

# Spatial structure of semi-natural and plantation stands of Scots pine (*Pinus sylvestris* L.) in northern Scotland

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## Summary

The success of current initiatives to maintain and enhance the area of and the special habitats provided by the remnant semi-natural pinewoods of northern Scotland will depend upon foresters' ability to foster more natural structures in even-aged plantations through stand manipulation. However, there is little information on the structures and spatial patterns that can be found in Scottish pinewoods; such knowledge could be used to design appropriate silvicultural regimes. A study was carried out to compare spatial structure in three 0.8–1.0 ha plots in the Cairngorms National Park; one plot was a 78-year-old plantation stand, the other two were semi-natural stands with trees up to 300 years old. Basic mensurational data showed that the semi-natural stands were characterized by a wider range of tree sizes and more large (>50 cm d.b.h.) trees. Spatial structure was evaluated with a range of different indices: the aggregation index of Clark–Evans (CE), the uniform angle and diameter differentiation indices, Ripley's *L* function of tree spatial distribution, pair and mark correlation functions and experimental variograms of tree diameter. The CE revealed a regular distribution in the plantation with the semi-natural stands having a random pattern. Further analysis of the latter stands indicated that, in each case, the older trees in the stand were regularly distributed while the younger ones were clustered. There was little difference in uniform angle values between the stands while the diameter differentiation distributions suggested greater variety in diameter within the semi-natural stands than in the plantation. The Ripley's *L* function showed that trees in the plantation were regularly distributed at close distances but clustered over wider distances. There were differences in pattern between the semi-natural stands; in one, trees were clustered because the positions of the younger trees were influenced by past regeneration trials, whereas in the other stand a random pattern was observed. Similarly, the variogram indicated widespread homogeneity in diameter within the plantation, while the semi-natural stands showed high variation at close spacing because of competition followed by spatial autocorrelation up to ~20 m distance. Thereafter, one of these stands had a very different pattern because of a more intensive regeneration history. All the indices, apart from uniform angle, were able to discriminate between the plantation and the two semi-natural stands, but only the more detailed spatial indices were capable of identifying differences within the latter. The implications of these results for management strategies in plantations are discussed.

## Introduction

Scots pine (*Pinus sylvestris* L.) is the most widely distributed conifer species in the northern hemisphere with a European range stretching from the Urals to the Atlantic and from the Barents Sea to the Mediterranean (Nikolov and Helmisaari, 1992). It is one of three conifer species native to Great Britain with a natural distribution confined to the northern Highlands of Scotland, where ~18,000 ha of ancient semi-natural (The term 'ancient semi-natural' is used (Anonymous 2003)) in Britain to identify woods composed of locally native trees and shrubs which are derived from natural regeneration rather than planting (i.e. semi-natural). A wood is classed as 'ancient' when it is known to have occurred continuously on the site since at least 1750 (in Scotland) and often considerably earlier (Anonymous, 2003)) pinewoods survive (Mason *et al.*, 2004). The area of these remnants (hereafter called 'the native pinewoods' or 'Caledonian pinewoods') represents ~1 per cent of the original area covered by the natural pine forests 4000 years ago (McVean and Ratcliffe, 1962). These forests were progressively reduced in extent over the centuries through a variety of unsustainable practices such as overgrazing, burning and exploitation (Steven and Carlisle, 1959; Smout, 1997). Despite their much reduced area, the native pinewoods are an integral part of some of the most cherished landscapes in the Scottish Highlands which attract visitors from many parts of Britain and the wider world. The need to conserve and restore these pine forests has been increasingly recognized (Stevenson and Peterken, 2004) since the publication of the first authoritative survey some 50 years ago (Steven and Carlisle, 1959). These forests contain a number of rare species of fauna and flora that, in Britain, are dependent upon the favourable habitat provided by the native pinewoods. Examples include the capercaillie (*Tetrao urogallus* L.), crested tit (*Lophophanes cristatus* L.) and twinflower (*Linnaea borealis* L.). As a result, the native pinewoods are recognized as a priority habitat under the EU Habitats Directive (Mason *et al.*, 2004) and a Pinewood Habitat Action Plan (Anonymous, 1995) has been published. The latter aimed to increase the area of the remnant pinewoods by 35 per cent by 2005 and also sought to create 25 000 ha of new native

pinewoods through a mixture of natural colonization and planting.

Because of their high conservation and landscape value, there has been very little timber production from any of the pinewood remnants during the last 50 years. Most Scots pine timber harvested in Britain is derived from 220 000 ha of plantations located on nutrient poor and free draining mineral soils throughout the country, where the species provides acceptable timber yields with moderate establishment costs (Mason, 2000). The prevailing silvicultural system used in the plantations is patch clearfelling with artificial regeneration and a rotation age of ~60–80 years. Perhaps because of the prevalence of this even-aged management system, to date little consideration has been given to the potential role of Scots pine plantations in the proposals for the restoration and expansion of the native pinewoods. This is despite there being ~100 000 ha of such plantations within the native pinewood zone in northern Scotland (Mason *et al.*, 2004). However, recent studies have shown that pine stands of plantation origin where the overstorey trees have been retained for periods of perhaps 120–150 years can provide suitable habitat for species of high biodiversity value (Humphrey *et al.*, 2003). Therefore, alternative approaches to the management of Scots pine plantations may have an important role to play in the development of an expanded pinewood ecosystem in northern Britain. Unfortunately, there is little tradition of using alternative systems to clearfelling and artificial regeneration in the management of Scots pine forests in Britain, although there are reports of shelterwood and seed tree systems on private estates with extensive pine plantations (e.g. Guillebaud, 1933; Hart, 1995).

In addition, one concern over the future of the native pinewoods involves the lack of regeneration that is apparent in many of the remnant woodlands. This is believed to be due to a variety of reasons including heavy deer pressure, severe competition from ericaceous shrubs, a lack of adequate regeneration niches and reduced seed yields because of an ageing tree population (Nixon and Cameron, 1994; Scott *et al.*, 2000; Mason *et al.*, 2004). Because many of the mature trees in these remnant stands are over 200 years of age, the habitat is increasingly vulnerable to disturbance and tree mortality and the consequent

loss of the structural features (e.g. coarse woody debris, hollows in old trees) required for many of the specialist pinewood species disturbance. The new native pinewoods created in recent decades will take many years to develop these desirable features. This again suggests that modified management of pine plantations may have a role to play in sustaining key features of the native pinewood habitat.

Appropriate application of principles derived from knowledge of stand dynamics is an important element in successful restoration of forest ecosystems with a complete range of stand structures. Pine plantations in Scotland under conventional silviculture are largely comprised of stands in the 'stand initiation' and 'stem exclusion' phases (*sensu* Oliver and Larson, 1996). By contrast, the larger native pinewoods contain structures characteristic of all four phases of stand development (Summers *et al.*, 1997; Mason *et al.*, 2004). In particular, it is argued that many of the biodiversity and spiritual values associated with the pinewoods are linked to the presence of open stands with a mosaic of large trees of 50–100 cm d.b.h. (Gill, 1995). Thus, the presence of capercaillie is positively influenced by the combination of such structures with abundant ground cover of bilberry (*Vaccinium myrtillus* L.) (Kortland, 2003). Stands of this type are considered to be characteristic of the 'old growth' phase in Scottish pine forests (Mason, 2000) and one aim of management of plantations is to foster the development of old growth features through thinning (Taylor, 1995). This is primarily achieved by regimes that increase the small-scale spatial variation by creating a mosaic of heavily thinned areas that alternate with untouched groups. These approaches have similarities to the variable density thinning (VDT) promoted in north-west America as a means of improving ecosystem diversity in second growth conifer forests (Carey, 2003). In Sweden, VDT has been proposed as means of promoting within stand structural diversity in Scots pine forests (Fries *et al.*, 1997). This approach is combined with the indefinite retention of 5–20 seed trees ha<sup>-1</sup> as a means of increasing the occurrence of old trees within regenerated stands. A similar approach termed 'group thinning' with a mixture of denser groups and a more heavily thinned matrix has been proposed for beech (*Fagus sylvatica* L.) forests in central Europe (Kato, 1979).

While the ideas behind VDT appear reasonable, there is uncertainty as to the scale and pattern in which such regimes should be applied. Most attempts to introduce VDT in pine stands in Britain have used subjective adjustment of thinning schedules used to maximize timber production in even-aged plantations (e.g. Taylor, 1995). Such approaches fail to define the desired spatial arrangement in the stands being manipulated and there is a consequent risk that the structures produced may not be the most appropriate for biodiversity and that there may be some intervening loss in timber production and quality.

One way of improving guidance on the appropriate patterns and intensity of VDT is to base this on comparative analysis of spatial patterns of tree distribution and other structural parameters in both existing 'old growth' pine stands and younger ones of plantation origin. Pommerening (2002) reviewed a number of spatial indices that could be used to characterize stand structures and having applied them to a range of German stands suggested how these might be used to measure differences between forests over space and time including the impact of differential harvesting. Such studies have indicated that more intensively managed stands tend to show a more regular arrangement of stem distribution than that occurs in more natural ones and that this regularity is particularly noticeable at comparatively short distances. However, while these findings conform to general understanding of the impact of silviculture upon Scots pine forests in northern Scotland, there are no published data to show whether the detailed results obtained in other countries can be readily extrapolated to British site types and conditions. One advantage of these indices is that they can be derived from data collected in small plots used in forest inventories and other types of monitoring (Pommerening, 2002, 2006).

In this paper, we present the results from a study of the diameter and age-class distributions and spatial structure of three Scots pine stands in north-east Scotland of different ages and with varying management histories. We compare the information provided by an aggregate index of spatial structure and two neighbourhood-based indices against the more detailed analysis provided by functions based upon known tree positions and sizes. We discuss how the results might

inform ways of promoting more natural structures in Scots pine plantations.

## Materials and methods

### *Sample sites*

The three stands are located in Glen More and Abernethy forests within the Cairngorms National Park (57° 30' N and 4° 15' W). Both these forests are considered to form part of the native pinewoods of Scotland (Steven and Carlisle, 1959) and have been dominated by Scots pine for several millennia (Mason *et al.*, 2004). The stands called 'young' and 'old' Glen More occur within 1 km of each other at an altitude of ~330 m a.s.l., while the Abernethy stand occurs ~10 km to the north-east at a similar elevation. Mean annual rainfall is ~900 mm, while mean annual temperature is ~6.0°C. The soils are typically free draining podzols with occasional weak iron pans, while the vegetation is dominated by *Calluna vulgaris* (L.) Hull, *Vaccinium myrtillus*, *V. vitis-idaea* L., *Deschampsia flexuosa* (L.) Trin. and the mosses *Polytrichum commune* Hedw. and *Hylocomium splendens* (Hedw.) Br. Eur.. This forest type is typical of the native pinewoods of north-east Scotland and is considered to be similar to the acidic pinewoods of Scandinavia (Rodwell and Cooper, 1995).

Both Glen More and Abernethy forests were exploited for their timber in previous centuries. Management practices before 1750 are little known but are likely to have involved selective exploitation of a range of tree sizes for local use (see Smout, 1997 for discussion of the history of forest management on an adjacent forest). From ~1780 until 1850, there were periods of intense harvesting in both forests which severely depleted the growing stock of mature trees (Dunlop, 1997).

The extent of the exploitation in Glen More was so extreme that by 1850 local foresters reported that few large trees of harvestable quality could be found (Dunlop, 1997). For the following half century Glen More was mainly managed as a sporting estate for deer stalking. The forest was acquired by the Forestry Commission in the early 1920s following further felling during the 1914–1918 war. The 'old' stand was an area of

~5 ha reserved in 1930 for research experimentation when it was described as having a 50–80 per cent coverage of old pine trees (MacDonald, 1952). A number of small-scale regeneration experiments were carried out between 1930 and 1938 and thereafter it has been maintained as a non-intervention reserve to examine the long-term natural dynamics of pine stands (MacDonald, 1952; Henman, 1961; Thompson *et al.*, 2003). The 0.8-ha plot described in this paper is that part of the old stand most intensively studied in recent years (Edwards and Rhodes, 2006). The 'young' Glen More plot was part of a 30-ha stand planted in 1926 on the site of an old stand that was felled during the 1914–1918 war. The stand had been thinned at least three times on an 8- to 10-year cycle between 1956 and 1996. In 2003, six 1 ha plots were installed as part of an experiment to compare the effect of different patterns and intensities of thinning upon subsequent stand structure. The data presented in this paper are for the control plot (i.e. not thinned in 2003/2004) in the experiment, selected as being typical of older pine plantation stands in the region.

Abernethy forest formed part of the Seafield estates which were well-known in the first part of the last century for being the only example in Britain where natural regeneration of Scots pine had been successfully promoted over a long time period and on a large scale (Guillebaud, 1933). The main silvicultural system used was a uniform shelterwood with a seeding felling overstorey density of ~250 trees ha<sup>-1</sup> followed by progressive removal of the overstorey as natural regeneration developed (Guillebaud, 1933). This system was gradually abandoned after 1945 and greater emphasis was given to patch clearfelling systems. Despite this, Abernethy is the largest remnant of Caledonian pinewood forest in Scotland with considerable diversity of stand structure (Summers *et al.*, 1997). A change of ownership in the 1980s resulted in much greater emphasis on conservation and amenity objectives and there has been no systematic management for timber in the last two decades. The Abernethy plot forms part of a 20–30 ha area of similar structure which shows no evidence of timber harvesting for at least 30 years and is considered to be developing towards a structure typical of semi-natural pinewoods (C. Edwards, personal communication).

### Assessments

A standard set of tree parameters was assessed in the three plots between 2000 and 2003. The plots were all either square or rectangular in layout. Diameter at breast height (1.3 m above ground: d.b.h.) and height of all trees of >7 cm d.b.h. were recorded, together with their  $x$ ,  $y$  positional coordinates mapped to the nearest 10 cm using a Criterion laser supplemented by compass and tape measure as necessary. An increment core was taken from all trees at 1.0 m above ground in the old Glen More and Abernethy plots and age (at 1.0 m) calculated from counting of rings via a travelling microscope using standard procedures (Stokes and Smiley, 1968). We did not take cores in the young Glen More stand because the planting history and age could be confirmed from local records. At Abernethy and in the old Glen More stand, any dead trees or those where increment cores were unobtainable (<1 per cent of the total) were excluded from the analysis.

### Spatial indices

The indices we used to analyse the data from the three stands were the following. Details of the formulae used to calculate each index are given in Table 1 together with other supporting information. In the paragraphs below we provide a brief overview of each index:

- 1 The 'aggregation index' of Clark and Evans (1954) where the average distance between trees and their nearest neighbours ( $r_A$ ) is compared with the expected mean distance if the trees were randomly positioned ( $r_E$ ). Values of CE lie between 0 and 2.1491; if the index is <1, there is deemed to be clustering, while values of >1 denote regularity. A completely random pattern will have a value of 1. The significance of any deviation from an index value of 1 can be tested using the SD of  $r_E$  in a randomly distributed forest of given density (Kint *et al.*, 2000).
- 2 The 'uniform angle (contagion) index' ( $W_i$ ) of von Gadow *et al.* (1998) which can be used to evaluate small-scale pattern based on the regularity of the positions of the four nearest neighbours to a given tree (Pommerening, 2002; Aguirre *et al.*, 2003). Pommerening (2002) followed Albert (1999) in suggesting

that mean  $W_i$  values of <0.5 indicates a regular distribution, values of 0.5–0.6 characterize a random distribution, while those >0.6 are found with clumped distributions. Comparing the distribution of the five possible values of  $W_i$  (0, 0.25, 0.5, 0.75 and 1.0) provides more detailed insight into structural variability within a stand (Aguirre *et al.*, 2003).

- 3 The 'diameter differentiation index' ( $T_{ij}$ ) which provides information on the spatial distribution of tree sizes (Pommerening, 2002). Values of the index vary between 0 and 1, where low values indicate that the neighbouring trees are similar in size to the reference tree while high values indicate variation in diameter between neighbouring trees.
- 4 Ripley's 'K function' ( $K_r$ ) was developed to analyse mapped spatial point data (Ripley, 1977) and has been used in forestry to describe spatial structure on a continuous basis (Stoyan and Penttinen, 2000). It provides an indication of how many trees are within a given distance from the average tree.
- 5 We calculated the  $K$  statistic for each stand using a SAS macro SPATIAL (Moser, 1987). The statistic was estimated in half metre increments up to a distance of ~80 m and a kernel width of 1.9 m. Where required, prior to calculation the tree coordinates were rotated to form a classically orientated rectangular lattice and translated to have a (0,0) origin.
- 6 We renormalized the  $K$  function through the  $L$  function (Wiegand and Moloney, 2004) to make variance constant and easier to interpret. This approach avoids some of the problems associated with large variations in values of  $K$  at short distances where it is based on few data. Note that the standard graphical outputs from Moser (1987) used in this paper show values of  $r - L(r)$  so that positive values indicate regularity and negative values signify clumping.
- 7 The 'Pair' ( $g_r$ ) and 'Mark' (diameter) ( $k_r$ ) 'Correlation' functions are based on point process statistics for pairs of trees and depend upon the distance between trees ( $r$ ) (Penttinen *et al.*, 1992). These functions can be plotted as a graph showing either the pattern of variability of tree locations ( $g_r$ ) or the mutual interaction of trees in terms of an attribute ( $k_r$ ), in this case diameter (Pommerening, 2002). When trees are distributed at random,  $g_r = 1$ , while

Table 1: A list of the spatial indices and functions used to analyse data from three Scots pine stands in north-eastern Scotland.

Index	Formula	Where	Interpretation	Key References
Aggregation	$CE = \frac{r_A}{r_E}$	$r_E = \frac{1}{2\sqrt{\frac{N}{\lambda}}}$ A = area of the forest stand and N = number of trees	Values of CE 0-2.1491; <1 indicates clustering; >1 denotes regularity; 1 = random	Clark and Evans, 1954; Kint <i>et al.</i> , 2000.
Uniform angle (contagion) index	$W_i = \frac{1}{n} \sum_{j=1}^n v_j$	$v_j = \begin{cases} 1, & \alpha_j < \alpha_0, \\ 0 & \text{otherwise} \end{cases}$ $\alpha_j$ = angle with tree $j$ , $\alpha_0$ = standard angle and $0 \leq W_i \leq 1$	Values of $W_i < 0.5$ = a regular distribution, 0.5-0.6 = random, >0.6 = clumped. Calculated with $n = 4$ nearest neighbours	von Gadow <i>et al.</i> , 1998; Pommerening, 2002; Aguirre <i>et al.</i> , 2003
Diameter differentiation index	$T_{ij} = 1 - \frac{\sum_{j=1}^n \min(DBH_i, DBH_j)}{\sum_{j=1}^n \max(DBH_i, DBH_j)}$	$DBH_j$ = diameter tree $i$ $DBH_j$ = diameter tree $j$ $T_{ij} \in [0, 1]$	Values of $T_{ij}$ 0-0.3 = small differentiation, 0.3-0.5 = moderate, 0.5-0.7 = large, 0.7-1.0 = very large differentiation. Calculated with the single $n=1$ nearest neighbour	Pommerening, 2002
Ripley's L function	$L(r) = \sqrt{\frac{K(r)}{\pi}} - r$	$K(r) = \frac{1}{N\lambda} \sum_{i=1}^n \sum_{j=1}^n I_{ij}(r)$	$I_{ij}(r) = 1$ if the distance between the points $i$ and $j \leq r$ ; 0 otherwise	Ripley, 1977; Stoyan and Penttinen, 2000; Wiegand and Moloney, 2004
Pair Correlation function	$g(r) = \frac{d}{dr} K(r)/(2\pi r)$	$r \geq 0$	<1 typically clustering >1 inhibition 1 = random	Stoyan and Penttinen, 2000
Mark (Diameter) Correlation function	$k_m(r) = \text{mean}(m_1 m_2) / m^2$	$m_1$ = diameter tree 1 $m_2$ = diameter tree 2 $m^2$ = squared mean diameter mean () = mean function	For diameter, often $k_m(r) < 1$ for small $r$	Pommerening, 2002
Experimental variogram (Diameter)	$\gamma(r) = \text{mean}\left(\frac{1}{2}(m_1 - m_2)^2\right) / m^2$	$m_1$ = diameter tree 1 $m_2$ = diameter tree 2 $m^2$ = squared mean diameter mean () = mean function	$\gamma(r)$ describes tree interaction at large $r$ and environmental factors at small $r$	Kuuluvainen <i>et al.</i> , 1996; Stoyan and Penttinen, 2000.

values greater than 1 indicate, for the particular distance, a higher frequency of occurrence than in a random process. Should this be found for short inter-tree distances, then this can be an indication of clustering as is found in dense groups of regeneration. Where  $k_r$  is concerned, a tendency for values to be less than unity at close distances reveals that both trees in a pair have smaller diameters than is found over the stand as a whole. This can also be a consequence of inter-tree competition in dense groups of regeneration (Pommerening, 2002).

- 8 We also explored the spatial pattern and spatial autocorrelation of tree diameter in the three stands using an ‘experimental variogram’  $\gamma(r)$  analysis for each site. The variograms were isotropic and had a lag spacing of 1 m. The output from this analysis is a plot of  $\gamma(r)$  as a function of distance. As the distance between points increases, the diameters become increasingly dissimilar and the variance increases. This continues until the points are so far apart that they are not related to each other and the plot approaches a flat horizontal line. The distance within which samples are still autocorrelated forms the ‘range’ (Kuuluvainen *et al.*, 1996).

We used the ‘CranCod’ software package (Pommerening, 2005, 2006) to help with the analysis of the spatial data, the calculation of the various indices and the spatial functions. We explored various methods available in ‘CranCod’ of adjusting for edge effects that would be incurred by trees within a plot having their nearest neighbour outside the plot and therefore unrecorded. The one used for the data presented here is the NN1 technique which uses a variable buffer zone around the edge of the plot based on the spatial arrangement of the trees. One advantage of

this method is that it was designed to work with nearest neighbour techniques and it was shown to reduce bias effectively in a comparative study of several different edge correction techniques (Pommerening and Stoyan, 2006). The large size of the plots each with >100 trees will have limited, any of errors associated with this method of edge correction (Pommerening and Stoyan, 2006).

## Results

### *Tree assessments*

Tree density ranged from slightly more than 1000 stems  $\text{ha}^{-1}$  in the young Glen More stand to ~370 at Abernethy and ~270 at old Glen More (Table 2). Tree heights were similar for all sites at ~15–17 m. The highest basal area was found at Abernethy and the lowest at old Glen More. Large trees of over 50 cm d.b.h. were only found in the old stands with both sites having a few trees larger than 100 cm d.b.h.

The diameter distribution at young Glen More showed a clear peak in the 10–20 cm class with few trees in the larger d.b.h. classes (Figure 1). There was a similar, but lesser, peak in the old Glen More stand but here there were substantial numbers of trees in the larger sizes. At Abernethy, most trees were found in the 30–50 cm range with a lower percentage in the immediately adjoining size classes and a few very large trees.

The age-class distribution at old Glen More was bimodal, with ~60 per cent of trees of ~20–60 years of age and another group of between 160 and 220 years (Figure 2). At Abernethy, some 85 per cent of the trees were between 80 and 120 years, with slightly fewer than 10 per cent of the stand between 180 and 320 years.

Table 2: Basic stand and mensurational details for three experimental Scots pine stands in northeast Scotland

Name	Plot area (ha)	Date plot established	Trees ( $\text{ha}^{-1}$ )	Tree age (years)	Top height (m)	Basal area ( $\text{m}^2 \text{ha}^{-1}$ )	Maximum d.b.h. (cm)	Number of trees >50 cm d.b.h.
Young Glen More	1.0	2003	1012	78	15.9	37.4	40	0
Old Glen More	0.8	1930	274	20–225	16.5	25.9	100	48
Abernethy	1.0	1997	368	50–315	17.9	47.3	115	39

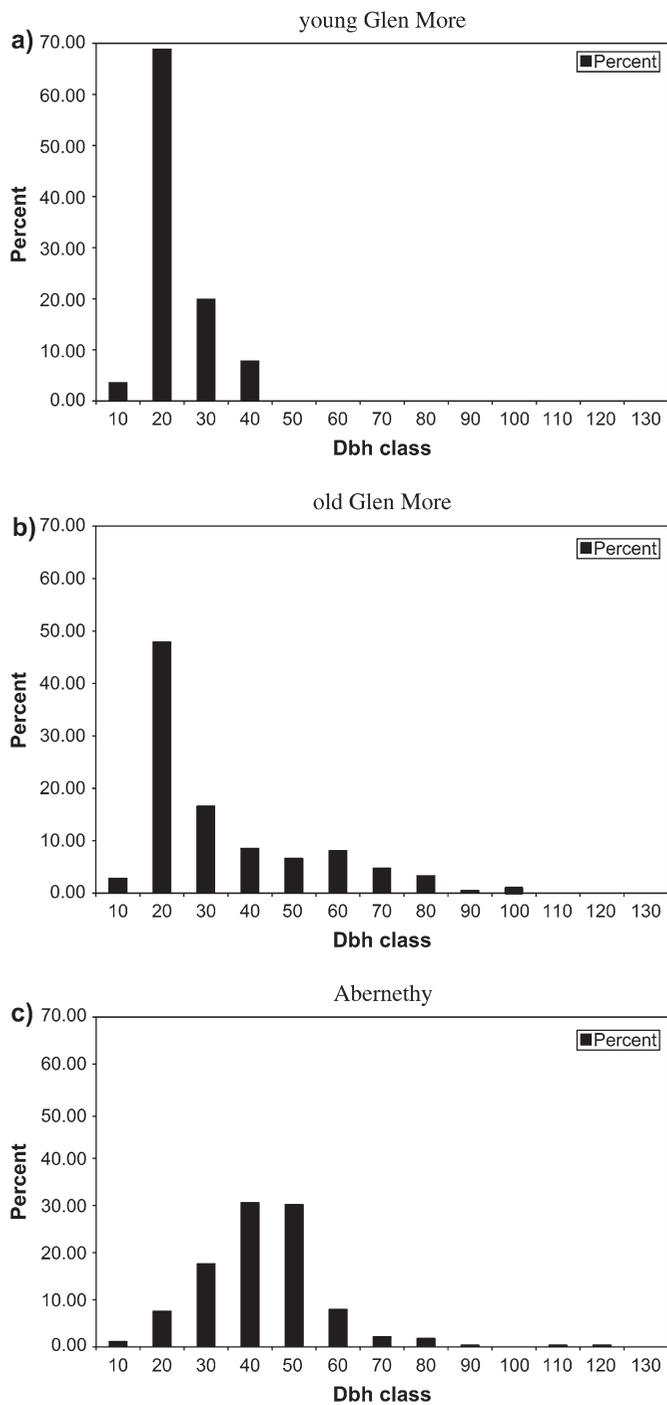


Figure 1. Percentage diameter distribution by 10 cm d.b.h. classes for the three Scots pine stands. (a) Young Glen More, (b) old Glen More and (c) Abernethy.

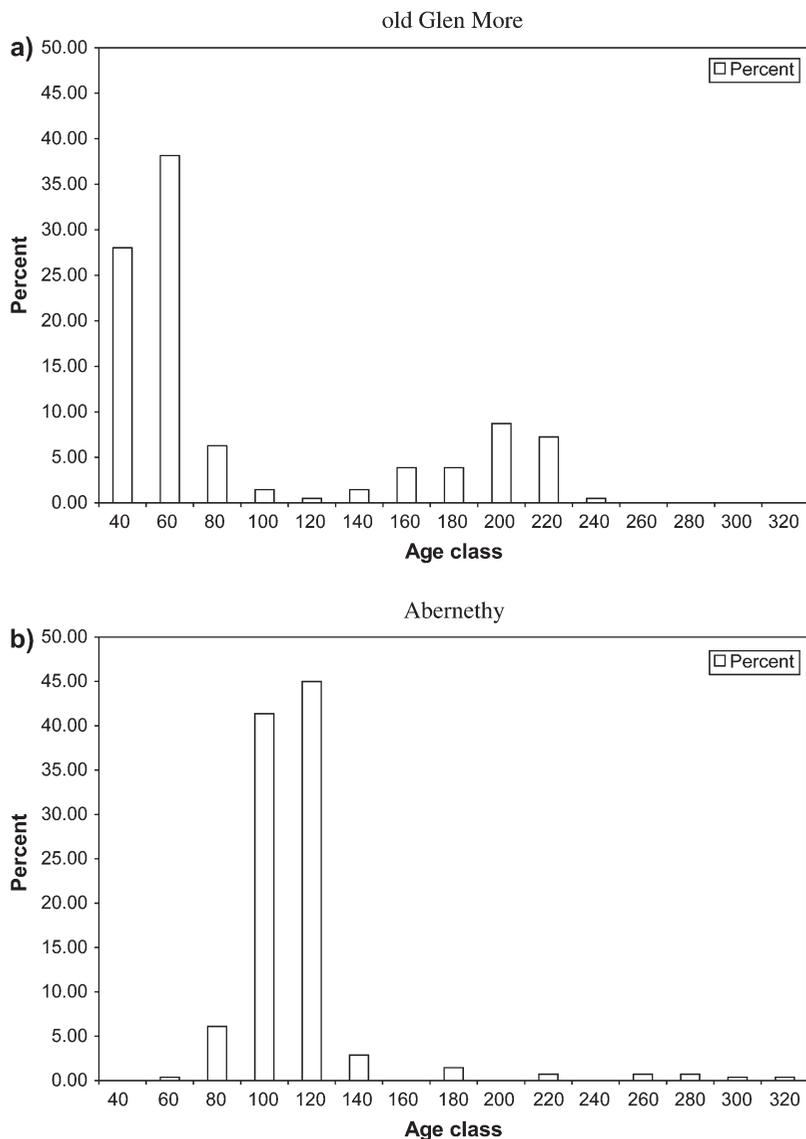


Figure 2. Percentage age-class distribution for (a) old Glen More and (b) Abernethy.

There was a positive relationship between increasing diameter and tree age at old Glen More and Abernethy with respective correlation coefficients ( $r$ ) of 0.66 and 0.56. However, there was considerable scatter in the data and the relationship differed between sites. Thus, a tree of ~50 cm d.b.h. at old Glen More might range from less than 80 to over 210 years in age, whereas at Ab-

ernethy the equivalent range might be from 70 to ~130 years old.

*Spatial indices*

Values for aggregation, uniform angle and diameter differentiation are given in Table 3. In young

Table 3: Comparison of three different spatial indices in the experimental Scots pine stands.

Stand	Indices		
	Clark-Evans (CE)	Uniform angle ( $W_i$ )	Diameter differentiation ( $T_i$ )
Young Glen More	1.07	0.48	0.26
Old Glen More	0.90	0.53	0.30
Abernethy	0.94	0.51	0.29

Glen More the estimate for aggregation showed a regular tree distribution very highly significantly ( $P < 0.001$ ) different from a random distribution. By contrast, the values for the stands at old Glen More and Abernethy were indicative of a clumped ( $P < 0.01$ ) and a random distribution, respectively. However, at the latter sites, we can also separate the trees into an 'older' and 'younger' cohort based on the ages of the trees (Figure 2). At old Glen More the older cohort was defined as the trees that existed before the regeneration experiments in the 1930s and the younger one those that developed as a result of these interventions. The aggregation estimate for the former was 1.00, indicating a random pattern, while an estimate of 0.64 for the young cohort showed highly significant clumping ( $P < 0.01$ ). At Abernethy we used 150 years to separate the older from the younger cohort. The younger trees were again clumped (0.87;  $P < 0.01$ ), and there were only 12 trees in the older category, too few for a reliable estimate.

The mean value of the uniform angle index was similar in all three stands, although the lowest value (0.48 in the plantation; Table 3) was within the range considered typical of a regular distribution. Examination of the proportion of the different values also showed no major differences between the three stands other than a slightly higher instance of trees with value 1.0 (i.e. a clumped distribution) at Abernethy and old Glen More.

The mean diameter differentiation values also showed little variation between the three stands (Table 3). This lack of differentiation was also evident in the analysis of the proportions. The

only minor difference was that more than 60 per cent of the trees at young Glen More belonged to the first diameter differentiation class (i.e. their immediate neighbours were within 70 per cent of their own diameter) compared with 50 and 60 per cent at Abernethy and old Glen More.

### *Spatial functions*

The actual positions of the trees in each plot are shown in Figure 3 together with the estimated values of  $L$  in relation to the value for a completely random distribution and the associated 95 per cent confidence limits.

At young Glen More, there appeared to be weakly significant regularity at very close spacings of 1–2 m. However, this trend was reversed with increasing distance so that from ~5 until 50 m there was significant clustering in tree distribution. In old Glen More, there was randomness at very short distances, but thereafter significant clustering between ~3 and 20 m and again beyond 40 m. Between 20 and 40 m, the pattern of tree distribution did not seem to deviate from randomness. At Abernethy, there was no evidence of significant deviation from randomness at any distance up to 50 m.

We explored patterns of distribution with age of tree by separating the trees at old Glen More and Abernethy into older and younger cohorts using the same age discriminators as in the aggregation analysis (see above). At Glen More the younger cohort was significantly clustered at all distances from 2 to 50 m, with this being particularly pronounced at ~10 m (Figure 4). There was much higher variation associated with the distribution of the older trees, presumably because of fewer individuals, but there was again clustering between ~5 and 35 m. At Abernethy, the results revealed few significant differences from randomness.

### *Pair and mark correlation functions*

The pair correlation function indicated appreciable differences in spatial pattern between the three stands. In young Glen More, there was only a suggestion of clustering at very close spacing (0.5 m), but thereafter the pattern approximated to a random distribution (Figure 5a). Old Glen

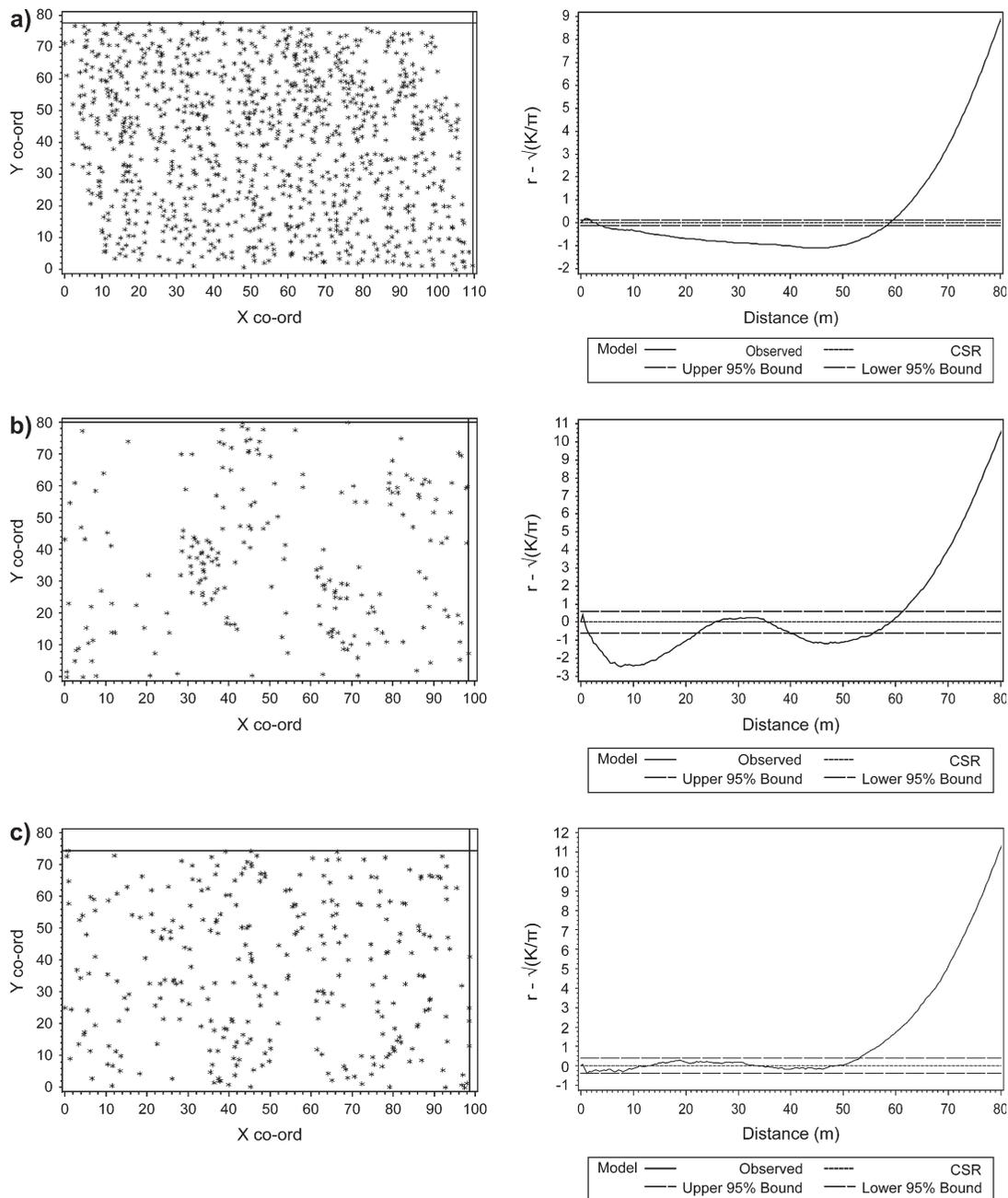


Figure 3. Spatial stem distribution and Ripley's L function for (a) young Glen More (rotated 32°), (b) old Glen More and (c) Abernethy (rotated 15°).

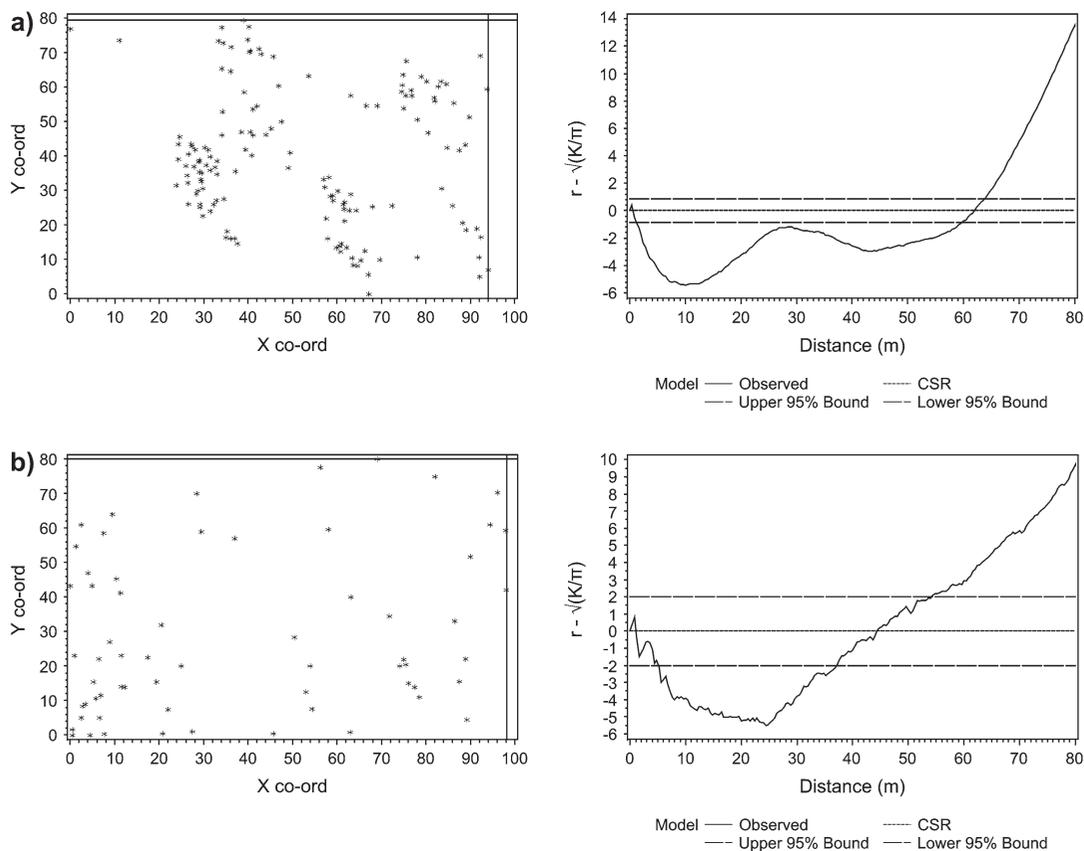


Figure 4. Spatial stem distribution and Ripley's L function for (a) the young trees at old Glen More and (b) the old trees at old Glen More.

More (Figure 5b) showed much greater evidence of clustering at all distances up to 12–13 m. There was also an indication of fewer inter-tree distances at ~20–25 m, possibly revealing some inhibition process between trees. At Abernethy (Figure 5c), clustering was found over a range of inter-tree distances up to ~3–4 m, but thereafter a random pattern prevailed.

In the plantation origin stand (young Glen More), there was little evidence of spatial correlation of diameters at any distance. By contrast, at Abernethy and particularly at old Glen More, the trees at closer distances tended to have smaller diameters than would be expected for a random process. The distances where such differences were evident were very similar to those for which a clustering effect was evident.

#### Experimental variograms

The patterns of variance in diameter with increasing spacing showed appreciable difference between the three stands (Figure 6). Young Glen More had the most homogeneous pattern with comparatively little difference in diameter with a high variance value at ~2 m distance, slight auto-correlation between 3 and perhaps 20 m where a sill seemed to occur. The old Glen More stand had a very different pattern with high variance at the closest 1 m spacing, strong positive auto-correlation between ~5 and 25 m, a decline in variance until ~35 m, followed by moderate auto-correlation until ~50 m where a sill may occur. At Abernethy, the pattern had many similarities to old Glen More at the closer distances, but there

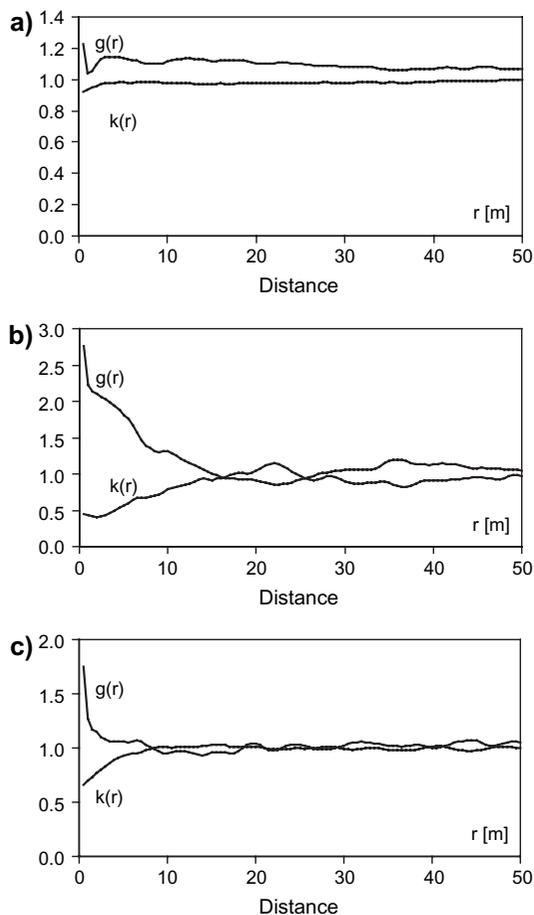


Figure 5. Correlation functions for tree position (pair –  $g(r)$ ) and mark i.e. diameter ( $k(r)$ ) in relation to distance ( $r$ ) for (a) young Glen More, (b) old Glen More and (c) Abernethy.

appeared to be a sill reached at ~15–20 m. The exponential model provided a reasonable fit to the data at the young Glen More and Abernethy stands, but did not describe the pattern evident in the old Glen More stand.

## Discussion

There is increasing recognition that the spatial pattern of tree positions and sizes within stands can be a major influence on the flow of benefits provided by forests. However, most traditional

assessments used in forestry to describe stands (e.g. basal area, diameter distributions) do not give any information on such patterns and the assessments are interpreted through guidance in stand management tables which are predicated on maximizing timber production. Other patterns may be more appropriate in situations where amenity or biodiversity are major objectives of management and so better understanding of spatial structure could be helpful in providing improved guidance for multi-purpose management (Pommerening, 2002).

The three stands selected for this study occurred within close proximity on similar sites, were of similar height and yet had contrasting structures. The young Glen More stand showed the restricted range of diameter and comparatively high stocking density characteristic of an even-aged stand being managed for timber production with thinning at regular intervals to remove a percentage of the trees. It exemplifies a type of structure widely found in financially mature Scots pine plantations in northern Scotland. The two semi-natural stands had a number of common features such as a much wider range of ages than the young Glen More stand with older trees exceeding 200 years (Glen More) or 300 years (Abernethy). The diameter distributions were also much wider with each having ~15 per cent of trees with diameters more than 50 cm and a few of 100 cm or more. Thus, both stands possessed structural features such as large old trees and a wide range of tree sizes considered characteristic of old Caledonian pine-wood stands (Steven and Carlisle, 1959; Mason, 2000). Similar characteristics have been reported from natural pine stands in Finland where studies of diameter distributions have shown a wider range of diameters and more large (>40 cm diameter) trees in natural compared with managed pinewoods (Rouvinen and Kuuluvainen, 2005).

There were also substantial differences between the two semi-natural stands, in common with other recent studies in Scottish pinewoods (Edwards and Mason, 2006). The Glen More stand, with a lower basal area, had a diameter distribution which, with the exception of the smallest size class, showed similarities to the negative exponential ('inverse J') pattern considered to be characteristic of irregular stands that are thought to be self-sustaining (Hett and Loucks, 1976; Nyland, 1996). Puumalainen *et al.* (2002) reported that

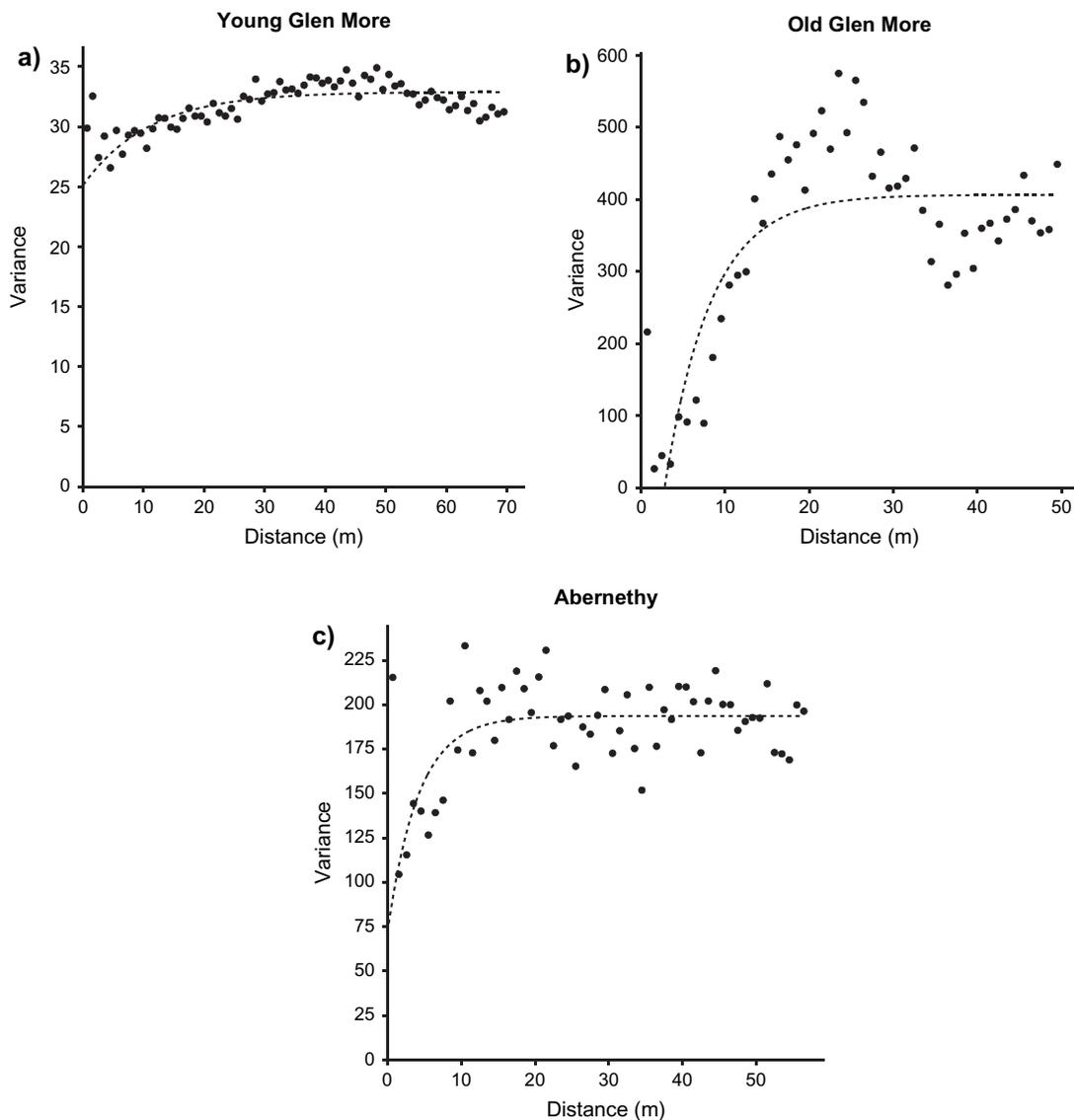


Figure 6. Experimental variogram showing variance of tree diameter as a function of distance for (a) young Glen More, (b) old Glen More and (c) Abernethy.

a similar distribution has been found in a range of boreal forest types. They suggest that this is a successional stage that occurs several decades after an event promoting a cohort of regeneration (e.g. fire, scarification). By contrast, at Abernethy there was a much higher basal area and the diameter distribution showed a peak in the

middle sizes but with a wider spread than found in the young Glen More stand. The diameter distributions did not reflect the age-class distribution at either site, in line with other reports that have shown wide variation around the expected positive correlation between diameter and age in Scottish pinewoods (Nixon and Cameron, 1994;

Edwards and Nixon, 1997; Edwards and Mason, 2006).

Initial examination of the spatial distribution of the trees showed a few differences between the plantation and the semi-natural stands. The aggregation index suggested a regular pattern in the young Glen More stand and a random or clumped distribution in the two older stands. Kint (2003) used the same index to show that Scots pine stands of 70–160 years in forest reserves in The Netherlands tended towards either a regular or a random pattern, with the latter characteristic of lower stand densities. Pommerening (2002) also reported regularity in two younger stands of conifers and broadleaves with randomness in an older mixed broadleaved stand. There was little difference between the three stands in the mean value of the uniform angle index. Other studies (Pommerening, 2002; Aguirre *et al.*, 2003) report similar mean values in the range of 0.51–0.57. Neumann and Starlinger (2001) also found this index to be less sensitive to differences in neighbourhood pattern.

Kent and Dress (1980) used a modelling approach to show that regular patterns of tree distribution would become random over time, assuming random mortality and no regeneration. However, where regeneration occurs and becomes established, it may be necessary to separate the various cohorts within a stand since in both semi-natural stands the aggregation index showed a regular distribution in the older cohort and evidence of clumping in the younger one. Similar patterns of clumping in younger cohorts have been reported for natural Scots pine stands in Latvia (Brumelis *et al.*, 2005).

More detailed analysis of tree spatial distribution using Ripley's  $L$  function highlighted additional differences between stands. At young Glen More, a more complex pattern was revealed than was apparent using the spatial indices. There was evidence of regularity at very close spacing presumably reflecting the original planting pattern of ~1 m spacing that was the norm in the 1920s. The clustered distribution revealed from ~5 to 50 m is thought to be a consequence of the local thinning regime which involved selective removal of better quality co-dominant stems for telegraph poles (D. Jardine, personal communication). This will have had the effect of allowing groups of subdominant trees to survive longer than might be expected under normal low thinning regimes.

This pattern is different from that at old Glen More where there was a 'wave-like' distribution with greatest evidence of clustering at ~10 and 45 m distances. This pattern appeared to reflect the distributions of the older and younger cohorts. Clustering in the older trees was most evident at a distance of 15–25 m, and this pattern suggests that these trees were not retained for silvicultural reasons as 'seed trees' since a more regular pattern would have been evident. The 'wave-like' pattern appeared to be caused by the distribution of the younger cohort that was affected by the layout of the 1930s regeneration trials. The latter used a plot size of 20 by 20 m but only those treatments with simulated strip cultivation at 1 m spacing were successful (Thompson *et al.*, 2003; Edwards and Rhodes, 2006). Thus, the peak at 10 m appears to be caused by plot size with groups of regeneration in the cultivated treatments, while that at 50 m reflects the distribution of cultivated plots. Over time, increased competition among the regeneration may result in a move towards randomness or even regularity as a consequence of self-thinning (Kent and Dress, 1980; Stoyan and Penttinen, 2000).

By contrast, in Abernethy the distribution of all stems appeared to be random. Examination of the younger cohort gave a suggestion (very weakly significant at best) of clumping at 5–10 m. This probably reflects groups of successful regeneration occurring away from the light and moisture competition exerted by the mature trees (Valkonen, 2000). Kuuluvainen *et al.* (1996) found a random pattern in a natural Norway spruce stand in southern Finland, while a managed stand showed regularity at distances of up to 4 m because of the effect of low thinning.

Further evidence of clustering in these stands is provided by the pair correlation function. In all three cases, the tendency for more trees at close spacing suggests an effect due to the occurrence of groups of regeneration. This is surprising for the plantation stand and appears to indicate that there was also some natural seeding on this site. The general trend is distinct from that reported from a number of plantations in continental Europe where there is often inhibition at close spacings because of the effect of planting distance and subsequent thinning (Penttinen *et al.*, 1992; Pommerening, 2002). At young Glen More and Abernethy, the range of distances over which

interaction between trees was observed is less than 10 m in line with other reports (Stoyan and Penttinen, 2000). However, at old Glen More, the range at 15 m is appreciably greater as a result of the impact of the regeneration experiment.

The mean values of diameter differentiation indicated comparatively little difference between stands. Pommerening (2002) recorded a much higher mean value for a two-storied mixed broadleaved stand (0.42) compared with two regular conifer and broadleaved stands (0.25 and 0.21, respectively). It is surprising that there was not a greater difference between the young stand and the two older ones, given that the latter had greater variations in diameter and age. This may reflect the light-demanding nature of Scots pine, in that regeneration develops in clumps in gaps in the canopy, but is rarely found under an intact canopy (Malcolm, 1995). The dominant trees in the clumps grow comparatively rapidly towards the canopy so that it is unusual to find more than two layers within a stand. Kuuluvainen *et al.* (1998) also noted a bimodal distribution of heights (i.e. only small and large trees) in a natural Scots pine stand in eastern Finland. A consequence of this gap-based regeneration process is that nearest neighbours will tend to be of more similar size than might be found in more intimate stand structures containing more shade-tolerant species. The mark correlation function also indicated that all three stands tended to have more similar diameters at close spacing, probably as a result of the pattern of regeneration.

Examination of spatial distributions of diameters using variograms indicated similarities but also differences in patterns between the sample stands. In all cases there was high variance at close distances of 1–2 m (Figure 6). This trend has been reported in other studies (Kuuluvainen *et al.*, 1996, 1998; Kint *et al.*, 2003) and is considered to be the consequence of asymmetric competition for light between trees growing in dense clumps of regenerated trees. The occurrence of this peak in the planted stand (young Glen More) is slightly surprising since Kuuluvainen *et al.* (1996) did not find high variance at close spacing in a managed Norway spruce (*Picea abies* Karst.) stand. This is probably an artefact of the local thinning regime as discussed above. Beyond 3–5 m, at all sites there was positive autocorrelation up to a distance of ~12–20 m, suggesting a pattern of

neighbouring trees of roughly equal size competing with each other. The correlation was greater in the two natural stands than in the planted and managed stand, suggesting that a consequence of thinning was to reduce neighbourhood competition while making the overall stand more homogeneous. Beyond 20–25 m, there was little evidence of systematic pattern in either the young Glen More or Abernethy stands, but in old Glen More there was high variance at ~25 m followed by positive autocorrelation between 35 and 50 m. This has similarities to the 'wave pattern' of tree distribution noted above and reflects the effect of the regeneration plots established in the 1930s. The high variance at 25 m suggests asymmetric competition between the mature overstorey trees and the regenerating cohort. The overall pattern from Abernethy was similar to that reported from natural pine and spruce stands in Finland (Kuuluvainen *et al.*, 1996, 1998).

One outcome of this study is to indicate the variety of structural pattern that can be found within semi-natural stands in the Caledonian pinewoods. The reasons for such differences may often be a consequence of site history. At Glen More, the oldest trees (160 years or more of age) are likely to have regenerated following the heavy fellings of the early nineteenth century (Smout, 1997). The sizeable cohort of younger trees (40–80 years of age) reflects the favourable regeneration conditions provided by strip cultivation in the experiments carried out in the 1930s (Edwards and Rhodes, 2006). By contrast, at Abernethy there are 12 trees of over 150 years of age, while the majority of the trees in the stand are between 90 and 130 years old. This distribution would be compatible with Guillebaud's description (1933) of the uniform shelterwood system used on Seafeld estates. Thus, a series of seeding fellings would have been started in the 1880s with progressive removal of the overstorey as the regeneration developed. The reason for the retention of the few remaining old trees is unclear, but it is possible that these were destined for a local market requiring very large dimension timber. These differences suggest that it would be unwise to assume that there is a single model for the development of old pinewood stands. There may be a range of stand structures appropriate to this phase of stand development. Pommerening (2002) also pointed out that there might not be

uniformity in 'natural' stand structures between reserves, let alone between forest types.

## Conclusions

In these semi-natural pinewood stands, measurements based on tree dimensions alone do not give sufficient insight for informed analysis of past history and evaluation of future management. Particularly in older stands with few records of past interventions, it is essential to complement tree measurements with information on tree age to give adequate understanding of stand history. Without the tree age data, it would be possible to misinterpret the diameter distribution at old Glen More as an example of an all aged irregular stand when it is mainly composed of two cohorts with an age difference of ~100 years (see also Kerr and O'Hara, 2000).

When combined with age data, spatial indices have the potential to provide greater understanding of stand development as shown by the different values for the aggregation index of the two cohorts at old Glen More and at Abernethy. However, in this study, neither the uniform angle nor the diameter differentiation index proved sensitive to variation in stand spatial structure, although alternative formulations such as expressing diameter indices in relation to diameter class may be more effective (A. Pommerening, personal communication). A problem with spatial indices is that they provide a snapshot of average dispersion within a stand but are less effective in revealing the detailed pattern and causal processes (Stohlgren, 2002; Kint *et al.*, 2003). They do have the advantage of not requiring specific tree positions to be determined and the data can be collected in routine inventories.

The various spatial functions and the variogram of tree diameter provide greater insight since they revealed substantial differences between the underlying patterns in the two older stands. They also indicated subtle differences in spatial pattern in the plantation stand that were not evident from the indices. The disadvantage with such functions is the cost of obtaining tree positional data. The advent of remote sensing technology may start to make such intensive measurements more realistic, at least in research programmes dealing with applied stand dynamics.

An ultimate aim of this study was to see whether the information could be used to formulate preliminary guidance on how to develop more natural structures within pine plantations. Current pine plantation management is producing stands with more uniformity of tree sizes and a different spatial pattern than can be found in semi-natural stands. Yet these results, and other studies (Edwards and Mason, 2006), reveal the extent to which the 'natural' structure of old Caledonian pinewood stands in Scotland are often a legacy of forest management decades or even centuries ago. Therefore, the issue is not whether plantations can be converted to more natural structures but how this is best achieved. One feature of this study is that the major differences in spatial structure between stands occur at distances of less than ~50 m. This suggests that any attempt to foster greater variation in plantation stands (e.g. through VDT) should take place at a comparatively intimate scale of perhaps 10–20 m. A possible approach compatible with this scale would be to use a modified crown thinning regime which progressively removed the competitors to 50–100 potential dominant trees per hectare. One consequence could be to increase the range of diameters compared with current plantations while avoiding the development of the regular structure characteristic of thinning from below (Pretzsch, 1998). Such an approach would also promote trees with the potential to develop into the large diameter specimens characteristic of the native pinewoods. This would be compatible with greater use of shelterwood or seed tree silvicultural systems in pine plantation management. Indeed, evidence from this study is that the larger trees characteristic of semi-natural pinewood stands may often be the remnants of past seeding fellings (e.g. Abernethy). Studies in Scots pine forests in central Spain also suggest that shelterwood systems can increase structural and spatial diversity (Montes *et al.*, 2005). Thus, greater use of silvicultural systems associated with Continuous Cover Forestry (Mason *et al.*, 2004) can be seen as a means of developing an integrated management of the whole pinewood resource in northern Scotland.

However, this hypothetical approach still lacks information on the appropriate intensity and timing of thinning to produce a more natural

structure from a younger regular plantation stand. To achieve this goal, two aspects need to be pursued. Firstly, further spatial analysis of both young and especially old pinewood stands needs to be undertaken. The latter is of particular importance because of the substantial difference that this study has revealed between two semi-natural stands growing in the same region. Such investigations should provide a better understanding of the range of structures that can be found in old stands in the native pinewoods. However, we also need to confirm that the patterns found in the plantation stand are an adequate reflection of those found in other pine plantations in northern Scotland. Secondly, simulations of the effect of different patterns of thinning should be undertaken to see the outcome of a range of potential VDT strategies. Such simulations are needed because of the lack of long-term datasets showing how stands respond to different interventions. They should be based on the use of single-tree, distance-dependent growth models to 'grow' alternative stand structures over time and check their suitability for purpose (Stoyan and Penttinen, 2000). Without the knowledge gained from such research, there is a danger of silvicultural regimes being implemented to 'naturalize' pine plantations that do not produce desired structural outcomes and fail to optimize habitat provision, amenity value or timber quality.

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#### Conflict of Interest Statement

None declared.

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