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WIND-DRIVEN GAP FORMATION AND GAP EXPANSION IN SPRUCE FORESTS OF UPLAND BRITAIN

C P Quine
Forest Research, Roslin, Midlothian, United Kingdom. chris.quine@forestry.gsi.gov.uk

Abstract

Many studies of windthrown gaps commence after formation, and assumptions are commonly made that such gaps have formed in the most recent and notable strong wind event. However, studies in a number of forest types have suggested that gap expansion can be important. Five forest areas in upland Britain were monitored by transect survey over 6 winters to record gap formation and expansion. Continuous measurements of wind speed and direction were made on an open site in close proximity. At all sites there was an increase in gap area and gap numbers but the magnitude and nature of the change varied substantially. At three sites, there were modest increases in gap area, due largely to small-scale extensions to existing gaps. Only a few new gaps formed, and these were small (less than 0.005 ha). At two sites there were substantial changes in gap area due to gap formation and expansion, related to storm events with return periods of 5-30 years; but at only one of these sites did gap formation predominate (gaps up to 0.15 ha). Wind speeds were higher (27-33 m s^{-1}) during periods in which new gap formation was observed than periods in which only gap expansion (20-24 m s^{-1}), or no change in gaps were observed (19-22 m s^{-1}). The processes of gap formation and expansion are discussed in relation to wind climate and the spatial and temporal variability in occurrence of strong winds. Implications for gap dynamics, model development and risk perception are identified.

Introduction

Much of the literature relating to windthrown gap and patch formation in natural and managed forests describes studies in response to discrete events causing substantial change, or assume that a single event has caused the structural change (Everham III & Brokaw, 1996; Foster & Boose, 1992; Grayson, 1989). However, in some regions wind damage or disturbance has been observed to have a more frequent, endemic or chronic component. Past studies in upland Britain found rates of endemic windthrow of 2-8% area windthrown per year, rather than the 4-30% in single catastrophic events. Such increments were incorporated into a British hazard classification with an implicit assumption that they would occur annually (Miller, 1986; Quine, 1995). Since then the importance of temporal variation in wind climate has been recognised, and this has led to the development of a risk rather than hazard model (Gardiner & Quine, 2000). Expansion of existing gaps was held to be an important component of endemic windthrow (Neustein, 1972) but an emphasis on monitoring of whole forests, and the imprecision of geo-referencing in the photographic interpretation process has prevented this being confirmed (Quine & Bell, 1998). In general, the characteristics of individual gaps has attracted less attention than measurements of the proportion of windthrow formed within the stand or management unit.

Factors controlling the formation of new gaps are poorly understood. Gaps form when the applied force exceeds the resistive force of trees – but both these vary spatially. Resistance to windthrow will vary due to conditions of root anchorage (water-logging, root rot, mechanical impediments to rooting), while the applied force varies with canopy structure, proximity to edges, and random location of the strongest gusts. Rather more is understood of the consequences of gap formation. The bio-mechanical response of trees on newly created edges has been shown to be slow and involves an initial increased allocation to root growth, followed by stem and crown adaptation (Urban *et al*., 1994; Valinger, 1992). 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 (Ray & Nicoll, 1998). 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).

The purpose of this stand-based study was to establish an understanding of gap occurrence in planted forests in upland Britain, assess the relative importance of gap formation and expansion, and explore the relationship with aspects of wind climate.

Methods

Windthrow monitoring areas. The work took place within 5 of 8 monitoring areas previously established to provide data for wind risk model development and validation (Quine & Bell, 1998). Each is an area of 400-1200 ha representing varied topography, soils and wind climate but predominantly planted with Sitka spruce (*Picea sitchensis*) between 1948 and 1963. Transects were installed at 100 m spacing, with start point and bearing dictated by access to the compartment. In a baseline survey, every gap intersected by the transects was measured (Quine, 2001a).

Return transects. A subset of the transects were selected for repeat visits to record changes to pre-existing 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. Top height of stands varied between 16 and 24 m at time of sampling and further details of the site and stand can be found in (Quine, 2001b). Approximately 12300 m of transect was sampled at monthly intervals over the winters 1993/94 to 1998/99. Distance and bearings were taken to describe gap perimeter and re-measured after expansion. Perimeter measurements were plotted to scale, digitised, and imported into IDRISI GIS within which area, perimeter and gap centre (location in x and y relative to a post providing local reference point) were computed. Change in shape of expanding gaps was summarised by calculating the fractal dimension D (twice the slope of the regression line of *log* area against *log* perimeter) prior to and after expansion.

Measurements of wind speed and direction. Wind speed and direction was recorded at 10 m above ground at a well-exposed reference site in each monitoring area from 1988 to 1999, and for shorter intervals at a number of other sites to explore topographic variability (Quine, 2000). Wind speed is summarised here as hourly maximum gust. Scaling from hilltop reference sites to transect location was achieved using regressions developed between the long-term and short-term sample sites.

Results

Change in gap numbers and area. At all monitoring sites there was an increase in gap area and gap numbers during the study. However, there were substantial differences between sites in the proportion of increase due to new gap formation or existing gap expansion, and in the numbers of gaps that formed or remained unchanged. Details are given in Table 1.

	Carradale West Scotland	**Cwm Berwyn, Mid Wales**	**Glentrool South-west Scotland**	**Kielder* North-east England**	**Rosarie North-east Scotland**
Gap Numbers					
At start	16	19	23	28	18
New gaps	7	2	23	1	2
Expanding gaps	7	4	13	2	8
Unchanged gaps	8	15	14	26	9
Gap Size					
Range and mean gap size at start (m^2) *standard error*	11 – 4999 403 *308.5*	11 – 1546 337 *110.6*	6 – 359 53 *16.6*	4 – 1235 133 *49.3*	16 – 695 109 *42.1*
Range and mean gap size at end (m^2) *standard error*	11 – 5200 497 *252.2*	7 – 1546 370 *109.6*	6 – 3450 340 *100.5*	4 – 1495 139 *55.4*	21– 2528 259 *130.7*
Range and mean of new gaps (m^2)	9 – 214 46.4	7 7	14 – 1493 210	31 31	26 – 45 35.5
Area Windthrown					
% area at start *standard error*	9.9 *0.418*	6.3 *0.186*	5.7 *0.141*	8.6 *0.208*	6.9 *0.059*
% area at end *standard error*	16.5 *0.545*	7.3 *0.206*	23.0 *0.487*	8.9 *0.216*	9.5 *0.196*
Ratio of area of new gap: expansion	0.43	0.05	2.75	0.12	0.26

TABLE 1 – Summary statistics of gap changes for 5 monitoring sites. * Kielder had a shorter monitoring period as the stand was felled prior to the 1998/99 winter.

The magnitude of change varied substantially between sites. At two sites (Glentrool and Carradale) there was substantial change in both gap numbers and gap area. Expansion in total gap area occurred via extension, coalescence and formation of new gaps up to 1500m^2 in size. The magnitude of change was particularly marked at Glentrool where the area of new gaps exceeded that of expansion. At the other three sites, the change in gap area and numbers was modest. Expansion of gap area occurred largely by small-scale extension to a small proportion of the gaps, and new gaps were small (less than 50m^2). Coalescence with pre-existing gaps, not previously intersected by the transect, created some apparently larger shift in gaps. Overall, gaps that expanded were significantly larger prior to expansion than those which remained unchanged (Kolmogorov-Smirnov test, Mean starting gap area for no change gaps 98.1 [n=72, SD 214.7], Mean starting gap area for changing gaps 434.1 [n=29, SD = 957.2], $p<0.025$). However, at all sites at least half of the gaps remained unchanged, and at Kielder, over 90% of the gaps showed no expansion.

Change in gap shape and location of gap centre. Gap shape as described by fractal dimension *D* became more complex with expansion. Overall, the value of D increased from 1.22 (1.12-1.29) at start to 1.29 (1.14-1.48) at end indicating increasing complexity in gap shape; a value of 1 would indicate the gaps were circular. There was little change in the location of the gap centres at 3 sites, confirming the small scale of expansion relative to the size of the existing gap. At Glentrool and Carradale sites, and where there was coalescence, larger shifts in gap centre were found. These shifts were not unidirectional, and indicate that the gaps did not migrate solely in the direction of the prevailing wind.

Periods of change. The number of periods (between visits) showing change are summarised in Table 2. The change that occurred was concentrated into a very few episodes, and overall there were more periods with expansion than with new gap formation.

Site	**Total number of periods**	**Number with no change *(%)***	**Number with new gaps**	**Number with expanding gaps**
Carradale	45	38 *(84%)*	1	6
Cwm Berwyn	49	45 *(92%)*	2	2
Glentrool	44	39 *(89%)*	4	1
Kielder*	29	21 *(72%)*	1	7
Rosarie	48	38 *(79%)*	2	8

Table 2. Summary results of change periods for each site. * shorter monitoring period

The relationship between the type of change within a period (no change, expansion of existing gaps and small new gaps <100m^2, formation of substantial new gaps >100m^2) and the wind speeds recorded was examined. Wind speeds were significantly higher during periods with new gap formation than for periods of expansion or no change. (Table 3, Figure 1).

Site	**Mean of Maximum Gust (m s^{-1}), during periods of no change**		**Mean of Maximum Gust (m s^{-1}) during periods with expansion of gaps**		**Mean of Maximum Gust (m s^{-1}) during periods with new gaps**	
	Reference Mean *st.dev*	*Scaled*	Reference Mean *st.dev*	*Scaled*	Reference Mean *st.dev*	Scaled
Carradale	28.9 *4.8*	21.9	32.2 *7.4*	21.7	45.0	32.8
Cwm Berwyn	24.1 *5.3*	19.0	25.8 *6.4*	20.3	-	-
Glentrool	29.1 *5.9*	21.8	33.6 *7.9*	21.8	36.0	26.6
Kielder	26.3 *4.5*	19.3	27.4 *4.7*	20.5	-	-
Rosarie	23.1 *4.1*	20.8	27.0 *6.0*	23.8	-	-

Table 3. Change period summary for 1993-1999 for the 5 sites –wind speed recorded during periods of no new gaps and periods of new gap formation. Scaled wind speeds were estimated for the topographic location of the study stands using regressions between long-term reference sites and shorter term sampling of locations nearby.

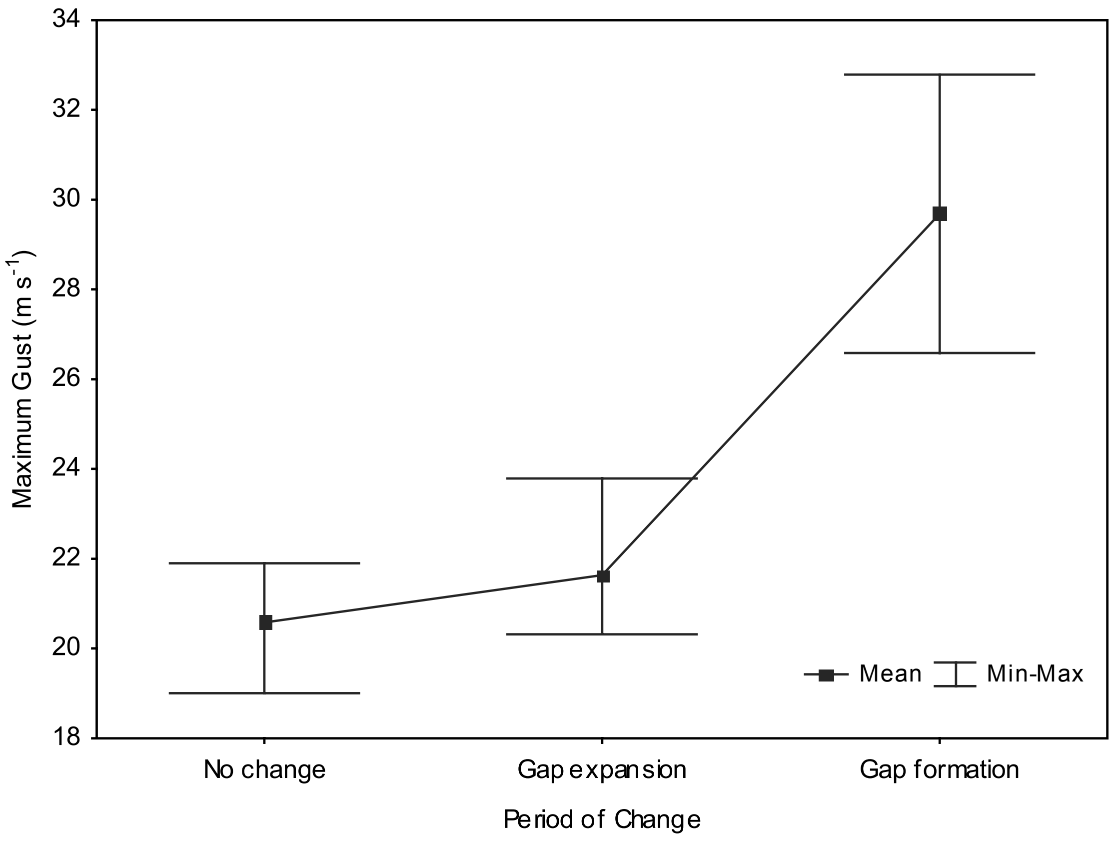

Fig. 1: Wind speeds experienced during periods of no change, gap expansion and small gap formation, large gap formation and expansion for 5 sites combined.

The rarity of the wind speeds that occurred during the return period transect studies were assessed, by calculating the return period (average interval between wind speeds of the magnitude experienced), and examining the record to establish the time since last exceedance. At the end of the monitoring period, 3 sites experienced the most powerful winds for 5 to 30 years. The results are summarised in Table 4.

Winter	**Carradale**		**Cwm Berwyn**		**Glentrool**		**Kielder**		**Rosarie**	
	RP	YSE	RP	YSE	RP	YSE	RP	YSE	RP	YSE
58-88	>50		3		>50		29		23	
89-93	5		8		38		8		>50	
93/94	5	< 1	12	< 5	10	< 4	2	< 2	10	< 1
94/95	5	< 2	3	< 1	1	< 1	1	< 1	5	< 1
95/96	1	< 1	1	< 1	1	< 1	1	< 1	10	< 2
96/97	5	< 2	1	< 2	1	< 1	3	< 4	1	< 1
97/98	2	< 2	1	< 3	1	< 2	2	< 2	1	< 1
98/99	39	< 30	1	< 1	6	< 5	8*	< 6*	1	< 1

Table 4. Summary of rarity of wind speeds experienced during the monitoring period of the return plots. Return period (RP) (years) – estimation of average interval likely between wind speeds of the magnitude experienced during the winter period. YSE - number of years since wind speed experienced during the monitoring period was last equalled/exceeded. * Study stand at Kielder had been felled.

Discussion

Formation of new gaps. The initial baseline survey (Quine, 2001a) confirmed that gaps were prevalent in stands at all sites despite the comparative youth of the forests. At three of the sites only one or two new small gaps subsequently formed during transect monitoring, contributing less than a third to the small windthrown increment. At two of the sites (Glentrool and Carradale), there was a more substantial increase in the number of gaps, equivalent to a 43-100% increase in gap number and a 5-396% increase in total windthrown area. However, at these sites the change was also restricted to 1 and 4 periods, so was not common or as prevalent as gap expansion. 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.

Expansion of existing gaps. At the four sites other than Glentrool, more gaps expanded than formed during the monitoring, the area of expansion was greater than the area of new gaps, and expansion happened in more periods than gap formation. Gap expansion tended to be by small-scale attrition at the edges of the larger gaps, leading to greater complexity in gap shape as indicated by the increase in the Fractal D measure. The gaps that expanded were larger than those that did not, but the two groups could not be distinguished by size alone. The direction of gap spread was variable, particularly where the degree of change was slight. 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. The vulnerability of edge trees has previously been demonstrated around artificially created circular gaps in similar spruce forests in South Scotland (Ae forest) and North-east England (Redesdale forest) (Neustein, 1968). 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 29 $m\ s^{-1}$) 50 km distant at Eskdalemuir. However, at all sites, at least 50% of the gaps remained unchanged in size. This may reflect a proportion of older gaps, ones which formed under particularly extreme conditions, or where the site vulnerability was restricted in spatial scale.

Wind strength and recurrence. Wind speeds during periods of new gap formation were higher than those occurring during periods with gap expansion or with no change; the latter differed little. The wind speeds associated with new gap formation were consistent with those previously observed (Mason & Quine, 1995; Pontailler *et al.*, 1997) whereas the speeds associated with expansion were generally lower. The lack of discrimination between periods of no change and expansion may reflect the lack of an aspect effect, the importance of storm sequences, antecedent site conditions, and additional abiotic factors e.g. wet snow. The major changes in gap numbers 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 with gust speeds which had not been exceeded for 6-30 years. The pre-existing large number of gaps 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 & Bell, 1998) and Table 4 shows a number of extreme wind speeds prior to the transect study. There were insufficient examples of new gap formation to allow the derivation of clear dose/response relationships between increase in gap area and wind speed. There are complex interactions between absolute magnitude, and time since last exceedance, which are liable to have a role in determining the amount of damage in any one event. Sites separated by short distances (e.g. Kintyre and Glentrool) have surprisingly different records of past severe storms and thus a diverse legacy due to time since prior exceedance.

Gap size distribution and processes. The results confirmed the skewed nature of the gap size distribution in these planted forests with a preponderance of gaps less than 100 m^2. Similarly skewed distributions have been identified in natural forests. Runkle (1982) fitted the lognormal distribution to his gap size data, and interpreted this as size being the result of many essentially random processes whose effects were 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 these distributions to summarise their data. However, the predominance of expansion over new gap formation (at least in 4 of the sites), raises questions over the validity of such assumptions in these forests. The evidence from Glentrool shows that large gaps can form in a single event and not just by expansion leading to a slow increase in gap size. This suggests there may be separate processes acting to form gaps of different size, and may also explain the apparent lack of mid-sized gaps. The application of the negative exponential continuous distribution to discontinuous fire patch size classes has been criticised, and it has been suggested that such a model may be unable to satisfactorily 'simulate' infrequent large fires (Li, 1996). 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.

Implications for forest structure. Are these forests governed by a 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 replacement 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 January 1968 storm (Holtam, 1971; Quine *et al*., 1999).

Conclusions

The investigation has clarified the relative importance of gap formation and expansion in the planted spruce forests of upland Britain. Very strong winds produce new gaps at a range of sizes from single tree to many hectares, but occur only every 5-30 years. In intervening periods, more modest winds (perhaps exacerbated by wet snow) produce small gaps (generally less than 0.01ha) and cause expansion on the perimeters of existing gaps. The skewed gap size distribution may reflect both these pathways, rather than one process. The rate of gap area increment is highly variable, and values obtained from short periods of monitoring may be misleading. There is relatively little difference in magnitude between the wind speeds that cause new gap formation and those that result in no change – indicating substantial sensitivities of changing wind climate, and the potential for substantial changes in regime depending upon topographic and regional location. It is unclear whether such processes are a particular feature of extreme wind climates, or are more prominent in young planted forests, than older natural forests, where individual tree senescense and mortality may have a significant role in contributing to tree vulnerability.

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