

An Approach to Predicting the Potential Forest Composition and Disturbance Regime for a Highly Modified Landscape: a Pilot Study of Strathdon in the Scottish Highlands

Christopher P. Quine, Jonathan W. Humphrey, Karen Purdy and Duncan Ray

Quine, C.P., Humphrey, J.W., Purdy, K. & Ray, D. 2002. An approach to predicting the potential forest composition and disturbance regime for a highly modified landscape: a pilot study of Strathdon in the Scottish Highlands. *Silva Fennica* 36(1): 233–247.

The existing native forests of Scotland are fragmented and highly modified and none are 'natural'. There is considerable interest in expanding the area of this oceanic boreal forest and restoring forest habitat networks to benefit biodiversity. However, unlike regions with substantial remaining natural forest, it is difficult to provide reference values for forest composition and structure using methods related to historical variability. An alternative approach is to combine models that predict woodland type from knowledge of site conditions, and disturbance regime from knowledge of the disturbance agents (particularly abiotic agents).

The applicability of this approach was examined as part of a public participatory planning exercise in a highly managed landscape in Eastern Scotland. Models of site suitability (Ecological Site Classification) and wind disturbance (ForestGALES) were combined to determine potential woodland composition and structure, and derive options for native woodland expansion. The land use of the upper Strathdon catchment is currently dominated by agriculture and planted forests of non-native species, and only small fragments of semi-natural woodland remain (<0.5% of the land area). Model results indicated that a very substantial proportion of the land area could support woodland (>90%) but of a restricted range of native woodland types, with Scots pine communities predominant. Structural types likely to be present included wind-induced krummholz (treeline) forest, forest with frequent stand replacement by wind, and also a large area where gap phase (or some other disturbance) would predominate. The merits of the approach are discussed, together with the difficulties of validation, and the implications for the management of existing forests.

Keywords wind disturbance, site suitability, restoration, catchment planning

Authors' address Forestry Commission, Northern Research Station, Roslin, Midlothian EH25 9SY, United Kingdom **E-mail** chris.quine@forestry.gsi.gov.uk

Received 30 October 2000 **Accepted** 22 January 2002

1 Introduction

1.1 General Context

The long history of settlement, deforestation and agriculture has led to Britain having little forest cover. At the start of the twentieth century only 5% of the land was covered by trees and this had risen to approximately 12% by the end of the century through planting, largely of exotic conifers, on marginal agricultural land. The initial objective for this expansion was timber production but British forest policy, in common with developments in many other Western countries, now embraces a broader range of objectives. The last decade has seen changes in forest practice that reflect increasing public pressure for planting of new-native woodlands, restoration of native woodlands from plantations, and a continued increase in woodland cover. There is also greater public participation in forest planning, and some explicit attempts by planners to incorporate community aspirations. However, in the absence of natural forests to act as templates, there are many options. The potential in managed and productive land uses are relatively well understood, but the scope for more 'natural' options, as expressed in public preference, is more problematic.

In Scotland, there is particular interest in expanding the area of 'Caledonian' pine forest, and in restoring a landscape with appropriate forested networks (Peterken et al. 1995). Such natural forests of Scots pine (*Pinus sylvestris* var. *scotica* (Willd.) Schott) and birch (*Betula* spp) would be oceanic boreal in character (Kuusela 1992; Worrell 1996) and have similarities with those of south-west and southern Norway; however, the forests do not contain Norway spruce which did not naturally colonise Britain after the last glaciation. The remnants of semi-natural forests are extremely scarce and as a consequence there is little to guide the forest restoration in terms of proportion of forest type and location in the landscape. Some guidance is provided by paleo-ecological studies with pollen assemblages providing clues to composition (Tipping et al. 1999) and macro-fossils providing indication of past extent. However, there are limitations to this

approach in the extent of climate change since the pollen was deposited, and in the future, and changes to soil character such as the increase in extent of blanket bog.

As a consequence, there has been increasing interest in the application of models that describe current site suitability for tree species or woodland communities. Such models can be developed both for productive tree species, and for native woodland types (Pyatt 1997; Pyatt et al. 2001). Predictive models of suitability were initially developed as site-based tools (Rodwell and Patterson 1994; Pyatt and Suárez 1997) but recently have been extended to operate at the landscape scale (Macmillan et al. 1997; Clare and Ray 2001).

The structure and composition of many natural forests is determined by the disturbance regime (whether abiotic or biotic). An understanding of the disturbance regimes can allow natural forests to act as templates to inform forest management (Bergeron et al. 1999; Cissel et al. 1999). However, the remnant semi-natural forest in Britain has been highly modified by centuries of exploitation by man and over-grazing by herbivores (Fuller and Gill 2001). There are no natural forests left that can provide unequivocal evidence of disturbance regime or the resultant forest structure. The maritime character of the climate indicates that wind is likely to be an important disturbance agent that will govern the structure of forests (Quine et al. 1999). In contrast, natural fire is extremely rare; a situation similar to coastal Norway (Rolstad et al. 2001). Management of productive forests is constrained by frequent strong winds (Quine 1995; Quine et al. 1995). A model (ForestGALES) has recently been developed to calculate the risk of windthrow in managed forests, by combining data on tree characteristics and wind climate (Gardiner and Quine 2000).

1.2 Specific Context – Participatory Planning in Strathdon

The particular context for this study was provided by a participatory planning workshop held in September 1999 in Strathdon (NE Scotland) under the auspices of the CROSSPLAN project funded

by the EU Northern Periphery Programme (Bell and Komulainen 2001). The main aims of the workshop were to integrate an ecological analysis of the Strathdon catchment with socio-economic and cultural analyses of the local community and to explore mechanisms for improving public participation in the design planning process.

The principles underlying the ecological analysis were that forest ecological processes must be considered in rural/landscape planning, and that site suitability (for native and non-native woodland types) and woodland development dynamics constrain options for change.

1.3 Purpose of Study

The purpose of the work, using Strathdon as a case study, was to

- 1) Modify two existing models, largely used within productive forest management, to be applicable to natural woodland.
- 2) Explore their use to predict the potential extent, composition and disturbance-related structure of restored native woodland

Note that the potential for an expansion of productive woodland was provided to the workshop but this is not reported here.

2 Methods

2.1 Models Used

2.1.1 Ecological Site Classification

The Ecological Site Classification (ESC) provides a methodology for objectively assessing and classifying a site in terms of its ecological potential for the suitability and yield of a range of tree species or of native woodland communities (Pyatt and Suárez 1997; Pyatt et al. 2001). Site suitability is determined by a combination of climate and soil variables (Wilson et al. 2000), in a manner similar to that used in British Columbia and elsewhere (Pojar, et al. 1987). The National Vegetation Classification identifies 19 native woodland

types (and many sub-types) and 6 scrub types (Rodwell 1991), and these form the basis for the ESC predictions of native woodlands.

The four variables used to describe climate are accumulated temperature, moisture deficit, windiness and continentality. Accumulated temperature (AT) represents the warmth needed for tree growth, and is calculated as day degrees above a threshold of 5 degrees C. Moisture deficit (MD) reflects the water availability during the growing season, and is calculated as the excess of evaporation over precipitation. The 'Detailed Aspect Method of Scoring' (DAMS) is an index reflecting locational and topographic influences on mean windiness which can be used to reflect physiological constraints of wind on tree growth (Quine and White 1993; Quine and White 1994). Continentality expresses the seasonal variation in climate and ESC uses the Conrad index (Birse 1971; Bendelow and Hartnup 1980). Values for these four climate variables have been calculated at a resolution of 250 m for the whole of Britain using climatic data and topographic models (Pyatt et al. 2001).

The two soil quality variables are Soil Moisture Regime (SMR), describing soil wetness and Soil Nutrient Regime (SNR), describing nutrient availability. Soil nutrient regime (SNR) can be predicted from soil type, humus form, or the presence and abundance of field layer vascular plants as indicators (Wilson et al. 1998; Wilson et al. 2000; Hill et al. 1999). Soil moisture regime (SMR) can be estimated from soil type or derived from topographic factors.

2.1.2 ForestGALES

The ForestGALES model calculates the threshold wind speed required to break or to overturn a typical tree, based on mechanical characteristics of the stem form and the species (Dunham et al. 2000; Gardiner and Quine 2000). The likelihood of the threshold wind speed being exceeded is assessed for location in the country and topography, using a conversion of mean wind speed to extreme wind speed. Mean wind speed is estimated using the DAMS system that combines the influence of regional location, elevation, topographic shelter, funnelling and aspect on site

windiness. The probability of the extreme wind speed is derived by conversion of DAMS into parameters of the Weibull distribution for wind speed (Quine 2000). Damage to the typical tree can be interpreted as catastrophic damage to the stand.

2.2 Study Site Details

Strathdon is a catchment in the Eastern Highlands of Scotland, the river Don draining the North-eastern flank of the Cairngorm mountains and reaching the North Sea at Aberdeen (Fig. 1). The study area comprised the valley of the upper Don catchment (Latitude 57°20'N, Longitude 3°1'W), and extended to 284 km². The area has an elevation range of 200–800 m, the valley sides are convex and relatively smooth, and the valley bottom is generally flat and broadens downstream (Fig. 2). The underlying bedrocks are basic igneous (Dalradian schists and granite intrusions) and there are locally important glacial and fluvio-glacial deposits. A range of soils have developed based on material and topographic position; many are of poor nutrient status, but are generally well-drained (Heslop and Bown 1969). There are localised gley soils on terraces but peat is restricted to flatter areas above 650 m.

The climate is continental (in British terms) with cold winters, and a short (<200 days) but intense growing season. Conrad index values range from 6.1 to 6.7 for the study site. Annual temperature range is typically –20 to +25 degrees C, with monthly means ranging from +1 (January) to +13 (July) degrees C. There is a strong

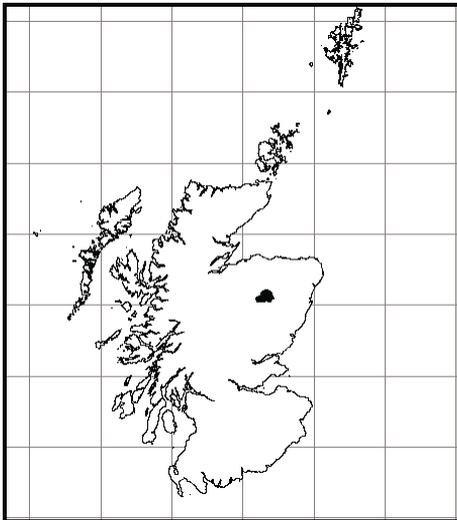


Fig. 1. Location of Strathdon study site in Scotland, with 100 km National Grid. Centre of study site has Latitude 57°12'N, Longitude 3°05'W.

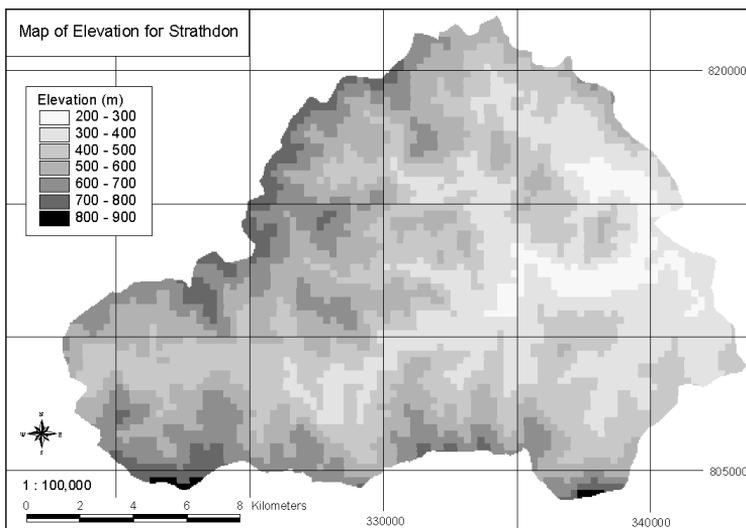


Fig. 2. Elevation map of study area derived from 1:50000 Ordnance Survey Digital Terrain Model.

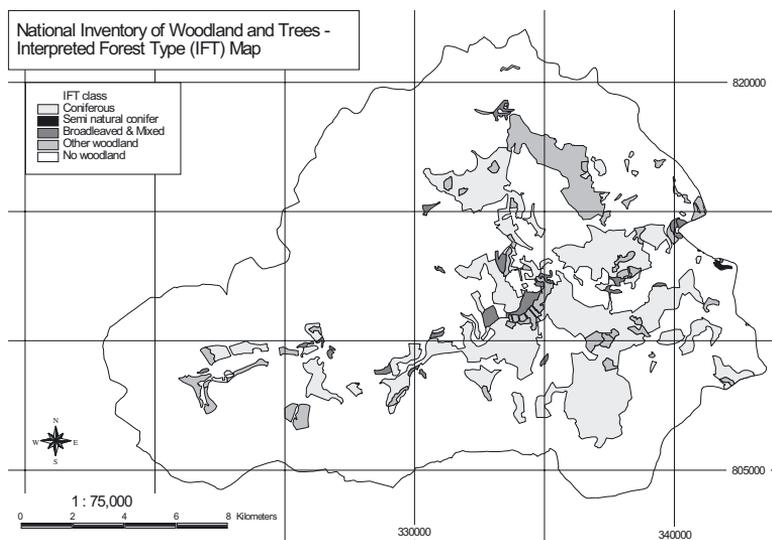


Fig. 3. Current forest cover of Strathdon derived from National Forest Inventory.

topographic control of climate with severe conditions at high elevations. Accumulated temperature (AT above 5 degrees) ranges +950 at 200 m, to +250 at 800 m, precipitation from 870 to 1100 mm, and moisture deficit (in the growing season) from +75 mm to -75 mm. Extreme temperature minima reflect topographic drainage and are lowest in valley situations. Snow cover varies from 10 to 60 days, and constitutes less than 40% of total precipitation. Wind speeds are generally lower than in the exposed west of Scotland, but there is some localised funnelling – the DAMS values for Strathdon range from 6 to 24, indicating a range in mean wind speed of approximately 2 to 8 ms⁻¹.

The current landscape of Strathdon reflects a long history of intensive management, with low forest cover (Fig. 3) and land use that is strongly compartmentalised. In the valley bottoms, agriculture, and particularly silage production, predominates. The lower slopes have marginal pasture or planted forests (frequently of exotic conifer species, many planted since 1945). At the highest elevations are moorlands (*Calluna*-dominated heaths) managed by burning to favour conditions for red grouse (*Lagopus lagopus*), and also deer stalking. The forest history reflects that of the region with a long history of management and use of clearfelling and replanting as

the main form of management (Tuley 1987). As early as 1507 forest rights were being granted to land-owners in Strathdon (Matthews 1976), tree-planting was recorded from 1745, and by 1792 there were ‘no natural woods of any consequence’ (Anderson 1967). Therefore, native woodland cover is very sparse, with small birch woods on the valley sides, small pockets of woodland in the riparian zone, but no pinewood remnants. Current forest cover is shown in Fig. 3.

2.3 Derivation of Native Woodland Suitability from ESC

Application of the Ecological Site Classification to Strathdon involved the preparation of maps reflecting the four climate variables, and the two soil variables. A rule-base developed to reflect the suitability of combinations of these factors for the native woodland types was applied to the conditions present in the study area. Maps reflecting the particular features of interest were produced in ARCVIEW GIS.

The provision of the soil data was most problematic because of the lack of digital soil data at an appropriate scale and with sufficient coverage. Soil quality was estimated from the Land Cover of Scotland dataset (LCS88) derived from aerial

Table 1. Climate and soil rules for determining suitable native woodland communities. Possible values for SMR: VW = very wet, W = wet, VM = very moist, M = moist, F = fresh, SD = slightly dry, MD = moderately dry. Possible values for SNR: VP = very poor, P = poor, M = medium, R = rich, VR = very rich, C = Carbonate.

Woodland Community	AT	MD	DAMS	CON	SMR	SNR
W4 <i>Betula pubescens</i> – <i>Molinia caerulea</i> woodland	>500	All	<20	All	W or VM	P or M
W7 <i>Alnus glutinosa</i> – <i>Fraxinus excelsior</i> – <i>Lysimachia nemorum</i> woodland	>800	All	<19	All	W, VM or M	R or VR
W9 <i>Fraxinus excelsior</i> – <i>Sorbus aucuparia</i> – <i>Mercurialis perennis</i> woodland	700–900	<120	<20	<11	VM, M or F	R or VR
W11 <i>Quercus petraea</i> – <i>Betula pubescens</i> – <i>Oxalis acetosella</i> woodland	700–1800	>20	<19	<11	M or F	P, M or R
W17 <i>Quercus petraea</i> – <i>Betula pubescens</i> – <i>Dicranum majus</i> woodland	>700	<100	<20	<16	M, F or VM	P or M
W18 <i>Pinus sylvestris</i> – <i>Hylocomium splendens</i> woodland	>400	All	<20	1–10	VM, M, F or SD	VP
W18 <i>Pinus sylvestris</i> – <i>Hylocomium splendens</i> woodland (krummholz)	>400	All	20–24	All	All	All
W19 <i>Juniperus communis</i> spp. <i>communis</i> – <i>Oxalis acetosella</i> woodland	600–1400	All	<19	<16	M, F or SD	P or M
W20 <i>Salix lapponum</i> – <i>Luzula sylvatica</i> scrub	<800	<80	<20	<16	VM, M or F	P or M

photography. LCS88 contains digital information on vegetation community cover at the 1:25 000 scale for the whole of Scotland (Macaulay Land Use Research Institute 1993). SMR and SNR values were ascribed to the various land cover classes, using a combination of previous ground survey of soils and indicator plants, and interpretation of existing soil maps. Values for SMR ranged from Fresh to Wet and SNR from Rich to Very Poor.

The rules for determining suitable native woodland communities are shown in Table 1. The ‘Map Query’ Tool in ARCVIEW was used to find the areas which matched the woodland community criteria from the climate and soils layers. Where more than one woodland type was indicated as suitable, a hierarchy was applied based on field observations within Strathdon of the remaining woodland fragments; in essence we considered the most important factor to be soil nutrient regime, followed by warmth, and wind tolerance. Thus, in areas where NVC woodland type W17 (*Quercus petraea*–*Betula pubescens*–*Dicranum majus*) and W11 (*Quercus petraea*–*Betula pubescens*–*Oxalis acetosella*) were both suited edaphi-

cally, W11 was chosen on warmer parts. Similarly for W17 and W18 (*Pinus sylvestris*–*Hylocomium splendens*) in similar areas climatically, W18 was chosen on the very poor soil types, and W17 on the slightly better soils.

2.4 Derivation of Forest Structure Using ForestGALES

ForestGALES has been developed using destructive sampling of trees in productive, managed forests. No such data are available to represent the mechanical properties of trees in British native woodlands, so three assumptions were necessary to proceed with this study. Firstly, because the model has been developed for coniferous trees, the calculations were limited to Scots pine. Note, that this is the only native stand-forming conifer, and is the major component of the Caledonian forest; results from the ESC predictions (see below) indicate that over half of the study area would be most suited to pine-dominated communities. Results from comparisons between the ForestGALES model and a Finnish model

Table 2. Disturbance related structure classes for Strathdon based on DAMS score

Description score	Class type	Definition	Rule – DAMS
Above treeline – no trees present	Above treeline	Beyond the limit of known Scots pine growth	>24
Krummholz and severely wind swept trees; trees adapted to severe wind regime and not susceptible to widespread windthrow – fine grained disturbance predominates	Krummholz	Between limit of productive woodland and treeline	>20 and <=24
Mosaic of large scale even-aged patches with frequent disturbance	Stand replacement	Cumulative probability of windthrow >0.5 within 100 years	>15 and <=20
Mosaic of occasional large scale even-aged patches within matrix of older forest where fine-grain disturbance occurs	Shifting Mosaic	Cumulative probability damage <0.5 within 100 years but >0.5 within 300 years	>13 and <= 15
Forest in which fine grained disturbance predominates and no large-scale patches are present	Gap phase	Cumulative probability <0.5 within 300 years	<=13

(HWIND) have suggested relatively small differences in tree stability between Scots pine and Norway spruce (with the latter tending to be more unstable) (Gardiner et al. 2000). Model runs of HWIND for Scots pine, Norway spruce and Birch showed that species differences were generally less than the differences due to change in stand parameters as a result of management (Peltola et al. 1999), although birch, when leafless, was substantially less vulnerable. Secondly, Forestry Commission yield tables (Edwards and Christie 1981) provide the necessary physical dimensions of the stems, but no such models are available for the native woodland types. A single yield table (Scots pine, yield class of 8) was selected regardless of topographic position or soil; this yield class is the most common in existing productive stands in the catchment (S. Brown, pers comm.); the yield table for an initial plant spacing at establishment of 1.8 m, and mortality with no operational thinning was used. Thirdly, the available yield model does not extend beyond a stand age of 100 years, this final value was assumed to hold for the succeeding 200 years because at this age the change in threshold wind speed was slight.

The vulnerability of Scots pine was assessed by calculating the threshold wind speed required to over-turn, or snap, the mean tree at various stages in the stand growth up to 300 years of age assuming a freely draining soil. The likelihood of these threshold wind speeds being exceeded was assessed for a number of topographic positions represented by a range of DAMS values. The annual probability of damage was calculated and a cumulative probability derived (Moore and Quine 2000).

Five disturbance-related structure classes were defined based on the frequency, and implicit scale of likely wind disturbance and structure types identified in the literature on wind disturbance (Quine et al. 1999) (Table 2). On the most exposed sites is a zone (Above Treeline) where wind exposure and lack of warmth make tree growth impossible. Below this is a zone (Krummholz), where growth of woody plants is possible, but will be limited to dwarf or other highly adapted forms; these are unlikely to be overturned by strong winds as the canopy of the stand is streamlined. In the zone of good tree growth, there is a zone (Stand replacement) where probability of catastrophic disturbance is very

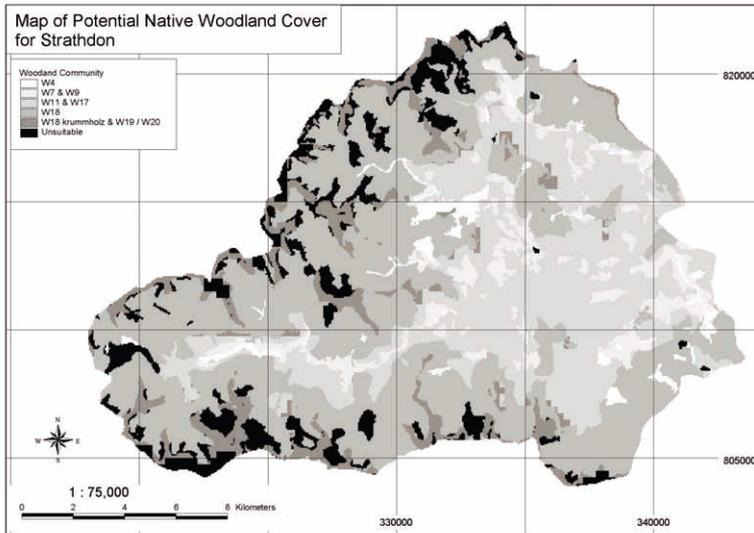


Fig. 4. Map of potential native woodland cover developed using the Ecological Site Classification. See Table 1 for further description of native woodland types.

high and likely to lead to a mosaic of even-aged patches of several hectares. In the most sheltered zone (Gap phase), catastrophic disturbance is extremely rare, and there is adequate time in the intervening periods for an uneven structure to result. In between these two zones is an intermediate zone (Shifting mosaic) where a mix of even-aged patch and diverse remnant may emerge – depending upon the precise frequency of the strong winds and rate of recovery of the forest.

Mapping of the structure classes is possible by allocating DAMS scores as thresholds for each zone, thereby representing the likelihood of critical wind speeds. The thresholds were identified by interpretation of the cumulative probability results for Strathdon and using established relationships for treelines and wind-adapted pine forest (Hale et al. 1998). Note that a single set of DAMS threshold values were sufficient as the modelling had only considered a single species and soil type.

3 Results

3.1 Native Woodland Suitability Maps

The predicted native woodland cover for Strathdon is shown in Fig. 4. Over 90% of Strathdon is potentially wooded, more than four times the current area covered by all types of forest. Only a limited range of native woodland types are predicted, but only the highest ground is identified as being unsuitable for tree growth (Table 3). Important elements of the forested landscape would include – a significant zone of krummholz or sub-alpine woodland at high elevations; pine woodland (W18) covering at least half of the area and in particular the current extensive upland heaths; and Oak/birch woodland (W11) covering the better soils of the lower valley slopes (25% of the land area). The other wetter and richer woodland types (W4, W7 and W9) are predicted to form a minor (<10% of the land area) yet important component of habitat diversity.

Table 3. Area of predicted NVC woodland communities for Strathdon (not including constraints of current buildings, forests etc).

Woodland community	Area(ha)	%land area
W4 <i>Betula pubescens</i> – <i>Molinia caerulea</i> woodland	786	2.8
W7 <i>Alnus glutinosa</i> – <i>Fraxinus excelsior</i> – <i>Lysimachia nemorum</i> woodland	1783	6.3
W9 <i>Fraxinus excelsior</i> – <i>Sorbus aucuparia</i> – <i>Mercurialis perennis</i> woodland	283	1.0
W11 <i>Quercus petraea</i> – <i>Betula pubescens</i> – <i>Oxalis acetosella</i> woodland	7150	25.2
W17 <i>Quercus petraea</i> – <i>Betula pubescens</i> – <i>Dicranum majus</i> woodland	189	0.6
W18 <i>Pinus sylvestris</i> – <i>Hylocomium splendens</i> woodland	13415	47.2
W18 <i>Pinus sylvestris</i> – <i>Hylocomium splendens</i> woodland (krummholz)	2145	7.5
W19 <i>Juniperus communis</i> spp. <i>communis</i> – <i>Oxalis acetosella</i> woodland	221	0.8
W20 <i>Salix lapponum</i> – <i>Luzula sylvatica</i> scrub	15	0.1
Unsuitable	2404	8.5
Total	28391	100.0

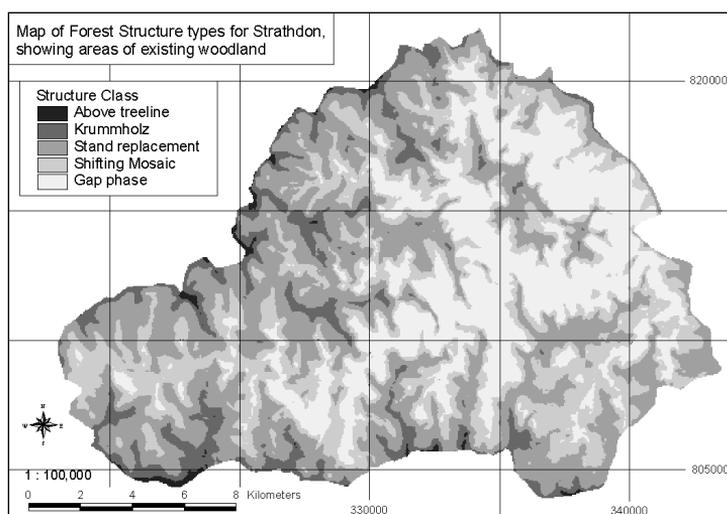


Fig. 5. Map of wind disturbance structure classes developed using the ForestGALES model. See Table 2 for further description of structure classes.

3.2 Maps of Woodland Structure Classes

Results from the application of the ForestGALES model indicate that the full range of wind disturbance regimes/structure types could develop within the study area (Table 4, Fig. 5). Elevation, through its influence on wind speed, has a strong control on the spatial pattern. The zone unsuitable for tree growth is small (<1%) but below this is an extensive krummholz zone with wind-adapted woody plant growth. The majority of the landscape is composed of the three zones where

Table 4. Area of Strathdon falling in different disturbance related structure classes

Class type	Area(ha)	% land area
Gap phase	7082	24.9
Shifting Mosaic	7749	27.3
Stand replacement	10997	38.8
Krummholz	2364	8.3
Above treeline	199	0.7
Total	28391	100

Table 5. Area of current woodland cover falling into different disturbance related structure classes.

IFT Woodland Class type (from Fig. 3)	Structure Class (ha)				
	Gap phase	Shifting mosaic	Stand replacement	Krummholz	Total area
Coniferous	1594.2	1478.5	920.2	2.5	3995.5
Mixed	130.2	19.0	11.7	0	161.0
Young trees	300.5	233.2	251.7	0	785.5
Ground prepared for planting	7.2	63.5	0	0	70.7
Shrub	39.2	20.5	1.2	0	61.0
Felled	77.5	32.5	36.0	0	146.0
Other	126.7	12.2	0	0	139.0
Broadleaved	60.7	34.7	13.2	0.5	109.2
Semi natural conifer	0	6.7	4.7	0	11.5
Total area	2336.5	1901.0	1239.0	3.0	5479.5
% of potential wooded area in class	33.0	24.5	11.3	0.1	19.3

tree growth is possible, but where the structure is determined by differences in the disturbance regime. The “stand replacement zone”, where catastrophic disturbance is likely to lead to a mosaic of even-aged patches, covers almost 40% of the area and is concentrated on upper valley slopes where wind exposure is severe. In the most sheltered parts of the valley is a significant extent of the “gap-phase” zone, indicating potential development of an uneven-aged stand structure with “old-growth” characteristics.

The proportion of the existing woodland area found in each zone is given in Table 5. The results show that around 80% of the current forest is located in the two sheltered zones, and that there is a marked decline in proportion remaining as the wind disturbance becomes more extreme.

4 Discussion

4.1 Validity of Approach

In many regions, studies of the composition and structure of existing natural woodland, and an understanding of the natural or historic variability is a valuable guide to ecological management of landscapes (Landres et al. 1999; Parsons et al. 1999). A variety of techniques including disturbance regime analysis, and empirical estimation of past composition and structure can help to provide reference conditions (Moore et al. 1999; Cissel et al. 1999; Swetnam et al. 1999), and may be viewed as preferable to a delphic approach

using expert panels (Hessburg et al. 1999). However, there are serious limitations to the natural variability approach where the landscape is highly modified. For example, in Scotland, the remaining area of native pinewood is approximately 18000 ha (Jones 1999) and none of it is in pristine condition. Historical reconstruction can aid decision-making – for example through analysis of paleo-ecological evidence to guide restoration (Tipping et al. 1999). In the Strathdon area for which we were asked to provide an ecological analysis, there was no such investigation. In such circumstances, where current conditions bear little relationship with past natural variability or desired future condition, Landres et al. (1999) acknowledge that the natural variability approach may not be immediately applicable. Instead, restoration may be the best course of action, followed in time by less-intensive management under a natural variability approach (Wallin et al. 1996). In this study, a hybrid approach has been adopted, where predictions of possible natural variability are used to guide the prospects (and choices) for restoration. Model predictions, based on best expert judgement, known site requirements of native woodland types, and a mechanistic treatment of the interaction of trees and wind (the main abiotic disturbance agent), provides the coarse-filter required for planning the direction, not the detail of restoration of native woodland.

4.2 Implications of Predictions

The application of ESC and ForestGALES to predict the ecological potential of Strathdon has indicated that a substantial proportion of the catchment could support native woodland communities. The range of woodland types is limited by the climate and soil characteristics, which also restrict the species choice for productive woods (results not provided here). The mix of structure classes predicted for Strathdon reflects the dramatic change in environmental conditions over short distances due to the effects of topography/elevation. However, much of the potential woodland could achieve substantial age (size) without likely stand-replacement disturbance, and permit the development of a diverse stand structure. The majority of the current woodland is found in the two most sheltered zones, where a varied structure appears possible – but the majority of these stands are currently managed through a silvicultural system i.e. clearfelling that prevents diverse structure and is more akin to a stand replacement regime. This reflects the dominance of investment and risk management, rather than broader ecosystem values, in the recent management of the Strathdon forests.

There is an almost complete lack of woodland in the krummholz zone, reflecting observations elsewhere in Britain and supporting the current interest in restoring treeline woodlands and montane scrub (Gilbert et al. 1997; Forestry Authority (Scotland) 1998). Arguably, the lack of forest in the most exposed zones may reflect the relative ease of destruction of forest by man when the environmental conditions are already severe.

4.3 Assessing the Value of the Predictions

It is impossible to formally validate the model predictions at present but support for their overall validity can come from a variety of sources.

At the most basic level, no existing woodland is present outwith the boundaries of the predicted woodland area. Limited field observations have indicated regenerating Scots pine trees on patches of unburned high elevation heathland, in the zone predicted as suitable for pine woodland. The contrast in amount of ‘unwooded’ area between the

ESC (8.5%) and ForestGALES (0.7%) predictions reflects the difference between the general environmental limitations (warmth, windiness and soil), and the wind-only limitation.

Comparison of results with predictions of an alternative woodland suitability model applied to the wider Cairngorms area (Towers et al. 1999) indicate broad agreement in extent – for a larger study area (Strathdon and Glenlivet), 9.2% was identified as unsuitable for tree/shrub growth compared to 8.5% from the ESC predictions. A formal comparison of these alternative models of woodland suitability has highlighted the influence of different resolutions of input data, but confirmed reasonable agreement over composition and extent (Towers et al. 2001).

During the participatory planning workshops, local managers accepted the general validity of the forest cover predictions. However, local inhabitants were surprised at the extent of the potential woodland, believing the highly managed heather moorland to be natural.

Clear-felling, during the World Wars and subsequently, has truncated the age-class and structure development in most of the existing forest areas. As a consequence, even the areas of non-native conifers give little guide to the potential disturbance regime. However, small areas of ‘policy’ woods surrounding the Estate houses in the valley bottoms indicate the potential for trees to survive several hundred years and grow to large dimensions. This indicates that diverse ‘old growth’ stands could be a structural element in a more natural forested landscape. The youthfulness and small area of forest in the stand replacement zone means that the predictions of frequent catastrophic disturbance are difficult to assess. There has been recent windthrow on wetter soils in this zone, and it might be possible to use historical aerial photographs to provide more evidence. Extensive damage to forests in the region occurred in a storm in 1953 (up to 25% of mature forest), with maximum gusts of 50 ms⁻¹ experienced in Aberdeen (Lines 1954; Quine 1988).

4.4 Potential Improvements to the Models

There is clearly scope for further refinements to the modelling, particularly in the application of

ForestGALES to broadleaved trees and to natural woodland types. The calculations of critical wind speed for Scots pine would benefit from improved mensurational data for 'natural' stands, including estimates of anchorage and canopy roughness of 'old growth' stands, as tree characteristics are an important influence on threshold wind speeds (Gardiner et al. 2000). There is a general lack of information about the stability of broadleaved trees and associated woodland types, and this would require substantial fieldwork to gather the necessary stem and root characteristics for each species required. However, such parameterisation for other woodland types has proved possible (Ruel et al. 2000).

The location and proportion of the different structure classes is very sensitive to the decisions made over the relationship between frequency of disturbance and structural development. It is possible that comparisons with other maritime areas as well as more continental examples of the boreal forest could inform these choices. At this stage it is not possible to be more precise about the spatial detail within the structure zones, or of the range of gap/patch sizes that might be found. The spatial pattern would reflect the mosaic of varying site conditions, the particular features of damaging winds (e.g. landform aspect versus wind direction) and the initial conditions; again, this might be informed by comparisons with similar, more natural forests in other countries (Quine et al. 1999). At present, a single disturbance type, strong winds, is considered and the role of wet snow, fire and biotic agents such as herbivory, fungal infection are not considered. Both the ESC and ForestGALES predictions would be enhanced by better site characterisation and in particular high resolution soils data.

4.5 Potential for Restoration of Native Woodland

There are substantial biological and socio-economic obstacles to woodland restoration and expansion. Expansion will only occur if there are changes in support for agriculture, or a decline in the demand for sporting shoots for grouse and deer. Even then the potential may be limited by continued herbivory, by community aspira-

tions, and by other nature conservation requirements. The potential woodland cover is reduced by approximately 50% if constraints of built-up areas, recreation areas, existing productive woodland, and designated Sites of Special Scientific Interest are incorporated in the analysis. The latter reflect the uniqueness of the landscape in European terms, and the importance of the heathlands for a range of open ground species (particularly of birds). The lack of forest has contributed to the local community placing a high value on an open landscape, and considering this to be the natural state.

The most obvious mechanism to achieve a rapid expansion of woodland area is by planting, but there is a general preference for natural regeneration as a means of restoration (Ratcliffe et al. 1998). The lack of local seed sources would then be an important constraint on the rate by which an increase in woodland cover could be achieved. For example, the W11 Oak/birch community would tend to be dominated by birch as there is very little oak within Strathdon, possibly reflecting past preferential exploitation.

5 Conclusion

The highly modified landscape of Strathdon presents a substantial challenge to those wishing to consider future ecological potential and encourage development of forested networks. The high degree of past management is a serious limitation to the use of 'natural' woodland as a template for future action. The application of models that codify the best current understanding of site suitability of appropriate woodland types and likely frequency of disturbance, provides a promising method to guide restoration and expansion of forest in such circumstances. The extent to which the forest area can be restored is limited by a wide range of social and economic demands, as well as by the biological limitations that are addressed by the existing models.

Acknowledgements

Discussions with Simon Bell stimulated the application of the models to the Strathdon catchment and he led a valuable discussion of the results at the workshop. Steve Brown and Bill Rayner provided much useful information on Strathdon and the soil quality estimation. Dr Eeva Korpilahti provided valuable suggestions for improving the paper.

References

- Anderson, M.L. 1967. A history of Scottish Forestry, volumes 1 and 2. Nelson, London. 662+654 p.
- Bell, S. & Komulainen, M. (Eds.). 2001. CROSS-PLAN: Integrated participatory planning as a tool for rural development. Kajaani, University of Oulu. 109 p.
- Bendelow, V.C. & Hartnup, R. 1980. Climatic classification of England and Wales. Soil Survey Technical Monograph 15. Rothamsted Experimental Station, Harpenden. 27 p.
- Bergeron, Y., Harvey, B., Leduc, A. & Gauthier, S. 1999. Forest management guidelines based on natural disturbance dynamics: stand- and forest-level considerations. *The Forestry Chronicle* 75(1): 49–54.
- Birse, E.L. 1971. Assessment of climatic conditions in Scotland, 3: The bioclimatic sub-regions. Macaulay Land Use Research Institute, Aberdeen. 12 p.
- Cissel, J.H., Swanson, F.J. & Weisberg, P.J. 1999. Landscape management using historical fire regimes: Blue river, Oregon. *Ecological Applications* 9(4): 1217–1231.
- Clare, J.D. & Ray, D. 2001. A spatial model of ecological site classification for forest management in Britain. Proceedings of the 4th AGILE Conference on Geographic Information Science, Brno, April 19–21, 2001. Masaryk University, Brno. p. 93–111.
- Dunham, R., Gardiner, B., Quine, C. & Suarez, J. 2000. ForestGALES: a PC-based wind risk model for British forests – Version 1.3 User's Guide. Forestry Commission, Edinburgh.
- Edwards, P.N. & Christie, J.M. 1981. Yield models for forest management. Forestry Commission Booklet 48. HMSO, London. 32 p.
- Forestry Authority (Scotland). 1998. Treeline woodlands and the woodland grant scheme. Guidance Note. Forestry Commission, Edinburgh. 8 p.
- Fuller, R.J. & Gill, R.M.A. 2001. Ecological impacts of increasing numbers of deer in British woodland. *Forestry*, 74(3): 193–200.
- Gardiner, B.A. & Quine, C.P. 2000. Management of forests to reduce the risk of abiotic damage – a review with particular reference to the effects of strong winds. *Forest Ecology and Management* 135: 261–277.
- , Peltola, H. & Kellomäki, S. 2000. Comparison of two models for predicting the critical wind speeds required to damage coniferous trees. *Ecological Modelling* 129: 1–23.
- Gilbert, D., Horsfield, D. & Thompson, D.B.A. (eds). 1997. The ecology and restoration of montane and subalpine scrub habitats. Scottish Natural Heritage Review 83. Scottish Natural Heritage, Battleby. 128 p.
- Hale, S.E., Quine, C.P. & Suárez, J.C. 1998. Climatic conditions associated with treelines of Scots pine and birch in Highland Scotland. *Scottish Forestry* 52(2): 70–76.
- Heslop, R.E.F. & Bown, C.J. 1969. The soils of Candacraig and Glenbuchat. Soil Survey of Scotland, Bulletin 1. The Macaulay Institute for Soil Research, Aberdeen. 116 p.
- Hill, M.O., Mountford, J.O., Roy, D.B. & Bunce, R.G.H. 1999. Ellenberg's indicator values for British plants. ECOFACT Volume 2, Technical Annex. Institute of Terrestrial Ecology, Huntingdon. 46 p.
- Jones, A.T. 1999. The Caledonian pinewood inventory of Scotland's native Scots pine woodlands. *Scottish Forestry* 53(4): 237–242.
- Kuusela, K. 1992. Boreal forests – an overview. *Unasylva* 170: 22–25.
- Landres, P.B., Morgan, P. & Swanson, F.J. 1999. Overview of the use of natural variability concepts in managing ecological systems. *Ecological Applications* 9(4): 1179–1188.
- Lines, R. 1954. Investigations into damage by the gale of January 31st 1953. In: 1954 Report on Forestry Commission Research. HMSO, London. p. 47–49.
- Macaulay Land Use Research Institute. 1993. The land cover of Scotland 1988. Macaulay Land Use Research Institute, Aberdeen.

- Macmillan, D.C., Towers, W., MacLeay, S. & Kupiec, J. 1997. Modelling the potential distribution of the native woodland resource in the Cairngorms. *Scottish Forestry* 51(2): 70–75.
- Matthews, J.D. 1976. The evolution of the forests. In: Edlin, H.L. (ed.), *Forests of North-east Scotland: Forestry Commission Guide*. Edinburgh, HMSO. p. 7–13.
- Moore, J. & Quine, C.P. 2000. A comparison of the relative risk of wind damage to planted forests in Border Forest Park, Great Britain and Central North Island, New Zealand. *Forest Ecology and Management* 135: 345–353.
- Moore, M.M., Covington, W.W. & Fulé, P.Z. 1999. Reference conditions and ecological restoration: a southwestern Ponderosa pine perspective. *Ecological Applications* 9(4): 1266–1277.
- Parsons, D.J., Swetnam, T.W. & Christensen, N.L. 1999. Uses and limitations of historical variability concepts in managing ecosystems. *Ecological Applications* 9(4): 1177–1178.
- Peltola, H., Kellomäki, S., Väisänen, H. & Ikonen, V.-P. 1999. A mechanistic model for assessing the risk of wind and snow damage to single trees and stands of Scots pine, Norway spruce, and birch. *Canadian Journal of Forest Research* 29(6): 647–661.
- Peterken, G.F., Baldock, D. & Hampson, A. 1995. A forest habitat network for Scotland. Research, Survey and Monitoring Report 44. Scottish Natural Heritage, Battleby. 122 p.
- Pojar, J., Klinka, K. & Meidinger, D. 1987. Biogeoclimatic ecosystem classification in British Columbia. *Forest Ecology and Management* 22: 119–154.
- Pyatt, D.G. 1997. A site classification for Scottish native woodlands. *Botanical Journal of Scotland* 49(2): 455–467.
- Ray, D. & Fletcher, J. 2001. An ecological site classification for forestry in Great Britain. *Bulletin* 124. Forestry Commission, Edinburgh. 74 p.
- & Suárez, J.C. 1997. An ecological site classification for forestry in Great Britain, with special reference to Grampian, Scotland. *Technical Paper* 20. Forestry Commission, Edinburgh. 96 p.
- Quine, C.P. 1988. Damage to trees and woodlands in the storm of 15–16 October 1987. *Weather* 43: 114–118.
- 1995. Assessing the risk of wind damage to forests: practice and pitfalls. In: Coutts, M.P. & Grace, J. (eds), *Wind and trees*. Cambridge University Press, Cambridge. p. 379–403.
- 2000. Estimation of mean wind climate and probability of strong winds from assessments of relative windiness. *Forestry* 73(3): 247–258.
- & White, I.M.S. 1993. Revised windiness scores for the windthrow hazard classification: the revised scoring method. *Research Information Note* 230. Forestry Commission, Edinburgh. 6 p.
- & White, I.M.S. 1994. Using the relationship between rate of tatter and topographic variables to predict site windiness in upland Britain. *Forestry* 67(3): 245–256.
- , Coutts, M.P., Gardiner, B.A. & Pyatt, D.G. 1995. Forests and wind: management to minimise damage. *Forestry Commission Bulletin* 114. HMSO, London. 24 p.
- , Humphrey, J.W. & Ferris, R. 1999. Should the wind disturbance patterns observed in natural forests be mimicked in planted forests in the British uplands? *Forestry* 72(4): 337–358.
- Ratcliffe, P.R., Peterken, G.F. & Hampson, A. 1998. A forest habitat network for the Cairngorms. Research, Survey and Monitoring Report 114. Scottish Natural Heritage, Battleby. 85 p.
- Rodwell, J.S. (ed.). 1991. *British plant communities, Vol. 1. Woodlands and scrub*. Cambridge University Press, Cambridge. 395 p.
- & Patterson, G.S. 1994. Creating new native woodlands. *Forestry Commission Bulletin* 112. HMSO, London. 74 p.
- Rolstad, J., Gjorde, I., Storanet, K.O. & Rolstad, E. 2001. Epiphytic lichens in Norwegian coastal spruce forest: historic logging and present forest structure. *Ecological Applications* 11(2): 421–436.
- Ruel, J.-C., Quine, C.P., Meunier, S. & Suárez, J.C. 2000. Estimating windthrow risk in balsam fir stands with the ForestGales model. *The Forestry Chronicle* 76(2): 329–337.
- Swetnam, T.W., Allen, C.D. & Betancourt, J.L. 1999. Applied historical ecology: using the past to manage for the future. *Ecological Applications* 9(4): 1189–1206.
- Tipping, R., Buchanan, J., Davies, A. & Tisdall, E. 1999. Woodland diversity, palaeo-human ecology and some implications for conservation management. *Journal of Biogeography* 26(1): 33–43.
- Towers, W., Malcolm, A., Hester, A., Ross, I. & Baird, E. 1999. Cairngorms forest and woodland framework. The Cairngorms Partnership, Grantown-on-Spey. 68 p.

- , McKeen, M., Hester, A.J., Malcolm, A., Ray, D., Quine, C.P., Gray, H. & Stone, D. 2001. A preliminary comparison of outputs from the Ecological Site Classification (ESC) and the Native Woodland Model (NWM). Research paper F00A104, Scottish Natural Heritage, Battleby.
- Tuley, G. 1987. Forestry and land use near Aberdeen in North-east Scotland. *Forestry* 60(1): 135–151.
- Wallin, D.O., Swanson, F.J., Marks, B., Cissel, J.H. & Kertis, J. 1996. Comparison of managed and pre-settlement landscape dynamics in forests of the Pacific Northwest, USA. *Forest Ecology and Management* 85: 291–309.
- Wilson, S.M., Pyatt, D.G., Malcolm, D.C. & Connolly, T. 1998. Ecological site classification: soil nutrient regime in British woodlands. *Scottish Forestry* 52(2): 86–92.
- , Pyatt, D.G., Malcolm, D.C. & Connolly, T. 2000. The use of ground vegetation and humus type as indicators of soil nutrient regime for an ecological site classification of British forests. *Forest Ecology and Management* 140(2–3): 101–116.
- Worrell, R. 1996. The boreal forests of Scotland. Forestry Commission Technical paper 14. Forestry Commission, Edinburgh. 42 p.

Total of 54 references