falling on cedars, Bloomsbury.

6.1 INTRODUCTION

In a self-perpetuating forest, the rate of gap formation by disturbance must be balanced over time by the rate of gap-filling by tree growth. The physical characteristics of gaps are determined by their origin (e.g. disturbance agent) and in turn influence the environmental conditions that control tree growth. The following review is limited to gaps formed by the destruction of overstorey trees involving the action of strong winds. Gaps formed by fire, insect outbreaks etc are likely to differ in important characteristics.

Gap formation is important for maintenance of certain species in forests, particularly trees that are not shade tolerant. For example Veblen (1985a) found that large gaps were important for retention of *Nothofagus dombeyi*. However, gap formation does not always leads to the perpetuation of species in the overstorey at the time of the disturbance. For example Battaglia *et al.* (1999) documented removal of *Pinus taeda* (canopy dominant), but its lack of replacement in subsequent regeneration, and Drobyshev (2001) observed the replacement of Norway spruce by deciduous species. Such compositional changes depend upon the interaction of the ecophysiology of the species present, and the characteristics of the gaps that have formed.

In a very few forests, gap formation and gap size may be unimportant. For example, gap dimensions are not important in the northern boreal forest because light is not limiting due to the sparse canopies (Steijlen et al. 1995). However, in my study forests the canopies are very dense (closely spaced, unthinned) and gap dimensions are likely to be important.

6.2 Mechanisms of gap filling

Gap formation may bring about changes in environmental conditions at the forest floor, and some of the changes are potentially beneficial for tree regeneration either from newly fallen seed or by activation of a dormant seedbank (Pascarella 1997). Removal of some of the overstorey trees leads to increased light levels – and may also affect either directly or indirectly, other aspects of the micro-climate such as temperature and moisture. However, the effects are unlikely to be uniform across a gap, and may extend beyond the margin of the gap, for example as enhanced light penetration into northern edge of gaps in the Northern Hemisphere (Canham et al. 1990). The exposure of mineral soil may provide a suitable germination site (Hutnik 1952), and indirectly, there may be benefits of the repression of herbaceous vegetation by fallen trees (Everham III and Brokaw 1996). However, some of the changes may also be detrimental, for examples due to extreme micro-climatic conditions such as drought, the attraction of herbivores to open areas (Messier et al. 1999b), and the development of a competitive ground flora.

There are four possible outcomes in response to gap formation – filling by seedling growth, filling by vegetative re-growth of fallen or snapped trees, filling by lateral crown development from edge trees, or failure to fill. The relative importance of these mechanisms has been found to vary between forest types due to species ecophysiology, shade tolerance, canopy cover, spacing , and with gap size (Coates and Burton 1997). Each outcome will now be considered in more detail.

6.2.1 *Seedlings*

Gap formation may stimulate growth of seedlings in response to the altered conditions in the gap. The seedlings may exist prior to gap formation (advance regeneration) and be 'released' by the enhanced light availability. Alternatively, seedlings may germinate after gap formation and grow in the improved conditions – eventually to be 'recruited' into the sapling and tree population. The rapidity of response to the gap formation will depend upon the presence of advanced regeneration, or a seedbank, and the frequency of seed production from neighbouring canopy trees.

Gap size, particularly gap opening, plays an important role in governing the light conditions at the forest floor. Small gaps will favour shade tolerant species, or result in only partial recruitment. Large gaps are required by shade intolerant species (Messier et al. 1999a), but even then the species may be out-competed by advanced regeneration of shade tolerant species. There are likely to be complex interactions with aspects of resource availability, but Messier has proposed the concept of maximum sustainable height to reflect the limitations to seedling growth due to light availability (Messier et al. 1999a).

Gap opening, rather than gap cover, is likely to represent the role of gaps in enhancing the light environment, and hence the predominant use of aperture rather than area in this chapter (see 3.4.3).

The process of windthrow may create particularly suitable seedbeds through soil and vegetation disturbance, and in time through the supply of rotting wood (Harmon 1987, 1989, Harmon and Franklin 1989). However, shading by rootplates and fallen stems may be detrimental, and some of the substrates may be unstable (e.g. sloughing of old bark from fallen stems).

Gap expansion may have particular implications. Observations have suggested that gap expansion can lead to release of regeneration that has formed on the margin of gaps (Lees 1969, McNeill and Thompson 1982). A number of episodes of gap expansion may be required for the regeneration to reach the canopy (Liu and Hytteborn 1991). However, a continuous input of deadwood and fallen trees may smother emergent regeneration (Everham III and Brokaw 1996). Expansion may lead to a spread in age/size of regeneration across a gap – for example as a form of wave (Perkins et al. 1992, Rebertus and Veblen 1993a). The directional fall of trees, leading to an abrupt edge of standing trees and a 'ramp' of fallen trees may lead to markedly different conditions across the gap (Jackson et al. 2000).

6.2.2 Sprouting of existing stems

A variety of vegetative propagation methods may be stimulated by gap formation. These include sprouting from snapped and fallen trees, layering from branches of fallen trees, and upturning of original canopy branches. Sprouting is a mechanism that has been frequently observed in tropical forests, for example after hurricane disturbance. In temperate forests, the evidence is conflicting. Peterson found sprouting unimportant in his study of mixed forests in Eastern USA (Peterson and Pickett 1991). However, Rebertus and Veblen (1993b) found sprouting important in temperate Nothofagus forests in Chile and Ohkubu *et* *al.* (1996) identified sprouting from stools important in Japanese beech. Sprouting may be from buds that are at rest, inhibited or quiescent (Morey 1973).

6.2.3 Canopy growth of edge trees.

Lateral growth of existing branches of edge trees and vertical height growth can lead to gap contraction and closure, thereby reducing available light and possibly limiting the potential for seedling regeneration, especially of shade intolerant species.

The rate of gap closure can be very variable and dependent upon crown morphology. Runkle documented closure in Eastern USA hardwood forests over a series of repeat measurements, with lateral extension rates of 4-25 cm/year (Runkle 1985, Runkle and Yetter 1987, Runkle 1998). Differences have been noted between Eastern USA deciduous trees and the conifers of the boreal forest and attributed to crown dimensions e.g. relatively narrow crowns of conifers (Messier et al. 1999a). Complete closure of small gaps is possible through a combination of vertical development and lateral extension in Douglas fir (Wardman and Schmidt 1998)). Kirby and Buckley (1993) found gap contraction rather than expansion after the 1987 storm in South-east England. Valverde and Silvertown (1997) found that a canopy opening of 12% took 9 years to close in a British temperate deciduous forest.

6.2.4 Failure of gap-filling

In the absence of successful regeneration, or insufficient lateral growth of trees, it is possible that the gap may fail to fill and therefore persist. This may be due to a hostile micro-climate, for example in mountain forests through excessive irradiance (Brang 1998) or increased depth and prolonged snow cover (Brett and Klinka 1998). Regeneration may be unsuccessful due to competing vegetation that already exists (Holsten et al. 1995) or becomes established before the tree seedlings (Taylor and Zisheng. 1988, Clinton et al. 1994). The long-term persistence of unfilled gaps is hard to establish due to the limited time-scale of many studies. However, change in climatic conditions, or secondary disturbance e.g. by herbivores may create subsequent opportunities for seedling establishment. Vera (2000) has suggested that herbivores were responsible for maintaining an open primeval forest.

6.3 Fundamentals of Sitka spruce regeneration

The regeneration ecophysiology of Sitka spruce is now briefly reviewed in order to consider the species-specific characteristics that may influence the mechanism of gap filling.

6.3.1 Seed production

In British conditions, Sitka spruce flowers freely from around age 20 to 25 (Malcolm 1987), and occasionally as young as 10 to 15 years (Petty et al. 1995). However, large numbers of cones and seed are not normally produced until the age of 35 to 40 years (Nixon and Worrell 1999).

The process of seed production takes two years. Initial bud formation occurs in July of the first year, flowers develop and there is a pollination period of 1 to 2 weeks in the following spring (Owens and Molders 1980), and seed is shed starting in October of the second year (Philipson 1997). However, seed release is variable and in practice may occur whenever suitable dry conditions occur between October (second year) and April (third year) (Philipson 1997) – that is 19-30 weeks after pollination (Owens and Molders 1980). There is no long-term retention of seed in the cone and the seed has short viability once shed so that there is no long-term seed bank.

Flowering and cone development are controlled by a variety of weather and climatic conditions so that seed production in any one year is variable, and difficult to predict. In the British uplands, coning occurs regularly and heavy coning appears to occur every 3 to 5 years. For example, Petty *et al.* (1995) surveyed coning in Kielder for the period 1974 to 1993 and found no year without cones, and good coning at least every 3 years. In Oregon, Pacific North-west it has been reported that there is one year of 'crop failure' in a period of 4 years was reported (Ruth and Berntsen 1955 in Mair 1973). However, others have reported that cone crop failure is rare (Owens and Molders 1980). Physiological stress of a tree, such as through sudden exposure at a gap edge, can lead to short-term enhancement of seed production.

Trees may hold 1000-3000 cones in heavy coning years. The potential number of seeds per cone has been estimated as 284, but lack of pollen commonly reduces the actual number to around 41 seeds/cone (Owens and Molders 1980). Seed production of 0.3-22.0 million seeds per hectare has been recorded in British spruce forests (Mair 1973), and seed viability is commonly 70-80% (Nixon and Worrell 1999).

6.3.2 Seed dispersal

The average weight of Sitka spruce seed is around 2.50 mg. Most Sitka seed is not dispersed far. Mair (1973) found that 68-98% of seed was deposited within 20m of a forest edge of 20m tall trees, but a very small percentage of seed travelled farther than 50m in winds of 3.4 m s^{-1}, with convection currents aiding dispersal. Viability increased with distance from seed source (D Malcolm, pers comm).

Studies of seed dispersal in other species have shown that a very small percentage of seed may travel long distances in large updraughts, contributing to a low level seed rain that does not have a marked distance from source distribution (Greene et al. 1999). Redistribution of seed after fall is possible, particularly on relatively smooth surfaces (Johnson and Fryer 1992), including snow. Seeds may be lost to voles, mice, fungi, insects and birds (Scarratt 1966) in (Nixon and Worrell 1999).

6.3.3 Germination and seedling establishment

Germination of Sitka spruce seed occurs largely in spring and early summer following dispersal, but may be delayed by soil temperatures of less than 10 degrees C, and by drought – both conditions may be accentuated under intact forest canopies. Germinants may emerge in profuse numbers, and densities of 400,000 per hectare have been observed on clear-fell sites in Britain (Nixon and Worrell 1999).

Nursery experiments found that germination was most successful with partial shade (up to 50% full sunlight) (Fairbairn and Neustein 1970). Other studies have failed to show an effect of light levels on germinant survival, as distinct from the marked effect on seedling survival (Greene et al. 1999). There is a rapid loss of germinants due to drought (Nixon and Worrell 1999), a variety of insects, slugs and rodents (Scarratt 1966) and competition with vegetation. Losses by November can reach 20-30% of germinants (McNeill and Thompson; Lees 1969). In the Pacific North-west, moss layers inhibit the survival of germinants because the hypocotyl of Sitka spruce is approximately 14mm in length, compared to a typical moss depth of 44 mm (Harmon and Franklin 1989).

Losses of seedlings (ie after 1 year survival of germinants) can also be high with a reduction in density by as much as 75% between years 0 and 4 (Nixon and Worrell 1999). Losses have been attributed to a variety of causes, including drought and heat lesions (Lees 1969), vegetation competition (Lees 1969), browsing by deer and rodents, and defoliation by insects.

6.3.4 Seedling establishment in gaps and openings

The ecological niche associated with Sitka spruce in its natural environment, where it occurs in communities with the much more shade tolerant western hemlock, is large gaps and sudden disturbance. Taylor (1990) quotes requirement for gaps greater than 400 m^2, and preferably 800-1000 m^2. In contrast, Lees (1969) showed satisfactory growth in centre of gaps of 405m^2 in the Forest of Ae, Scotland. This apparent discrepancy may be understood by considering the difference between gap cover and gap opening (see 3.4.1) (Jennings et al. 1999). The edge trees in the Forest of Ae were approximately 15m, whereas those in the Pacific North-west were at least 45m high (see Table 3.3). In the study site used by Lees, the diameter of the gaps was approximately 1.5 times the tree height. Harmon suggested a canopy opening of approximately 30% for growth of Sitka spruce. (Nixon and Worrell 1999) suggest gaps with a diameter of 1 to 2 times tree height as required for Sitka. There is limited evidence of continued recruitment of seedlings within gaps – Taylor found a spread of seedling ages in his natural gaps, and new germinants were observed 8 years after the creation of the openings in Ae forest (McNeill and Thompson 1982).

In Britain there have been a few observations of 'spontaneous' regeneration following canopy removal. Regeneration followed row thinning 23-25 years after planting (Davies 1954), and 10 m high regeneration was observed where there had been windthrow or clearance of road-lines (Dannatt and Davies 1970). However, most experience has been of regeneration following clearfelling on sites of several hectares. Densities as high as 27000 stems per hectare have been recorded on clear-fell sites at age 5, and 4900 stems per hectare after 20 years at a site in Ae forest, South Scotland subject to no managed intervention (Nixon and Worrell 1999). The resultant stems are slender (measurements at Ae gave a top height 16.8 m, mean dbh 12.8 cm) and the trees may be vulnerable to damage by snow. Heavy snowfall in February 1996 led to damage to 14% of stems in the self thinning plot, compared with 2-5% in plots with wider spaced stems (W.L.Mason, pers comm).

Sitka spruce is classed as intermediate in shade tolerance (Wright et al. 1998) and this permits it to persist in partial shade prior to release by higher light levels. Lees (1969) suggests that Sitka spruce seedlings survive best in partial shade and grows best in higher light levels. There have been few studies of the release of seedlings from shade, but there are observations of this process from Ae (McNeill and Thompson 1982). Nixon and Worrell (1999) (appendix) suggest, without presenting any evidence, that it may be necessary to release Sitka seedlings once they reach 1m, otherwise growth stagnates and they become vulnerable to insect attack. Defoliation by *Elatobium* was linked to the death of 10yr old Sitka seedlings in partial shade (Brown and Neustein 1970 in Nixon and Worrell 1999).

A number of microsites have been identified as particularly favourable for the establishment of Sitka spruce seedlings. In particular, mineral sites, and deadwood logs appear to be particularly valuable microsites (Taylor 1990, Deal et al. 1991), and organic substrates on British clearfells (Nelson and Nixon 1992).

6.3.5 Vegetative regrowth of Sitka spruce

There appears to be no reference to vegetative re-growth in studies of natural stands. However, in Britain, Sitka spruce has a reputation for surviving for some years following windthrow, necessitating less urgency in clearance than other coniferous species such as pine (Hibberd 1987). After catastrophic windthrow in 1968 in the Carron Valley, West Scotland, Sitka spruce were observed to survive by producing adventitious roots from fallen stems into the rootplates of underlying trees (D.C. Malcolm, pers comm). Sitka spruce frequently produces adventitious roots as a seedling (Coutts et al. 1990).

In certain conditions, in addition to the extension of existing lateral branches, Sitka spruce has been observed to produce profuse epicormic shoots, also known as 'water sprouts' (Herman 1964). This is commonly observed after thinning, and felling of roadlines.

6.4 Investigation of gap filling in planted spruce forests

As a result of the review of available literature, the following hypotheses are proposed -

- *Gap filling will occur in the wind-created gaps.*
- *The dominant mechanism of gap-filling will vary with gap size.*
- *The rate of gap filling will depend upon filling mechanism and gap size.*

6.5 Methods of investigating gap-filling

Two investigations were carried out to pursue the hypotheses relating to the mechanisms of gap-filling following windthrow. These were -

- Survey of return transects Autumn 1996 – 1998. To provide data on the occurrence of gap-filling, the mechanism of gap filling, and the role of gap size.
- Destructive sampling of transects at Kielder and Rosarie. To provide data on the rate of gap filling.

6.5.1 Return transects study

The return transects in the 5 monitoring areas (see Chapter 3) were visited in Autumn 1996, 1997 and 1998 (except Kielder – Bellingburn, absent in 1998 due to felling). The timing of the survey was determined by the need to define gaps in advance of the winter, but also afforded an opportunity to record the presence of germinants at the end of the main period of emergence. Gap size as opening was measured as mean skyview (see 3.4.3). Observations were made at each gap of the presence/absence of germinants, seedlings, epicormics (horizontal and vertical), and whether fallen trees were dead or alive. Height of seedlings and length of epicormics were estimated to classes (<25cm; 25-49; 50-74; 75-99; 100-124; 125-149; 150-174; 175-199; 200cm+). Species of trees at gap edge, presence of thinning and ploughing, and direction of fall of trees was recorded in latter surveys.

Data were summarised for all areas combined and by individual monitoring area. Subsequent analysis was carried out largely on the combined data and only for gaps within Sitka spruce stands that had not been thinned. The distribution of mean skyview was not normally distributed; a log transformation was insufficient to correct this. Differences in gap size (mean skyview) for various grouping variables were therefore assessed by non-parametric tests. The Kolmogorov-Smirnoff test was used for fill type groupings, and Kruskal-Wallis test for Monitoring areas comparisons (Statistica manual). Relationships between presence of germinants, seedlings and vertical epicormics were tested using the Pearson Chi-squared test applied to two-way tables.

6.5.2 Destructive sampling of transects at Kielder

A return transect within the Bellingburn block, of Kielder forest that was located in a compartment due for felling was selected for destructive sampling of seedlings. The compartment (3509) had been planted as a 2 row:2 row mixture of Sitka spruce and Scots pine in 1951, but the Scots pine had subsequently died out and the canopy was formed by Sitka spruce. There were 29 canopy gaps intersected by the transect, of which 8 had been formed by overturning of trees, 7 were due to the snap of large (canopy) trees, 9 had been formed by the suppression of smaller trees, and 6 reflected a combination of factors. Only in 5 gaps were there large numbers of trees, whilst in 18 of the gaps, 3 or less trees had been responsible for the gap creation. A roadline was cut through the eastern section of the compartment in 1991; the date was established from aerial photographs dated January 1991 (compartment intact) and December 1991 (roadline present).

The purpose of the sampling was to acquire material to permit the rate of gap filling to be established. Sampling was undertaken in early spring 1998, prior to the growing season. 5 large gaps and the roadline were sampled for seedlings; no seedlings were found in the small gaps or closed forest. All gaps, the roadline and previously established basal area plots at 100m spacing along the transects were sampled for the presence of epicormics on standing trees. The procedures were -:

- *Large gaps* – A baseline parallel to the long-axis of the gap was established, and used to stratify the gap into 10m zones. Sample points within the zone were established by selecting an x and a y coordinate using random numbers. At the sample point, a circular plot was established and divided into 4 quadrats. For a smaller circular centre plot, a count was made of all seedlings. For each quadrat, the largest seedling was measured, the substrate recorded, and the seedling removed for subsequent measurements of diameter, and annual growth increment. The largest epicormic branch within reach was taken from the nearest live sample tree. A similar methodology was deployed for the roadline, except that the epicormic sampling was restricted to the edge row of trees. In addition, I sampled, non-randomly, a number of additional seedlings where these appeared significantly larger than those collected in the random sample, and also wedges from standing trees where a scar was present due to the impact of a falling tree.

- *Small gaps and plots.* At each small gap and closed plot, the absence of seedlings was confirmed. Standing trees at the edge of the gap, and trees within the basal area plot were investigated, and the largest epicormic shoot below 2m trunk height was measured and removed.

The Kielder samples were grouped into gaps, and roadside for the purpose of the analysis. The data on epicormics were analysed in four groupings – large gaps (ie the 5 sampled for seedlings), small gaps (ie other gaps in compartment – largely < 3 trees/gap), plots ie intact forest, and roadside samples.

6.5.3 Destructive sampling of transects at Rosarie

The Kielder samples were supplemented with limited numbers from Rosarie. Sampling of return transects in the Greenhill block of Rosarie Forest was conducted in 3 compartments (4264, 4265, 4271), planted 1951/52. A total of 13 gaps within Sitka spruce, plus the adjacent roadside were examined in late September 1999.

The return transects were traversed. At each gap, a temporary plot was established, centred on the topex post (post B – centre of gap); the plot was circular and of 2m radius, and divided into 4 quadrants – NE, SE, SW, NW. The largest seedling in each quadrant was removed for measurement, and the substrate on which it was growing was recorded. The largest seedling elsewhere in the gap (but outwith the circular plot) was also removed. The procedure was repeated at each basal area plot along the transect, with the circular plot centred on the plot centre pin. Plots within stands of species other than Sitka spruce were excluded, as were plots where there was an unusual degree of sidelight, making them unrepresentative of 'closed' forest conditions; this occurred where there was a short distance to a forest ride.

6.5.4 Ageing of seedlings, epicormics and scars

Seedlings were aged by inspection for annual whorl, or surface scar. The greatest difficulties were experienced where growth remained slender, and the initial whorls had been suppressed, by the growth of surrounding vegetation. In such circumstances, it was hard to distinguish the annual whorl or scars, and the ages should therefore be regarded as approximate and likely underestimates. Epicormics were aged by inspection for annual whorl or surface scar. Wedges were aged after cleaning the cut surface, and counting rings formed since the scar – in particular in the callous formation at the edge of the scar.

6.6 Results – Return transects

6.6.1 Basic data on gaps

Results from the three years were similar, but those from 1997 were most complete due to subsequent felling at Kielder. Results quoted are for 1997, unless otherwise noted. A total of 109 gaps were surveyed across the 5 monitoring areas on approximately 12000 metres of transect. Mean skyview ranged from 0 degrees to 65 degrees but with a skewed distribution with many small gaps and few large gaps (mean 13.4 degrees, median 6.75 degrees, mode 0 degrees). The gap size distribution by area was also highly skewed (minimum $4m^2$, mean 408 m^2, maximum 7878 m^2). Data were summarised by monitoring area and combined. (Table 6.1).

Fallen trees and branches of the original canopy remained alive in over half of the gaps; and in 40% the original leader was upturned. Epicormics were also present in half of the gaps in the horizontal form, but in a quarter of the gaps there were also vertical epicormic branches showing apical dominance. The length of the vertical epicormics ranged from <25cm to >200cm.

Table 6.1 Summary table of means for presence of various gap-filling mechanisms in 1997 for individual monitoring areas and all areas combined. Unthinned Sitka spruce stands only.

Site	No of gaps	Living fallen trees % of gaps	Up-turned leaders % of gaps	Epicormics % of gaps	Horizontal epicormics % of gaps	Vertical epicormics % of gaps	Germinants % of gaps	Seed-lings % of gaps
Glentrool	25	80	44	72	68	8	44	12
Carradale	19	58	37	32	32	16	37	32
Kielder	30	20	13	17	17	10	90	17
Tywi	19	89	79	79	79	68	37	53
Rosarie	16	62	56	56	56	31	94	31
Combined	109	58	42*	49	99	24	61	27

(*Note includes hung-up trees).

Germinants were present in two-thirds of the gaps and seedlings were present in one-third of the gaps. Seedling height ranged from <25 cm to 200cm. The substrates on which the tallest seedling were found were 41% on rootplate, 24% on undisturbed forest floor, and 10% on pit and floor/plate, 3% on floor/plate/pit and other, and the observation was missing on 2 (7%). In 31 gaps there were neither seedlings nor vertical epicormics.

There appeared to be some differences between monitoring sites. The Tywi site had the largest mean gap size, and also the highest proportion of surviving fallen trees, epicormics present, vertical epicormics present, and lowest proportion of gaps with germinants (Figure 6.1). However, the causation is beyond the scope of this study and is not explored further.

6.6.2 Groupings of presence/absence by gap opening

The use of gap opening (mean skyview) to discriminate between presence/absence of the various groups was explored (Table 6.2). Exclusion of gaps with a skyview of zero altered mean skyview but did not affect the direction or significance on any of the relationships.

Table 6.2 Analysis of mean skyview by grouping variable for 1997 data

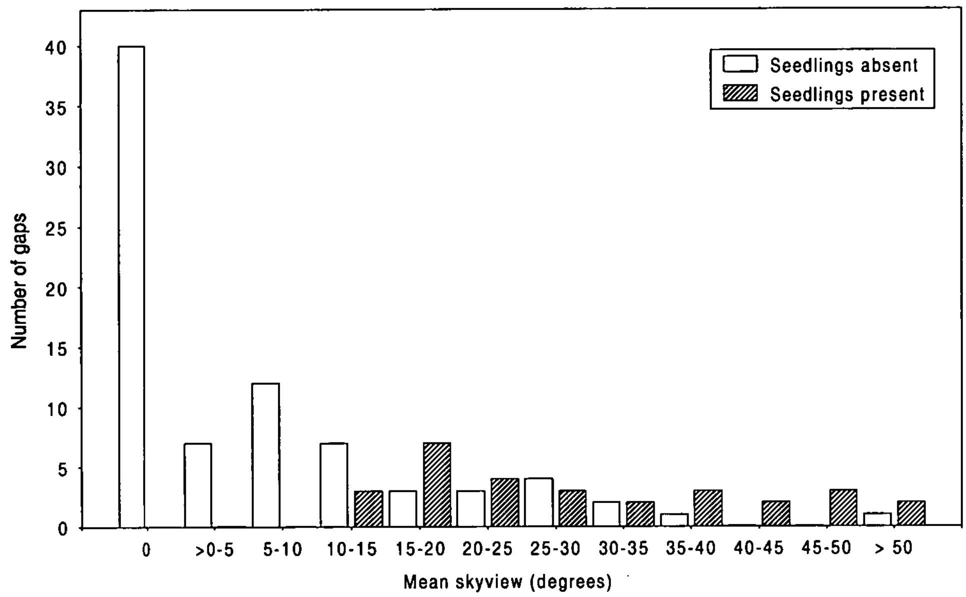
Grouping Variable (GV)	Mean Skyview (degrees) where GV present	Mean Skyview (degrees) where GV absent	Kolmogorov-Smirnov test; p-level
Fallen Trees Alive	20.9	3.0	<0.001
Epicormics	23.1	4.1	<0.001
Horizontal Epicormics	23.0	11.3	<0.10 ns
Vertical Epicormics	30.0	14.6	<0.005
Canopy live	21.2	4.1	<0.001
Leader upturn	19.4	9.0	<0.025
Germinants	16.2	8.8	<0.10 ns
Seedlings	29.8	7.4	<0.001

Mean skyview was significantly greater where fallen trees were alive than where dead, where epicormics were present than where absent, where vertical epicormics were present than where only horizontal epicormics were present, and where seedlings were present than where absent. Mean skyview was not significantly greater where germinants were present than where absent.

Gap opening was significantly greater for gaps with seedlings (mean of mean skyview 29.8 degrees) than those without seedlings (mean of mean skyview 7.4 degrees) (Kolmogorov-Smirnov test, $p<0.001$); seedlings were not found in gaps with mean skyview of less than 14 degrees (Figure 6.2). A similar threshold is found for vertical epicormics (Figure 6.3).

Figure 6.1 Photograph of epicormic sprouting from fallen trees in a gap intersected by the return transect at Kielder.

Figure 6.2 Gap opening (skyview) where Sitka spruce seedlings present/absent



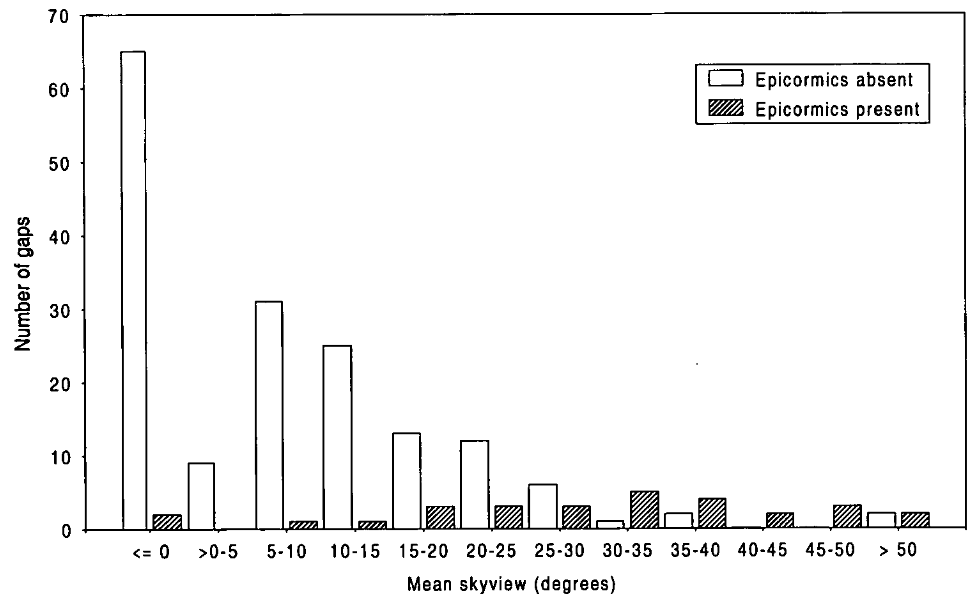
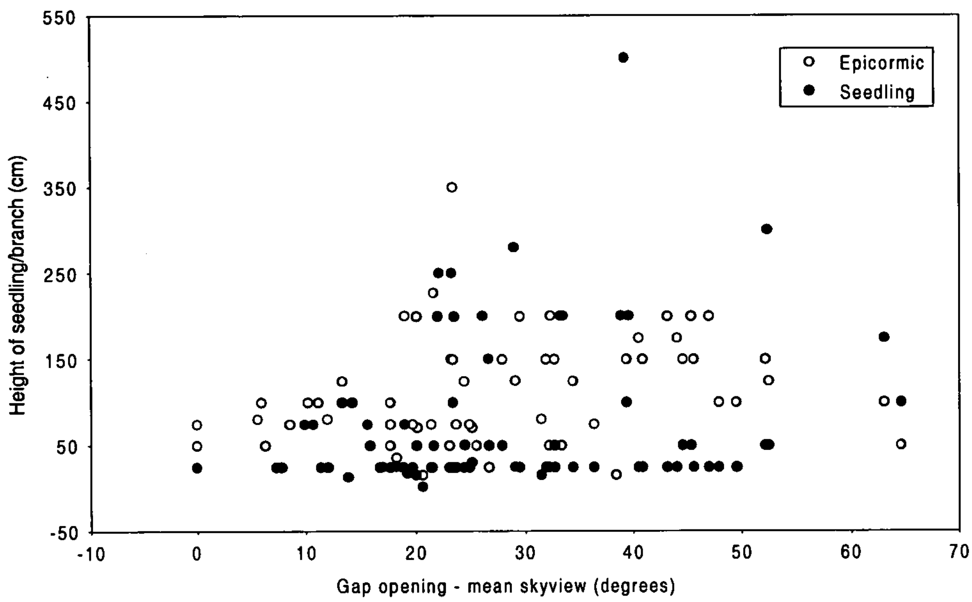


Figure 6.3 Gap opening (skyview) where vertical epicormics were present/absent

The inter-relationship between the presence of germinants, seedlings and vertical epicormics was examined through Pearson Chi-squared tests on 2-way cross-tabulations of presence and absence. There was a positive relationship between presence of vertical epicormics and presence of seedlings (Chi 18.48, $p<.00002$, df=1) and between germinants and seedlings (Chi 10.21, 1df, $p=0.0014$). In contrast, the presence of germinants and vertical epicormics were not related (Chi 1.47, 1df, $p=0.2254$).

A comparison between the skyview and height of the seedlings or epicormics indicated that recorded height increased with gap opening (Figure 6.4).

Figure 6.4 Relationship between height of seedling or epicormic branch, and gap opening



6.6.3 Groupings of presence/absence by gap area

Gap area was significantly greater for gaps with seedlings (mean gap area 1123 m^2) than without (mean gap area 149 m^2) (Kolmogorov-Smirnov test, $p<0.001$). Although most gaps less than 100 m^2 contained no seedlings, the discrimination was not so complete as with gap opening and the smallest gap with seedlings observed was 12 m^2.

6.6.4 Closure by lateral expansion of edge trees.

It had been hoped that the repeat measurement of skyview would provide estimates of the rate of lateral canopy closure. However, the repeat measurements, at times by different observers, were insufficiently precise to achieve this, although there were a number of instances of small gaps which closed so that it was no longer possible to measure skyview.

6.7 Results – destructive analysis

At Kielder, a total of 108 seedlings were sampled from 5 gaps and a further 20 seedlings were obtained from the roadside. 89 epicormics branches were sampled from standing trees and 6 epicormic branches from leaning or fallen trees within gaps.

At Rosarie, 21 seedlings were obtained from gaps, and a further 8 from the roadside.

6.7.1 Dimensions and rate of growth of seedlings

Summary statistics are provided for Kielder (Table 6.3) and Rosarie (Table 6.4).

Table 6.3 Kielder - Descriptive statistics for within gap seedling samples

	Number	Mean (*SE*)	Minimum	Maximum
Random samples				
Height of largest (cm)	65	13.7 *0.779*	4.4	37
Root collar diameter (mm)	65	1.1 *0.115*	0.1	4.2
Age (years)	65	4.1 *0.169*	2	8
Seedling numbers (per 1m^2 plot)	18	19.1 *5.065*	0	79
Non-random samples				
Height of largest (cm)	36	47.1 *5.206*	7.8	109.0
Root collar diameter (mm)	35	8.4 *1.313*	0.7	25.8
Age (years)	36	5.5 *0.377*	2.0	12.0

Table 6.4 Rosarie - Descriptive statistics for plot and roadside seedlings.

	Number	Mean (*SE*)	Minimum	Maximum
plots seedlings				
Height of largest (cm)	21	16.8 *2.259*	4.5	40.5
Root collar diameter (mm)	21	1.9 *0.334*	0.2	6.0
Age (years)	21	5.3 *0.372*	3	8
roadside				
Height of largest (cm)	8	53.5 *17.024*	11.5	144.0
Root collar diameter (mm)	8	10.2 *3.006*	2.1	26.0
Age (years)	8	6.1 *0.875*	3	10

At Kielder, analysis of the results (plot seedlings only) by gap indicated no significant differences in height, root collar diameter or age between the 5 gaps. Analysis of the results by substrate indicated significant differences in height, root collar diameter and age between the three substrates. The seedlings that had grown on the rootplates were taller, thicker and older than those sampled from the forest floor. (Table 6.5).

Table 6.5 Effect of substrate on seedling growth – results of Tukey's HSD test

Substrate type (number of samples)	Height (cm) (mean, *SE*)	Root collar diameter (mm) (mean, *SE*)	Age (years) (mean, *SE*)
Substrate: floor (42)	10.6 *0.855*	0.8 *0.099*	3.3 *0.263*
Substrate: rootplate (26)	16.0 *1.617*	1.5 *0.237*	4.5 *0.319*
p-level, Tukeys HSD	***0.013***	***0.010***	***0.034***

6.7.1.1 Rate of gap filling by seedlings

At Kielder, the rate of gap-filling was investigated by comparing the cumulative height increment for seedlings from gaps and roadside samples. The rate of growth was highest in the roadside, and slowest in the gaps. Fitted lines (2nd order polynomials) indicated that height increment increased almost exponentially with age for the roadside seedlings, but more linearly for the randomly sampled seedlings in the gaps (Figure 6.5). A period of at least 10 years was required for a seedling height of 50cm to be obtained. Comparison between the largest seedlings (non-randomly sampled) and the roadside seedlings indicated greater similarity in development of height growth (Figure 6.6). A height of 50cm was exceeded within 6 years, and 1m by 8 years.

6.7.1.2 Seedling Increment and gap size.

The relationship between age and height increment was examined in more depth by combining the Kielder and Rosarie data. For each gap, a regression of increment on age, forced through zero was obtained. The correlation between the regression coefficients (ie slope) and mean skyview and gap area was investigated. This indicated a highly significant relationship between rate of growth and size of gap (r=0.8927 for area, and 0.8808 for skyview) (Figure 6.7) but gave no indication of the critical coefficient for survival.

Figure 6.5 Mean height growth of random seedling samples versus roadside seedlings. (Fitted lines Gap 5 =0.075+2.805*x-0.095*x^2; Gap 8=0.036+3.082*x+0.187*x^2; Gap 9=0.159+1.646*x+0.577*x^2; Gap 14=-0.138+2.755*x-0.006*x^2; Gap 15=0.071+2.033*x+0.377*x^2; Roadside=-1.528+4.79*x+1.086*x^2.)

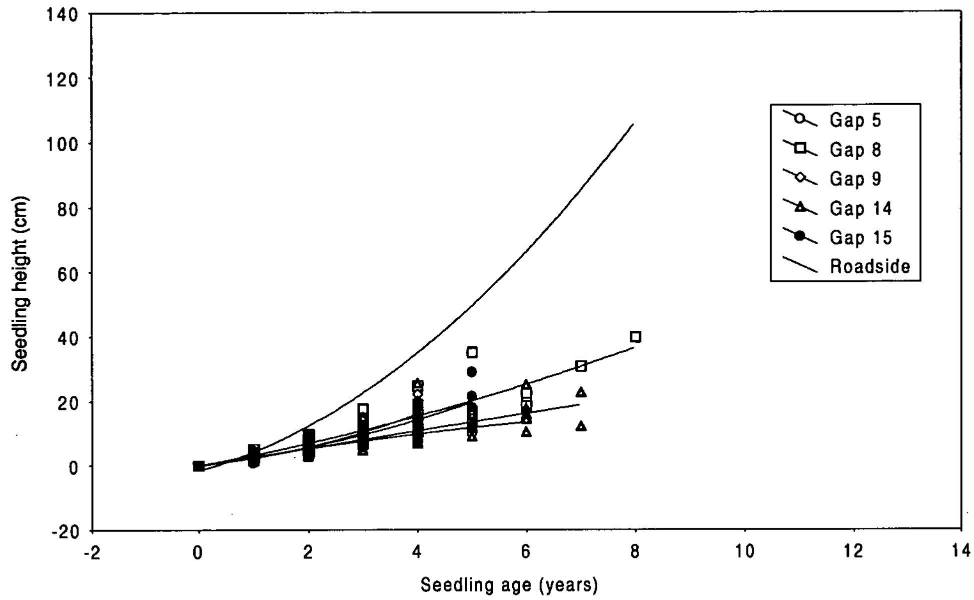


Figure 6.6 Mean height growth of non-random seedling samples versus roadside seedlings. (Fitted lines Gap 5-0.285+2.812*x+0.106*x^2; Gap 8 =1.646-1.45*x+1.135*x^2; Gap 9=0.677+0.321*x+0.954*x^2; Gap 15 =1.526-1.673*x+1.983*x^2; Roadside =-1.528+4.79*x+1.086*x^2.)

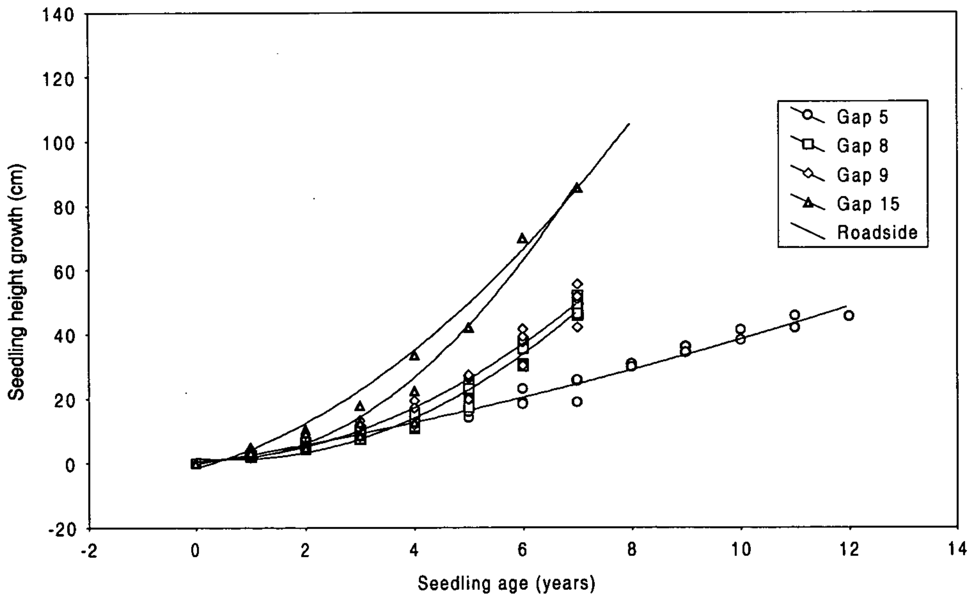
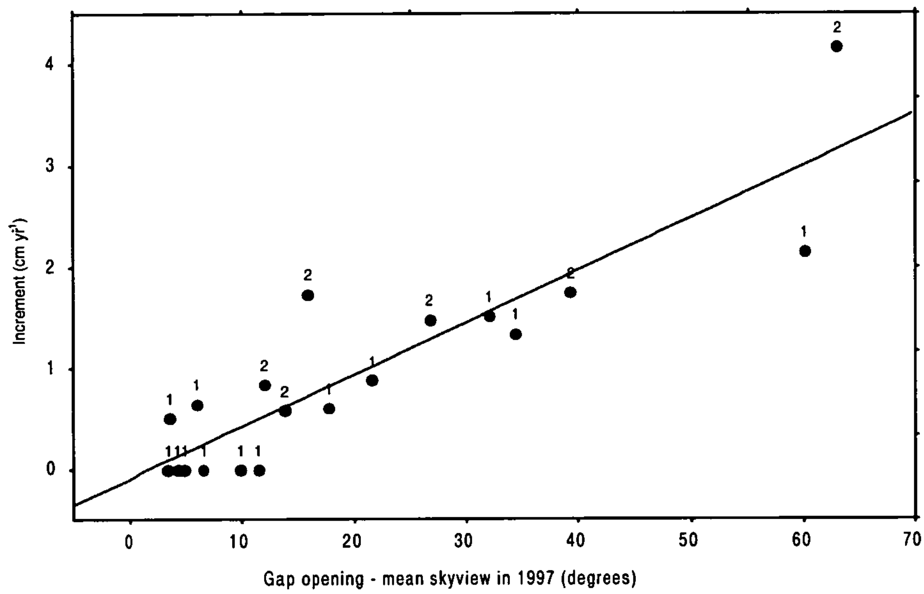


Figure 6.7 Effect of gap size, expressed as gap opening, on seedling height growth for Rosarie (1) and Kielder (2); (Fitted line y= -0.095+0.052*x.). Increment calculated as a linear approximation per gap.



6.7.2 Dimensions and rate of growth of epicormics

At Kielder, epicormic age ranged from 2 to 13 years old, and the age of the epicormics in the large gaps and by the roadside was greater than in the closed gaps and plots within the forest. Epicormic morphology differed between locations within the sampled stand, with shoots being longer, thicker, and older in large gaps (the 5 from which seedlings were sampled) and at roadside compared with small (closed) gaps and in plots in intact forest. (Table 6.6). There were insufficient samples to identify distinctive differences on fallen trees.

The height and basal diameter was significantly (positively) correlated for large gaps (r = 0.73, n=37; length=28.706+5.804*diameter) and roadside (r = 0.86 , n=10; length =-9.647+7.08* diameter), but not for small gaps (r =0.14 , n=23; length =6.09+1.094* diameter) and within-stand plots (r = 0.01, n=19; length =8.892-0.047* diameter).

Table 6.6 Effect of gap size on epicormic morphology at Kielder. Large gaps = those sampled for seedlings.

Gap category (number)	**Branch length (cm) (mean, *se*)**	**Branch basal diameter (mm) (mean, *se*)**	**Age (years) (mean, *se*)**
Large gaps (37)	62.9 *4.375*	5.5 *0.459*	8.1 *0.308*
Small gaps (23)	9.23 *1.427*	2.9 *0.179*	3.2 *0.314*
Roadside (10)	92.1 *5.616*	14.4 *0.681*	7.0 *0.211*
Intact forest (19)	8.8 *1.045*	2.7 *0.219*	3.1 *0.206*
Kruskall-Wallis ANOVA by ranks, H(3,89), p level	***66.69, p=0.0000***	***43.69, p=0.0000***	***64.08, p=0.0000***

6.7.2.1 Rate of growth of epicormics

There was evidence that branch increment responded to gap formation, and this was most marked in comparisons of increments for the branches from closed gaps and intact forest (Figure 6.8), large gaps (Figure 6.8) and roadside trees (Figure 6.10).

Figure 6.8 Epicormic branch increment by calendar year – closed gaps (solid line) and intact forest (dashed line).

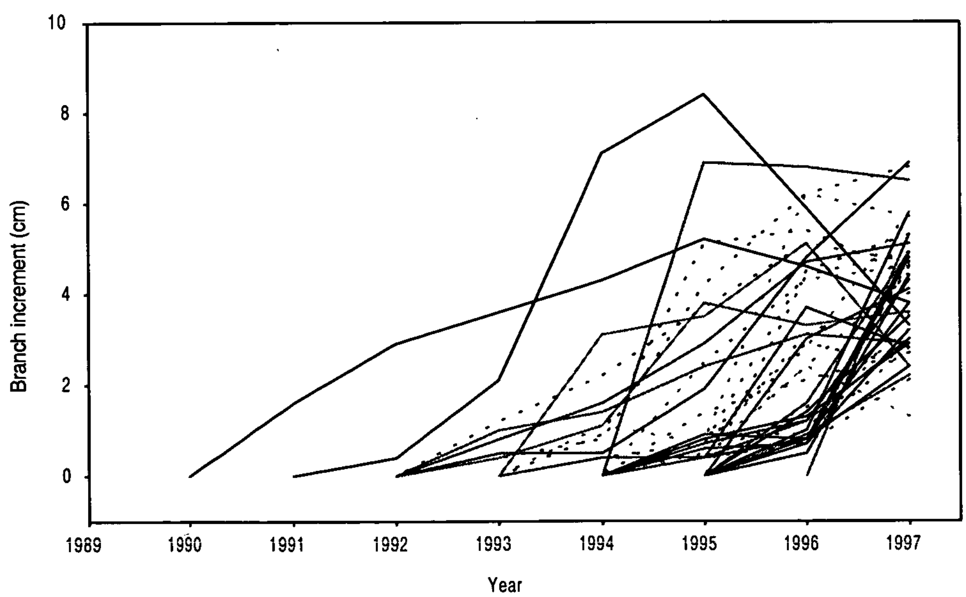


Figure 6.9 Epicormic branch increment by calendar year - 5 large gaps.

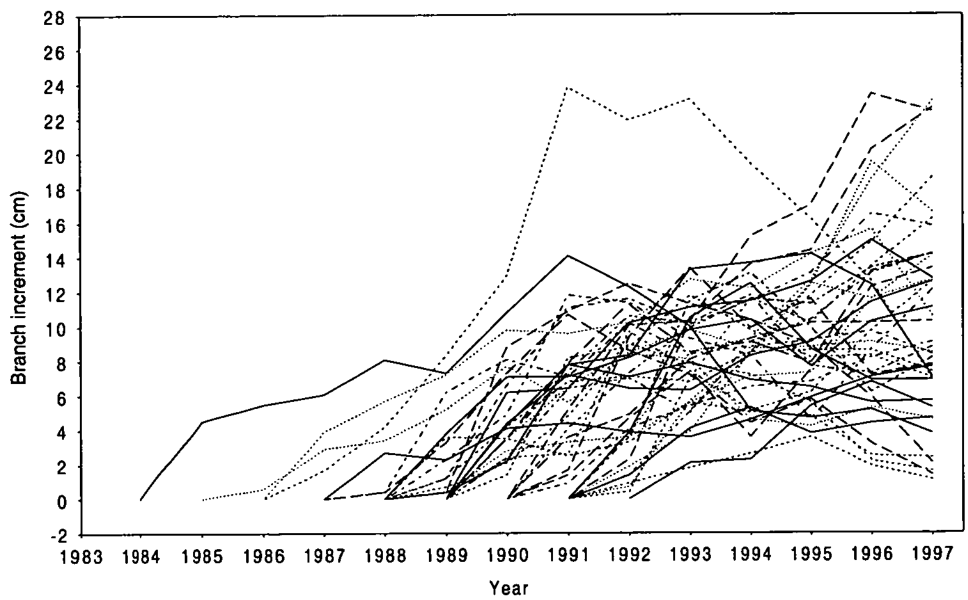
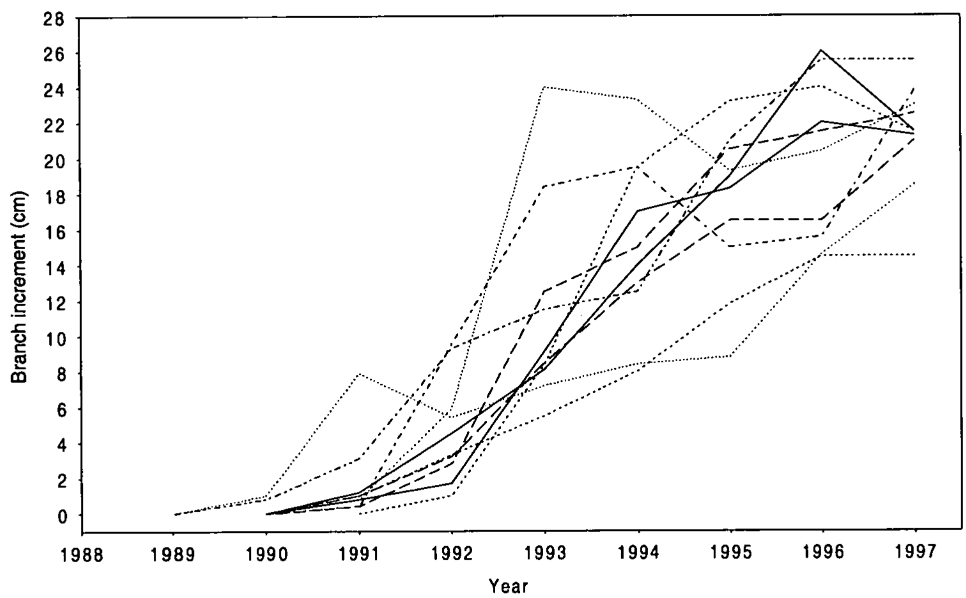
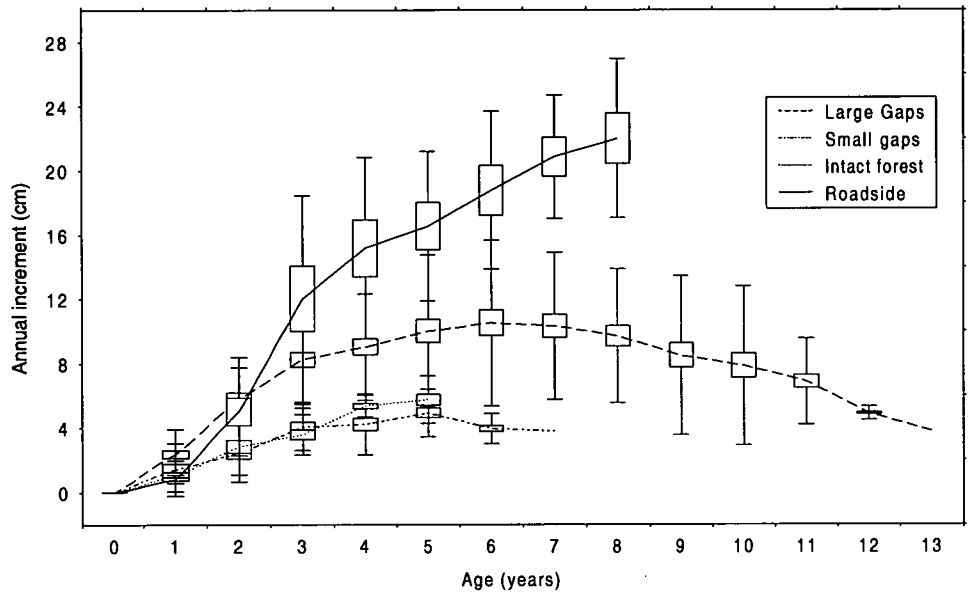


Figure 6.10 Epicormic branch increment by calendar year - Roadline branches. Note that the roadline was cut between January 1991 and December 1991.



Comparison of mean annual increment by age of branch for the four groupings (Figure 6.11) showed that increment peaked and declined in large gaps around year 6 and small gaps around year 5. The epicormics on the roadside showed a greater rate of extension, and although some reduction in rate of increase of increment there was no apparent decline. In the forest plots there was no decline in mean annual increment, but no branches greater than 5 years in age. Inspection of plots for individual branches indicate that decline does occur as early as 2 years old in this population.

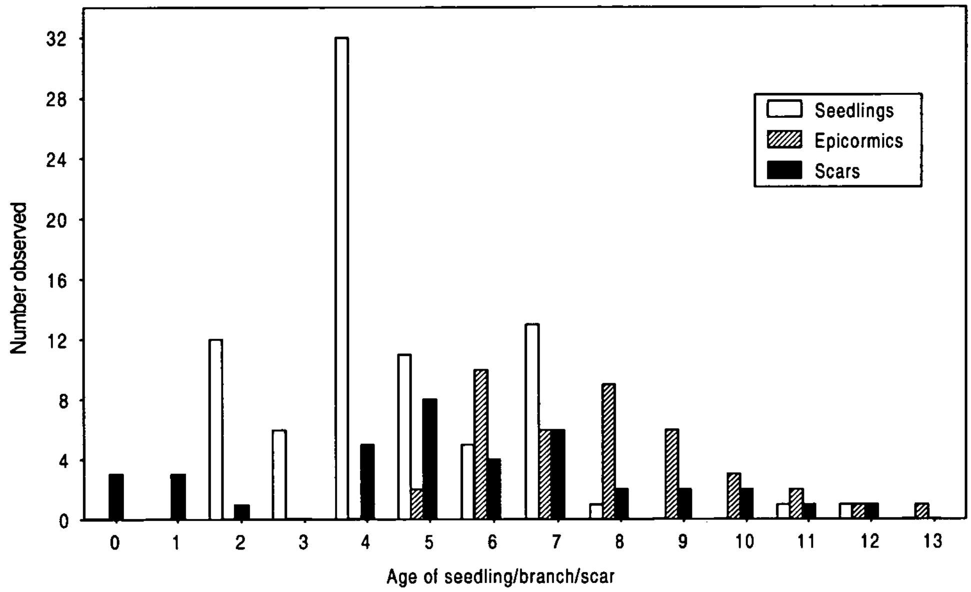
Figure 6.11 Mean epicormic branch increment by age in four locations. Box Mean+/- SE, Whisker +/- SD



6.7.3 Timing of gap formation and filling

At Kielder, seedling age in the 5 large gaps ranged from 2 to 12 years old, and this accorded with the dating of the gaps from both epicormics and scars caused where standing trees had been hit by falling trees. As these samples combine both random and non-random samples, no form of statistical inference is attempted. However, the qualitative comparison (Figure 5.11) indicates that there is no apparent delay in the commencement of gap filling.

Figure 6.12 Age distribution of seedlings, epicormics, and scars from standing trees



6.8 DISCUSSION

6.8.1 Occurrence of filling

The results from the transect surveys confirm that gap-filling is occurring in wind-formed gaps of Sitka spruce in the British uplands. Seedling establishment, vegetative re-growth from fallen trees and lateral growth from edge trees were observed. Seedlings were widely present, despite the periodicity of seed production, grazing by mammals, and potentially hostile micro-climate. Epicormic sprouting from standing, snapped and fallen trees is contributing to the vegetative re-growth that fills some gaps. This latter mechanism has not been reported for Sitka spruce in its natural environment, and bears more resemblance to responses to gap formation in tropical forest ecosystems.

In gaps of sufficient size, seedling regeneration appears likely to predominate as more gaps had seedlings present than had vertical epicormics, but there were apparent differences between sites and epicormics were particularly common at Tywi. Further work would be required to identify whether such differences reflected timing of survey relative to good regional seed years, or whether it reflects site conditions that favour particular filling mechanisms.

Not all gaps are filling by seedling regeneration or epicormic growth. Gaps where these are absent span a wide range of gap sizes but it is unclear whether this reflects true failure to fill, for example due to excessive browsing pressure or competitive ground flora (including mosses), or whether it reflects the comparative youthfulness of the gaps and periodicity in seed production. However, I am not aware of any long-established gaps of significant size remaining empty within the monitoring areas. Because of the youthfulness of the gaps, it is not possible to address the processes that may occur as the gap has nearly filled such as the possibility of wind abrasion of terminal shoots affecting form and growth rate (Wierman and Oliver 1979, Larson 1992).

6.8.2 Filling by seedlings

The presence of germinants of Sitka spruce is not dependent upon the existence of gaps. Germinants (but not seedlings) were present within the intact parts of the monitored stands, and their presence within gaps was not related to gap size; in addition, they were present in more gaps than seedlings. This accords with other work that indicates that initial survival of germinants is related to their size, and only later becomes influenced by light availability and shade tolerance (Greene et al. 1999). Light levels in intact stands of unthinned Sitka spruce are too low to permit seedling development (Hale, 2001). Germinant and seedling presence was positively related, possibly reflecting the adequacy of seed supply from surrounding crops. There was an indication that development of germinants and vertical epicormics are to a degree exclusive. This may be due to the shading of suitable substrate where epicormics are present.

Seedlings were observed in a large number of gaps, so there is considerable potential for self-perpetuating stands to develop. Certain substrates, such as upturned root-plates, produced by windthrow appear particularly favourable for seedling regeneration. A number of studies have shown this in other forests – for examples Taylor (1990) found that 88-97% seedlings in 6-11% of ground surface. Benefits of such microsites include drainage, freedom from browsing (Long et al. 1998), and enhanced light levels above any competing ground layer (McKee et al. 1982, Harmon and Franklin 1989). Clinton and Baker (2000) found photosynthetically active radiation (PAR) levels to be 3 times higher on mound top than pit bottom. Taylor and Zisheng (1988) found that a raised woody substrate was advantageous where bamboo impeding regeneration, whilst Hornberg *et al.* (1997) found that the raised site prevented smothering by bryophytes. However, Harmon and Franklin

(1989) also caution that although survival seedlings may be very low on forest floor, they have better long-term prospects because of competition and instability on logs. Hence Deal *et al.* (1991) found 67% of spruce to occupy mineral and mixed soil microsites.

Development of germinants into seedlings only occurs given a gap of sufficient size, larger than those provided by natural mortality within plantations. There appears to be a threshold around 15 degrees mean skyview below which there is no significant development of seedlings; a similar threshold may exist for development of vegetative re-growth. This skyview equates to 30 degrees mean gap aperture, or 0.17 skyview fraction of the hemisphere. Assuming a circular gap, a gap diameter of around 0.53 of tree height is required to achieve this aperture, and the minimum gap area varies with tree height (Table 6.7). Such a gap size also equates to approximately 9 trees at 0.9m spacing under an intermediate thin regime, and 7 trees at 1.7m spacing under same regime.

Table 6.7 Gap size required to achieve mean skyview suited to seedling and epicormic growth.

Tree height (m)	Gap area (m^2)	Gap radius (m)
10	22	2.7
20	89	5.3
30	201	8.0
45	452	12.0
70	1095	18.7

Note that this is the apparent minimum gap size for seedling survival and growth in unthinned conditions. The destructive plots confirmed a relationship between rate of growth and gap size, so that gap size above this threshold is likely to be beneficial to seedling development.

The gap size identified here (0.17 of hemisphere) is certainly substantially smaller than the optimum identified in the literature. For example an opening of 0.3 of hemisphere was suggested by (Harmon 1987, Taylor 1990) and 45-55% plan view was proposed as critical canopy cover for Sitka seedling establishment in the absence of significant sidelight (Nixon and Worrell 1999). This may reflect the difference between the survival threshold and the optimal growth threshold, similar to the findings for Douglas fir where a relative light index of 0.2 is sufficient for survival, but 0.4 or greater is required for optimal growth (Mailly and Kimmins 1997). An opening that is equivalent to a gap size of around 200m^2 for 30m stands is consistent with the regeneration of hybrid spruce [the complex of white spruce

(*Picea glauca* (Moench) Voss), Sitka spruce (*P. sitchensis* (Bong.) Carr.) and occasionally Engelmann spruce (*P. engelmannii* Parry ex Engelm.)] across range of gap sizes (3 classes 10-300, 301-1000, 1001 – 5000) (Coates in prep). Hybrid spruce numbers increased with increasing gap size, and mean height increased substantially in gaps >1000m in 30 m tall stands ie >1.2 D/H (Coates in prep).

Spatial heterogeneity of regeneration has not been captured here, except by the difference between the random and largest seedlings sampled in the Kielder gaps. However, other authors have suggested that this will be important. There is marked asymmetry of illumination within gaps in high latitudes, and tree height strongly influences direct radiation (Canham et al. 1990). Conditions of partial shade can be beneficial for growth and survival (Lees 1969, Wright et al. 1998). There are different criteria of success for 'silviculture' and 'ecology'; whilst a single regenerating seedling per gap that grows on to maturity may be sufficient for self-perpetuation, this will not necessarily achieve other silvicultural objectives. A greater uniformity of regeneration is likely to be desired, and hence the need for a broader spread of desirable conditions, and larger gaps (Lieffers et al. 1999). Diffuse light is likely to be particularly important in a cloudy, maritime environment such as Britain.

Most of the results here are for seedlings that are barely established and so the findings require confirmation (see chapter 7).

There was an effect of gap size on rate of gap filling shown by the height/age growth of seedlings, with the rate of growth being somewhat less than the 'free-grown' seedlings represented by the roadside samples. Although growth increases exponentially if conditions are satisfactory, many of the seedlings were increasing in a linear fashion. Although not explicitly representing rate of filling, the relationship between gap size and height found in the return plots implies a similar effect (Figure 6.4). Results from chapter 5 indicated that small gaps and large gaps may form together, and so there is not necessarily a correlation between gap size and age that would militate against this interpretation. Rather it could be taken as evidence of the concept of maximum sustainable height (Messier et al, 1999), with the scatter below the threshold line reflecting age, nutrition, browsing etc. The implications of the effect of expanding gaps (increasing gap area, thereby increasing growth versus contracting gaps – loss of foliage) are not clear. The population of slow-growing seedlings could be regarded as a form of advance regeneration awaiting an improvement in conditions to achieve full establishment. However, Taylor (1990) suggested that spruce was less good at using multiple episodes than other species.

An implication of the slow growth, and possible thresholds to height growth, is that time to fill may be substantial, and certainly more than might be assessed on the basis of silvicultural work on growth following planting on afforestation or large restocking sites. This would in turn influence the turnover rates calculated for study areas.

6.8.3 Filling by vegetative re-growth

A substantial number of fallen trees remained alive at the time of survey, and many showed a form of growth response – either through upturning of the leading shoot, or production of epicormic branches. Some of the branches were assuming apical dominance (vertical epicormics), and in places these were greater than 2m tall (see Figure 6.1). Epicormic presence varied between areas, and was most prevalent in Tywi; this may be related to the youthfulness of the forest, gaps that are relatively large, and overturned trees remaining rooted into plough ribbons. Observations in gaps in Kielder indicate that these new stems may not be stable, and some were observed to have torn from the stem, possibly with loading from snow. However, these shoots had arisen from the side of the fallen stem, and may therefore be unstable. Elsewhere in Kielder, I have observed epicormics of at least 10m in height, and the local manager has reported felling of sites where the individual stems from such shoots were approximately $0.3m^3$ in volume (G Gill, pers comm). The survival of such trees may be enhanced by production of new roots from the fallen stem into the rootplates upon which the stem is resting; this has been observed in the Carron Valley following the 1968 windthrow (D Malcolm, pers comm), and in my own observations in Kielder. Similar observations in the literature are scant but, in Atlantic rain forest of Brazil, survival of sprouts as separate trees has been observed following eventual decomposition of the original stem (Negrelle 1995). In areas prone to snow creep, some trees produce vertically growing adventitious roots described as sustenacular roots (Tanabe and Onodera 1996).

Results from the destructive sampling at Kielder indicate that even in the intact stand, there are epicormic shoots. These may reflect changing canopy conditions such as loss of foliage through Elatobium attack (Redfern et al. 1998) but, as evidenced by the branches in the large gaps and roadside, they have the potential to respond dramatically to enhanced light.

Farr and Harris (1971) noted the production of such shoots after thinning, with 62% of stems bearing epicormic shoots in the thinned treatment and only 32% in the unthinned treatment. Isaac (1940) found that there were vigorous epicormic shoots within 20m of a cut roadline, but few shoots beyond 30m; Herman (1964) recorded an increase in vigour of epicormic shoots following thinning in a 110 year old stand. Studies in other species, particularly Douglas fir (Bryan and Lanner 1981), have identified the production of epicormic shoots as a mechanism for re-building crowns following damage or to ward off senescense (Bryan and Lanner 1981, Ishii and Ford 2001). The frequent production of shoots within the stand may reflect constant changes in canopy condition, or some form of opportunistic resource awaiting enhanced conditions. An implication is that shoots may already be present as trees fall, and therefore provide a rapid response to the gap creation provided the trees survive.

This mechanism bears closer similarity to recovery of tropical rather than temperate forests following wind disturbance. For example, sprouting has been observed on 61-82% of trees in tropical forests hit by hurricanes (Bellingham et al. 1994, Negrelle 1995), but 17-25% in temperate forests (Peterson and Pickett 1991, Bellingham et al. 1996). It does not appear to have been remarked upon as a mechanism within natural forests of Sitka spruce, and highlights the need for care over transference of knowledge. This may be due to lack of study, or to different gap-forming processes, with premature windthrow in Britain and senescense in the Pacific North-west; for example, in Taylor's study, 84% of gaps were due to stem snap, 12% due to windthrow, 4% due to standing death (Taylor 1990). Epicormic sprouting is not universal amongst conifers, and similarly the ability to survive following windthrow appears variable. Norway spruce does not produce such shoots, but does re-orientate the leading shoot, and can layer from side branches (Svensson and Jeglum 2001). Layering is also common in Black spruce (Greene et al. 1999, Paquin et al. 1999) and this can produce a 'bud bank' providing regeneration potential akin to seed banks.

Results from the return plots indicate that there is a gap size effect on presence and absence of vertical epicormics, but that the lower threshold is not as marked as for seedlings. Some form of threshold would be anticipated due to the light requirements of foliage, but the lack of discrimination may reflect the location of the remainder of the crown in conditions of relatively good insolation, particularly if trees are 'hung-up' in neighbours.

The increment of epicormics on standing trees increased, but then tailed off perhaps due to other crown re-building. It is interesting, but possibly coincidental, that the peak of growth after 5-8 years is similar to that found in tree roots when responding to the creation of a gap edge (Urban et al. 1994). I do not have adequate data to quantify the rate of filling achieved by vertical epicormics, but it may be rapid. For example, the maturity of the foliage, and their position may make them more resistant to browsing, and the established root system may provide for more rapid growth. There are some studies that indicate a more rapid establishment of sprouts than seedlings – for example in Japanese beech forests with sprouting from upturned stools and edge trees (Ohkubo et al. 1996). However, there must be competition with other branches and a susceptibility to snow (tearing) and sun-scalding/drought leading to death of the cambium. A number of fallen stems had dead cambium on the uppermost surface. There may be implications for wider dynamics, such as the provision of breeding material for insects such as *Ips typographus*.

6.8.4 Lateral closure

A number of gaps closed due to lateral and vertical growth of edge trees. The repeat measurements of skyview were too imprecise to record the rate of this closure. However, it is possible to estimate the rate from other work on crown development. The rate of closure is slow and only of significance for small gaps; for a gap with skyview of 15 degrees, a 50% increase in height growth of perimeter trees gives only a 5 degree loss in skyview. Furthermore, there is a limit for horizontal spread that is related to tree size. Assuming free growth, the crown width of Sitka spruce of 70cm dbh will be approximately 1350cm (Tabbush and White 1988), occupying an area of 143 m^2. If such a tree were 35m tall, the maximum gap that could be filled would be 0.38 d/h.

There are a number of interesting implications from this process. One is the integration of deadwood within a closed stand, thereby providing a future substrate (in the form of rotted wood) for regeneration of species, but also of great value for biodiversity of lower plants (Humphrey et al. in prep).

6.9 Conclusions concerning gap-filling

Nixon and Worrell (1999) suggest the following conditions as necessary in planning for successful natural regeneration – parent trees, receptive site conditions, adequate coning/seed production, suitable microclimate for germination and growth, low browsing. Furthermore, they suggest an optimum timing for felling in preparation as October to March following a good August cone production. The first set of conditions appear to be substantially provided within gaps formed by windthrow, and the occurrence of windthrow from winter gales fits perfectly the recommended timing!! Results from this study indicate that seedlings are becoming established in the larger windthrown gaps, and that some of these have achieved 'establishment' as defined for silvicultural purposes. There is some way to go before the gaps can be said to have filled. On the other hand, there is no evidence of long-term failure of gaps to fill.

7 A case study of Birkley Wood, Kielder - a self-perpetuating stand of Sitka spruce?

"Loss is nothing else but change, and change is Nature's delight."
Marcus Aurelius quoted by J Raban, 1999 'Passage to Juneau: a sea and its meanings.', Picador, 435pp.

7.1 Introduction

The findings of the earlier chapters indicated that many of the processes required to produce self-perpetuating stands are occurring in upland spruce forests. Thus, gaps appear to form or expand to provide the size of opening required for Sitka spruce to regenerate; there is regular seed supply; and there are examples of seedlings of Sitka spruce in the wind-formed gaps. The rate of gap formation and filling appears to be such that the possibility of stands being overwhelmed by catastrophe, leading to regeneration failure, does not seem great.

The validation of these findings is problematic, due to the relative youthfulness of the existing upland forest and the necessarily long-term study implied. The scope of this chapter is therefore limited to an investigation of one of the oldest Sitka spruce stands in the British uplands – Birkley Wood in Kielder forest. Recent changes to the stand structure induced by wind will be examined to see whether they support the hypothesis of self-perpetuating stands, and whether they provide insights into the structural development of old-growth stands. The relevance of this investigation has been heightened by proposals to establish natural reserves within spruce forests as part of the Forestry Commission's compliance with UKWAS guidelines (S.Hodge, pers comm).

Birkley Wood was once regarded as the most remarkable couple of hectares of Sitka spruce in upland Britain. This reputation reflected views of its apparent stability; at a time when many stands appeared to be windthrown by the time they reached a height of 20 m, Birkley had achieved almost 30 m. Recent research and experience of other maturing stands has indicated that the stability is not unique, that earlier predictions were pessimistic (Quine 1995), and that other stands have achieved heights of 30 m without destruction by wind (Mason and Quine 1995). However, Birkley Wood remains extremely valuable as an old spruce stand on an exposed site.

7.1.1 Objectives of study at Birkley Wood

The objectives of the study at Birkley Wood were to -

- *To observe the process of stand break-up and identify the forest structure that develops*
- *To consider whether the evidence supports the hypothesis that self-perpetuating stands of Sitka spruce will develop spontaneously through windthrow and subsequent regeneration.*

7.2 Description of study site

Birkley Wood occupies a gentle east-facing slope (< 4 degrees) at an elevation of 229m on a broad interfluve between the Comb and Tarset valleys, east Kielder (OS 1:50000 Sheet 80, The Cheviot Hills, GR NY 773 912). There is little topographic shelter (total topex of 20) as the region is characterised by gently rolling hills and subdued topography. Rainfall is approximately 1000 mm per year and around 50% is lost through interception (Anderson and Pyatt 1986). However, the soil is a typical peaty gley derived from Carboniferous sediments, with a peat layer of 10-20 cm, and a clayey subsoil. As a consequence, the site is poorly draining, and borehole water levels ranged from 15cm-85 cm when monitored under the intact forest canopy (Anderson and Pyatt, 1986).

The Wood is approximately 1.9 ha in extent and was planted in 1923, as a Sitka spruce/Scots pine mixture at a spacing equivalent to 6719 tree/ha; this type of mixture was common in the early phase of upland afforestation. The planting year and form of the Sitka component indicate that the provenance may be Washington rather than Queen Charlotte Island (D Malcolm, pers comm). The Forestry Commission acquired the Wood in 1947 and planted the surrounding area between 1952 and 1953. The land to the north, north-east and north-west was planted with Sitka spruce/Scots pine in row mixture and has remained separated from the Wood by an open ride. Norway spruce was planted to the south and south-east, and the unplanted strip separating this compartment from the Wood has since closed over by growth of the edge trees. Table 7.1 provides details of observations that precede the data collected in this study (commencing in 1987)

Table 7.1 History of Birkley Wood; source – unpublished correspondence in Forestry Commission experimental files.

Date	Description	Data
1923	Planted. 'Estimates planting at 4' centres – mixture Sitka spruce/Scots pine@ 1:1 and 2:2 rows. Planted direct (no turves)'. Notes from J.O.Scott (ex Head Forester of Tarset) by Keith Wilson	Initial spacing 1.22m
1946	'about 3 acres .. is very fair but about 1 acre on the southwest side is poor, unfortunately this wood has been extensively damaged during military training … as a background for machine gun targets. … No commercial value though they are certainly valuable for the shelter they provide for the stock'. Forestry Commission Acquisition Schedule	Age 23 – Mean height 10m 1500cu ft/acre
1948	Ploughing visible around, and some patchiness in Wood itself. Aerial photos (Ex RAF 540/A/382.nos 5087 and 5088) Vertical , approx 1:15000 scale	
1951	The area was cleaned (and attempts at draining) 1951 but trees on drain edges tended to blow.	
1952 1953	Compartment to N, NE + NW planted with Sitka spruce /Scots pine in row mixture, to S+ SE planted with Norway spruce	
1955	Thinned (Windblow) FY 1955 – 274 cu ft – Ex Compartment card -	10 cu m
1960	Thinning FY 1960 – 8127 cu ft Ex Compartment card. 'A low thinning (only true thinning the area has had) was given in 1960.' Notes from J.O.Scott	290 cu m thinned
1963	Assessment of crop at 30.9.63 - Sub Compt C, area 4 acres, Sps SP/SS top ht 44/61ft, %50/50, GYC 80/140	Age 40 – Top Height 18m
1965	Thinned (Windblow) FY 1965 – 497 cu ft – Ex Compartment card	18 cu m thinned windthrow
1974	Crop survey 1974 – Top heights – SS 24.2m (range 22.6-25.4), SP 16.5m (15.2-17.2)	Age 51 – Top Height 24m
1978	Mean ht SS – 25.5m; Top ht SS – 26.7; GYC – 14; Mean dbh – 40.6 cm; No trees per ha – SS 420; SP 125; Falstone Experiment 1/77 in 3 plots of 0.015ha	Age 55 – top height 26.7m
1980	'There are at present three blown trees on the site…' – Letter from R Semple (Principal District Officer, Kielder) to D G Pyatt, 5.6.80	
1984	'There are pockets of windblow which suggest the stand may not last much longer' Diary of W L Mason, Silviculturist 31.7.84	
1984	Pocket of wind throw visible by eye on aerial photos – Forestry Commission : Kielder Forest: 1:15000, photos 2 362 and 2 361 of run 8423;.	
1984	Removal of windthrown trees – Number of trees removed = 27, Volume: = 48.5 cu m; Extraction was by forwarder. No standing trees were taken. No other measurements are available.' (source J3 Note from John Harpin dated 10.1.92)	48.5 cu m removed - windthrow
1984	'Several large wind blown SS have been recently cleared ..One windblown SS remains. Water lying in the drain which cuts through the lower part. Hand draining on 27.11.84. Diary E Baldwin/ P Gough, Research foresters	Last 'activity'
1986	"Since the last visit to this experiment, more trees have been blown down by winter gales. Most of the eight recent trees concerned are on the edges of the main existing area of wind damage. This suggests that the plantation may now have a limited life…' Diary of 7.2.86 by P Gough and J Stannard (Research Foresters)	
1987	26 trees flat, few more leaning and signs of pumping throughout. - Diary of B. Reynard (Research forester) following 2 days measurements 31.3.87	

7.3 Data Collection

7.3.1 Tree location

A complete survey of all trees was undertaken in August 1988. As a preparatory measure, a 20 m by 20 m grid was installed in the Wood using a baseline formed by the eastern boundary of the Wood. This created 51 plots and the corners of these were marked with wooden pins. The plots were temporarily divided into four 5 m by 5 m plots using marker poles and the location of each tree was estimated and drawn onto the plot map, and annotated with species and the diameter at breast height. The slope within the plot was measured and marked on the plot map, as were the cut stumps from the 1984 windthrow clearance.

Co-ordinates giving the location of each tree were derived from the plot diagrams using the south-eastern corner as the origin, and the eastern boundary as the baseline to create a local referencing system. These locational data were subsequently used to create the stand maps within the geographic information system (GIS).

7.3.2 Tree dimensions

Stem diameters were recorded during the 1988 survey and again in 1993; the latter are used in this analysis. For each accessible fallen tree, measurements were taken of total height, height to first green branch, height to first green whorl, and direction of fall. In addition, for the first 35 trees, the depth and breadth of the root plate was recorded. The cut stumps from the 1984 windthrow clearance were examined in 1990. Stumps were identified as cut in 1984 by large size, freshness of cutting scars, and lack of rotting wood; they were clearly distinguishable from those of the previous felling in 1965. Direction of fall was estimated from chainsaw cut marks, the lie of the root plate, remains of snedded branches, and damage to neighbouring trees.

7.3.3 Tree status

Recording of the presence of all windthrown trees began in March 1987. Initially, a form was completed for each fallen tree, recording tree dimensions, position relative to other trees, and root-plate dimensions. The first map of fallen trees was drawn up in April 1987, and until 1990 was marked with each new fallen and leaning tree. In 1990, the map-based recording was stopped, and the status of each tree was recorded on a listing of numbers that had been painted on to the trees. The status codes are reproduced in Table 7.2. For the period 1990 to 2000, the Wood was visited at approximately monthly intervals during winter periods (early August – end of March). At each visit the trees within the wood were examined for change in status. In practice, this was relatively simple for fallen, snapped and leaning trees. However, it was more problematic for pumping trees. The soil-root interface of these trees has been partially severed and the swaying of the tree in wind causes water and soil particles to be expelled from beneath the root-plate. The observation is dependent upon the coincidence of saturated conditions and sufficient wind at the time of the visit. As this was infrequent, it was decided that trees would remain classed as pumping from the time of first observation rather than permit return to the 'standing' class.

Table 7.2 Coding used in recording the status of trees in Birkley Wood

Code	Description	Re-code for GIS analysis
0	Standing (other than noted below)	Stable
1	Pumping (water expelled by root-plate movement)	Vulnerable
3	Leaning (stem could revert to vertical; no rootplate tearing)	Vulnerable
4	Pumping and leaning	Vulnerable
5	Hung up (leaning and dependent upon support - likely to fall if support removed; roots exposed at edge of root-plate)	Windthrown
7	Flat (unable to fall further)	Windthrown
8	Crown snap/damage	Vulnerable
9	Stem snap	Windthrown

7.3.4 Regeneration of Sitka spruce

Preliminary observations of regeneration were made in September 1996. These indicated that there was ample seed supply, and evidence of seedlings becoming established. In November 2000, a further survey was conducted to record the presence/absence of regeneration, and relate this to the development of gaps as analysed from the tree location and status data. In order to relate the findings to those of the GIS analysis, the original network of plot pins was used as the sampling framework. A random location of sample points was impractical due to the extreme difficulties of access; a systematic survey was therefore conducted.

During the establishment of the plots for stem mapping (see above), a pin had been placed in the south-east corner of each plot. The site of each of these pins was revisited (or in the case of the pin itself being missing, the location was established using the tree map and the numbered trees) and a temporary circular plot of 2m radius was established, centred on the pin. The height of the tallest regenerating Sitka spruce within this plot was measured, the age was estimated from whorl counts, and the substrate on which the seedling was growing was identified. The estimated age should be regarded as a minimum, as whorl identification was difficult close to the ground, particularly where there was a competitive grass, moss or other seedling layer that suppressed the branches; however, non-destructive sampling was desirable. Samples were not taken where pins lay outwith the boundary of the Wood. A few additional large seedlings were measured from within the permanent plots, but the data associated with these are only used in mapping.

7.4 Data preparation and processing

7.4.1 Gap formation and expansion

Data giving the location of each live tree at the time of the 1988 survey were imported into IDRISI geographic information system (GIS), together with the boundary of the Wood. A raster image of the tree location was produced. The Thiessen Polygon (Voronoi tessalation) interpolation routine was used to allocate the intervening space to the closest feature (tree), resulting in the entire Wood being divided into a series of irregular shaped polygons. It was assumed that this allocation approximated the division of canopy space between irregularly spaced trees whose crowns form a complete canopy by touching but not interlocking. The resulting polygons enable an area to be assigned to each tree, and thus a gap area if it becomes windthrown. The gap defined in this way is akin to the canopy gap of Runkle (see 3.4.1). Derivation of an expanded gap would have required subjective interpretation of the location of the boundary linking the standing edge trees for each gap and each time step.

The map of tree areas was linked to an attribute file describing the status of the trees (as Table 7.2) for each time step (visit). The polygons were then re-coded to take on the value of the attribute file – allowing a map to be derived for each visit showing areas of stable, vulnerable, and windthrown trees. The area of the Wood occupied by trees of each status was calculated for each time step. A further calculation (after performing a group command on each image to identify contiguous groups of pixels), derived an area for each windthrown gap (or island of standing trees within a gap) for each period. To produce a time-series of change in area for each gap, it was necessary to manually compare the gaps from one time step to another; this was due to the limitations of the IDRISI group module which numbers the groups independently for each image. The changes of area were summarised in a data file, for subsequent plotting and processing.

A subset of the visits that occurred closest to mid-summer were used to generate statistics on changes per annum. The annual maps were overlaid to produce a composite map of gap age in the year 2000; it was re-orientated to magnetic North from the local co-ordinate system.

The extent to which the expansion of gaps was related to the trees identified as vulnerable (pumping and/or leaning) was explored. For each time step, the new gap area was compared with the area identified as vulnerable in the preceding visit.

The direction of spread of the largest gap was studied by computing the gap centre for each annual time step. This involved clipping the image of the whole Wood to the extent of the largest gap, recoding other gaps as background, and then using the IDRISI module Center to calculate the x and y co-ordinates, as well as the standard radius and coefficient of dispersion. Trigonometric adjustment was subsequently applied to locate the centre points in a grid based on magnetic North, rather than the local grid.

7.4.2 Regeneration

Data from the GIS analysis describing the age of the gap at the sample point were added to the field survey data. The map of gap age was sampled using an image of the set of 2m radius plots, and the maximum, minimum, and average age for the gap/plot intersection was recorded. Preliminary analysis of the gap size distribution allowed the identification of 2 groups – sample locations with no gap or small gaps (below the seedling survival threshold identified in Ch 6), and locations in large gaps (above the threshold). Data were summarised, and analysed within group.

7.5 Results

7.5.1 Trees in Birkley Wood

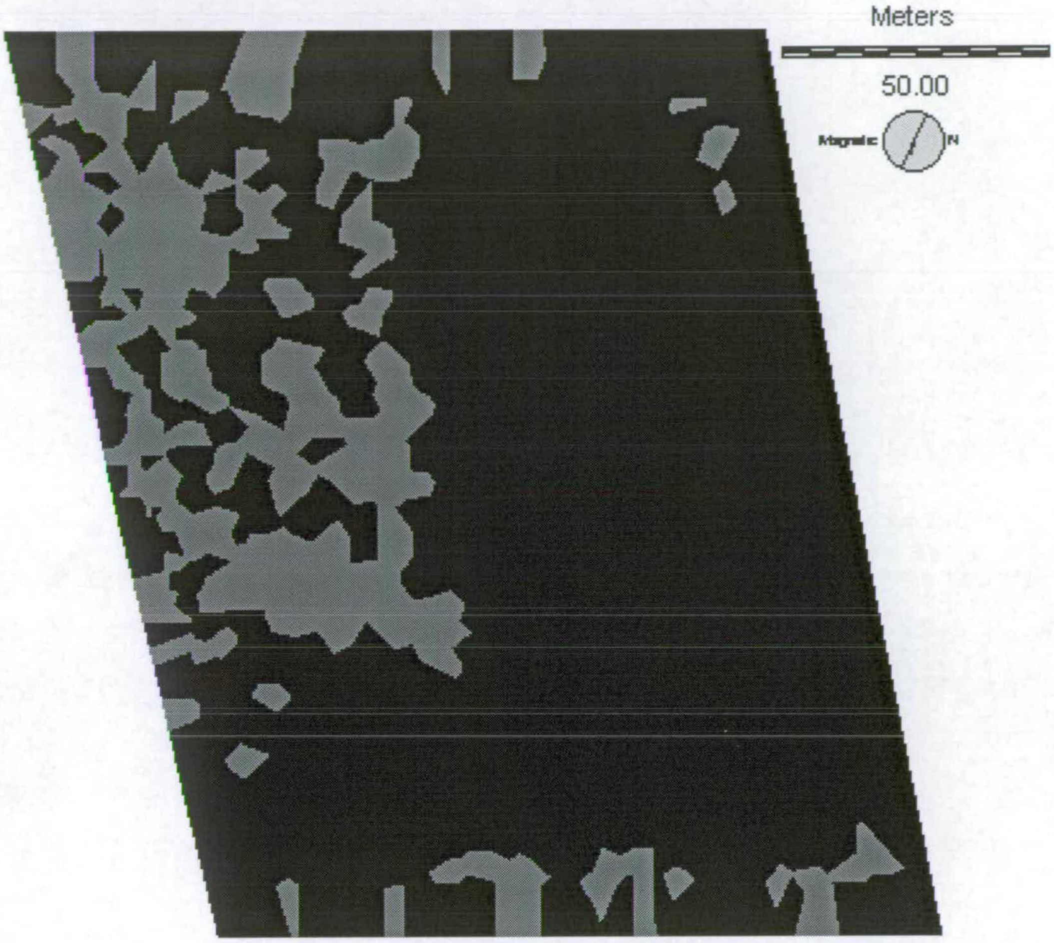
Basic mensurational data for the stand are provided in Table 7.3. In 1993 the Wood was dominated by Sitka spruce both in terms of numbers, and individual tree size. Sitka spruce occupied 80% of the area of the wood as allocated by the Thiessen routine. The Scots pine were largely confined to the boundaries of the Wood, and to an area of poorer growth in the south and west (Figure 7.1.).

Table 7.3 Basic mensurational data for trees in Birkley Wood.

	DBH (cm) of all living trees in 1993	**Height (m) of fallen trees**	**Root plate depth (cm) of fallen trees**	**Root plate radius (cm) of fallen trees**
Sitka spruce (Sample size)	594 (equivalent to 305/ha)	108	33	27
Mean (*SD*)	42.8 (*13.9*)	30.3 (*3.18*)	42.9 (*8.3*)	165.3 (*33.3*)
Minimum – Maximum	5.5 – 87.5	14.8 - 35.2	23 – 55	101 – 228
Scots pine (Sample size)	214 (equivalent to 110/ha)	N/a	N/a	N/a
Mean (*SD*)	26.8 (*5.32*)	N/a	N/a	N/a
Minimum – Maximum	15.2 – 41.8	N/a	N/a	N/a

The allocation of area to individual trees by the Thiessen module gave a mean area of 22.9 m^2 and a range of 1.6 – 173 m^2. The area occupied by free-grown trees of the diameter range at Birkley would be 5.8 – 182 m^2, using Tabbush and White's predictive equation (Tabbush and White 1988). A comparison of the whorl diameter observed in a sample of 24 fallen trees at Birkley, and the free grown prediction indicated that crown width was approximately two-thirds that of free grown (mean 0.64, range 0.38-0.93).

Figure 7.1 Map of species distribution in Birkley Wood in 1993 as represented by the allocation of area within the wood to individual trees using the IDRISI GIS Thiessen module. Key – Black = Sitka spruce, grey = Scots pine. Oriented to local grid.



In March 1987 there were 53 windthrown trees in the Wood, including the cut stumps from the 1984 windthrow clearance. By March 2000, there were 208 windthrown trees in the wood, a further 107 trees were classed as vulnerable, and 509 appeared stable; the loss of trees through windthrow in the Wood averages 13.7 per year (equivalent to 7 trees per ha per year). The changes in the intervening periods are summarised in Figure 7.2. New trees were windthrown in 38 out of the 88 periods, and there was change in the number of vulnerable trees in 44 out of the 74 periods monitored. Some trees remained vulnerable for substantial periods. For example, of the 48 trees identified as pumping in March 1990, 24 remained so at March 2000 whilst 20 were windthrown, and 4 developed a lean and were pumping.

The direction of fall of the windthrown trees is summarised in Figure 7.3, which show a predominance of fall in a north-easterly and easterly direction, and none in a westerly or north-westerly direction.

Figure 7.2. Change in numbers of stable, vulnerable and windthrown trees between 1984 and 2000. Each point represents the status recorded at a single visit.

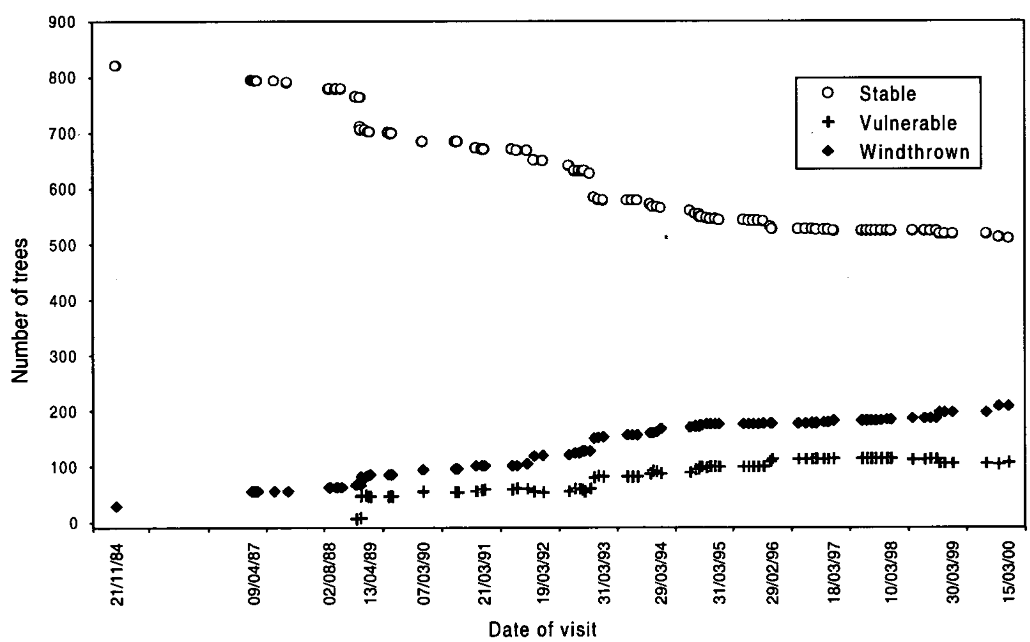
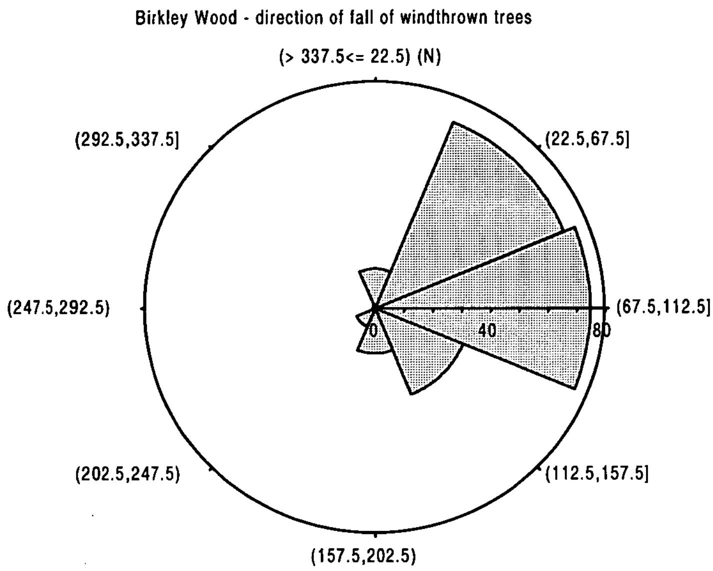


Figure 7.3 Direction of fall grouped in eight sectors for windthrown trees at Birkley Wood.



7.5.2 Gap formation and expansion

7.5.2.1 Numbers and areas

The change in number and area of windthrown gaps is summarised in Table 7.4 which shows an almost 10-fold increase in gap area and 3-fold increase in gap numbers between 1984 and 2000. There is a substantial increase in mean and maximum gap size, but decrease in median, indicating increased skewness of the distribution. The windthrown area is dominated by the largest gap.

Table 7.4 Change in gap size and numbers over the monitoring period

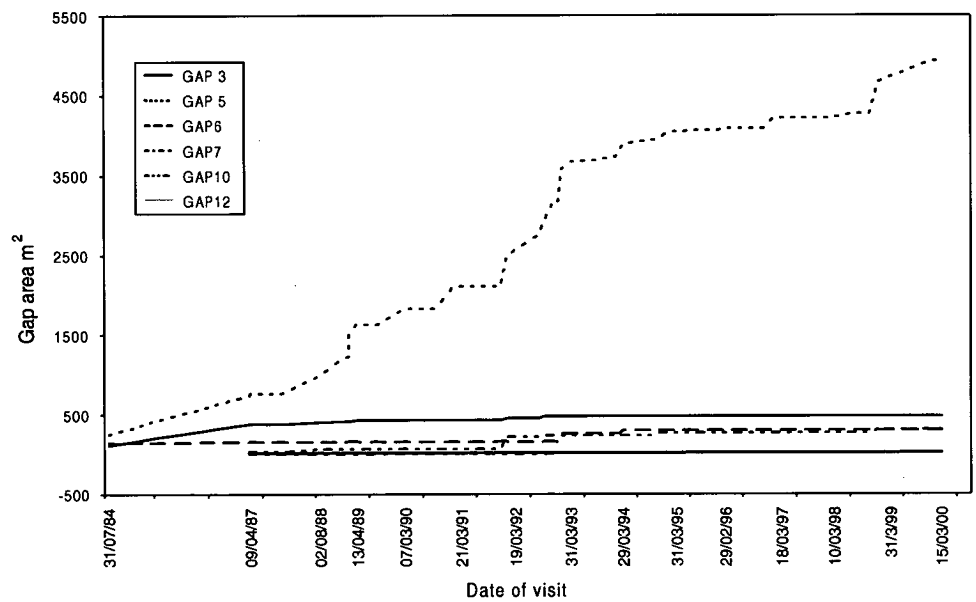
	Total Gap area m^2	**% of Wood in Gaps**	**Number of gaps**	**Mean gap size m^2 (*SD*)**	**Median gap size m^2**	**Maximum gap size m^2**	**Maximum as % of total gap area**
1984	774	4.0	6	128.9 (*69.0*)	114.8	252.9	32.7
2000	6316	32.6	16	394.7 (*1219.2*)	24.9	4936.2	78.2

During the period of monitoring, 31 gaps were identifiable at some period, but 15 lost their identity through coalescence. None of the gaps formed since 1984 became substantial in size, and new gaps only contribute 13.7% of the total increase in gap area, the remainder being expansion of pre-existing gaps. At the end of the monitoring, 11 gaps (including one present from 1987) had not changed in size. New gaps formed during 13 periods (of the 38 during which windthrow was observed, and of the 88 overall).

The expansion process was dominated by one gap that was present at the start of the monitoring and subsequently expanded to absorb a number of other gaps (Figure 7.4); the pulses of expansion represent both new expansion, and also coalescence (ie apparent rather than real expansion). Some 'islands' of standing trees within gaps were remarkably persistent, lasting for at least 12 years.

The windthrow that occurred was separated into that involving trees classed as vulnerable, and that involving apparently stable trees; 54% was of trees previously classed as stable.

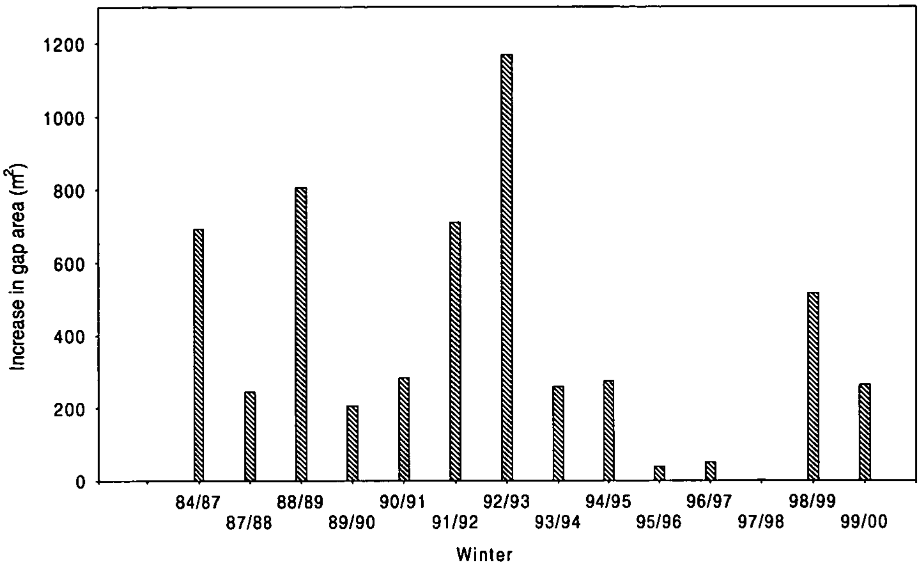
Figure 7.4 Change in gap area for expanding gaps within Birkley Wood.



The annual increment of gap area varied substantially between winters (Figure 7.5) with a mean of 394 m^2 /annum (2% of the area of the Wood) and a range from zero to 1169 m^2 (6%

of the area of the Wood). The composite map of gap area, giving age of gaps and illustrating their distribution and spread around the Wood is shown in Figure 7.6.

Figure 7.5 Annual (each winter) increment in gap area.



7.5.2.2 Relationship between increase in gap area and wind climate

The relationship between the increase in total gap area and the strength of the wind was explored using data for each period between visits from 1988 to 1999. The increase in gap area (new and expansion combined) was expressed as a percentage of the existing gaps, and as a percentage of remaining intact forest (matrix). In both cases, the relationship was non-linear, and fitting a piecewise linear regression with breakpoint, rather than an exponential proved to give a better proportion of variance explained. (Figure 7.7;Table 7.5).

Table 7.5 Summary of piecewise linear regression with breakpoint fitted to data relating percentage increment in gaps with wind speed during the period. (Coefficients apply to independent variable of daily maximum gust m s^{-1} at Caplestone Fell)

	Constant Line 1	**Coefficient Line 1**	**Constant Line 2**	**Coefficient Line 2**	**Break-point**	**% Variance explained**
% Intact forest	0.0519	0.0041	-7.321	0.2842	0.395 (27.2 m s^{-1})	82.2 (*N=72, R=0.91*)
% Existing Gaps	-0.3489	0.0241	-23.502	0.9672	1.650 (26.0 m s^{-1})	80.3 (*N=72, R=0.90*)

Figure 7.6 Composite map of gap age. Key – grey scale – annual time steps between White = gap of 16 years and Black = gap of 0 years (ie no gap present).

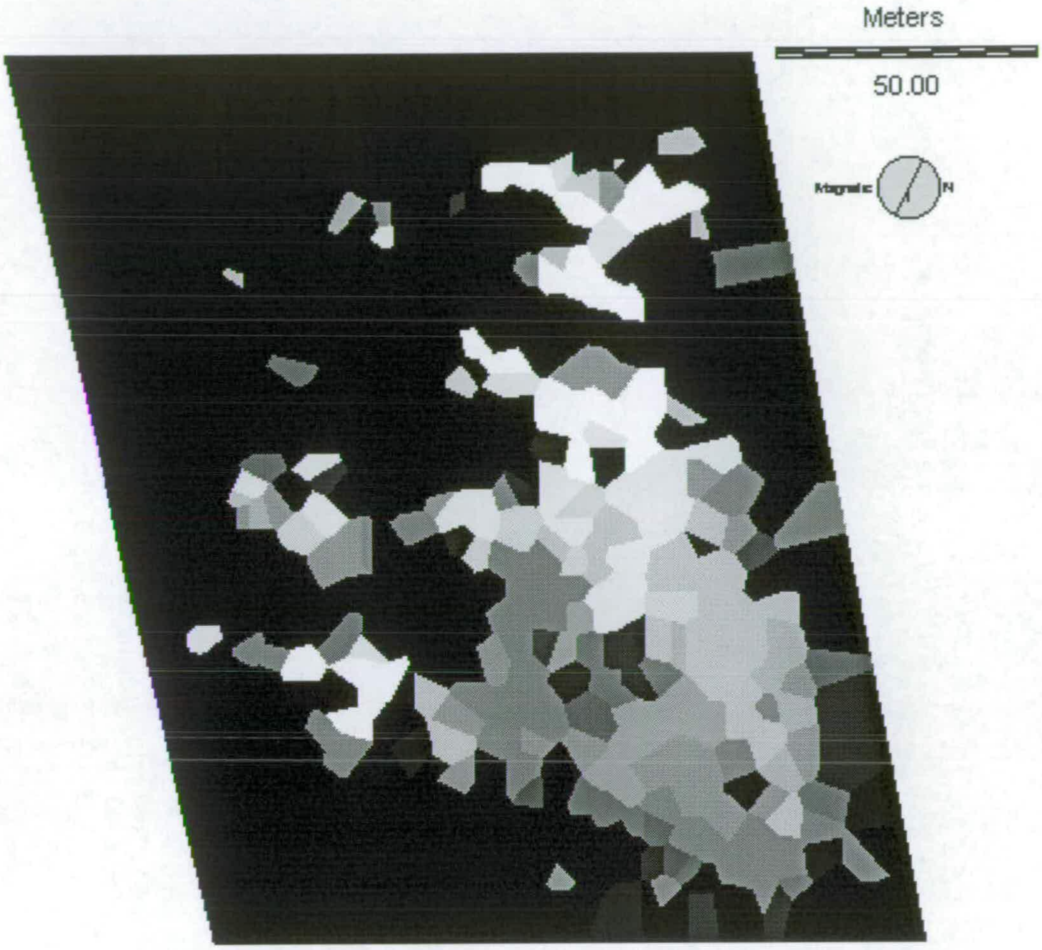
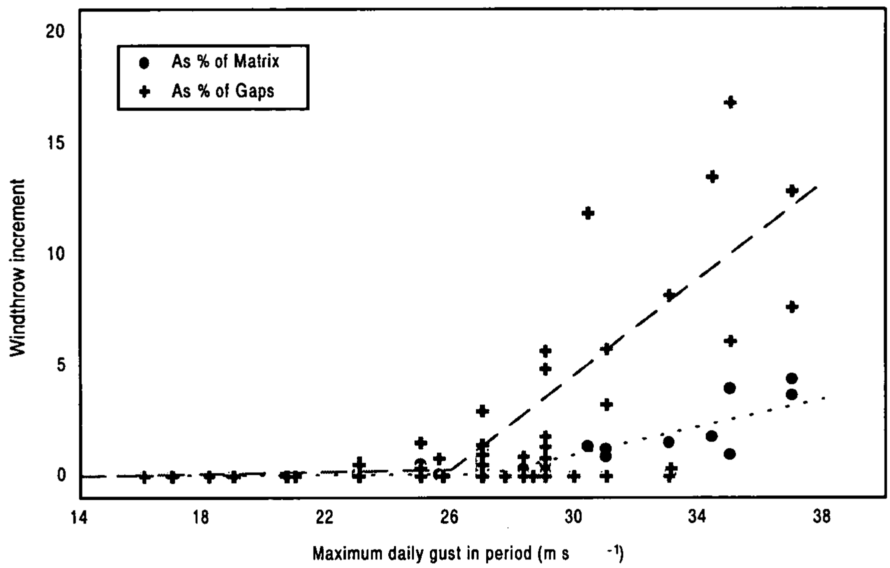


Figure 7.7 Relationship between wind speed and increase in gap area, expressed as a percentage of area already in gaps, and percentage of area intact.



The wind speeds experienced during periods of no change, and periods of change were compared (Figure 7.8). Periods with windthrow that included trees classed as stable had significantly higher wind speeds, than periods with windthrow only of vulnerable trees or periods with no change (Kruskal-Wallis test: H (3, =79) = 19.999, p = 0.0002) but not periods involving an increase in vulnerable trees.

7.5.2.3 Direction of gap expansion

The composite figure of gap age (Figure 7.6) shows the general spread of the gaps. The direction of spread of the largest gap was summarised by calculating the centroid for each time step in which the boundary changed. The change in centroid co-ordinates is summarised in Figure 7.9 which indicates a move in a south-easterly direction, with a bearing of 139 degrees linking the 1984 and 2000 positions.

Figure 7.8 Wind-speed recorded during different classes of periods of change. (Overall mean 27.0 m s^{-1}; no change 24.6 m s^{-1}, newly vulnerable trees 25.87 m s^{-1}, vulnerable windthrow 27.28 m s^{-1}, stable windthrow 29.93 m s^{-1}).

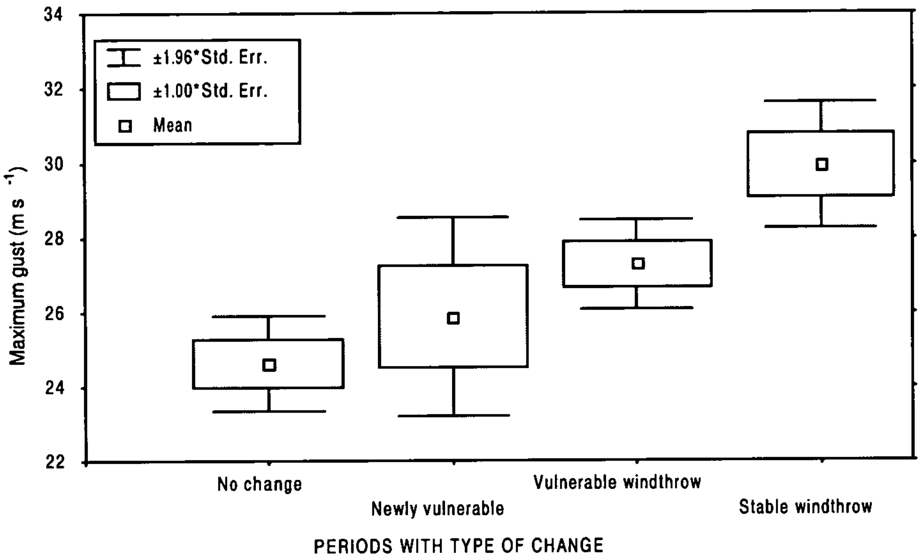
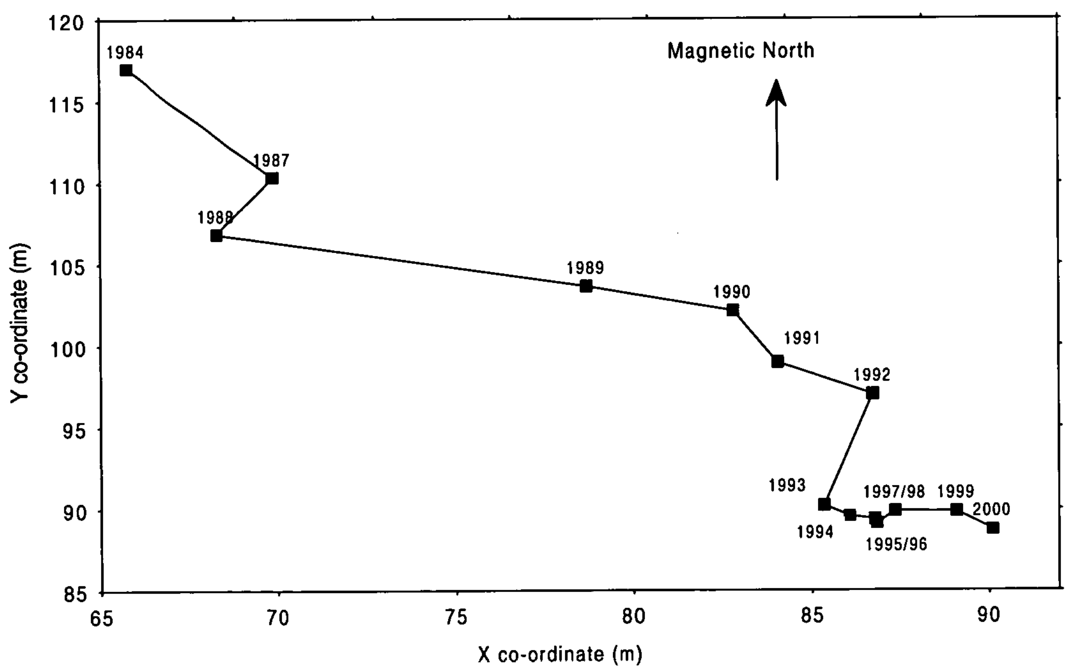


Figure 7.9 Change in position of the centre of the largest gap during the monitoring.



7.5.3 Regeneration of Sitka spruce

Sampling was undertaken at 43 pin sites, and regeneration of Sitka spruce was found at 34 of these. Height ranged from 5 to 800 cm (mean 100, SE 25.1), and minimum age from 1 to 11 years (mean 5.3, SE 0.57). The majority of the seedlings sampled were growing on a substrate of the forest floor (31) with only 1 sample on a root-plate, and 2 on fallen stems.

The gaps from which the samples were taken ranged in size from zero (intact forest) to 4936 m^2. There were 3 gaps below 30 m^2, and 5 gaps in excess of 300 m^2. Assuming a tree height of 30m and circular gaps, the aperture (skyview fraction) of the largest gaps ranged from 0.19 to 0.58 of the hemisphere (see 3.4.3), whilst that of the smallest ranged from 0.03 to 0.06. The aperture of the largest 5 was above the critical aperture of 0.15 identified earlier. The samples were divided into two groups – group 1 (no gap or small gap below threshold), and group 2 (medium to large gaps above threshold).

The association between height of seedling and age was examined using Spearman R Rank correlation. Height was correlated with both field-measured age, and with gap age (derived from the GIS analysis). For Group 1 (no gap or small gap below threshold), there was a significant correlation between height and age, but not between height and gap age (the majority of samples having a gap age of zero). For group 2 (medium to large gaps above threshold), there was a significant correlation between height and both age and gap age, with the latter being the strongest. Table 7.6 summarises the results.

Table 7.6 Spearman R correlation between Seedling height and age of seedling and age of gap.

	Valid numbers	**Spearman R**	**t (N-2)**	**p level**
Group 1; height and field age	21	0.957	14.365	.000000
Group 1 height and gap age	21	0.315	1.446	.164314
Group 2 height and field age	22	0.765	5.312	.000034
Group 2 height and gap age	22	0.794	5.832	.000010

Analysis confirmed that seedlings were larger and older in the large gaps (group 2) than in the small gaps or where gaps were not present. Table 7.7 summarises the results from the Kolmogorov-Smirnov Test.

Table 7.7 Summary results for age and height for seedlings grouped by gap size.

	Group 1 **Valid n=21**	**Group 2** **Valid n=22**	**p level**
Mean height of seedling (cm) ***SD***	22.9 *(38.79)*	173.9 *(203.4)*	$p < .001$
Mean age of seedling (years) ***SD***	3.7 *(3.31)*	6.8 *(3.5)*	$p < .05$

An interpolated map of height of regeneration is shown in Figure 7.10, which bears a qualitative resemblance to the composite map of gap age, giving support to the link between gap presence and regeneration development. The extent of the regeneration is also illustrated in Figure 7.11.

Figure 7.10 Interpolated map of regeneration height for Birkley Wood. Key – Height range of 0-1000 (Black – white) divided into 15 steps (of 71cm). Maximum height of regeneration within boundary of wood is 800 cm (13th step).

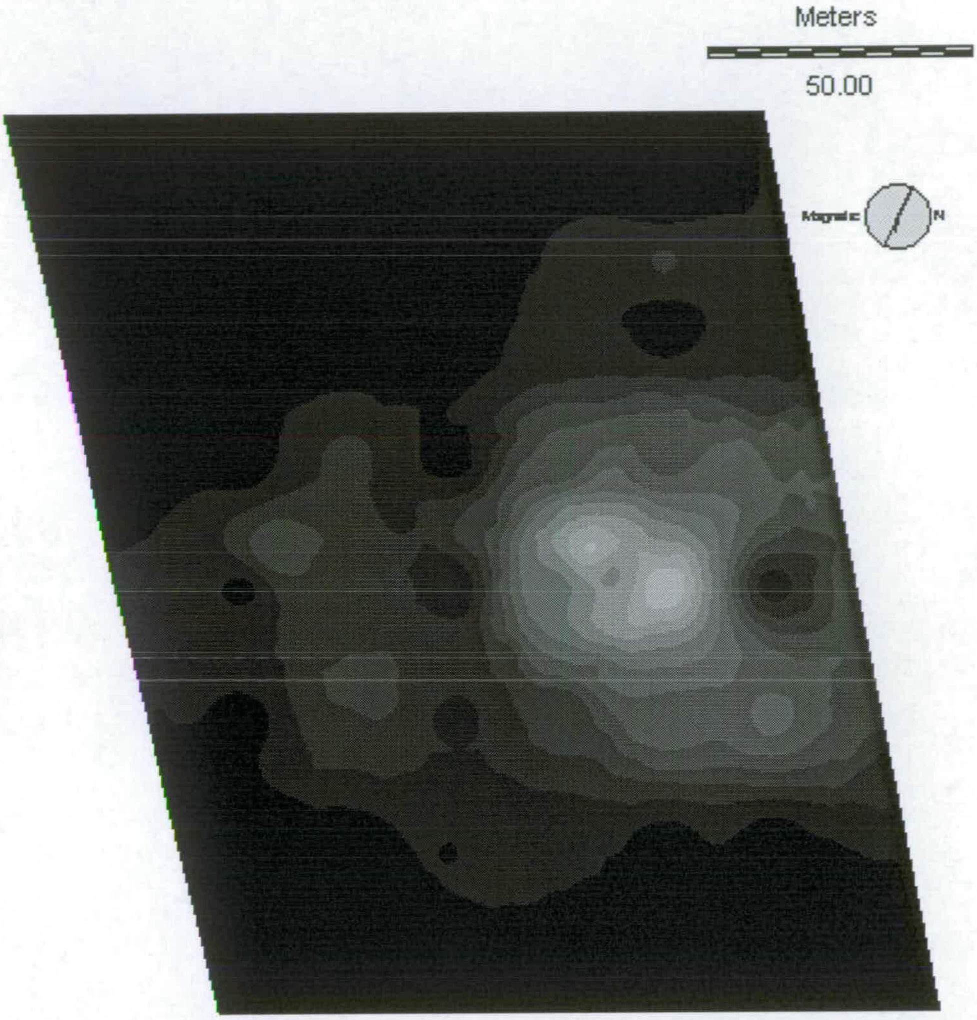


Figure 7.11 Photograph of regeneration within and at edge of largest gap in Birkley Wood.

7.6 Discussion

7.6.1 Gap formation and expansion

There have been substantial changes in the structure of Birkley Wood over the period 1984 to 2000. Windthrow has increased through processes of expansion of existing gaps, and formation of new gaps. Many of the new gaps have proved to be transient, and in time have lost their identity due to coalescence with a small number of older, expanding gaps. However, a proportion of the new gaps have neither expanded nor been absorbed into another gap. A single gap has expanded to dominate the windthrown area of the Wood, and as a result the gap size distribution is highly skewed. The direction of expansion accords with the prevailing strong winds, but there is some difference between the mean direction of expansion of the largest gap, and the mean direction of windthrown trees within the Wood; this veer may be due to funnelling induced by stable edge trees.

There was considerable variation in windthrown increment from year to year – and one winter with no change in windthrown area. The events that caused the greatest increase in windthrown area in Birkley Wood were also important within the region. The magnitude of increase in gap area is determined by strength of wind speed experienced during the period, with little windthrow below wind speed of 26-27 m s^{-1}. Scaling the wind speeds to the local site (through regressions between Caplestone Fell and Birkley Wood – open and restock sites; Ch 4) indicates a critical wind speed of 16-17 m s^{-1} for the commencement of windthrow; such wind speeds occur in most years. This threshold is somewhat lower than the only direct observation of windthrow in Britain (Oliver and Mayhead 1974), and model calculations (Gardiner et al. 2000). However, the former refers to stable trees on a freely draining site, and the latter is for damage to the mean tree. In contrast, the speeds at Birkley Wood reflect damage to a mix of vulnerable and stable trees, and the speeds causing damage to the latter were higher. Note that the period of quiescence in the late 1990's, including a winter with no increase in windthrown area, coincides with the period of return transect monitoring at Kielder, and is consistent with the lack of change noted in Figure 5.4.

There are insufficient periods with very high wind speeds to indicate whether the amount of windthrow increases linearly with wind speed beyond the threshold. However, wind speeds causing windthrow of stable rather than vulnerable trees were higher, so the relationship may be complex, and involve multiple thresholds. Many of the vulnerable trees were located close to gap edges. This may reflect the severity of conditions at that location (increased wind speed, disrupted local drainage), but contributes to the increased likelihood of expansion rather than new gap formation for modest wind speeds.

Despite the substantial changes, there is still a large part of Birkley Wood that is not windthrown. At the mean rate of gap increase from the recent monitoring, it would take another 34 years for the remainder of the Wood to be blown – and even at the maximum rate, it would take 11 years. Of course, this is a gross simplification, and ignores enhanced vulnerability due to age/increased height, and also the possibility of storms more severe than experienced during the monitoring period. Calculations for the mean Sitka spruce tree (Table 7.3) using the ForestGALES model suggest a return period of around 40 years for overturning (and 140 years for breakage); this reflects damage akin to a stand replacement event. These predictions suggest that there is still time for establishment of regeneration on the site to produce a self-sustaining stand.

7.6.2 Regeneration – gap filling

Five of the 16 gaps present in 2000 were of sufficient size to permit the establishment of Sitka spruce (using the thresholds identified in Chapter 6), and further expansion will improve the light environment. A small number of trees have survived as 'islands' within gaps – in some cases for as long as 12 years, and may have a role in providing local seed, particularly if they cone more profusely due to the enhanced exposure and scope for crown development.

Survey confirmed that gaps are filling with regeneration of Sitka spruce in Birkley Wood. Seedlings are larger and older in the presence of substantial gaps, than where gaps are not present, or provide a very small aperture to the sky. The tallest regeneration in the largest gap is 8 m tall and therefore close to cone-bearing size. The annual increment on this seedling and its neighbours approximate 1 metre per year, indicating successful establishment and likely onward growth. The seedling height is approaching one-third of the stand height – a definition of a filled gap used by Runkle (1985). The aperture of the largest gap is approximately 0.52-0.58, exceeding the optimal identified by Taylor (1990), and approximating a D/H ratio of 2, identified by Malcolm et al (2001). Therefore, it appears that Birkley Wood may be self-perpetuating without direct human intervention.

In contrast to the results summarised in Chapter 6, the majority of the sampled seedlings occupied microsites of the forest floor and not those of the root-plate. This may reflect the instability or transient quality of the root-plate microsite. For example, personal observation suggests that seedlings on root-plates are susceptible to drought, and that lumps of soil fall from the root-plate during periods of freeze/thaw (Figure 7.12). It may be that the forest floor position becomes more favourable as the gap size increases (better lighting), and that the windthrow provides a barrier to mammalian herbivores. This ground-level dominance of regeneration is consistent with some of the results from the Pacific North-west (Harmon and Franklin 1989, Deal et al 1991). However, some types of substrate associated with old stands of Sitka spruce in the Pacific North-west have yet to develop. For example, soil mounds due to the complete weathering of root plates, and rotten stems and stumps, are still scarce. Although most fallen stems remain relatively intact, there are seedlings establishing in litter collecting on the surfaces of the stems; fallen Scots pine stems have rotted faster and spruce seedlings are present on some where the breakdown is particularly advanced. The regeneration is almost exclusively Sitka spruce; there are occasional birch, rowan and bird cherry that appear to be particularly prevalent on root-plates. Only one Scots pine seedling has been observed in the Wood, and it has now disappeared, and no regeneration of Norway spruce has been seen, despite coning within the neighbouring stands.

Observations in other old spruce stands in the British uplands indicate that the regeneration in Birkley Wood is not unique. Archie's Rigg, another mature stand in Kielder set aside as a non-intervention reserve, also exhibits active gap-filling. Stems created by both seedling regeneration and epicormic sprouting were over 20 years of age and had reached heights of approximately 10 m in 2001 (personal observation). The latter mechanism is not occurring in Birkley, and though there has been substantial epicormic development on standing trees, most fallen trees have died. The reasons for this varied response are unclear, though may be related to differences in moisture availability on a gley versus peat site, or differences in insolation of exposed root-plates related to gap size and orientation.

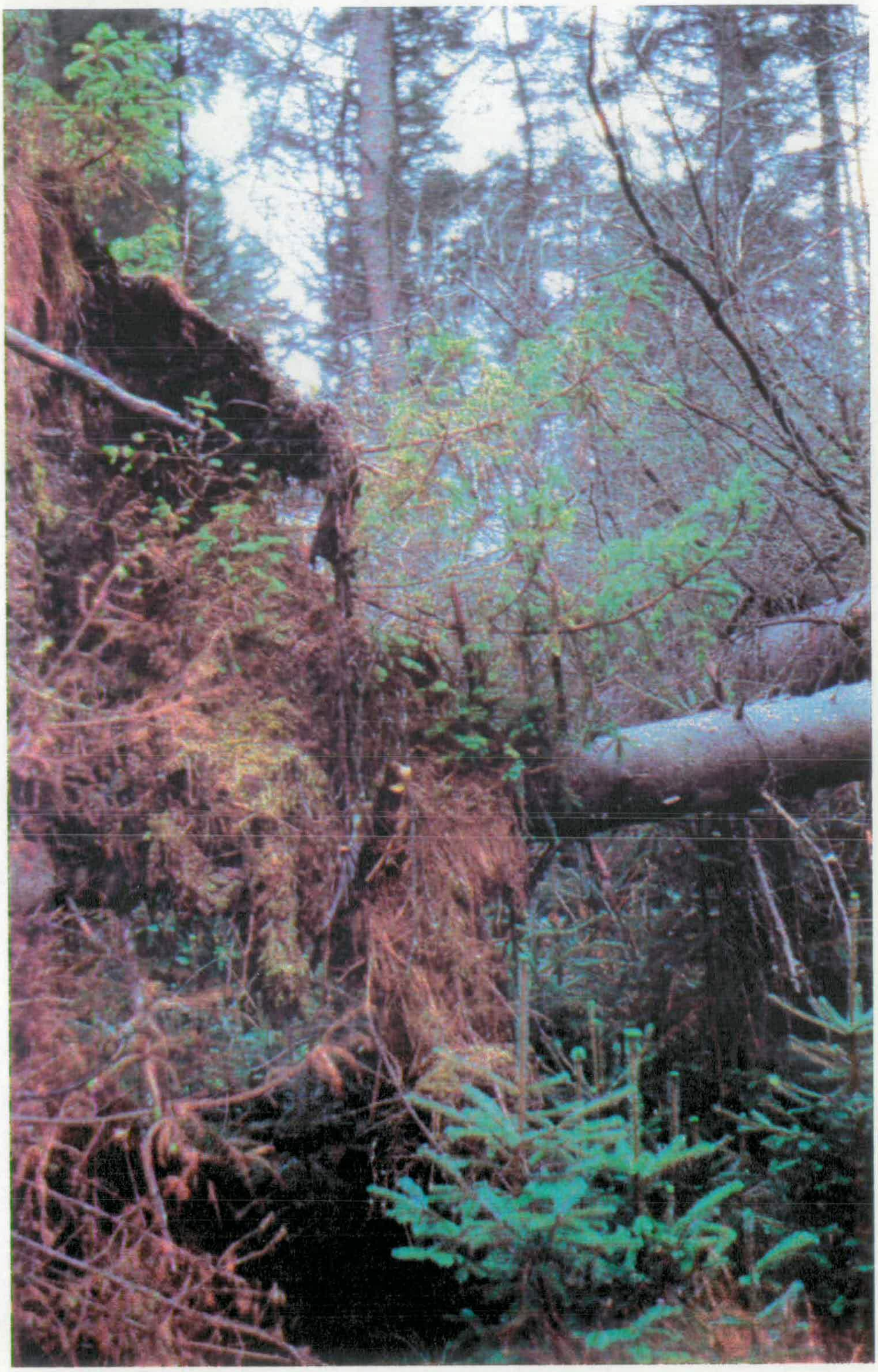


Figure 7.12 Photograph illustrating instability of regeneration developing on overturned rootplate compared with regeneration established on the forest floor.

The link between gap age and seedling age, and the down-wind expansion of the largest gaps indicates that gap filling may not be uniform, but reflect the gap expansion. It seems possible that a partial wave, of the form described by Rebertus (1993) and Perkins (1992) could emerge. However, the lack of extreme insolation or dessication causing tree death, and the variability in direction of strong winds is likely to prevent a true wave forest developing. The composite map of gap age indicates numerous lobes of expansion for the largest gap, not all of which accord with the general direction of expansion.

7.6.3 Comparison with other stands

The mensurational characteristics can be compared with published yield class tables for Sitka spruce (Edwards and Christie 1981) (Table 7.8). The spruce component of the Wood appears most similar to the Thinned yield table. The windthrow-induced mortality (Figure 7.2) is approximately 40% higher than this model predicts for the equivalent period.

Table 7.8 Stand data from Sitka spruce yield tables; table entry nearest to age 70 selected – not interpolated

Yield table (Sitka spruce Yield Class 14)	Stocking at age 70	Top Height at age 70	Mean dbh at age 70	Mortality between age 60-75 tree numbers/ha/yr
No thin, initial spacing 1.4m	1345	28.6	27	16.4
No thin, initial spacing 2.4m	784	27.8	33	6.1
Intermediate Thin, initial spacing 2.4m	340	28.6	39	4.8

The use of figures averaged for the stand does not reflect the substantial variability in stocking across the site. For example, in the densest plot (plot 41), the 1993 stocking was equivalent to 625 spruce/ha, with a mean dbh of 34.1cm; this appears closer to the No thin 2.4m spacing model.

Comparisons with data from natural stands in the Pacific North-west can be made, but are complicated by the presence of western hemlock. Generally, stocking of Sitka (>5cm dbh) in mature and old-growth stands has been found to be less than 100 stems/ha, with 150 – 600 stems of hemlock (Alaback and Juday 1989, Taylor 1990, Deal et al. 1991). Stands described by Day (1952), particularly those from Graham Island (Tlell transect), have more comparable densities (mean stocking of 415/ha, plot means 198-642) and dimensions of spruce (mean height of 31 m and dbh of 42 cm), but the total stocking including the hemlock is 1347stems/ha. Although measurements of regeneration will in due course add to the stem numbers in Birkley, the structural differences due to the lack of shade tolerant species and shrub layer is apparent in these comparisons with natural stands.

British yield tables for Sitka spruce currently end at age 75-80 (Edwards and Christie 1981), giving little clue to the potential further development of the trees in Birkley Wood. Published height/age curves for the Pacific North-west give some indications of the rate of height growth – for example, Farr (1984) for South-east Alaska and Nigh (1997) for the Queen Charlotte Islands, British Columbia. Top height measurements in Birkley (Table 7.1) seems to accord with a Site Index of 24 (Nigh, 1997) or a pre-metric Index of 80 (Farr, 1984). Using these curves, the suggested height of the original trees in 11 years time (maximum rate of windthrow) is 34-37 m, and in 34 years time (mean rate of windthrow) is 37-41 m. If the stand were to remain to age 400, Nigh's equation suggests a top height of 56 m would be reached (Nigh, 1997). If the existing regeneration follows the same growth curve, it will reach 12 m in 11 years time and 21-23 m in 34 years time. This indicates that the regeneration would reach 1/3 height of any remaining original canopy trees at original stand age of 95, ½ by 110, ¾ by 150 and 9/10 by 230. Some recently exposed trees at gap edges appear to be losing crown dominance, and displaying 'bent tops' (D Malcolm and C Quine, pers obs). This may be indicative of root problems, such as waterlogging due to disrupted drainage, and suggests that height increment may tail off rapidly in the future.

7.6.4 Calculation of turnover time

Calculation of turnover time using different estimates of gap formation gives widely different answers. Taking the cumulative windthrow at the start of the monitoring (4% in 1984), gives a turnover time of 775-1025 years depending upon whether the first 20 or 30 years is treated as fill time (ie trees not vulnerable). Taking the annual rate of windthrow recorded during the monitoring suggests anything from 17 years (maximum rate) to 50 years (mean rate); whilst extrapolating these rates forward suggested total area windthrown in 11-34 years ie at age 88 to 113. Arguably, the most realistic method, that more closely meets the assumptions, is to take the cumulative windthrow to date, and assume a fill time of 20-30 years; this gives a turnover time of between 132 – 163 years. This would imply a canopy residence time of 102 - 143 years, and a stand height of around 43-47 m. This assumes no continuing trend in age-related vulnerability, otherwise recent annual rates, or more severe may apply.

7.6.5 Uncertainties over future development

In addition to the rate of further gap expansion and development, there are a number of uncertainties over future stand development. There may be a shortage of potassium, and particularly available nitrogen on this organic soil, and the latter deficit may be made more serious by the very dense regeneration. The soil-churning effect of the windthrow may have some beneficial effect on soil development; approximately 26% of the forest floor would be disturbed by overturning root plates assuming the dimension and stocking indicated in Table 7.3. This is likely to have a beneficial effect in disrupting the humus layer and creating a micro-topography that may include more spots that are freely-draining, but may disrupt the general site drainage and therefore adversely affect the growth of the original trees. The stability of regenerating trees on root-plates and other raised micro-sites is uncertain, and may be adversely affected by the small volume of soil available for rooting, and the erosion of these mounds and root-plates. It is unclear how rapidly other species will colonise given the scarcity of local seed sources, and rapid establishment of the spruce. The lack of long-term studies in natural woods (Peterken and Stace 1987, Peterken and Mountford 1996), and the substantial differences in forest type, means that there is little basis for conjecture.

The annual rate of windthrow is variable, the fraction of the Wood in gaps is increasing, and gap filling is only just commencing. In these circumstances, the assumption of 'steady state' necessary to calculate turnover time is bold. An implication is that, in time, there may be a shifting mosaic of wind-formed gaps of different scales, and filling at different rates - which perhaps can only be summarised at a larger spatial scale than this study has addressed.

7.7 Conclusions concerning Birkley Wood

The study of Birkley Wood provides evidence that self-perpetuation should develop in Sitka spruce in upland Britain. Wind-formed gaps span a range of size from those that permit survival of seedlings in sub-optimal light conditions, to gaps that provide optimal conditions and permit rapid growth of seedlings. Neither seed supply nor herbivory appears to limit regeneration, and the rate of increase in gap area is sufficiently slow to permit establishment of a new generation before the original stand is lost.

8 General Discussion and Final Conclusions

"The Yoghan* tongue ...proceeds as a system of navigation. Named things are fixed points, aligned or compared, which allow the speaker to plot the next move...Here are just a few of their synonyms: - ...A tangle of trees that have fallen blocking the path forward – A hiccough...." Bruce Chatwin, 1977, In Patagonia. Picador. **[Yoghan – Indians in Tierra del Fuego]*

8.1 The role of wind in the ecology of upland spruce forests

In 1982, Major General Moore remarked that windthrow was the 'outward and visible sign of silvicultural failure' within the British forest industry, and proposed 'oceanic forestry' to confront the problem (Moore 1982). Whilst, such a sentiment may remain true for those concerned with economic outputs of the forest, those with a broader view of forestry may not regard windthrow as universally a bad thing. In the ecology of forests, disturbance has an important role in shaping and rejuvenating ecosystems. Even in spruce plantations, there are benefits from windthrow through the introduction of structural diversity. The gaps that are formed provide diverse habitats where a ground flora can establish, and to which invertebrates, mammals and birds are attracted. For example, raptors such as Goshawks (*Accipter gentilis*) use root-plates as plucking perches (Petty 1996), and Capercaillie (*Tetrao urogallus*) benefit from the development of a ground flora and access to shoots and buds (Picozzi et al. 1996). In time, the deadwood can be valuable for a range of lower plants, as well as cavity-nesting birds.

The extent to which windthrow within a stand is regarded as damage or as structural change depends upon the objectives of management. Over the past twenty years there has been a dramatic change from a production-oriented approach to forestry in Britain, to a broader, multi-purpose forestry that encompasses other ecological and social goals. A consequence of this has been longer retention of existing stands to minimise visual change, and obtain ecological benefits. In turn, this provides greater scope for natural agents, such as wind, to shape stand structures. Britain has a particularly extreme wind climate, which is comparable with only a few other maritime regions of the world. The strength of the wind varies through time and over space, and gaps are formed in spruce forests by the action of particularly strong winds. The interaction of wind and the spruce forests commonly found in upland Britain, has been the topic of this investigation – and in particular, whether self-perpetuating stands of spruce might result. Unlike many studies, this has been in the context of planted forests of exotic species, rather than natural, unmanaged stands.

8.2 The potential for self-perpetuating stands of Sitka spruce

8.2.1 Will self perpetuating stands develop?

A number of conditions necessary for self perpetuation were identified earlier (1.4.4), and are now reviewed in the light of the findings of this study.

i. Stands live to seed-producing age. Spruce forests generally survive destruction by strong winds beyond the age necessary to produce viable seed.

ii. Windthrown gaps provide appropriate substrates. Windthrow results in the formation of a range of gap sizes, and in some instances, gap size increases through subsequent expansion; a variety of micro-sites are produced by the overturned trees. The range of observed gap size encompasses the minimum required for Sitka spruce to survive, and larger gaps in which the species can grow optimally.

iii. Dispersed seed reaches appropriate substrates, and seedlings establish. Seedling regeneration is present in a substantial proportion of the larger gaps, indicating an adequate seed supply, and suitable micro-sites. Some seedlings are 'established' indicating successful early survival despite competition from ground vegetation and browsing by herbivores.

iv. Growth of saplings is sufficient to compete with other tree species. The rate of incursion by other tree species appears slow.

v. Gaps fill as fast as they are produced. Calculations of turnover rates for the study sites indicate that the forests are not in a steady state, and that this condition cannot be tested at present. However, some gaps are filling by lateral closure from edge tree growth, and others are filling by sprouting from fallen spruce stems. In some gaps the seedling regeneration is approximately one-third of the height of the surrounding trees, almost of cone-bearing size, and therefore close to achieving the status of a viable new generation.

vi. The developing structure is not overwhelmed by catastrophe. The oldest stands indicate that structure is unlikely to be overwhelmed by catastrophic levels of damage, and that the structures are relatively resilient to change.

Therefore, many of the individual components necessary for a self-perpetuating forest have been found to be present where strong winds act to form gaps in otherwise uniform spruce forests. However, whether these conditions are sufficient remains problematic – and the youthfulness of the study forests limits the existence of complete examples (as well as particular features found in natural stands – such as rotten deadwood as seedling microsites). Speculation is still required to consider the future existence of self-perpetuation of Sitka spruce.

8.2.2 Consequences for stand structure

The process of gap formation and filling will result in more diverse structured stands. A range of stand structures will exist, ranging from fine-grain multi-stage stands, to stands with a mosaic of relatively even patches (Table 8.1). Although there are a number of uncertainties over the long-term dynamics, it seems unlikely that catastrophic damage will frequently overwhelm the development of these diverse stand structures. Instead, a mosaic of patch ages will develop within the boundaries of the initial stand. The boundary of individual gaps may migrate downwind, resulting in an evolution of conditions within the gap that may produce a form of partial wave forest.

It is likely that Sitka spruce will remain the predominant species in the next generation of these stands. The conditions are very similar to those to which it is adapted in the Pacific North-west, and there is a scarcity of other trees species providing alternative seed sources in the vicinity of many stands.

In the longer term, and a rate dependent upon gap size and local seed sources, it is likely that other tree species will colonise and become a component of the spruce stands. In particular, more shade tolerant species (Mason et al. 1999) such as western hemlock, Norway spruce, grand fir, western red cedar, field maple and sycamore may become established in the smaller gaps where they will have a competitive advantage. It is also possible that some broadleaves, such as birch, may provide a pioneer/shrub layer, similar to that present in boreal and temperate forests. An increasing broadleaved component is likely, but it seems unlikely that Sitka spruce will fail to maintain a presence in these areas.

Additional dynamics to this pattern could be provided by i. locally extreme herbivory by deer, reducing regeneration and preventing the establishment of palatable but shade tolerant species; ii. climate change such as additional storminess or episodes of wet snow affecting the frequency of gap formation, iii. Further introductions of alien species – for example *Ips typographus* could have an influence on mortality of edge trees and surrounding stands.

Table 8.1 Possible structural variants in future self-perpetuating Sitka spruce forests. Note that in addition, semi-permanent open areas may develop where herbivory or competition from the ground flora prevents tree regeneration.

GAP SIZE AT FORMATION	SUBSEQUENT FILLING PROCESSES	RESULTANT STRUCTURE *Equivalent silvicultural system*
Small gaps (<0.15 Skyview Fraction) Without subsequent expansion	Occlusion through lateral and vertical growth of edge trees. Germinants present but no seedlings	High forest with wider spaced trees. Potential for shade tolerant ground layer, linked with early provision of deadwood (e.g. lower plants). *cf selective thinning*
Small gaps (<0.15 Skyview Fraction) With subsequent expansion	Gap remains small or develops to Medium or Large	
Medium gaps (>0.15 - < 0.5 Skyview fraction). Without subsequent expansion	Lateral growth Germination and establishment of seedlings	High forest with gaps partially filled with seedlings on most favourable micro-sites *cf group selection*
Medium gaps (>0.15 - < 0.5 Skyview fraction). With subsequent expansion	Germination and establishment of seedlings, release of advance regeneration	High forest with gaps, where expansion gives directional trend in age/size of establishing regeneration – partial wave form to gap filling, stature decreasing down-wind *cf group selection (multiple intervention)*
Large gaps (>0.5 Skyview fraction). Without subsequent expansion	Germination and establishment of seedlings	High forest with even-aged/sized patches, rapidly filling *cf group selection – clearfell*
Large gaps (>0.5 Skyview fraction). With subsequent expansion	Germination and establishment of seedlings, release of advance regeneration and formation of new cohort in expanded zone	High forest with patches consisting of even-aged zones reflecting expansion episodes *cf strip felling – clear fell*

8.2.3 Consequences for populations of Sitka spruce within the landscape

At the landscape-scale, the pattern of forest development will depend upon the degree to which management is withdrawn from the upland forests, the range of site conditions encompassed within the area, and the proximity of other tree species. Given the suitability of Sitka spruce to the site conditions found over large parts of upland Britain, and its adaptation to regeneration within gaps and patches, it seems extremely likely that a population of Sitka spruce will persist in upland Britain. If a large area were left to natural processes, it seems likely that a mosaic of stand types would develop. On the most exposed sites, this might be a shifting mosaic with repetitive, but variable, disturbance akin to some Nothofagus forests in South America, and some spruce - hemlock forests in South east Alaska. The proportion of stands in the different stages, and structure types would depend upon the frequency of disturbance – and this is likely to depend upon the topographic and site type variability within the landscape. A study of stand types on Kuiu island, South east Alaska illustrates the assemblies of stand types that can result (Nowacki and Kramer 1998). Approximately 35% of the forested landscape reflected sheltered conditions conducive to old-growth development, 15% was very wind prone and dominated by single cohort stands (with individual patches of 400ha), and 50% was intermediate and susceptible to occasional extreme events. A study of Glen Affric, using ForestGALES to calculate the probability of damage to Scots pine and then inferring resultant stand types, proposed similar assembly of stand types within a landscape. The model interpretations suggested that 25% of the area may be of the single cohort type, 18% may form 'old-growth', 42% be intermediate and the remaining 15% comprise tree-line woodland or open ground (Quine in press). It is likely that landscapes with substantial topographic shelter may contain relatively high proportions of stands with mature trees, and fine-scale disturbance predominant. In contrast, on exposed sites with little shelter, and with uniformly poor soils, may be dominated by young stands resulting from frequent, large-scale disturbance by wind. Self-perpetuating stands of Sitka spruce appear more likely in the latter type of landscape.

To what extent the stands are described as 'Sitka spruce stands' will depend upon local circumstances, and the definition used. However, on many sites it may take several generations for other species to become as numerous as spruce. For example, Wallace (1998) surveyed birch regeneration in upland spruce forests and found that regeneration was particularly dense within 200m of the seed source. However, 20% of her survey sites were located more than 1 km away form seed sources; there were regional differences in proximity of seed source. It is hard to conceive of a situation in which spruce could not find some suitable niche within the landscape – particularly if part of it remains as managed spruce forest, thereby ensuring additional seed sources.

Structural diversity, and a corresponding diversity of non-tree species, is assured – but tree species diversity is not. Although this may be of concern to the purist, there is increasing evidence that native species can utilise/adapt to the conditions provided by the exotic trees (Humphrey et al. 1998, Humphrey et al. 1999, Humphrey et al. 2000). It may well be best to consider Sitka spruce as a naturalised, long-established tree, having an associated food web of native species (Usher 2000), and concentrate on the benefits to be gained from ensuring structural diversity through provision for diverse age structures. The extent of human modification to the British landscape should make this relatively easy to accept, and in time it is even possible that spruce forests become valued cultural landscapes.

8.3 Practical applications

8.3.1 Silviculture beyond clear-felling

The type of forestry being practised in Britain is undergoing a revolution. The pursuit of afforestation, with optimal and uniform establishment of new forests, is being replaced with the need to develop a range of techniques to provide diverse, and sustainable forests. There is a need for new forms of silviculture (Malcolm 1997), but deriving these is difficult with no long-term trials, a lack of natural comparisons, and limits on the transference of knowledge from overseas. There is particular interest in more natural approaches that retain a continuous cover of forest and utilise natural regeneration, but this may prove difficult in the more exposed parts of Britain (Mason et al. 1999, Mason 2001).

The importance of trees in locking up carbon has also been identified as a means of tackling global warming, and forms of 'carbon forestry'proposed. One variant uses short rotations, with felling once maximum growth rate (and therefore rate of carbon-fixing) is achieved, so that carbon can subsequently be locked into wood products. An alternative form uses extended rotations, so that the carbon is locked in the trees rather than within wood products. The latter form suggests a greater opportunity for natural processes to occur and influence stand structure, and a need to understand the implications of stand dynamics on the carbon reservoir (Cannell, 1999).

This study has confirmed some aspects of the behaviour of Sitka spruce that are consistent with its performance in its home range of the Pacific North-west. This supports careful transference of information. A wider range of gap sizes has been studied than have been or can be by formal experimentation, saving substantial cost and development time, and supporting the concept of learning from nature (adaptive management). Some insights have been provided about the implications of gaps smaller than regarded as optimal (Malcolm et al. 2001), and the survival of seedlings in these appears more possible than previously expected (Quine 2001). Further consideration is needed to assess whether this reflects different criteria of success of silviculture and the ecology of self-perpetuation, or is a result of practical significance. For example, it could permit a more gradual process of stand opening that might have a number of benefits, such as reducing the rate of visual change.

Indications of the rate of 'turnover' of the stands in this study (see 5.4.5 and 7.6.4) will also inform decisions as to the benefits of extended rotations for carbon forestry. The rate of windthrow indicated here, and the guidance on stand-replacement disturbance provided by wind risk models such as ForestGALES, should guide both choice of site, and realistic assumptions over achievable lifespan. However, more study may be required of the rate of decay of fallen Sitka spruce in British conditions to understand the consequences of gradual stand disturbance for carbon retention.

8.3.2 The development of natural reserves

There have been a number of calls to diversify the age structure of the upland forests, and in particular to include long-term retentions (Peterken 1987). Recently, the UKWAS standard has specified that 1% of the plantation area should be treated as natural reserves, where there will be minimal intervention. Whilst the benefits are clear in semi-natural woodlands, the relevance for planted forests of exotic species is rather less obvious. Nevertheless, a reserve network will be established and the results of this thesis provide some insights into the likely development of the stands.

The results indicate that there is likely to be a protracted period of stand break-up, and an increasing diversity in structure which should benefit forest biodiversity. Results from Birkley Wood suggest that the turnover rate, required for disturbance to affect each point of a stand, may be of the order of 130-160 years. However, results from the Monitoring areas, indicate a broader range of turnover times, and some substantially shorter periods such as in Glentrool. It is likely that the rate of change will vary by location, and through time depending upon exposure and the particular sequence of extreme winds. Occasional, exceptionally extreme events, such as the storms of 1953 and 1968 can affect up to 25% of the mature forest in a region and create individual patches of windthrow greater than 100 ha. This indicates the importance of choosing a range of locations and aspects for establishment of reserves, and of selecting some of significant size to provide maintenance of some forest conditions after such events. It is highly likely that Sitka spruce will regenerate and persist in these reserves, as discussed above.

8.3.3 The wind climate of upland Britain, and the interaction of trees and wind

The wind climate measurements have provided valuable context for this study, but also have use at the landscape-scale. They illustrate the difference in wind climate between other forest areas that are often considered as parallels. In particular, the wind climate is far more severe than most of the European boreal forest, central Europe and most of North America. The comparison with other wind climates provided a major part of a review of the relevance of mimicking disturbance in upland Britain (Quine et al 1999) and context for a review of the potential impact of climate change (Quine and Gardiner, submitted). In addition, the derivation of the frequency of extreme winds through use of the Weibull distribution has been embedded within the ForestGALES wind risk program (Quine 2000). Finally, the threshold wind speeds identified in the initiation and expansion of gaps, provide validation for wind risk models and suggest ways of developing them to incorporate the variability of tree vulnerability within stands and gap expansion.

8.4 Lessons learnt and further opportunities

There was an almost constant tension between the need to service the generality of the thesis, with the need to address the lack of existing knowledge on significant components of the subject. There was also a tension in bounding the scale of the problem – and some of the concepts require new studies at a landscape scale. A more rapid selection of study gaps, and a greater concentration on this subset could have been beneficial – ageing of the gaps would have allowed any delays in establishment of regeneration, or turnover of seedlings where lighting was sub-optimal, to be better assessed. This would have been particularly useful in applying the results to new forms of silviculture. There was less change (e.g. gap formation and expansion) than anticipated at the start of the monitoring – it would have been better to have had a longer time-series, and a stronger link between the ground studies, and the aerial photographs would have helped. More could have been learned from a wider search of the oldest stands.

There are a number of opportunities for further research.

There is a need for further basic physiological studies of Sitka spruce – for example what controls the initiation, growth and persistence of epicormic shoots? How are sprouting shoots and new roots on fallen stems organised, and can individual shoots become independent from others produced from the same fallen stem?

There is scope for further study of the ecology of regeneration within the gaps. For example, which of the diverse range of micro-sites present within windthrown gaps is the most favourable in the long-term? Is the raised position of the rootplate unstable, and how long does it take for soil mounds to develop? How rapidly do deadwood microsites, as opposed to the unstable sites of the bark surface, become available for colonisation? How do seeds of other tree species arrive in windthrown gaps, and what are the implications of this for structural and compositional diversity?

Further study of gap formation and expansion may be worthwhile for development of risk models. Can the observations of vulnerable and stable trees provide material for the development of a wind risk model that incorporates stand variability?

Further monitoring of the oldest stands, and particularly those designated as natural reserves is likely to be rewarding, and provide some reference values for other planning and silvicultural systems.

Scaling up of the results to predict landscape development under various future scenarios of management would be interesting, albeit speculative. This could involve more detailed comparisons with other maritime areas such as Norway, South-east Alaska, and Chile, as well as combination of the stand dynamics findings (from this study) with that of wind risk modelling (ForestGALES).

8.5 Final remarks

It is hard to foresee upland Britain without a component of Sitka spruce, but equally hard to predict the degree to which this forest will be managed. Less than 25 years ago, there were enthusiastic calls for intensification of management and an emphasis on timber production (Davies 1978) and a scepticism that there was any nature conservation benefit from spruce forests (Usher and Thompson 1988). Currently, the trend is for a proportion of the forest to be developed for biodiversity benefits, even though the tree species themselves are non-native. This has led to the designation of areas for long-term retentions and 'natural reserves' and there is no doubt that this does provide opportunities for native (non-tree) species. However, so do the early seral stages created by felling.

The value, in an international context, of the recent trends to conserve and enhance biodiversity in British forests is almost impossible to judge. However, having seen recent felling of virgin boreal forest in Russia, one has to question the scale at which the biodiversity benefits are being gained. Does the modification of management and preservation as natural reserve of Sitka spruce stands in Britain, with an implicit loss of production, lead to greater felling of virgin forest? If so, the benefits of Sitka spruce retentions and reserves are less persuasive. Whether this study has any long-term relevance will depend upon the developments in international forest policy and practice.

Assuming that a proportion of the forest will be subject to less intensive or no intervention management, this study suggests that self-perpetuating stands of Sitka spruce will develop and persist in upland Britain. What will these stands look like? It is likely that over a period of 50-100 years a variable mosaic of a range of stand structures will form, many still dominated by Sitka spruce. In addition, some semi-permanent open spaces may develop where herbivory or competition from the ground flora prevents tree regeneration. In some cases, the development of moss layers and waterlogging of the site due to disrupted natural drainage may lead to paludification and bog development.

The location of these variants will depend upon differences in location, chance occurrence of extreme storms, and local variation in site type. In sheltered areas, and where no major storms have (by chance) hit, the stands will have small gaps, with advance regeneration, and some deadwood. In more exposed areas, and where major storms have occurred, larger gaps will have filled with relatively even-aged, uniform regeneration. In some intermediate sites (both within stands, and at variable locations), expanding gaps will provide an evolution of the gap structure – and a form of partial wave forest. Locally, and dependent upon the seed source, other species including native broadleaves will become established. In places where the small gap regime predominates, there will be greater potential for shade tolerant species to form communities. The structural and species diversification will result in an expansion of habitat types, to the benefit of a wide range of native woodland species.

Such developments will lend support to the following statement from a conference on the ecology of even-aged plantations held in Britain at a time when tree-farming was prevalent –

'The great accomplishments of foresters in deforested Great Britain are admirable... The first step was to establish the material base of the forest, ie to create biomass. It is possible to progress only after such a base has been created..'

Prof. D. Mlinšek, 1979

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10 Appendix

Why did the monkey fall out of the tree?....It was dead!

Why did the parrot fall out of the tree?......It was tied to the monkey!!

Why did the tree fall over?........It thought it was a game!!!

Unattributed, Alistair Quine (pers comm).

10.1 Additional data

Table 10.1 Storm Catalogue - known damaging to forests/trees only

Key - DATE - Year, month, day, new style, and first day if multiple day storms. L = 2 if Lamb remarks on forest damage, A = 2 if listed in Andersen 1954, A = 2 if listed in Anderson 1967, O = 2 if other source. Notes - Gradient wind of the 34 greatest windspeeds ex Lamb. Comments Lamb; Andersen; Anderson where appropriate. (wind speeds added from Dukes and Eden 1997 – in Hulme and Barrow 1997 Ch 13)

DATE	L	A	A	O	Area	Notes
1236				2	Wales	Linnard 1982 – Wales - p142 Probably the earliest documented instance of storm damage to trees and woods in Wales was in 1236, when many woods were 'rent' by a storm on the night before Christmas eve.
1688				2	Glen Tanar	source Irvine Ross, Pinewood symposium proceedings 1994 conference
1703 12 07	2	2	2		Mid/south Wales, S England;	150kts. Kent 17000 trees; Arniston;
1733				2	Glen Tanar	Source Irvine Ross, Pinewood symposium proceedings 1994 conference
1735 01 19	1	0	2			Hurricane;110kts
1737 01 05	1	0	2			Hurricane
1737 08 14	2				S E England, E Anglia	
1739 01 25	2	0	2		W/E Scotland, Central Belt	110. 60 yr Ash SW
1756 10 07	2	0	0		Cumbria - Penrith	150
1757 03 15					Wales	Linnard 1982 15 Mostyn - hundred oaks and also fir trees
1763 12 29			2			OSAS hurricane
1764 02 10			2			OSAS severe storm
1772 99 99			2			Violent wind
1773 01 99			2		Peterhead	Great many trees
1773 04 20	2				E Scotland, Aberdeenshire	(400 trees Kemnay)
1781 01 17			2		Foulis estate Ross-shire	6000 trees
1786 09 14	2	0	2		New Forest, Midlands; Drumlanrig	
1790 07 30			2		Aberdeenshire	Hail/ice
1791 06 10			2			Violent storm
1795 05 06	2				Sweden	
1796 01 24			2			severe storm
1799 12 25			2		Aberdeenshire	Belhelvie ,tempest
1806 12 25			2		Sutherland	Rosehall 1500, Balblair 250, Cyderhall
1810 11 10					Wales	Linnard 1982 Margam - 81 large oaks
1826 11 99		2	2		Atholl Est several thous;	hurricane
1827 03 99			2			snowstorm damage to Scotch, spruce and silver fir
1830					Hill of Cromarty, 4000 trees	Source – Hugh Miller 'My schools and schoolmasters' p381, Collins ex DBP
1835 11 18	1	0	2		Douglasdale	many trees
1838 02 24	1	0	2		Tullynessle	dreadful hurricane
1838 10 11	0	2	2		general to forests in England, local in S. Scot;	Careston and Dunnottar
1839 01 06	2	0	2		Ireland (.25-.5 mill trees), W Britain;;	100kts. S.W. Scotl silver firs at Balmaclellan Kirkbean, plantations at Inch; extensive damage to Lowther Castle, Penrith woodlands (Wheeler and Mayes 1997 p196); 'the night of the big wind' in Ireland – see p273 in W and M by Sweeney (Dublin Evening Post, 12 January 1839 "The damage which it has done is almost beyond calculation. Several hundreds of thousands of trees must have been levelled to the ground. More than half a century must elapse before Ireland, in this regard, presents the appearance she did last summer."Also Norway – D B Paterson pers comm 'a note from Helge Frivold that old spruce are exceptional in Trondelag region because they all blew down in 1839 storm'
1860 10 03	0	2	2		N Scotl	many trees glutted market, larch at Keppoch, Lochaber

1865 99 99	0	0	2		N Scot	4000 trees Craigleaa, Glengarry
1868 01 24	1	2	2		S Scotl; the North;	140.
1879 12 28	1	2	2		Argyll to Aberdeen, Braemar, Glen Lyon, Tay;	glut of market; (Tay bridge collapses);83000 trees on Atholl estates – Hunter 1883
1881 10 14	1	2	2		S Scotland enormous devastation esp SE; S and W ; Wales	(Fishing fleet disaster – 129 dead in Eyemouth);Atholl 13000 trees. Linnard 1982 14 Oct 1881 - Carmarthenshire to Denbighshire and Caernarvonshire
1882 01 06	0	2	2			Atholl est 20000 trees
1883 10 03				2		Atholl – 75000 trees – Hunter 1883
1883 12 11	0	2	0		Dumfries, Roxburgh and Argyll	
1884 01 26	2	2	2		Britain (1.2mill Drumlanrig, Cargen, Galloway); SW Scot same est; reduced acreage wdld Galloway by third, 50000 Sorn Ayrshire, Atholl 200000 1879-84;	140kts. Maxwell 1884 - Reproduced in Scottish Forestry 1974, vol 28(3) p242-243; excellent description of damage in SW Scotland. 1.2mill trees Drumlanrig, 1000 acres Forest Muir Wigtownshire; fir clad hills above Newton Stewart; Castle Kennedy and Monreith. Salt damage. Linnard 1982 - 26 Jan 1884 - 2nd generation larch plantation near Castle Madoc, Breconshire - some on site previously damaged in summer storm in July 1853.
1886 10 14	2	0	0		Ireland, Midlands, S coast England	
1886 12 08	2	0	0		Haverfordwest S Wales	
1892 99 99	0	0	2			terrific gale in Galloway
1893 11 16	2	2	2		N Ireland, SW Wales, E Scotland (Jedburgh, Aberdeen);	Sutherland 50000,perthshire/Forfar 1.85mill;72000 Banff est Alyth, Blair Atholl, 150000 Dunrobin, also Seafield; see also Dingwall 1991
1894 02 10	2	0	0		Denmark, also NE Germany	
1894 12 99	0	2	2		Argyll, Arran	40000 trees, Kirkcudbright, Perth; gale
1895 03 24	2	0	0		Midlands, Gloucester, Norfolk	(damage to Weasenham woods recorded in McIver survey of Irregular forests)
1902 12 25	2	0	0		Denmark	
1903 02 26	2	0	2		Ireland (4000 trees in Dublin park), Britain;;100000 Strathmore, million in Angus;	train blown over at Ulverston
1907 03 24				2		extensive damage to Morecambe (Tufnell in Wheeler and Mayes)
1911 11 99	0	2	2		local Central Scot;W N CL Scotl	Perthshire 100000 trees
1912 12 99	0	2	2		As 1911	
1915 99 99	0	0	2			severe gale
1922 07 99	0	0	2			DF plantations at Ring wood, Murthly whirling wind
1927 01 28	1	2	2		mid and w Scot Tay and Dee valleys; (Sea surge, flooding – W Ireland, W Wales, NW England);	87knots in Paisley – damage to Glasgow – Harrison in Wheeler and Mayes 1997 p219; ref to damage in Scottish Forestry, and note on sample plots lost – MacDonald, J 1928 – J For Comm (7)75-77.
1932 12 17	0	0	2		S Scot	
1935 10 18				2		A H Gosling – damage to plantations in Argyll (esp Larch – still in leaf) FC Journal 1936, 69-70.
1937 02 28	0	2	2		NW Britain - Kielder	severe gale; G L Batters FC Journal 1938, p144 – 35 yr old plantations and policy woods (??Kielder Castle); Brechfa – L Edwards p 146, trees on farmhouse
1940 01 27	0	0	2			glazed frost Welsh Border

1949 12 18	0	0	2			J Maxwell MacDonald Scott Forestry Vol 6(3)p82-83 Argyll. Also Dec '51 storm.
1951 12 30	1	2	2		N/NW Scotl	150. N/NW Scotl - 0.7mill cbf FCJL; = 4900cu m???; FC Ann Rep 1952, p 21-22; Borgie, Culloden, Alltcailleach – also private estates esp Alvie, Fyvie, Kiethhall, Dunkeld and Doune; 300000cu ft FC, 4mill Private
1953 01 31	2	2	2		Scotland	130. 45millcuft NE scotl;=1270000cu m;1.8mill cu m – Quine 1991 (9.7-25.3% of growing stock); Glen Tanar – windthrow source Irvine Ross, Pinewood symposium proceedings 1994 conference
1956 03 01				2	NE England	1 mill cu ft Pennine foothills Barnsley/Barnard Castle ref Dent 1960 Forestry p80 = 28000 cu m
1957 02 04				2		Scott Forestry editorial p59 - 7.6mill cu ft = 215000cu m;Quine 1989.
1961 09 16				2	N Ireland	Hurricane Debbie – windthrow in N.Ireland (see Bill Wright ICF News 3/96 p13)
1962 02 16	1			2	N E England	95. (Sheffield storm; also 103kt at Lowther Hill)(Aanensen, 1965;Quine 1989)
1965 07 21				2		tornado RHS garden at Wisley – 179 trees uprooted (Mayes 1997)
1968 01 14	2				Central Scotland	140. 1 – 1.64mill cu m (Quine 1991 – 15-30% of growing stock,Quine et al 1995);116 knots at GDF – p173 in Wheeler and Mayes 1997
1972 11 12	2					
1973 04 02	2					
1974 01 12	2				South Scotland	Quine 1989 South Scotland
1976 01 02	2				Midlands etc;	100. 0.96mill cu m Quine 1991 <5% growing stock
1982 03 02				2	Central Belt of Scotland	Internal FC note – some damage
1984 01 13	2				South-west Scotland	Quine 1989 South-west Scotland
1986 08 25				2	Ireland	Hurricane Charley, Flooding and tree damage – especially old deciduous – see Sweeney p266 in Wheeler and Mayes
1987 10 16				2	SE England	120. Grayson 1989;3.91mill cu m – 13-24% of growing stock
1988 02 09	1				SW England, Wales and SW Scotland	(6 dead in severe westerly gale).
1988 03 03	1					
1988 12 21	1					
1989 01 14	1					
1989 02 13	1				NE Scotland; to woodlands in Faroes – A L Sharpe diary August 1996)	damage to woods in Black Isle (Quine 1989)- also damage 123 knots at Fraserburgh – see Roy in Wheeler and Mayes 1997 p248
1989 12 16	1					Perry – 1997 notes severe in SW England
1990 01 16						(109knots at Fair Isle)
1990 01 25	1				Southern and Western Britain	(Burn's Day storm; Quine 1991 – 1.26mill cu m, 1-3% growing stock)
1990 02 03	1					
1990 02 26	1					
1993 01 17				2	Kelso damage	5th=Braer
1993 12 08					S W England, Midlands	Newspaper
1996 11 06					central Belt, W Argyll and Ayrshire	
1997 12 24				2	Ireland, Wales, NW England	Damage to squirrel reserve in Clocaenog; Eire – 360K cu m – TTJ vol 383, 6276, p3.
1998 12 26					Boxing Day Storm	Damage to many old trees; forests in Kintyre. Approx 850,000 cu m – GLEAN newsletter

Table 10.2 Between site correlations for maximum gust. Full table of between site correlations for maximum daily gust. See Table 4.1 for site details.

Correlations, Pairwise MD deletion (masthrdy.sta)

Smallest N=0, Largest N=2893

	KS	TI	MA	WF	ES	AB	MB	ST	DN	GT	DJ	BE	SK	LN	RO	RR	BA	SG	SR	KD	BL	BI	BR	KC	PL	CW	NM	OF	TW	DA	CB	GA	RS	GS	AO
KINLOSS	xxx	.59	.52	.53	.50	.33	.51	.53	.49	.48	.41	.51	.62	.60	.69	.82	.65	.68	.52	.59	.56	.48	.53	.65	.35	.37	.35	.42	.25	.19	.55	.50	.57	.57	.70
TIREE	.59	xxx	.77	.54	.54	.51	.75	.68	.81	.67	.64	.67	.80	.67	.68	.59	.64	.64	.75	.56	.46	.46	.49	.55	.60	.53	.43	.61	.42	.49	.55	.68	.68	.68	.60
MACHRI	.52	.77	xxx	.79	.55	.63	.83	.69	.80	.78	.77	.71	.62	.55	.53	.52	.51	.51	.60	.55	.55	.47	.53	.61	.59	.63	.49	.65	.54	.49	.46	.50	.65	.67	.36
W_FREUG	.53	.54	.79	xxx	.56	.69	.73	.53	.52	.80	.67	.51	.60	.44	.44	.54	.37	.27	.34	.60	.62	.34	.60	.69	.61	.57	.48	.72	.52	.50	.41	.22	.49	.45	.09
ESKDALE	.50	.54	.55	.56	xxx	.43	.59	.46	.57	.57	.57	.48	.45	.52	.50	.53	.53	.41	.48	.68	.69	.61	.67	.72	.67	.55	.32	.53	.34	.48	.44	.41	.52	.47	.38
ABERPO	.33	.51	.63	.69	.43	xxx	.60	.45	.56	.62	.63	.48	.46	.37	.36	.38	.43	.32	.51	.52	.51	.40	.48	.55	.65	.79	.66	.78	.64	.78	.21	.40	.39	.40	.17
MB	.51	.75	.83	.73	.59	.60	xxx	.84	.89	.86	.80	.83	.72	.67	.71	.64	.68	.67	.48	.69	.66	.60	.65	.67	.62	.65	.58	.68	.59	.63	.63	.80	.78	.82	.62
ST	.53	.68	.69	.53	.46	.45	.84	xxx	.88	.80	.77	.83	.73	.76	.75	.65	.74	.74	.75	.70	.65	.63	.65	.69	.71	.59	.47	.60	.58	.62	.72	.86	.87	.87	.71
DN	.49	.81	.80	.52	.57	.56	.89	.88	xxx	.84		.81	.78	.73	.75				.56	.74					.71	.56			.55	.63	.66	.86	.86	.86	.54
GT	.48	.67	.78	.80	.57	.62	.86	.80	.84	xxx	.90	.78	.69	.62	.66	.58	.67	.65	.48	.69	.64	.57	.61	.68	.60	.70	.56	.73	.66	.64	.63	.69	.72	.78	.52
DJ	.41	.64	.77	.67	.57	.63	.80	.77		.90	xxx	.80	.61	.60	.63	.78	.63	.54		.65	.62	.58	.61			.70	.68		.60						
BE	.51	.67	.71	.51	.48	.48	.83	.83	.81	.78	.80	xxx	.68	.71	.73	.68	.81	.74	.51	.68	.63	.69	.61	.63	.61	.57	.47	.60	.48	.59	.71	.80	.83	.84	.66
SK	.62	.80	.62	.60	.45	.46	.72	.73	.78	.69	.61	.68	xxx	.74	.78	.62	.72	.84	.65	.63	.55	.48	.51	.57	.60	.48	.33	.42	.47	.60	.62	.80	.74	.74	.74
LN	.60	.67	.55	.44	.52	.37	.67	.76	.73	.62	.60	.71	.74	xxx	.81	.72	.81	.78	.55	.72	.67	.61	.65	.72	.65	.45	.31	.46	.43	.56	.62	.83	.76	.76	.91
RO	.69	.68	.53	.44	.50	.36	.71	.75	.75	.66	.63	.73	.78	.81	xxx	.83	.89	.79	.55	.68	.62	.55	.60	.63	.61	.47	.30	.52	.49	.56	.60	.79	.73	.75	.78
RR	.82	.59	.52	.54	.53	.38	.64	.65		.58	.78	.68	.62	.72	.83	xxx				.66	.68	.79	.64	.63		.26	.22	.43							
BA	.65	.64	.51	.37	.53	.43	.68	.74		.67	.63	.81	.72	.81	.89		xxx	.73		.65		.64				.54			.45						
SG	.68	.64	.51	.27	.41	.32	.67	.74		.65	.54	.74	.84	.78	.79		.73	xxx		.66	.61	.64	.54			.50	.29		.30						
SR	.52	.75	.60	.34	.48	.51	.48	.75	.56	.48		.51	.65	.55	.55				xxx	.42					.36	.26			.23	.36	.44	.51	.48	.75	.48
KD	.59	.56	.55	.60	.68	.52	.69	.70	.74	.69	.65	.68	.63	.72	.68	.66	.65	.66	.42	xxx	.88	.82	.85	.83	.90	.62	.50	.54	.57	.69	.57	.78	.80	.73	.75
BL	.56	.46	.55	.62	.69	.51	.66	.65		.64	.62	.63	.55	.67	.62	.68		.61		.88	xxx	.88	.89	.86		.50	.40	.59							
BI	.48	.46	.47	.34	.61	.40	.60	.63		.57	.58	.69	.48	.61	.55	.79	.64	.64		.82	.88	xxx	.90			.51	.46		.51						

BR	.53 x .49 x .53 x .60 x .67 x .48 x .65 x .65 x x .61 x .61 x .61 x .51 x .65 x .60 x .64 x x .54 x x .85 x .89 x .90 x xxx x .86 x x .54 x .40 x .57 x x x x x x x
KC	.65 x .55 x .61 x .69 x .72 x .55 x .67 x .69 x x .68 x x .63 x .57 x .72 x .63 x .63 x x x x .83 x .86 x x .86 x xxx x x .78 x .46 x .64 x x x x x x x
PL	.35 x .60 x .59 x .61 x .67 x .65 x .62 x .71 x .71 x .60 x x .61 x .60 x .65 x .61 x x x x .36 x .90 x x x x x xxx x .52 x x x .47 x .70 x .54 x .73 x .76 x .65 x .50
CW	.37 x .53 x .63 x .57 x .55 x .79 x .65 x .59 x .56 x .70 x .70 x .57 x .48 x .45 x .47 x .26 x .54 x .50 x .26 x .62 x .50 x .51 x .54 x .78 x .52 x xxx x .94 x x .90 x .75 x .47 x .47 x .55 x .57 x .36
NM	.35 x .43 x .49 x .48 x .32 x .66 x .58 x .47 x x .56 x .68 x .47 x .33 x .31 x .30 x .22 x x .29 x x .50 x .40 x .46 x .40 x .46 x x .94 x xxx x x x x x x x x
OF	.42 x .61 x .65 x .72 x .53 x .78 x .68 x .60 x x .73 x x .60 x .42 x .46 x .52 x .43 x x x x .54 x .59 x x .57 x .64 x x x x xxx x x x x x x x
TW	.25 x .42 x .54 x .52 x .34 x .64 x .59 x .58 x .55 x .66 x .60 x .48 x .47 x .43 x .49 x x .45 x .30 x .23 x .57 x x .51 x x x .47 x .90 x x x xxx x .72 x .52 x .42 x .45 x .50 x .07
DA	.19 x .49 x .49 x .50 x .48 x .78 x .63 x .62 x .63 x .64 x x .59 x .60 x .56 x .56 x x x x .36 x .69 x x x x x .70 x .75 x x x .72 x xxx x .41 x .59 x .61 x .56 x .49
CB	.55 x .55 x .46 x .41 x .44 x .21 x .63 x .72 x .66 x .63 x x .71 x .62 x .62 x .60 x x x x .44 x .57 x x x x x .54 x .47 x x x .52 x .41 x xxx x .67 x .80 x .73 x .64
GA	.50 x .68 x .50 x .22 x .41 x .40 x .80 x .86 x .86 x .69 x x .80 x .80 x .83 x .79 x x x x .51 x .78 x x x x x .73 x .47 x x x .42 x .59 x .67 x xxx x .84 x .82 x .78
RS	.57 x .68 x .65 x .49 x .52 x .39 x .78 x .87 x .86 x .72 x x .83 x .74 x .76 x .73 x x x x .48 x .80 x x x x x .76 x .55 x x x .45 x .61 x .80 x .84 x xxx x .85 x .77
GS	.57 x .68 x .67 x .45 x .47 x .40 x .82 x .87 x .86 x .78 x x .84 x .74 x .76 x .75 x x x x .75 x .73 x x x x x .65 x .57 x x x .50 x .56 x .73 x .82 x .85 x xxx x .67
AO	.70 x .60 x .36 x .09 x .38 x .17 x .62 x .71 x .54 x .52 x x .66 x .74 x .91 x .78 x x x x .48 x .75 x x x x x .50 x .36 x x x .07 x .49 x .64 x .78 x .77 x .67 x xxx

Table 10.3 Between site regressions used to reconstruct daily time series for maximum gust. The key site (y) predicted from named site (x). See Table 4.1 and Table 4.2 for site details.

Kintyre, Meall Buidhe	**Glentrool, Mid Hill**
from Machrihanish y=3.885+0.873*x .	from W Freugh y=1.017+1.2*x .
from Tiree y=3.117+0.82*x .	from Machrihanish y=2.849+0.956*x .
from WFreugh y=2.441+1.077*x .	from Drumjohn y=1.462+1.156*x .
from Deucheran y=3.678+0.755*x .	from Meall buidhe y=1.726+0.927*x .
from Glentrool y=2.863+0.801*x .	from Strathlachlan y=3.642+0.864*x .
from Strathlachlan y=3.677+0.825*x .	from Bernice y=4.243+0.781*x .
from Bernice y=3.855+0.767*x .	
Rosarie	**Cwm Berwyn**
from Kinloss y=2.649+0.789*x .	from Aberporth y=1.211+0.78*x .
from Ben Aigan y=1.39+0.622*x .	from Nant-y-Maen y=1.218+0.839*x .
from Rosarie restock y=1.181+0.875*x .	from Cefn Fannog y=1.321+0.943*x .
from Leanachan y=2.44+0.836*x .	from Dalarwen y=6.373+0.867*x .
from Ben Staic y=2.658+0.455*x .	from Glentrool y=4.64+0.551*x .
	from Crookburn y=5.768+0.916*x . (few points)
Kielder, Caplestone Fell	
from Eskdalemuir y=5.887+0.777*x .	
from Bellingburn y=1.154+1.149*x .	
from Birkley Wood y=3.389+1.186*x .	
from Birkley restock y=2.028+1.244*x .	
from Crookburn y=2.882+1.111*x .	
from Plashetts y=2.445+1.148*x .	
from Leanachan y=4.856+0.825*x .	
from Strathlachlan y=4.561+0.649*x .	
from Deucheran y=3.965+0.617*x .	

10.2 Published papers related to thesis

1. Quine, C. P. 2000. Estimation of mean wind climate and probability of strong winds from assessments of relative windiness. Forestry **73**:247-258.

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Estimation of mean wind climate and probability of strong winds for wind risk assessment

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Summary

Assessment of the relative windiness of afforestation sites has enabled the development of site classification for species selection, growth rate and wind hazard. The current development of a quantitative classification of wind risk requires a method of estimating the probability of strong winds. The relationship between wind strength and probability is commonly derived from several years of measurements at the site of interest. This is not practical when assessing wind risk for a land use rather than a single engineering structure. However, the extreme value distribution that represents the relationship between strength and probability can be derived from the mean wind climate, as represented by parameters of the parent Weibull distribution. The relationship between these parameters and previous estimates of relative windiness developed from tatter flags is explored using wind measurements from reference sites in upland Britain. A strong relationship is established between a modified geographic predictor and the Weibull *c* parameter. Satisfactory predictions of the Weibull *c* parameter are obtained for a number of validation sites using this regression and the parameters are used to derive estimates of the 1:50 year return period wind speed. A relationship between predicted and measured wind speed is also found using a dataset derived from low elevation Meteorological Office sites, but an offset is found. It is unclear whether this reflects a difference between the wind climates sampled, the effects of local surface roughness, or differences in equipment sensitivity. Further work is required to extend the method to low wind speed and high roughness sites.

Introduction

There is a dearth of wind measurements in upland areas, and substantial topographic variation. Only recently, with the development of automated, battery operated wind-logging systems have measurements been taken in remote areas. Estimation of mean wind climate at different locations within a landscape is generally acknowledged to be problematic unless measurements are taken *in situ*. For example, many wind energy developers take on-site measurements and use measure/correlate/predict methods to relate their short-term measurements to longer term records at a low-lying Meteorological Office site (Derrick, 1992). Whilst such an approach may be appropriate in the siting of engineering structures such as wind turbines and communications masts, it is less practical for studies of a land use such as forestry. A number of techniques have been used to represent the wind climate of extensive forest areas including the use of topographic models in wind tunnel, computer-based numerical models, tree deformation indices, and a variety of geographic or topographic predictors such as elevation, aspect and topex (Ruel *et al.*, 1997). There is no agreement on the best practical method (Suárez *et al.*, 1999).

Britain's windy climate has an important influence on the development of planted forests, particularly in upland areas. Growth rate and survival are limited by the physiological and mechanical effect of wind, and strong winds can cause windthrow and wind snap in semi-mature and mature forests. Quantification of the spatial pattern of windiness has been important in determining the suitability of sites and selection of silvicultural techniques for afforestation. Choices have been based on site measurements using the rate of attrition of simple cotton flags ('tatter flags'), or prediction schemes based on the relationship between these measurements and geographic variables (Miller *et al.*, 1987; Quine and White, 1993, 1994). A number of studies have shown that tatter rate is well correlated with wind speed (Rutter, 1968; Jack and Savill, 1973; Quine and Sharpe, 1997) but have not developed an interpretation of tatter as wind speed. Predictions of windiness, expressed in units of tatter or arbitrary windiness scores, have been incorporated into tools to guide the selection of species (Ecological Site Classification; Pyatt and Suárez, 1997), prediction of growth rate (Worrell and Malcolm, 1990a, b; Bateman and Lovett, 1998) and appropriateness of thinning (windthrow hazard classification; Booth, 1977; Miller, 1985). The current scheme (Detailed Aspect Method of Scoring – DAMS) used in Britain is a modification of the regressions identified by Quine and White (1994), adapted for use by foresters to estimate the relative windiness of upland sites (Quine and White, 1993). It is believed to provide adequate representations for most upland areas, but may underestimate the windiness of the most exposed sites. Underestimation could occur because the rate of tatter is limited by the size of the flag, and because the topex system does not distinguish hilltop and plateau sites. A scheme to correct for the latter by using distance-limited and negative topex values has been proposed but has yet to be incorporated into the scoring system used by foresters (Quine and White, 1998).

A quantitative model of wind risk is now being developed, that will calculate the threshold wind speed for overturning and breakage, and then calculate the chance of this wind speed occurring for a particular site (Gardiner and Quine, 2000). This requires estimates of wind and particularly of extreme wind speeds with respect to geographic location and local topography.

Estimation of extreme wind speeds within a landscape is also difficult. Meteorologists and engineers have used a number of methods based on the Fisher-Tippett extreme value distributions to calculate the probability of a particular wind speed, or the speed likely to occur within a given period of time; the use of the Type I (FTI) distribution is now accepted to be more appropriate than Types II and III (Cook, 1985). Most methods provide an answer for a single location and require measurements on-site – even if only to allow formation of ratios with other sites. Three broad approaches have been developed (ETSU, 1997). The most straightforward is by direct measurement and statistical manipulation of the data, but this obviously limits the number of sites for which the calculation can be performed. If annual extremes are used, at least 10 years of data are required, and more than 20 years of data are necessary for reliable results (Cook, 1985); other techniques, such as Peak-Over-Threshold, require at least 5 years data. A number of simulation methods have been derived (e.g. Monte Carlo methods) but these are computer-intensive. Finally, there is the derivation of the extreme value distribution parameters from the parent wind speed distribution. An application of the FTI method using maxima from individual storms (periods of at least 10 consecutive hours with an overall mean wind speed greater than 5 ms^{-1}) has been developed in BS 6399 (British Standards Institute, 1995). This gives a method of calculating extreme wind speeds based on map and topographic factors, but is intended for site-specific calculations (siting of building) and is not easy to generalize or automate.

A promising alternative for our purpose would appear to be the derivation from the parent wind speed distribution – particularly given that the existing site assessment methods appear successfully to represent overall windiness. The wind climate of a site is commonly summarized using the Weibull distribution,

$$P_v = 1-\exp[-(V/c)^k] \quad (1)$$

where P_v is the probability of a value less than V occurring, c is a constant and k an exponent. The parameters c and k can be used to derive extreme value distribution mode and dispersion (see below).

The purpose of this study was therefore to investigate whether there was a relationship between existing methods of wind assessment (DAMS or tatter) and the Weibull parameters of the wind speed frequency distribution which can be used to derive the extreme value distribution. A subsidiary aim was to investigate whether a correction was needed to prevent the current DAMS system from underestimating windiness at exposed sites.

Methods

Study sites

The study formed part of a wider windthrow monitoring of eight forest areas in upland Britain (Quine and Bell, 1998). Sites for wind measurements were established in accordance with general practice – in open areas, with low surface roughness, and at a distance of at least ten times the height of the nearest obstacle. Data were collected at 29 sites ranging in elevation from 90 to 580 m (Table 1). Nine were reference sites at which measurements were carried out for the duration of the monitoring (1988–1997) (Quine and Bell, 1998); the remainder were established for shorter periods to sample a variety of topographic types within the study areas, and are used here as validation sites.

Measurements of wind climate

Tatter flags

Tatter flags were placed at 1.5 m on stakes at the foot of each reference mast, and changed every 2 months according to standard practice (Mackie and Gough, 1994). Initial observations at high elevation sites indicated that tatter rate was limited by the amount of available material. An additional flag was then installed and was changed monthly. Area of flag lost was measured by digitizing the boundary of the remaining flag, and was converted into a mean daily rate for each period (Mackie and Gough, 1994). Conversion of tatter into arbitrary DAMS score (as used by the existing windthrow hazard classification (Quine and White, 1993)) was achieved using the previous scaling relationship:

$$\text{DAMS} = 1.0656 * T + 7.69 \quad (2)$$

where T is tatter rate expressed in units of cm^2 day^{-1}.

Wind speed measurements

At each site, a 10 m mast was equipped with a Vector Instruments A100R anemometer, a Vector Instruments W200R wind vane, and a Holtech HAL 10 data logger. Logging occurred every 8 s, and histograms of the 225 values for each half-hour were stored on a removable memory card. Half-hour values were subsequently combined to give hourly mean wind speed and direction. Data availability varied from periods of 8 years for the reference sites to 1–4 years for the validation sites.

WA^{S}P (Wind Atlas Analysis and Application Program) (Mortensen *et al.*, 1993) was used to calculate overall mean wind speed, and Weibull c and k parameters from hourly mean wind speed and direction data for each site. WA^{S}P produces a table of the Weibull c (termed a by WA^{S}P) and k parameters for each directional sector, and for the overall distribution. The program ignores out-of-range values, and any wind speeds without an associated wind direction. The Holtech logging system does not record wind direction for wind speeds of 2 ms^{-1} or less to avoid spurious direction data when becalmed. For these cases an arbitrary wind direction was entered, thereby allowing the calculation of an overall Weibull c and k.

Measurements from Meteorological Office sites

For further validation of the relationship between DAMS and Weibull parameters, published data on mean wind speed of Meteorological Office sites were obtained from Monthly Weather Reports. Data were extracted for years 1988–90,

Table 1: Site details for reference and validation wind measurement sites

Windthrow monitoring area	Site	Elevation (m)	DAMS score	National Grid Reference
Reference				
SK	Ben Staic	411	26.5	NG299237
RO	Rosarie	330	17.1	NJ335448
LN	Leanachan Moor	140	15.1	NN187786
KN	Meall Buidhe	374	23.0	NR735325
CO	Strathlachlan	317	20.4	NS052962
CO	Bernice	370	19.3	NS116922
GT	Mid Hill	411	22.5	NX288895
KD	Caplestone	479	21.7	NY590875
TY	Cwm Berwyn	448	21.8	SN771595
Mean		364	20.8	
Validation				
SK	GlenMore	340	26.0	NG441418
SK	River Brittle	10	14.4	NG406229
RO	Rosarie RS	235	13.3	NJ340474
RO	Ben Aigan	470	20.6	NJ310481
LN	Aonach Mor	150	12.8	NN171771
KN	Deucheran	329	22.9	NR762442
CO	Glenshellish RS	270	16.4	NS117935
CO	Glenshellish Lower	90	12.4	NS109944
CO	Cruach Buidhe	568	26.6	NS125947
CO	Garrachra	275	16.2	NS100926
GT	Drumjohn	265	19.1	NX329845
KD	Bellingburn	360	17.3	NY676937
KD	Birkley Wood	180	13.5	NY766906
KD	Birkley RS	250	15.8	NY775918
KD	Crookburn	217	15.3	NY493789
KD	Plashetts	260	14.1	NY676909
TY	Dalarwen	250	11.5	SN788494
TY	Cefn Fannog	448	19.4	SN824505
TY	Nant-y-Maen	510	21.1	SN769592
TY	Ochr Fawr	520	19.0	SN733567
Mean		300	17.4	

Monitoring areas: Rosarie (RO), Skye (SK), Leanachan (LN), Cowal (CO), Kintyre (KN), Glentrool (GT), Kielder (KD), Tywi (TY).

summarized as a mean of the 3 years and transformed into an approximate Weibull *c* by multiplying the mean wind speed by 1.12 as recommended by ESDU (1987). Topographic factors necessary to calculate the DAMS scores were obtained from digital terrain models using the method described by Bell *et al.* (1995). Only sites in north and west Britain were considered and coastal sites were excluded.

Derivation of extreme value distribution from Weibull parameters

The method of ETSU (1997), which is itself based on a re-working of ESDU (1988a, b), was followed to derive extreme value mode and dispersion from estimates of Weibull *c* and *k*. ETSU (1997) recommend adjusting short-term (e.g. 2 year) Weibull estimates by reference to long-term *c* and *k* parameters from a nearby Meteorological

Office site. However, as 8 years of data were available for the reference sites, this step was not taken. The extreme value distribution is represented as an FTI distribution of the form:

$$P_x = \exp[-\exp(-y)] \quad (3)$$

where

$$y = a(x - U) \quad (4)$$

and P_x is the probability of an extreme value less than value x in one year; U is the mode (the most likely value of x), and the parameter a is the inverse of the dispersion and represents a measure of the variability of x (Figure 1). It has been found that equating x to the square of the wind speed (V^2) rather than wind speed (V) gives a better fit to wind speed maxima.

The extreme wind speed (V_T) corresponding to a return period, T (in years) is obtained from

$$V_T^2 = U - (1/a)(\ln[-\ln(1 - 1/T)]) \quad (5)$$

where

$$U = [c(U^{0.5}/c)]^2 \quad (6)$$

and

$$V_T = \text{sqrt}\ (V_T^2) \quad (7)$$

The value of $(U^{0.5}/c)$ in equation (6) is derived graphically by ESDU (1988b), but approximated well by a third order polynomial (ETSU, 1997)

$$(U^{0.5}/c) = (-0.5903k^3 + 4.4345k^2 - 11.8633k + 13.569) \quad (8)$$

The parameter $1/a$ in equation (5) can be obtained from

$$1/a = U/Ua \quad (9)$$

where the product Ua is known as the characteristic value and is usually approximately constant for an area which is comparatively small compared with the dominant storm mechanism (ESDU, 1987). ESDU (1988a) suggest a value of 5 for Ua as typical for climates with predominantly extratropical storm systems.

Results

Tatter rates recorded by monthly and bi-monthly flags

Comparison of the attrition rates of bi-monthly flags with those of the two corresponding monthly flags confirmed that lack of material was limiting the tatter rates recorded at exposed sites (Figure 2). Note that the sites at which this limitation was apparent were much more exposed than the majority of the flags used in the earlier development of the DAMS system (mean of 9 $cm^2\ day^{-1}$; Quine and White, 1993). Consideration of dimensions of flags and exposure periods indicated that a limit of 19 $cm^2\ day^{-1}$ was absolute for bimonthly flags. To reflect this limitation of available flag material on exposed sites, a function was proposed of the form:

$$\text{Potential tatter} = 38*\{1 - \text{sqrt}[1 - (\text{bimonthly tatter}/19)]\} \quad (10)$$

This modification was applied to DAMS (equation (2)) to give a revised index (NUDAMS); an approximate conversion is achieved by

$$\text{NUDAMS} = 4.592*\exp(0.08*\text{DAMS}) \quad (11)$$

Wind climate parameters

Table 2 gives Weibull parameters and mean wind speed for all sites. The ratio of the c parameter to the mean wind speed is close to the generally assumed value of 1.12 (in this case Weibull c = 0.179 + 1.144*mean wind speed). Values of the k parameter range from 1.64 to 1.82 between sites with a mean (all sites) of 1.73, lower than the 1.85 generally assumed for maritime climates (ESDU, 1987).

Relationship between Weibull parameters and NUDAMS estimates

A highly significant relationship was found between NUDAMS and Weibull c parameter for the reference sites (Figure 3). The best-fit linear regression (adjusted R^2 of 0.9548, $P = 0.000004$) was

$$\text{Weibull } c = -0.185 + 0.317*\text{NUDAMS} \quad (12)$$

The relationship between Weibull k and NUDAMS was not significant (adjusted R^2 of 0.345, $P = 0.06$) and so is not used further.

Equation (12) was used to predict the Weibull c parameter for the validation sites in the windthrow monitoring areas. The predicted Weibull c and measured Weibull c were highly correlated ($r = 0.907$) (Figure 4). A further test of the relationship was carried out using data from the

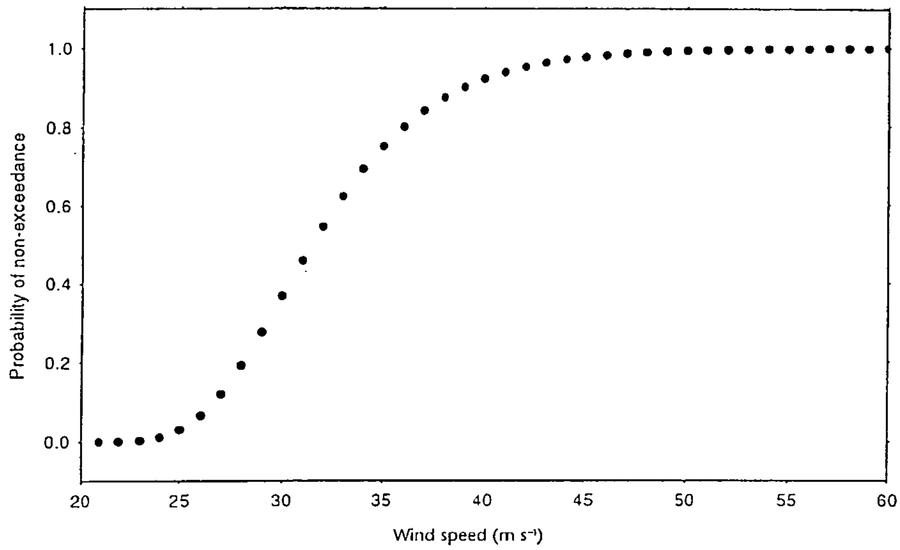

Figure 1. Illustration of the form of the Fisher-Tippett type I extreme value distribution [equation (3)] for a site with mode (U) of 30 m s^{-1} and value of a of 0.25. These figures represent a site such as Glasgow airport on the west coast of Scotland. The probability of non-exceedance is given: i.e. the probability that the maximum wind speed in one year does not exceed the wind speed x.

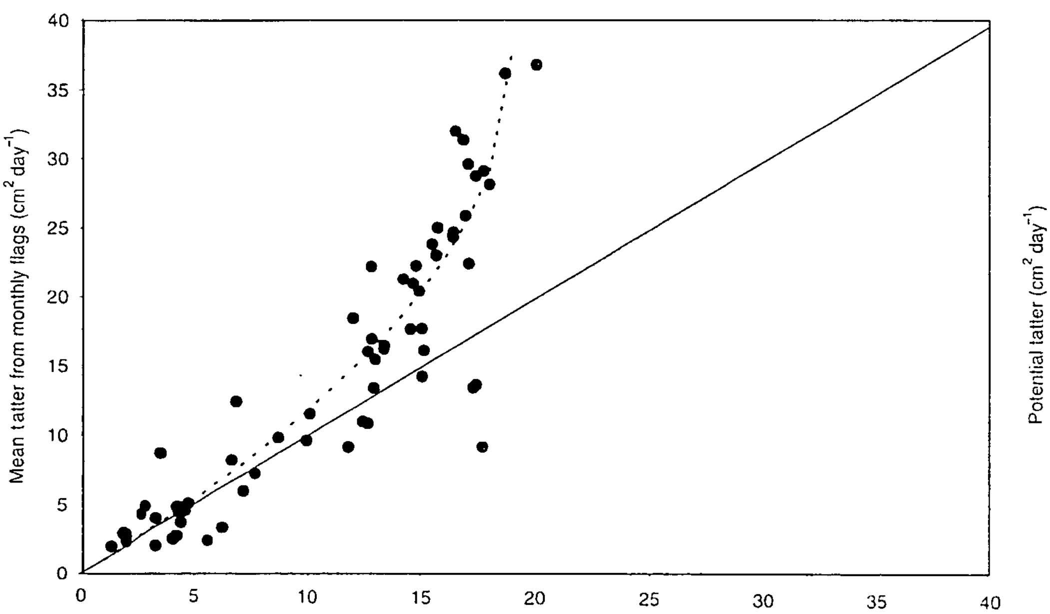

Figure 2. Mean tatter rate recorded using individual monthly flags compared with the tatter rate recorded for the same period using a single bi-monthly flag. Dotted line represents function to derive potential tatter from bi-monthly flags, unbroken line represents 1:1 line.

Table 2: Summary wind climate statistics for wind measurement sites

Windthrow monitoring area	Site	Weibull *c* parameter (m s^{-1})	Weibull *k* parameter (m s^{-1})
Reference			
SK	Ben Staic	11.7	1.86
RO	Rosarie	5.4	1.55
LN	Leanachan Moor	4.7	1.63
KN	Meall Buidhe	9.1	2.08
CO	Strathlachlan	7.4	1.85
CO	Bernice	6.5	1.63
GT	Mid Hill	9.6	1.93
KD	Caplestone	7.8	1.89
TY	Cwm Berwyn	7.6	1.95
Mean		7.75	1.82
Validation			
SK	GlenMore	11.5	1.91
SK	River Brittle	4.4	1.75
RO	Rosarie RS	5.1	1.77
RO	Ben Aigan	10.3	1.79
LN	Aonach Mor	4.1	1.51
KN	Deucheran	9.7	1.97
CO	Glenshellish RS	3.1	1.52
CO	Glenshellish Lower	3.9	1.54
CO	Cruach Buidhe	10.2	1.72
CO	Garrachra	3.9	1.24
GT	Drumjohn	6.1	1.94
KD	Bellingburn	4.6	1.88
KD	Birkley Wood	3.2	1.62
KD	Birkley RS	3.7	1.82
KD	Crookburn	4.1	1.58
KD	Plashetts	3.6	1.42
TY	Dalarwen	2.7	1.08
TY	Cefn Fannog	6.7	1.85
TY	Nant-y-Maen	7.4	1.91
TY	Ochr Fawr	4.7	2.08
Mean		5.65	1.70

Monitoring areas: Rosarie (RO), Skye (SK), Leanachan (LN), Cowal (CO), Kintyre (KN), Glentrool (GT), Kielder (KD), Tywi (TY).

Meteorological Office stations; note that the measured *c* was unavailable so an approximate *c* was obtained through multiplying the mean wind speed by 1.12. There was a high degree of correlation between the predicted *c* and approximate *c* (r = 0.855) but an offset was present (Figure 5).

Derivation of extreme wind speeds

Calculations were performed to obtain the mode and dispersion of the FTI distribution from the Weibull parameters at each site. For comparison, the FTI parameters were calculated directly from annual maxima for five of the reference sites which had an extended time series of 11 years; note, however, that this is still shorter than the recommended 20 or more years. The 1:50 year return period hourly wind speed (V_{50}) was obtained using equation (5) for both sets of values for the mode and dispersion. A good agreement was found between the two estimates (Figure 6; $r = 0.899$, $P = 0.0388$).

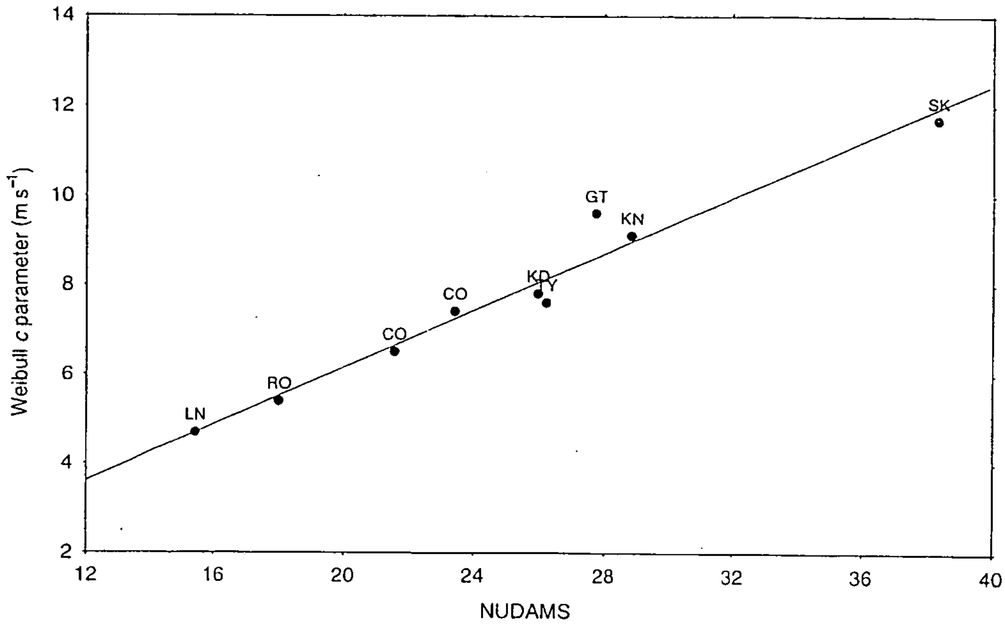

Figure 3. Relationship between Weibull *c* parameter and NUDAMS score for the reference sites; the NUDAMS score represents the DAMS score of the site modified to account for the underestimation of windiness due to lack of bi-monthly tatter material on the most exposed sites.

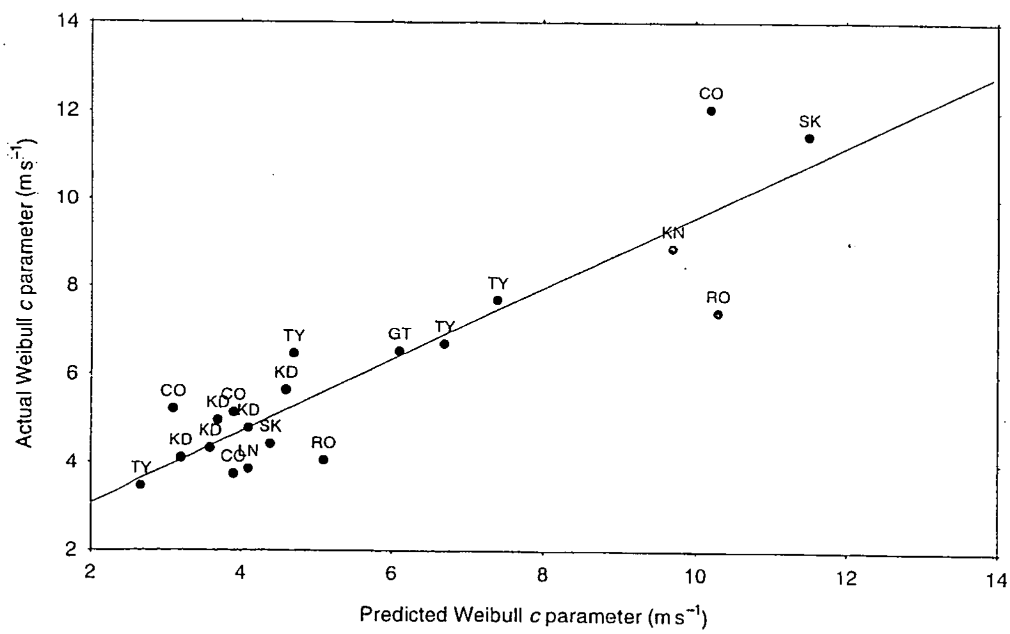

Figure 4. Relationship between Weibull *c* parameter measured at the validation sites and the predicted Weibull *c* parameter; the latter is obtained from the relationship between Weibull *c* parameter and NUDAMS for the reference sites (see Figure 3).

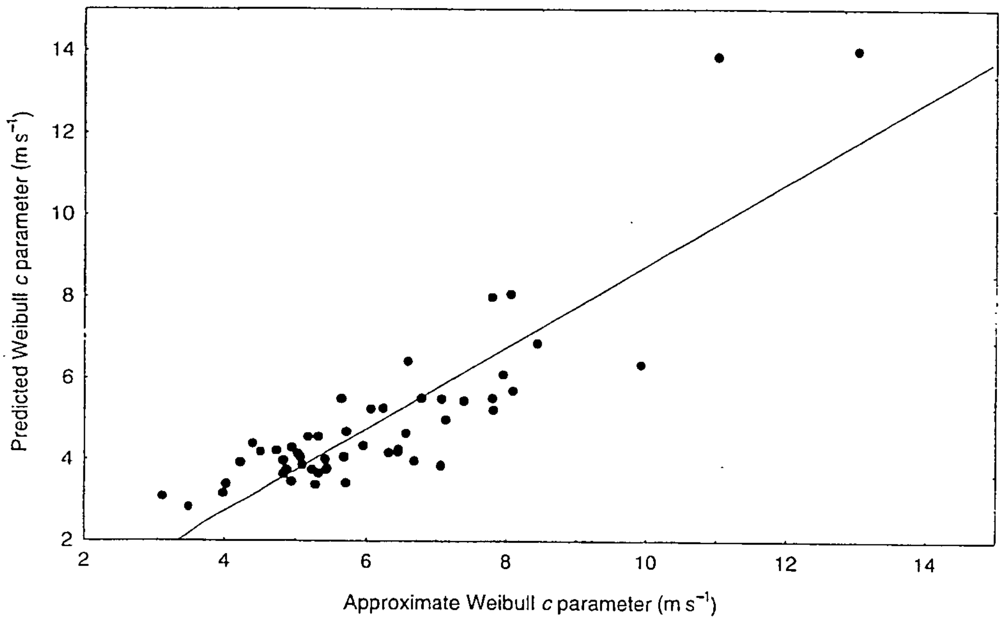

Figure 5. Relationship between the approximate Weibull c parameter obtained for Meteorological Office Sites (obtained by multiplying the mean wind speed by 1.12) and the predicted Weibull c parameter; the latter is obtained from the relationship between Weibull c parameter and NUDAMS for the reference sites (see Figure 3).

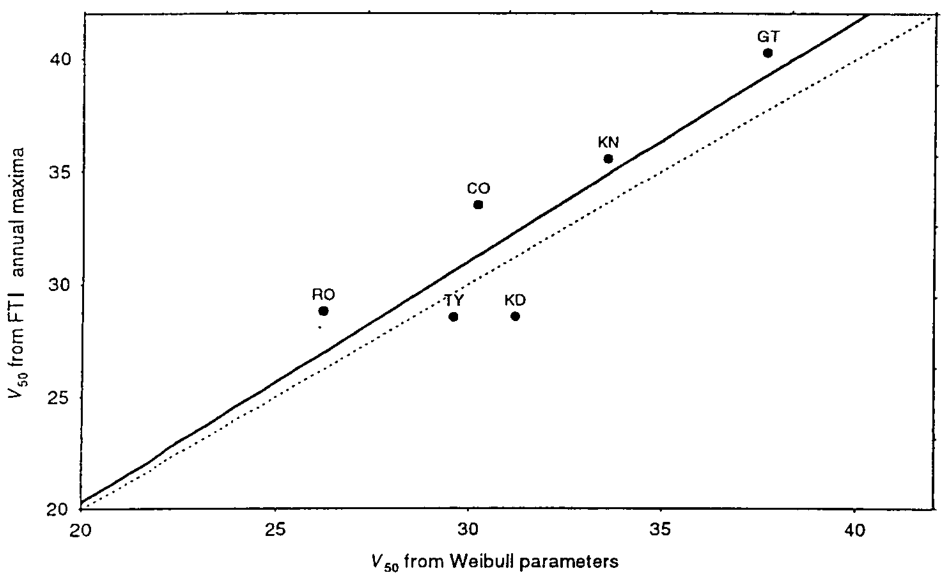

Figure 6. Relationship between the 1:50 year return period hourly maximum wind speed (V_{50}) derived from Weibull c and k parameters, and the V_{50} derived from the FTI mode and dispersion calculated using 11 years of annual maxima for five of the reference sites. (Continuous fitted line $r = 0.899$, $P = 0.0388$, $V_{50FTI} = -1.09 + 1.07 * V_{50W}$; dotted line represents 1:1 line.)

A conversion direct to VT50 from NUDAMS is possible, assuming a value of 1.85 for k, and using the relationship

$$V_{50} = -0.711 + 1.291*\text{NUDAMS} \quad (13)$$

However, this relationship is very sensitive to the c parameter value. For example, the offset indicated in Figure 4 equates to a difference of 5.2 m s^{-1} in V_{50}. A difference of 0.2 in the k parameter equates to a difference of 0.6 m s^{-1} in V_{50}.

Discussion

The study has confirmed that it is possible to relate estimates of relative windiness derived from tatter flags to statistical parameters of the distribution commonly used to summarize the mean wind climate. This confirms the soundness of the past approach. In the zone of main commercial expansion of forests, the relationship between relative windiness and wind speed is approximately linear. A modification was necessary to correct for possible underestimation of windiness at the most exposed sites but this has little effect except above the commercial limit for forestry (DAMS 19–20) (Pyatt and Suárez, 1997). The DAMS system may not discriminate between a range of low wind speed sites because the tatter flags have a start-up speed, and because surface roughness may affect wind speed to a greater degree than on exposed sites. The use of conventional bimonthly tatter flags is unlikely to provide adequate site discrimination where the mean wind speed is less than 4 m s^{-1} and greater than 8 m s^{-1}. The tatter flag technique must therefore be modified if such sites are to be sampled. On the windiest sites this will necessitate changing the flags more frequently. On less windy sites it may be necessary to trim the flags on a weekly basis; Rutter (1968) found that by removing the fringe of protective fray, further threads were shed more readily. Alternatively, a weaker material could be used – for example by soaking the standard material in dilute hydrochloric acid (D. Malcolm, personal communication). However, the increased availability of low-cost logging systems may make such developments unnecessary.

The relationship between NUDAMS and Weibull c parameter extends the usefulness of the windiness index to calculations of risk; through the step of deriving the extreme value distribution from the Weibull parameters it is possible to derive probabilistic estimates of the frequency of strong winds across a landscape. An initial comparison between estimates of the 50-year return period wind speed derived from the annual maxima and the Weibull parameters indicated that the approaches are consistent. However, there is scope for further refinement and testing as the values of the extremes are very sensitive to the parent distribution parameters. For example, a difference of 1 m s^{-1} in the Weibull c parameter translates into 4.1 m s^{-1} in the 50-year return period hourly wind speed: a difference of 0.2 m s^{-1} in the k parameter translates into 0.6 m s^{-1} in the 50-year wind speed. A difference of around 4 m s^{-1} is similar to that found in risk model comparisons of the threshold wind speed (wind speed required to cause windthrow) of Sitka spruce stands on wet gley soils and freely draining soils (Gardiner and Quine, 2000).

There are some weaknesses in the validation data. In particular the validation sites in the monitoring areas had shorter records than the reference sites, and so are more susceptible to annual variations in wind climate. For example, in a year by year analysis of the Rosarie data, there was variation in the Weibull c parameter between 5.1 and 6.7 m s^{-1}; but six of the seven annual values were between 5.1 and 5.6 m s^{-1}. The strength of the relationship between actual and predicted would be affected if the year of measurement at the validation site were atypical. The period of data for the reference sites may be insufficient to accommodate decadal variation in frequency of strong winds (Palutikof *et al.*, 1997). Such variation could affect the accuracy of any predictive system and emphasises the need for further measurement and validation. The validation data from the Meteorological Office sites were not ideal, being dependent upon the veracity of the mean wind speed to Weibull conversion. It is not possible to determine whether the offset in the relationship between actual and predicted Weibull c reflects some difference in wind regime (e.g. lower percentage of calms, effects of local roughness at low elevation sites) or equipment differences (use of a less sensitive anemometer and different logging system). More tests should be carried out in areas of low wind speed and high surface roughness, and with validation data sets of longer duration. A further opportunity might be to compare the results with estimates of BS 6399 (British Standards Institute, 1995).

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Short communication

A preliminary survey of regeneration of Sitka spruce in wind-formed gaps in British planted forests

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Abstract

A transect survey of wind-formed gaps was conducted in planted Sitka spruce stands in the British uplands. Observations were made of gap size (as cover and opening) and presence of regeneration. Gaps ranged in size from 4 to 7900 m^2, but the size distribution was highly skewed with a predominance of small gaps less than 100 m^2. Sitka spruce seedlings were present in 27% of the gaps, while germinants were present in 62% of the gaps. The largest seedlings most often occurred on raised positions provided by the upturned root plates. Mean gap size (cover and opening) was significantly greater for gaps with spruce seedlings than those without. Measures of gap opening provided the best guide to presence of regeneration, and no seedlings were observed in gaps with an aperture (proportion of hemisphere without canopy) of less than 0.15. This threshold is consistent with results from natural forests of Sitka spruce in the Pacific Northwest, whereas comparison of gap areas was less reliable due to the influence of tree height. The results provide guidance on the minimum size of opening required to regenerate Sitka spruce that has application in the development of new silvicultural systems.

Keywords: Adaptive management; Transformation; Windthrow; Canopy gap; *Picea sitchensis*

1. Introduction

Transformation of plantations to more diverse structures is an increasing ambition of forest management but places great demands on the understanding of ecological functioning and stand dynamics. In Britain, this is exacerbated by the brief history of planted coniferous forest (largely of exotic species), and the lack of natural forests that provide a valuable guide to managers in other regions such as Scandinavia and the Pacific Northwest of North America. The existing silviculture has evolved largely through empirical experimentation and extensive trials; as a result it is difficult to extrapolate this knowledge to new silvicultural systems.

The concept of learning from nature through adaptive and ecosystem management has been developed in North America to derive new methods in both forest design and stand management (Oliver and Larson, 1990; Coates and Burton, 1997). The purpose of this paper is to explore whether observations of the effect of windthrown gaps in planted forests can contribute to the development of silvicultural techniques.

The scope of this study is limited to single-species stands of Sitka spruce (*Picea sitchensis* (Bong) Carr.) in the British uplands. These are typically found on wind-exposed sites and moist soils and have been managed to a simple regime with no thinning, and with replanting after clearfelling of coupes of 5–40 ha (Mason and Quine, 1995). Despite the constraints

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imposed by wind (Quine et al., 1995; Gardiner and Quine, 2000), there is public pressure to adopt a finer scale of management, to make increasing use of natural regeneration, and to diversify species. However, it is likely that many of the stands will remain predominantly composed of Sitka spruce for at least the next rotation.

Sitka spruce is a hardy tree species of moderate/intermediate shade tolerance which produces seed regularly in British conditions from age 20–25 years (Malcolm, 1987; Petty et al., 1995). In its native habitat in the coastal forests of the Pacific Northwest (Peterson et al., 1997), and particularly in the north of its range, Sitka depends upon wind disturbance for its continued presence (Deal et al., 1991; Taylor, 1990, Harris, 1989). In Britain, the comparative youth of forests means there is a limit to the stand structure that has developed. However, the earliest plantings on exposed sites are now around 80-years-old (height in excess of 30 m) and display some attributes associated with the understory reinitiation and old growth stages of forest development (Oliver and Larson, 1990), due to the action of wind (J. Humphrey, personal communication).

As a preliminary study of the relevance of the gap-based approach (Coates and Burton, 1997) in these planted forests, I investigated gap occurrence and the evidence for gap filling taking place naturally, and compared these results with those from silvicultural and ecological studies in Britain and natural forests elsewhere.

2. Methods

2.1. Study sites — windthrow monitoring areas

Eight monitoring areas of 400–1200 ha have been located throughout upland Britain (Quine and Bell, 1998), representing varied topography, soils and wind climate. As part of the initial characterisation, transects were installed at 100 m spacing, with start point and bearing dictated by access to the compartment. For this study, a subset of transects in Sitka spruce stands in five areas were revisited and measurements taken of every gap intersected by the transect (defined as a band 1.5 m either side of the centre line). Gap is used here in the sense of a potential opening in the canopy caused by death/destruction of at least half a living tree — but without the upper boundary of 0.1 ha, or 1 tree height in diameter, proposed by Runkle (1992) and others. Measurements were taken of gap dimensions and opening (see below) and observations made in each gap of the presence/absence of Sitka spruce germinants (<1-year-old) and seedlings (>1-year-old); the size class of the largest seedling and the substrate type on which it was located (rootplate pit, rootplate, undisturbed forest floor, stem of fallen trees, other); the condition of the fallen trees (dead, living original canopy branches, original leading shoot upturned, presence of epicormic shoots). Data presented here relate to measurements taken in October 1997, when the stands were 35–50-years-old, and gaps were 1–13-years-old.

2.2. Quantification of gaps

It was necessary to use measures of gap cover and gap opening (Jennings et al., 1999), and for these measures to be applied to a large number of gaps, by a number of different observers. Two methods of measuring the gaps were used:

- A simple estimate of *gap cover* (gap area, m^2) was obtained in the form of the expanded gap (sensu Runkle, 1992). The area measurement of the 'expanded' gap was obtained by taking the distance and bearing between the trunks of the upright edge trees forming the perimeter of the gap. The data were entered as co-ordinates into the IDRISI GIS and the perimeter and area calculated for each gap from a raster coverage with a pixel size of 1 m^2.
- A measure of *gap opening* was developed by taking the angle from the approximate gap centre (intersection of long and short axes) to the gap outline (horizon formed by the top of the crown of the edge trees) using a clinometer at the eight principal points of the compass. *Mean skyview* was calculated as the mean of (90-i) where i is the angle of inclination to the canopy top for a given azimuth; *gap aperture* is given by (2 × mean skyview/180) and represents the proportion of the hemisphere in the gap opening assuming a circular gap. A mean skyview of 0° was obtained where a fallen tree indicated the presence of a gap, but no gap in the canopy was visible. Sophisticated measures (such

as hemispherical photographs) were felt to be inappropriate given the extensive nature of the study, and the lack of sidelight penetrating through unthinned, closely-spaced stands.

2.3. Analysis

Results for the five areas were combined for analysis. Test indicated that data on mean skyview and gap area were not normally distributed and could not be corrected by transformation. The non-parametric Kolmogorov–Smirnoff test was therefore used for comparisons of gap size with and without observed features of gap filling.

3. Results

3.1. Gap size distribution — area and aperture

A total of 109 gaps were intersected by approximately 12000 m of transect. The gap size distribution was highly skewed with a predominance of very small gaps and a small number of very large gaps. The skewed distribution was evident in results for both gap area (minimum gap size: 4 m^2, mean gap size: 408 m^2, maximum gap size: 7878 m^2) (Fig. 1) and gap opening (mean skyview: minimum 0°, mean: 13.4°, maximum: 64.6°).

3.2. Gap filling

Seedlings of Sitka spruce were present in 27% of the gaps, whereas germinants were present in 62% of the gaps. Seedlings were found on a variety of substrates but with a predominance on the upturned rootplate position (45%) compared with undisturbed forest floor (26%) and rootplate pit (11%). In 58% of the gaps, the fallen trees remained alive with survival of the original canopy, upturning of the leading shoot or formation of epicormic shoots.

Gap opening was significantly greater for gaps with seedlings (mean of mean skyview 29.8°) than those without seedlings (mean of mean skyview 7.4°) (Kolmogorov–Smirnov test, $P < 0.001$); seedlings were not found in gaps with mean skyview of less than 14° (Fig. 2). Gap area was significantly greater for gaps with seedlings (mean gap area 1123 m^2) than without (mean gap area 149 m^2) (Kolmogorov–Smirnov test, $P < 0.001$). Although most gaps less than 100 m^2

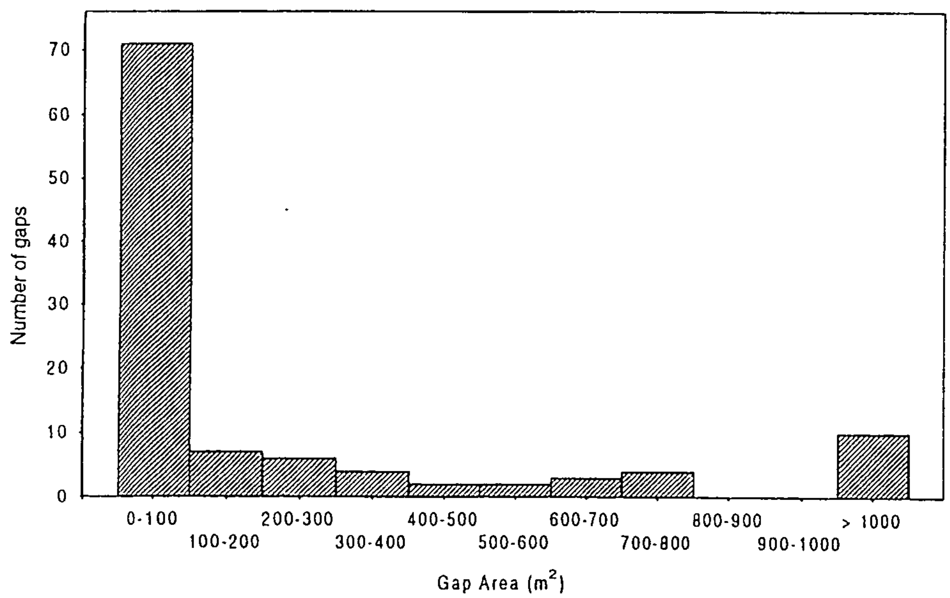

Fig. 1. Size distribution of 109 wind-formed gaps intersected by approximately 12000 m of transect through planted Sitka spruce forest. Gap size expressed as gap cover — area of expanded gap (m^2).

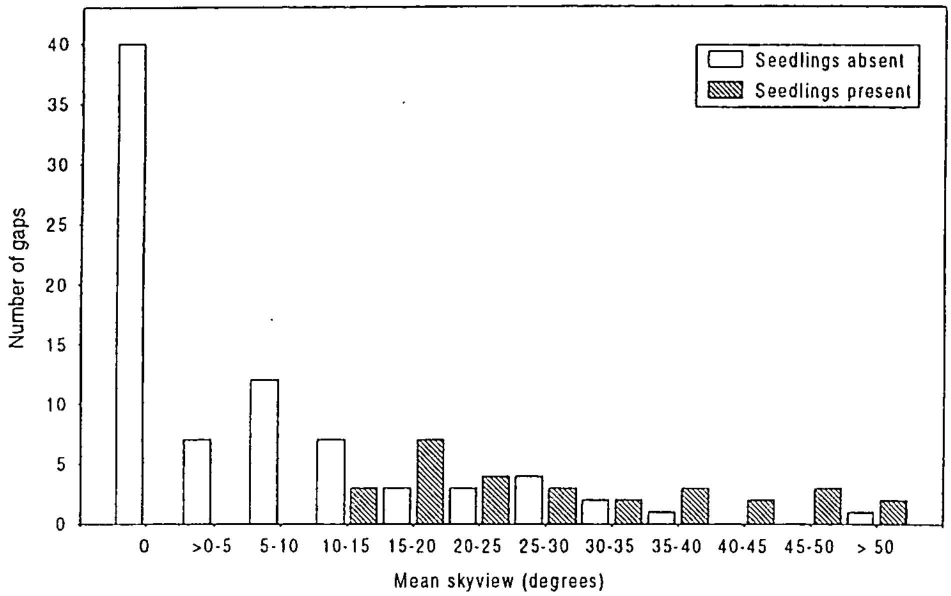

Fig. 2. Distribution of gap sizes with and without Sitka spruce seedlings present in 1997 survey. Gap size expressed as gap opening — mean skyview (degrees).

contained no seedlings, the discrimination was not so complete as with gap opening and the smallest gap with seedlings observed was 12 m^2.

4. Discussion

4.1. Gap size distribution

The range of gap sizes found as a result of strong winds in the planted forest encompassed those identified in the literature as suitable for Sitka spruce regeneration. The distribution, like those in natural forests was highly skewed, with a preponderance of small gaps. However, the size distribution is the result of multiple episodes (Quine and Bell, 1998) and is not in steady state but will change over time (Quine et al., 1999).

4.2. Mode of filling

Regeneration of Sitka spruce was shown to have occurred in wind formed gaps in upland planted forests, indicating a sufficient seed supply and the presence of favourable conditions. The favoured site of the upturned rootplate may reflect a number of factors — including relative safety from browsing, better aerated soil, and a better light environment elevated above the fallen yet living trees. Gaps of a range of sizes had no seedlings, but this may reflect the relative youth of the gaps, particularly unfavourable site conditions, or recent shortage of seed.

Regeneration occurred in gaps substantially smaller in area than identified as necessary in natural stands, but comparisons based on opening indicate closer agreement. Regeneration of Sitka spruce required a gap size greater than 400 m^2 and preferably 800–1000 m^2 in the Pacific Northwest (Taylor, 1990), while hybrid spruce (Engelmann's and Sitka) regeneration was found in gaps of 75–150 m^2 but preferred gaps greater than 1200 m^2 in interior British Columbia (Coates and Burton, 1997). Taylor's gaps were in stands of approximately 45 m height (Harmon, 1989), equating to an aperture of 0.22–0.24 as optimal and 0.16 as minimal (assuming circular gaps). Coates's gaps were in stands of approximately 30 m height (Coates, personal communication) giving an aperture of 0.10–0.14 as minimal and greater than 0.37 as preferred. The minimum mean skyview of 14° from the current study is consistent with these minima

Table 1
Gap diameter (as fraction of tree height) and gap area (m^2) required to achieve a specified gap aperture (proportion of the hemisphere in the gap opening) as influenced by border tree height assuming a circular gap

Gap aperture	Equivalent gap diameter	Equivalent gap area (m^2) for tree height (m) of				
		10	20	30	45	70
0.50	2.00	314	1257	2827	6362	15393
0.33	1.14	103	410	923	2077	5027
0.24	0.80	50	201	452	1018	2463
0.15	0.47	17	70	156	352	852

as it equates to a gap aperture of 0.15 for a circular gap.

4.3. *Preliminary guide for gap filling — practical applications*

The regeneration observed in the gaps provides preliminary evidence applicable to non-clearfell silvicultural systems (Table 1). This study indicates that a minimum gap aperture of around 0.15 is required, which is substantially smaller than the 0.3–0.5 aperture previously recommended for Sitka spruce (Nixon and Worrell, 1999). However, the relative youthfulness of the gaps limits this advice to the initial stages of regeneration, i.e. survival of seedlings, and not to the completion of gap filling.

5. Conclusions

This preliminary study has indicated that useful insights can be obtained by studying natural disturbance processes in planted forests. Much of the debate on the design of silvicultural systems and the acceptability of forest plans, concerns the spatial scale of harvesting operations. The results of this survey confirm that there is no single appropriate scale for the regeneration of Sitka spruce in Britain and that prescription of a single coupe size does not reflect the processes of change in natural or planted forests. This study has suggested a minimum gap size but further work is required to confirm whether this is sufficient for more than just the survival of seedlings. An estimate of gap opening, rather than cover should be more widely used in describing studies — even if foresters subsequently prefer area for planning purposes.

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Should the wind disturbance patterns observed in natural forests be mimicked in planted forests in the British uplands?

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Summary

Recent developments in UK forestry policy require the adoption of management practices that maintain and improve the biodiversity of managed forests. One approach is to use natural disturbance in unmanaged forests as a template for setting the scale, frequency and pattern of forest operations in managed forests. This review considers the relevance of this approach for conifer plantations in upland Britain.

The dynamics of British planted forests are compared with the disturbance dynamics of analogous natural forests with particular reference to disturbance by strong winds. Western hemlock–Sitka spruce (*Tsuga heterophylla–Picea sitchensis*) forests in the Pacific North-west of North America and particularly South-east Alaska provide the most promising comparison. There are few reports on disturbance in these forests, but the regime includes both gap-phase and stand replacement dynamics due to wind. However, the landscape proportion and pattern of resulting structural types are not well defined.

The dynamics of planted forests in Britain are dominated by rotational patch clearfelling which results in regular stand replacement and little possibility of the stands developing beyond the stage of stem exclusion towards old-growth. The pattern and timing of felling is driven by economic and visual amenity considerations rather than by an attempt to mimic natural disturbance patterns. Moreover, the structural complexity and remnant elements (such as deadwood, large trees, vegetation patches) left after large scale disturbance are rarely found after conventional timber harvesting.

The authors conclude that natural wind disturbance regimes have potential as a reference point for management in British upland forests but at present are not relevant as a model to mimic explicitly. This is because the biodiversity benefits of adopting a 'natural' approach in planted forests are unclear compared with management guided by other criteria such as rarity. Furthermore, the spatial and temporal pattern to be mimicked is not sufficiently well understood. Improved knowledge could inform decisions on the scale and distribution of harvesting across a landscape, and modify silvicultural operations to create and maintain the structures and patterns associated with natural disturbance. However, further research is needed to quantify the spatial and temporal characteristics of wind disturbance in upland forests in Britain and in natural forests elsewhere.

Introduction

Recent developments in UK forestry policy have emphasized the need to develop systems of sustainable forest management which maintain and enhance the biodiversity of both planted and semi-natural forests (Ratcliffe, 1993; Anon., 1994; Anon., 1995; Hodge *et al.*, 1997). Approximately 10 per cent of the land area of Great Britain is forested, and 58 per cent of this area (1.5 million ha) is dominated by plantations of introduced conifer species such as Sitka spruce (*Picea sitchensis* (Bong.) Carr.), Douglas fir (*Pseudotsuga menzieseii* (Mirb.) Franco) and Corsican pine (*Pinus nigra* var. *maritima* (Ait.) Melville) (Forestry Commission, 1995). Many of these forests have been established on open habitats with no recent history of woodland cover, and a minimal legacy of forest biodiversity (Hodge *et al.*, 1997). Although there have been studies of the ecology of these new forests (e.g. Ford *et al.*, 1979; Good *et al.*, 1990; Ferris-Kaan *et al.*, 1997), little is known about their long-term ecological potential (Ratcliffe and Peterken, 1995; Peterken, 1996; Newton and Humphrey, 1997). However, if levels of biodiversity are to be increased in managed forests, it is necessary to have some idea of what might be attainable (Ratcliffe, 1993).

Peterken (1996) suggests three strategies for management of native woodland for nature conservation. These are also applicable to conifer plantations (Table 1): management to promote natural woodland; traditional (or precautionary) management to maintain current nature conservation value; and designed management to meet specific objectives such as maximizing diversity or number of rare species. A number of studies have looked at aspects of the precautionary and designed management approaches (e.g. Watt *et al.*, 1997); none have investigated the potential for the 'natural' management of plantations in Britain, where management aims to mimic the structures

Table 1: Criteria for valuing plantation ecosystems for biodiversity and relationship to management aims (adapted from Newton and Humphrey, 1997, based on concepts in Ratcliffe, 1993)

Criteria	Description	Management aims*
Naturalness	Value attached to structures, composition and functions which are considered to be analogues of natural forest	*'Natural' management* – mimicking features of natural forests, creating new habitats
Diversity	Value attached to structures and functions which yield higher species or habitat diversity within site potential	*'Precautionary' management* – maintaining features already known to have high diversity, e.g. rides, riparian zones, remnant semi-natural habitats *'Designed' management* – introducing features for specific purposes, e.g. encouraging spread of *Betula* spp. for lepidoptera
Rarity	Value attached to structures and functions which provide for rare habitats or species	*'Precautionary' management* – retain rare species/habitats, e.g. red squirrel (*Sciurus vulgaris*), raised mires *'Designed' management* – introduce rare species, e.g. *Moneses uniflora* (one-flowered wintergreen) in pine plantations
Keystone species	Value attached to species which have a major role in ecosystem functioning (food webs etc.)	*'Precautionary' management*, e.g. large tree nesting sites for goshawks (*Accipter gentilis*) *'Designed' management* – introduce European beavers (*Castor fiber*), or top predators, e.g. wolf (*Canis lupus*)

* Adapted from Peterken (1996)

and functions of natural forest ecosystems. In North America and Scandinavia the principle of basing sustainable management of commercial forests on the dynamics of natural forest types is well established. Action plans for biodiversity accept this principle implicitly (e.g. National Board of Forestry (Sweden), 1996), as does the 'ecosystem management' approach with underpins forest management policy in the US and Canada (Salwasser, 1994; Kimmins, 1995). However, in these countries forestry has been based upon the 'natural' forest types and some vestiges of natural temperate and boreal forest remain to provide models (Hunter, 1990; Oliver and Larson, 1990; Peterken, 1996). The value of such an approach has been advocated for the management of plantation forests in Great Britain (Peterken *et al.*, 1992; Innes, 1993; Peterken, 1996) and Ratcliffe (1993) states that by mimicking natural ecosystems it is possible to set standards based on natural forests (e.g. Spellerberg and Sawyer, 1996). This would include the mimicking of natural processes as well as creating structural and compositional features (Ratcliffe and Peterken, 1995).

In this paper two questions are addressed:

1 Are there suitable parallels for planted conifer forests of upland Britain in the literature on disturbance in natural forests?
2 Is it possible to specify management practices in planted forests by reference to natural forest dynamics?

The focus for this review is primarily upland British conifer forests dominated by Sitka spruce. These woodlands broadly fall into the biogeographical zones of temperate evergreen rainforest, and boreal or sub-boreal rainforest (Lawford *et al.*, 1996; Worrell, 1996). The paper begins with a brief review of disturbance, its definition and quantification, then considers in more detail the effects of wind disturbance on forest structure and biodiversity.

Disturbance

Definition

Disturbance is a key process in natural forests providing the driving force for forest dynamics and regeneration through structural change, the initiation of secondary succession and creation of habitat diversity (Pickett and White, 1985; Foster, 1988; Runkle, 1990; Attiwill, 1994; Peterken, 1996). Disturbance may bring about change in forest ecosystems by:

- initiating mortality in dominant species or individuals within a patch (Battles and Fahey, 1996);
- bringing about structural change and habitat creation (Jonsson and Esseen, 1990; Oliver and Larson, 1990);
- creating pattern in the landscape (Foster and Boose, 1992; Johnson *et al.*, 1995);
- creating niches for tree regeneration (Takashi, 1994; Gray and Spies, 1996);
- maintaining biogeochemical cycling (Bormann *et al.*, 1995).

Natural disturbances are difficult to characterize but Pickett and White (1985) propose the following definition: 'a disturbance is any relatively discrete event in time that disrupts ecosystem, community or population structure and changes resources, substrate availability, or the physical environment'. Disturbance agents may be *endogenous* and *exogenous*, from biotic or abiotic causes, and encompass a very broad range of temporal and spatial scales, from processes occurring annually to those which may take millenia, from less than one hectare to millions of hectares (Table 2).

Quantification of disturbance regimes

Disturbance regimes are characterized by size of disturbance, frequency, and magnitude (Vitousek and White, 1981; Glenn-Lewin and van der

Table 2: Categories and types of disturbance relevant to forests

Category	Agent
Abiotic	Flood, wind, drought, fire, snow, frost, landslip, vulcanism, glaciation
Biotic	Insects and fungal pathogens, herbivores
Anthropogenic	Fire, harvesting, road-building, planting, site preparation, drainage, fertilization

Maarel, 1992). Size is usually expressed as area affected by a disturbance event. Frequency may be expressed as *recurrence interval* or *return period*, the mean time between disturbance events; *rotation* (or *turnover*) *period* is the mean time interval between successive disturbances of a particular forest stand or patch; *predictability* is a measure of variance in return interval. Magnitude is divided into *intensity* (a physical measure of the force of the event, e.g. wind speed) and *severity* (a measure of the impact on the community, e.g. biomass of trees blown down). Disturbance severity is not always a direct function of disturbance intensity, due to the interaction between disturbance, the successional state of the vegetation, and the physical characteristics of the land. For example, susceptibility to disturbance may increase with successional age (*biotic feedback*, White, 1987), as when fire fuels build up during post-fire succession (Heinselman, 1981).

Relationship between disturbance, forest dynamics and biodiversity

Disturbance rarely influences single species but usually affects species assemblages and successional pathways. Forest dynamics are determined both by the frequency and scale of disturbance and by the rate of subsequent recovery (Pickett and White, 1985). A general model of stand development is observable after disturbance (Oliver, 1981; Oliver and Larson, 1990, 1996):

1 *Stand initiation stage.* After a disturbance new individuals and species continue to appear for several years.
2 *Stem exclusion stage.* After several years new individuals do not appear and some of the existing ones die. The surviving ones grow larger and express differences in height and diameter; first one species and then another may appear to dominate the stand.
3 *Understorey reinitiation stage.* Forest floor herbs and shrubs and advance regeneration appear and survive in the understorey, although they may grow very little.
4 *Old growth stage.* Much later, overstorey trees die in an irregular fashion, and some of the understorey trees begin growing to the overstorey.

The length of time that any stand spends in each stage, and hence the relative proportion of the different stand stages within the forest will depend upon the interaction of forest character (e.g. growth rate and life expectancy of tree species) and the scale and frequency of disturbance. The composition and constancy of a landscape reflect the ratio of disturbance scale to landscape scale, and disturbance interval to recovery interval (Turner *et al.*, 1993).

A distinction is frequently made between fine-grained 'gap-phase' dynamics and coarser scale stand replacement dynamics although in practice these represent two points on a continuum of spatial and temporal scales. In gap dynamics, the structure of the forest is dominated by small gaps caused by the death of one or several trees and an all-aged mixed forest structure can develop (Rohrig, 1991); gap sizes range from < 25 m^2 to approximately 0.1 ha (Runkle, 1982). All-aged stands probably only develop when the interval between the occurrence of stand-level disturbances is substantially longer than the life span of the dominant tree species so that the prevalent changes are small in scale. In many temperate, broadleaved forests, gaps created by the death of dominant trees and the action of wind form at a rate of 0.5–2 per cent of the forest area per year (Abrell and Jackson, 1977; Runkle, 1985). The gap creation is central to the community dynamics of these forests (Pickett and White, 1985), by creating soil disturbance and niches for establishment of plants (Peterson *et al.*, 1990).

Stand replacement dynamics refers to the formation of larger patches, but these can range in scale from features that might be thought of as large gaps (around 1 ha) to patches of hundreds or thousands of hectares (Canham and Loucks, 1984; Foster, 1988). Stand replacement events such as extensive fires, storms and insect pests can foster the development of even-aged stands (Jones, 1945). In boreal forests, large-scale disturbance by fire can produce a landscape composed of a mosaic of even-aged patches which reflect the different lengths of time since each patch was last disturbed. The frequency of fire disturbance can be such that very few stands survive into the 'old-growth' stage (Johnson *et al.*, 1995) and in the northern boreal forests may be so frequent as to prevent any succession beyond initial pioneer communities.

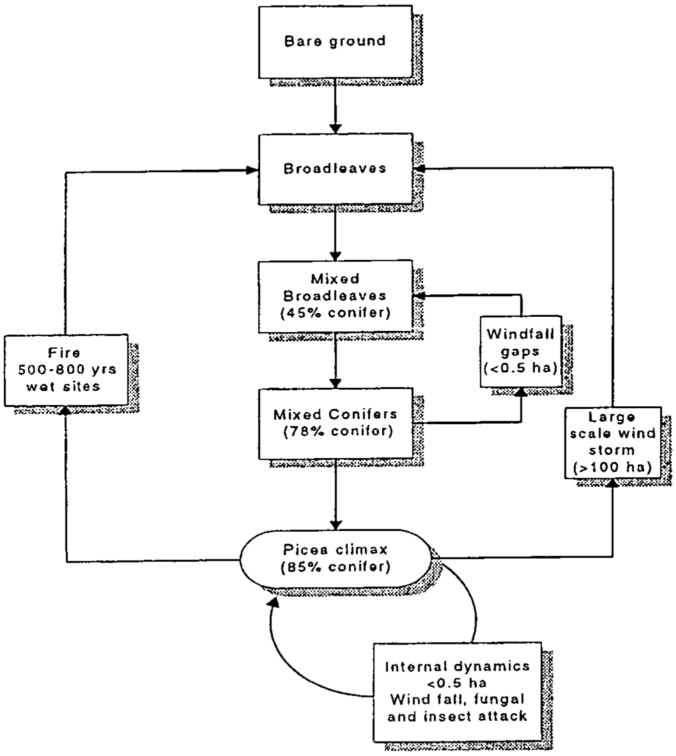

Figure 1. Model illustrating relationship between disturbance regime and dynamics of boreal *Picea abies* forests on mesic sites in sub-continental Russia (source: Syrjanen *et al.*, 1994).

In many forests, both gap-phase and stand replacement dynamics can occur. This is illustrated in Figure 1 which shows typical cycles of disturbance in mesic Russian boreal forests. This general model of forest dynamics applies in other forest types, although the species mix will differ, and the relative influence of gap-phase and stand replacement disturbance will vary greatly from region to region (Shuck *et al.*, 1994) depending upon climatology and biotic agents present. There is no clear process distinction between the two dynamics as evidenced by the range of gap/patch sizes that can form in a single disturbance event.

Random periodic disturbances can maintain high species richness and productivity and limit competitive exclusion (Loucks, 1970; Connell, 1978; Huston, 1979). The ecosystem response will be broadly influenced by the frequency, scale and type of disturbance. Large-scale disturbance generates pattern at the landscape scale, ensuring a continual turnover of different successional stages, and providing niches for early successional habitat and light-demanding species groups (Kuusela, 1990; Uuttera *et al.*, 1996). Gap phase disturbance promotes continuity of late successional habitat benefiting shade tolerant species, and species dependent on high levels of vertical structure within stands (Uuttera *et al.*, 1996). There is a very extensive literature on responses to disturbance and Table 3 provides examples in relation to wind and fire. There is very little information relating to the effects of disturbance on groups such as invertebrates and fungi.

Examples of forest management systems based on natural disturbance

When considering the implications of natural disturbance dynamics for forest management,

Table 3: Relative effects of fire and wind disturbance on components of biodiversity in temperate and boreal forests

Component of biodiversity	Disturbance agent	
	Fire	Wind
Canopy/understorey trees and shrubs	Benefits establishment of early successional tree species (e.g. broadleaves, like aspen (*Populus tremula*) and birch (*Betula* spp.), (Luken, 1990, Worrell, 1996); maintains tree species richness in coniferous forests in Pacific NW (Spies and Franklin, 1989): Promotes persistence of serotinous and fire resistant species (e.g. *Pinus contorta*)	Promotes increase in broadleaved tree component (especially fruit bearing species – Moore, 1987), species composition relates to gap size and relative success of shade tolerant and intolerant species
Deadwood	Burning of watersheds reduces their capacity to retain coarse woody debris, leading to loss of wildlife habitat (Young, 1994). Fire-scarred snags important for scarce invertebrates (see below)	Fallen deadwood provides habitat for regenerating trees, fungi, and insects (Ratcliffe, 1993) and snags provide rich habitat for lichens, bryophytes, insects and hole-nesting birds (Esseen *et al.*, 1997)
Field and ground layer vegetation	Promotes increase in diversity of ruderal herbaceous species, and reduces competitiveness of stress tolerant woodland species (Lewis and Harshbarger, 1976, Moore, 1996). Promotes abundance and diversity of understorey forbs and shrubs in eastern US deciduous forests (McGee *et al.*, 1995). The occurrence of rare herbs (e.g. *Astragalus penduliflorus*) in Swedish boreal forests is dependent on fire (Esseen *et al.*, 1997)	Pit and mound topography generates heterogeneity in vascular plant community composition in old growth forests (Runkle, 1981; Petersen and Campbell, 1993); maintains bryophyte diversity (Jonsson and Esseen,1990) and facilitates bryophyte dominance (Jonsson, 1993). Heterogeneity of light conditions maintains herbaceous understorey diversity in Sitka spruce old growth (Hanley and Bradley, 1997). Herbs preferentially colonize new treefall pits (Falinski, 1978, 1986; Buckley *et al.*, 1994). Creation of small gaps benefits persistence of stress tolerant woodland species, clonal reproduction etc. and reduces competitiveness of ruderals (Hughes and Fahey, 1991; Packham *et al.*, 1992)
Invertebrates	Insect attack regulates supply of dead trees which influences susceptibility of stands to fire (Schowalter *et al.*, 1981) in south eastern US pine forests. Fire destroys insect groups dependent on forest interior conditions in boreal forests (e.g. ants, *Formica* spp. – Punttila and Haila, 1996); and creates conditions which benefit early successional species dependent on open habitat conditions (Punttila and Haila, 1996) and rare saproxylics dependent on dead trees in burnt areas (Wikars, 1992; Kaila *et al.*, 1996)	Small gaps benefit species richness of insect groups such as butterflies (Greatorex-Davies *et al.*, 1994)

Table 3: Continued

Component of biodiversity	Disturbance agent	
	Fire	Wind
Mammals	Moose (*Alces alces*) benefit from creation of early successional habitat after fire (MacCracken and Viereck, 1990)	Western hemlock, Sitka spruce forests Pacific NW, small mammal diversity dependent on fallen deadwood (Carey and Johnson, 1995)
Birds	Early successional deciduous stands initiated by fire are important for maintaining bird diversity (Ericson, 1989), especially woodpeckers (Angelstam and Mikusinski, 1994) and hole-nesting species dependent upon fire-scarred snags (Esseen *et al.*, 1997)	Gap and closed canopy forest bird assemblages can be distinct (Coates and Burton, 1997); bird diversity increases after gap creation (Moore, 1987); upturned root plates and small pockets of windblow in upland forests in GB provide important feeding sites for raptors such as the goshawk (Petty, 1996)
Soil	Fire increases soil microbial activity, and maintains site productivity (Zackrisson *et al.*, 1996)	Soil productivity, and hence tree growth and diversity maintained by gap creation in Sitka spruce forests in Alaska (Bormann *et al.*, 1995)

Attiwill (1994) identified the need to specify the correct spatial and temporal scales. This is necessary since the ubiquity and scale of natural disturbance is such that *all* of man's activities (at least in terms of forest management) lie within the bounds that nature sets. There are a number of examples from boreal forests where regional forest planning and management is explicitly based on the temporal and spatial framework of fire regimes. Stuart-Smith and Herbert (1996) report on a scheme in Alberta, Canada, where felling coupes in boreal mixed forests are designed to encompass the range of disturbance scales caused by fire (< 1 ha to thousands ha); however, an upper bound to block size is imposed by social constraints. Within these stands, some vestiges of the previous stand structure are retained (as would happen with fire) such as large, standing dead trees, patches of vegetation in wetter hollows, small clumps of fire resistant trees etc. Little attention is given to the spatial arrangement of felling coupes across the landscape or to felling frequency. Bergeron *et al.* (1997) illustrate a slightly different approach for boreal mixed forests in Ontario. Here the focus is on ensuring that the age-class distribution and composition of stands within the forest landscape mirrors that created by fire. Frequency of felling is then the main vehicle for controlling these patterns. Delong and Tanner (1996) suggest that the complex spatial pattern created by wildfire in boreal forests could be copied by diversifying the size of harvesting units – allowing more large harvesting units (> 500 ha) with some biological retentions within these, and also more smaller felling coupes (< 50 ha) which mimic smaller scale fires. Fire disturbance also provides the basis for the ASIO management system in Swedish boreal forests (Rülker *et al.*, 1994). This system is based on the spatial patterns of soil moisture regimes; moist sites rarely burn, and these are dominated by gap-phase dynamics; drier sites burn more frequently, and stand replacement dynamics may occur. Four classes of site are identified: A – Almost never burns; S – Seldom, e.g. once every 200 years; I – Infrequently, e.g. once every 100 years; O – Often, e.g. twice every 100 years. Management aims to mimic the structural features of forest stands on these different site types and recommendations are given on scale of felling, and frequency of controlled burning. For example, in the A Class there is a presumption towards no forestry activity or selective felling, whereas in the O Class recommended measures include clearfelling with seed trees left, and controlled burning of the forest.

There appear to be no forest management systems that use wind disturbance of natural forests alone as a template, although recently a gap dynamics approach has been advocated for parts of British Columbia (Lertzman *et al.*, 1996; Coates and Burton, 1997). Wind is also included as part of a suite of natural processes to be used to guide forest management (B.C. Ministry of Forests, 1995; Petersen *et al.*, 1997).

There are doubts over the validity of considering felling as an imitation of fire or windthrow, given their very different impacts on the site, e.g. creation of deadwood, maintaining nutrient cycling, soil mixing etc. (Bradshaw *et al.*, 1992; Franklin, 1993). Even large-scale disturbance events leave a structural complexity and residues (including deadwood, remaining standing trees and patches of vegetation) which are usually eliminated by harvesting. The preservation of some of these structural elements is being addressed by the 'New Forestry' in North-west America. For example, stand management guidelines for maintaining biodiversity in coastal British Columbia have been built around six attributes (snags, large green trees, coarse woody debris, tree species diversity, understorey plant community, and vertical and horizontal structure). Methods have been proposed for modifying operations to retain these attributes (B.C. Ministry of Forests, 1992).

Characterizing wind disturbance in natural forests relevant to upland British forests

Clear evidence on the frequency and scale of the prevailing disturbance regimes is not available for natural forests in Britain, and analogues for the planted forests must be sought elsewhere. Ratcliffe and Peterken (1995) proposed that some overseas reference points for British forests can be found in: (1) natural boreal forests in Scandinavia, and (2) natural temperate and boreal forests in the Pacific North-west regions of Canada and the USA. However, while the link between climate and the nature of disturbance is firmly established, there are climatic differences between both these regions and Britain. Thus natural disturbance regimes in British forests (and within different parts of Britain) may differ markedly from those in Scandinavian and North American forests. It may be inappropriate to base the pattern and scale of forest management in British forests on these reference disturbance regimes. Furthermore the benefits of working within the limitations of the local site and microclimate types may be lost by adopting a regional approach (Mason and Quine, 1995).

There is a wide range of potential disturbance agents relevant to Britain's planted forests, including wind, fire, snow, ice, flooding, insects and fungi, herbivory, and effects of man. This review will concentrate on the effect of strong winds because this is widely acknowledged to be the most pervasive disturbance agent affecting existing forests in the British uplands. Lamb (1991) lists at least 21 storms that caused wind damage to forests in the period since 1700 and there is also paleo-ecological evidence that wind was shaping forests thousands of years ago (Allen, 1992). There have been at least five major storms this century that caused extensive damage – for example 8300 ha was windthrown in a single storm in 1968 and 16 500 ha in 1987 (Holtam, 1971; Grayson, 1989). In addition, lesser storms cause windthrow in many years and this endemic damage can add substantially to the area windthrown. In contrast, the loss through fire in the period 1970 to 1989 totalled 13 500 ha. The vast majority of fires are caused by humans (Aldhous and Scott, 1993), and less than 3 per cent of fires have lightning as a possible source of ignition. Peterken (1996) suggests that the role of fire in British forests may be very limited; only in the birch–pine forests of the eastern Scottish Highlands might fire be a significant natural factor, but the record is dominated by anthropogenic effects (ignition and suppression). Losses from snow are also occasional and of local importance (Wright and Quine, 1993; Nykänen *et al.*, 1997). The authors do not dismiss the role of other agents, particularly the very important biotic damage agents, but many of these are species/community specific and therefore drawing parallels with planted forests is more problematic.

Brief climatology of strong winds relevant to upland Britain

Strong winds affect forests in many parts of the world so there are numerous potential parallels. To fully understand the role of wind in causing disturbance it is necessary to know the frequency, intensity and extent of strong winds. There is considerable scope for confusion when comparing sources because of variable meteorological standards, confusion of terms describing the phenomena and the speed, inadequate coverage of instruments, and variable terminology of recurrence.

The mechanism by which strong winds originate can determine important features of the disturbance. Five types of strong winds have been identified (Cook, 1985; ESDU, 1987; Hunt, 1995; Wyatt, 1995):

- fronts, depressions and extratropical cyclones,
- hurricanes and tropical cyclones,
- thunderstorms,
- tornadoes,
- orographic and local winds.

Fronts, depressions and extratropical cyclones are a particularly important source of strong winds in maritime, temperate regions such as Britain. These large scale air masses (diameter of up to 4000 km) form on the boundary between cold polar air and warm subtropical air. In many temperate areas, such systems are at their most intense during winter months and whole regions can be simultaneously affected by strong winds. Individual storms may take 3 days to pass over a single locality, and because they also tend to occur in families of events, the sequence of strong winds may damage the soil/root anchorage of trees. Wind speeds up to hurricane force may be experienced in the most severe storms and particularly strong and localized winds occur as down drafts along intense gust fronts and squall in narrow belts 30 m by several hundred metres (Hunt, 1995). Wind speeds are strongest near coasts and can be enhanced by topography. Examples of forest disturbance through such strong winds come from: Britain and Western Europe (Mulder *et al.*, 1973; Quine, 1991); Pacific North-west of America (Ruth and Harris, 1979; Russell, 1982; Taylor, 1990); the South Island of New Zealand (Jane, 1986); and Tierra del Fuego (Rebertus *et* *al.*, 1997). Snow and ice can exacerbate the effect on forests especially in maritime areas (Bruederle and Stearns, 1985; Guild, 1986; Boerner *et al.*, 1988). The frequency of recurrence of damaging winds is very dependent upon location with respect to the typical storm tracks and to topography. There is a strong regional gradient, for example across Europe so that wind speeds are more extreme in Britain than in Scandinavia. In the northern boreal zone of Scandinavia, wind disturbance is negligible in non-inflammable Scots pine stands (Zackrisson *et al.*, 1995).

While thunderstorms, tornadoes, tropical cyclones and orographic winds cause extensive damage to forests in some countries (e.g. Somerville, 1980; Frelich and Lorimer, 1991; Peterson and Pickett, 1991; Tanner *et al.*, 1991) their relevance to British conditions is limited. Thunderstorms and tornadoes are rare – for example the return period for destructive tornadoes in central and western Europe is believed to be 1:10 000 to 1:100 000 at any one place; tropical cyclones do not occur and orographic winds are limited to certain localities, e.g. parts of eastern England (Aanenson, 1965).

Comparable regions

Detailed quantitative comparisons have not been possible between Britain and areas of natural forest owing to the difficulty of accessing suitable meteorological records. Britain has a simple climatology dominated by deep Atlantic depressions, but many parts of the world have a mixed climatology of strong winds; for example, the eastern seaboard of the USA experiences both tropical cyclones and tornadoes. In areas where strong winds are very rare, other disturbance mechanisms predominate – such as fire in continental Canada, and insects in eastern Canada. The authors believe it is best to compare regions where the predominant mechanism is similar and the most direct parallels therefore appear to be the Pacific North-west of America, Southern Chile and Argentina, Southern New Zealand, Japan as well as other parts of the extreme western seaboard of Europe. The Pacific North-west (including South-east Alaska) is used as a case study of the role of strong winds, because of the completeness of forest cover, the comparability of species, and the accessibility of the literature.

Case study area – Pacific North-west

The narrow coastal zone of the Pacific North-west of America (including Oregon, Washington, British Columbia and South-east Alaska), is dominated by hemlock–spruce forests and appears to provide a valuable reference point for upland spruce forests in Britain. In addition to the obvious similarities in tree species, there are parallels between the climatology of the two regions and similarities in circulation patterns that cause strong winds in the North Pacific and the North-west Atlantic. The polar front creates a storm track across the Eastern Pacific and depressions frequently end their development in South-east Alaska resulting in numerous storms with a winter peak in occurrence. Thunderstorms and tornadoes are extremely rare in the region.

Both Wood (1955) and Day (1957) remarked on the similarities between Britain and parts of British Columbia with respect to rainfall and temperature. Day (1957) noted that strong winds were not so persistent in his study areas of central Graham Island (Queen Charlotte Islands) and the coastal mountain range near Terrace as in west coast of Britain. However, wind speeds in the coastal margin of northern Washington, British Columbia and South-east Alaska are broadly comparable with those of mainland Britain. Peterson *et al.* (1997) observe that the highest average wind speeds in North America occur on the southern part of the Queen Charlotte Islands and that all windward slopes of the archipelago are prone to extremely high winds. Direct quantitative comparisons are difficult because of the scarcity of records and the predominant influence of locality, e.g. surrounding topography, surface roughness, local obstacles; many anemometers are situated at low elevation in proximity to settlements. Table 4 provides a direct comparison of named sites. The records indicate that in the coastal margin the mean wind speed varies from around 3 m s^{-1} to more than 8 m s^{-1} – comparable to that of Britain; the extreme wind speed, as characterized by the maximum gust occurring once in 50 years, varies from 36 to 49 m s^{-1} and is similar to that experienced at low elevations in Britain. However, there is a strong gradient between coast and inland, exacerbated by the high surface roughness of the forested land and the mountainous terrain (Anon., 1991). As a consequence wind speeds in inland British Columbia and Washington and inland Oregon are substantially lower than those experienced over much of Britain (see Moses Lake data in Table 4); exceptions occur in gaps in the mountain chain such as the Columbia River valley. Wind speeds at the coast also decline south of Washington with a result that coastal Oregon is also less windy. In South-east Alaska there are also some local bora-type winds – that is strong downslope winds in the lee of high ground, similar to those occasionally experienced around Sheffield, England.

It is also hard to generalize about soils and their similarities between the regions. However, Day (1957) investigated rooting depth of Sitka spruce at a number of sites in British Columbia, and found depths in excess of 2 m on freely draining podsols, but less than 30 cm on wetter clays and peats; the latter is similar to the shallow rooting found on the wetter peats and gleys in upland Britain.

Two stand types have been identified in the hemlock–spruce forest types in the Pacific North-west: (1) even-aged stands following catastrophic blowdown; and (2) multi-aged stands resulting from gradual but non-catastrophic attrition (Deal *et al.*, 1991). Sitka spruce can maintain a presence in forest communities in both situations (Taylor, 1990). It is not known what the proportion of the two stand types (fine grain and even-aged) is for any one region and selection of study sites and plot-based research may overemphasize the occurrence of fine-grain stands. A third stand type is apparent in the most exposed locations of South-east Alaska – a special structure of short stature, resilient forest (krummholz) forms in response to the severity of the conditions (Ruth and Harris, 1979).

Table 4: Comparison of wind data for selected sites in the coastal margin of the Pacific North-west of America and for Britain. Sources of data: Met Office, AWEA, National Record Office. The gust wind speed required to cause catastrophic damage is approximately 45–50 m s^{-1} (Quine *et al.*, 1995)

Site name, latitude and longitude	Geographic position	Elevation (m)	Annual mean wind speed (m s^{-1})	1:50 year maximum gust (m s^{-1})
Alaska				
Kodiak 57.45 N, 152.3W	Western end of Sitka spruce range, Coastal Island	32	5.4	47
Juneau 58.22N, 134.35W	Inner coastal passage, SE Alaska	6	3.9	38
Gulkana 62.09N, 145.27W	Inland SE Alaska	481	3.4	33
Washington				
Hoquiam 46.36N, 123.56W	Coastal South of Olympic Peninsula, Washington	8	5.5	45
Olympia 46.58N, 122.54W	100 km inland from coast, south of Olympic Peninsula, Washington	66	3.2	38
Moses Lake 47.11N, 119.2W	400 km inland from coast, Washington	361	2.8	33
Britain				
Benbecula 57.28N 7.22W	Western Isles of Scotland	16	6.9	50
Abbotsinch 55.52N 4.26W	West coast of Scotland, close to Glasgow	16	4.5	46
Fort Augustus 57.08N 4.43W	Inland west Scotland, within glen approx 100 km from coast	58	2.7	37
Great Dun Fell 54.41N 2.27W	Ridge top of Pennines	858	11.5	64

In Oregon, Washington and British Columbia fine grain disturbance appears to predominate; see for example the description of forests in the Hoh river area on the Olympic peninsula (Peterken, 1996). High rainfall and wet soils mean that fire is very rare in the coastal belt and only becomes a dominant influence further inland (e.g. in Douglas fir forest types). Lertzman and Krebs (1991) observed standing death to predominate in the mountain hemlock zone (canopy gap sizes 5–525 m^2, median 41 m^2). Edmonds *et al.* (1993) found that suppression, insect attack, fungal attack, and windthrow were all responsible for mortality over 5 years within small plots in the Olympic peninsula. Taylor (1990) identified a gap regime as important as Cascade Head, Washington and found that structural gaps were observable until at least 105 years old, when successors reach 25 m. He recorded gap dimensions by transect and aerial survey. In the transect survey he found canopy gaps ranging from 12 to 851 m^2, with a median of 233 m^2; but in a wider aerial survey (of approximately 300 ha – minimum mappable gap 1000 m^2) he found 'gaps' up to 2.3 ha. Harcombe *et al.* (1990) tentatively suggest a return period of once in every 450 years for stand-replacing disturbance by wind in the vicinity of Cascade Head. Lertzman *et al.* (1996) found that gap dynamics dominated forest dynamics in the Clayoquot sound, and suggested a turnover period of 350–950 years in the absence of large-scale disturbance. Most of these sites are not found in the windiest coastal margin of the PNW, and the sites of Juneau and Olympia (Table 4) are perhaps representative of the wind climate.

Wind has been identified as the key disturbance agent in the hemlock–spruce forest types of South-east Alaska (Bormann *et al.*, 1995). At least five major blowdown events have been experienced this century (Ruth and Harris, 1979). Topographic effects have been observed in patterns of damage resulting from these storms. Harris (1989) describes an aerial survey of approximately 500 000 ha productive forest land around Prince of Wales Island, South-east Alaska approximately 3 years after one of the five notable storms (November 1968). This coastal margin is windier than the preceding study sites and the wind climate of Hoquiam and Kodiak (Table 4) is representative. Blowdown was approximately 1.6 per cent of productive area, but 10.6 per cent of the hemlock–spruce forest type. He recorded 1010 patches greater than 0.8 ha (minimum mappable size) of which 50 per cent were partial windthrow and 50 per cent complete windthrow. Patch size ranged from 0.8 to 71 ha, with a mean of 7.45 ha; patches were estimated to be visible for 15 years after complete blowdown, which would indicate a turnover period of 140–930 years. Topographic and soil effects were observed but were confounded by growth rates and forest composition changes due to site types.

The Pacific North-west and particularly the coastal margin from North Washington to South-east Alaska does appear to provide a promising reference point. Both fine grained and stand replacing mechanisms exist within the same landscape/forest type. It is clear that a single gap/patch size (e.g. mean or median) cannot be considered as the full expression of a 'natural disturbance regime' of a locality or region. However, little has been published on the relative distribution of the different structures within the landscape and there is no detailed template for the spatial arrangement of gaps and patches. There is insufficient understanding of the controlling factors (e.g. soil and rooting depth) and the damaging agent (i.e. strength and frequency of strong winds, influence of topography) at the landscape scale.

Implications for British forests

Current dynamics of planted forests in upland Britain

The dynamics of planted forests in Britain are determined by the silvicultural regime established by the forest manager, the ecology of the planted forests, and the role of natural disturbances acting within these constraints. The scale of forest operations varies with site type, ownership, and external pressures such as forest design and landscape designations. The majority of upland forests are managed on a rotational patch clearfell system, with average sizes of clearfells in the range 30–100 ha, and felling and restocking occurring every 25–50 years (Figure 2 contrasts the gap size caused by chronic windthrow with the harvesting coupes planned in the vicinity). In terms of the Oliver and

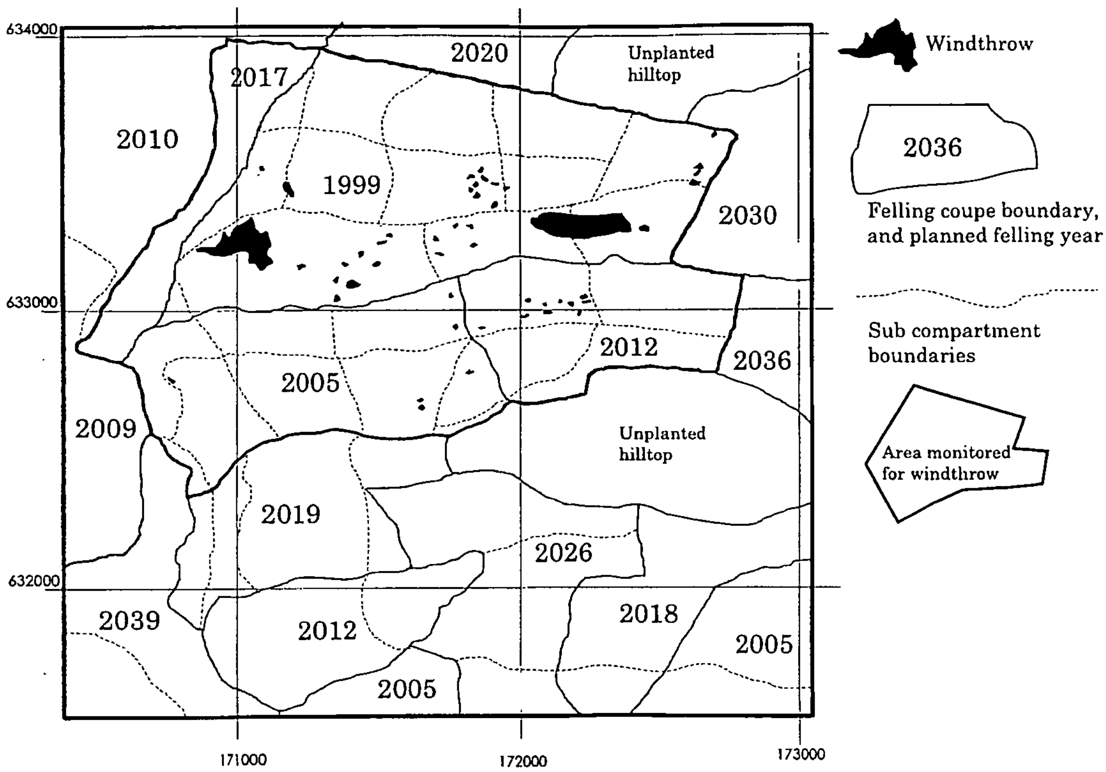

Figure 2. Natural and planned disturbance for a forest area in west Scotland – windthrow occurring by summer 1996 (stands in area planted 1959–1962), and harvesting coupes planned for the next 30 years. Gridlines oriented to National Grid at 1 km spacing.

Larson model, the vast majority of the forests will be maintained in the stem initiation and stem exclusion stages. Furthermore, the youth of these upland plantations has precluded the development of any stands into old-growth, even without the effect of harvesting.

The main natural disturbance agent in these forests is wind, which has primarily been regarded as a commercial constraint (Quine *et al.*, 1995); anticipatory felling has sought to avoid actual damage and arguably has prevented catastrophic disturbance from occurring. The effects of natural disturbance by wind are being monitored in a range of forests dominated by Sitka spruce (Quine and Reynard, 1990). These forests experience frequent windthrow and small gaps form in many years. Quine and Bell (1998) showed highly skewed gap size distribution from eight study forests, with many small gaps (less than 0.1 ha) and a small number of large patches up to 10 ha. There was a low annual rate of increase in windthrown area (i.e. largely less than 1 per cent) but evidence that this was highly variable through time. Less frequent, but catastrophic windthrow also occurs in these forests and can result in patches of excess of 100 ha (Figure 3). Storms such as that experienced in West Scotland in 1968 may disturb 3–25 per cent of the mature forest area in a region at one time (Holtam, 1971). It is difficult to predict the spatial and temporal dynamics of such stand-replacement events.

The impact of such wind disturbance on biodiversity in upland forests has been little studied. Small pilot studies have indicated that the abundance of bryophytes increases in gaps over 400 m^2 when compared with uniform closed canopy conditions (Quine and Humphrey, 1996). Petty (1996) has shown that upturned root plates and small pockets of windblow provide important feeding sites for raptors such as the goshawk

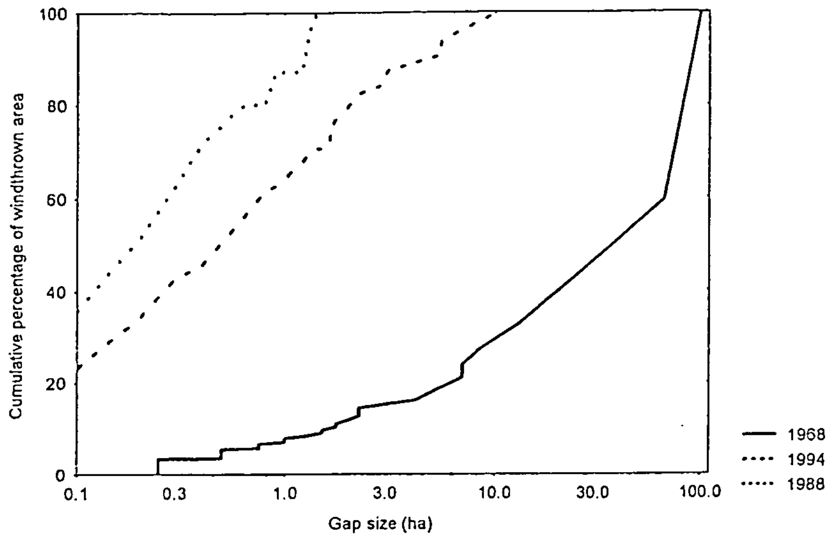

Figure 3. Gap size distribution for eight forest areas in upland Britain following chronic windthrow (1988 and 1994) contrasted with that occurring within a similar forest area following catastrophic windthrow (1968).

(*Accipter gentilis*). More studies are needed to examine the effects for a range of species groups. Knowledge of the natural dynamics of upland semi-natural woods is also limited. Available evidence suggests that in remnant native Scots pine (*Pinus sylvestris*) and oak (*Quercus* spp.) woods, fine grained dynamics predominate (Humphrey, 1992; Arkle and Nixon, 1996; Worrell, 1996), but larger patch dynamics due to fire or storm can occur (Backmeroff and Peterken, 1989; Peterken, 1996; Worrell, 1996) and may have been more apparent when the woodlands were extensive.

Speculations on potential patterns for British forests

Few other forested countries have a wind climate as severe as Britain. Evidence from relevant natural forests and the natural dynamics of the planted forests indicate that there is likely to be a mosaic of fine grain, coarse grain and wind-adapted forest types within a region such as upland Britain. In South-east Alaska, and in Britain, the recorded range of wind-induced natural gap sizes encompasses the range of coupe sizes which might be generated by conventional silviculture, from the selection method (individual trees) through to large scale patch clearfell (70 ha). The process of change and renewal is event-related (storm occurrence) with the implication that the scale of structural change will vary from year to year, and within sections of the forest. It should therefore be anticipated that both gap-phase and stand replacement dynamics will coexist within upland forests in Britain. The balance is likely to tip in favour of the dominance of gap-phase in the south and east of the country (less severe wind climate), and within forests where there is substantial topographic shelter or where freely draining soils predominate. By contrast, in the more northerly areas and on more exposed sites, it is possible that there are some areas where the stages of understorey reinitiation and old-growth would not be achieved for any significant time because of the frequency of wind-related disturbance. On the most exposed sites, a wind-adapted forest type would emerge.

Such possibilities are illustrated by results of a simulation of the frequency of windthrow in Glen Affric, Highland Region, Scotland. This is an area of 16 000 ha, of which approximately half is currently wooded. The elevation ranges from 60 to over 720 m, covering zones highly suitable for tree growth as well as sub-alpine plant communities. A variety of soils are found within the area including freely draining podsols, peats and gleys. A wind risk model (Forest*GALES*) (Quine and Gardiner, 1998) was used to calculate the cumulative risk of catastrophic windthrow for a Scots pine stand placed in different parts of the landscape. The placement reflected the range of wind climate found from the most sheltered parts of the forest, to conditions at the tree line; this reflects a range in mean annual wind speed from less than 3 m s^{-1} to greater than 9 m s^{-1}. The calculated frequency of catastrophic windthrow varied enormously – on the most exposed sites the model predicted a cumulative probability of 1.0 being reached within 70 years, but on the most stable sites the cumulative probability was less than 0.1 even after 300 years. A potential structural classification for the forest based on the likely frequency and scale of disturbance is illustrated in Table 5 and Figure 4. Although such a simulation depends greatly on assumptions (such as a wind climate without trend in severity) it does emphasize that the disturbance rate can vary as much at the landscape scale as it does over an entire region.

Table 5: Disturbance-related structural classes for Glen Affric (see also Figure 5)

Class	Description
1	Above treeline – no trees present (Above threshold of known examples of Scots pine – see Hale *et al.*, 1998)
2	Krummholz and severely wind swept trees; trees adapted to severe wind regime and not susceptible to widespread windthrow – fine-grained disturbance predominates (Above Ecological Site Classification threshold for commercial woodlands and in upper part of zone suitable for W18 woodlands – see Pyatt and Suárez, 1997)
3	Mosaic of large scale even-aged patches with frequent disturbance (Cumulative probability of catastrophic damage >0.5 within 100 years)
4	Mosaic of occasional large scale even-aged patches within matrix of older forest where fine-grain disturbance occurs (Cumulative probability of catastrophic damage >0.5 within 300 years)
5	Forest in which fine-grained disturbance predominates and no large-scale patches are present (Cumulative probability of catastrophic damage <0.5 within 300 years)

The development of 'old growth' gap-phase stands is particularly rare in the planted forests of Britain. The occurrence and persistence of such stands depends not only on the prevailing climate and disturbance regime, but also on soil conditions. Deep soils affording good root anchorage are necessary for the development of old-growth stands, and these are often restricted to lower slopes of valleys (Peterken, 1996). The majority of planted forests in upland Britain have been established on shallow wet soils, where rooting is poor, and the right climatic and edaphic conditions for old-growth development are more limited (Peterken *et al.*, 1992; Mason and Quine, 1995). Frequently the landscape elements with shelter from wind and with better soils, such as those close to watercourses, are being used for broadleaves or open space in the second rotation rather than providing stable sites for old growth Sitka. Recommendations in the UK Forestry Standard (Forestry Commission, 1998) that only 1 per cent of forests should be retained for the long term, probably underestimates the potential for such stands.

Conclusions

Natural wind disturbance, something to mimic or just a reference point for management?

In many countries the scale and nature of forest management systems are reportedly based on features of natural disturbance regimes (e.g. Rülker *et al.*, 1994; Delong and Tanner, 1996). However, there is a lack of landscape-level studies in most wind disturbance related studies, and many studies are carried out at the stand scale where plot selection precludes study of stand replacement events. Yet this is the level/scale at which management decisions are most likely to be framed in the context of biodiversity (Larsen *et al.*, 1997). For both scale and frequency of disturbance, it is the variability about the mean that is as important as the mean itself (McCarthy and Burgman, 1995) but this is rarely quantified and is hard to codify as a management method.

The benefits to biodiversity of basing the pattern and scale of forest management on natural disturbance regimes are less clear for British forests. There is little information on the effect of disturbance on biodiversity in these

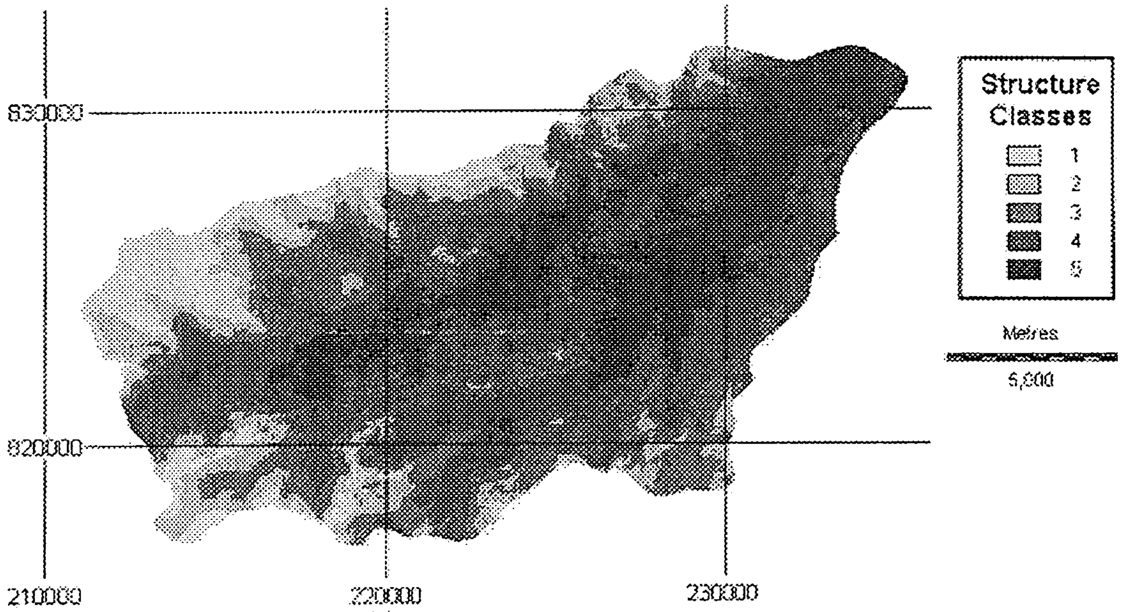

Figure 4. Predicted forest structure types for Scots pine forest in Glen Affric, North-west Scotland, based on an interpretation of the results of the Forest*GALES* wind risk model. Gridlines oriented to National Grid at 10 km spacing

planted forests, or of the long-term consequences of allowing disturbance to mould forest structure and composition. There are other pressures influencing management and the resulting forest structure; only at the stand level are natural processes likely to be given free rein.

It is clear that the current predominance of patch clearfell systems in upland forests is not closely related to natural disturbance patterns. The combination of short rotation lengths and large coupe sizes (5–100 ha) have no apparent parallel in comparable natural forests, where a mosaic frequently exists from fine-grained to stand replacement.

The authors propose that disturbance in natural forests can be used as a *reference point* for forest management rather than a model to mimic. The focus of interest should be the structural and spatial patterns created by disturbance in natural forests. Upland forests in Britain would be subject to both gap-phase and stand replacement dynamics. Evidence from the literature indicates that these processes have divergent effects on biodiversity; the former affects stand structure (in particular vertical structure of canopy and understorey layers); the latter creates spatial pattern in the landscape and maintains the full range of stand successional stages, including temporary open habitats. A realistic approach in upland conifer forests might be to ensure that management observes the need to maintain patterns and structure across the range of scales, consistent with other pressures. A combination of the Ecological Site Classification (ESC), (Pyatt and Suárez, 1997) and predictive models of the regime of various disturbance agents (e.g. Forest*GALES* wind risk model (Gardiner and Quine, in press)) could be used to identify likely natural disturbance regimes for different topographic units in upland forests. Silvicultural methods for upland Britain could be adapted to create and maintain the reference structures and patterns associated with these different dynamics within individual stands. Such measures would provide an element of naturalness in the designed forest, but the scope for achieving this will be constrained by other management objectives such as the economics of timber production, landscape design, public opinion, and the needs of keystone species such as raptors.

Proposals for further research

A number of research needs to develop the concept of disturbance as a reference point have been highlighted by this review. To carry this concept forward three strands of work are required:

1 Development of a predictive tool for disturbance regimes in upland forests by combining ESC with models predicting the occurrence of various disturbance agents.
2 Further contact with countries containing forests which appear to be appropriate parallels for British forests is necessary, with a particular emphasis on gaining a better understanding of the landscape level processes. Such studies might include greater use of remote-sensing in order to broaden the scale of study.
3 Further landscape-scale monitoring of disturbance is required in both natural and planted forests. In Britain it is proposed that change in structure in some large areas of forest across a range of different climate zones should be monitored. Identification of gap size distributions that occur could be considered as a valuable first step to quantifying landscape patterns. Part of these studies should be the monitoring of a small number of individual stands where intervention is minimized, and the assessment of their biodiversity to explore the impact of natural disturbance in planted forests; one large area of non-intervention would be preferable but may be unrealistic given economic pressures. In addition, there is a need to evaluate the relative benefits of retaining different quantities and types of structural/biological legacies (e.g. deadwood, clumps of broadleaves etc.) throughout a normal patch clearfell rotation. An experimental approach could be appropriate here.

Successional modelling is necessary to draw together these research strands and make long-term predictions about the development of forest structure under different regimes of natural and planned disturbance in upland forests. This is required for semi-natural forests as well as plantations, and will help managers investigate the potential long-term benefits to biodiversity of different management options.

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