Continuous cover forestry in British conifer forests

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Introduction

From the beginning of the 1990s a number of factors, such as the Rio-Helsinki process, the requirements of certification and an international movement favouring more natural forest management, all began to change thinking about appropriate silvicultural systems for plantation forests in Britain. This has resulted in a move away from the predominant silvicultural practice where even-aged stands of a few species are managed using the clearcutting system (Matthews, 1989) and the clearfelled areas are often 5-20 ha or more in size. The new silvicultural approach, generically known as continuous cover forestry (CCF), is based upon certain key principles such as a presumption against clearfelling, the use of natural regeneration and the creation of a varied stand structure containing a range of species (Mason *et al.*, 1999; Pommerening and Murphy, 2004).

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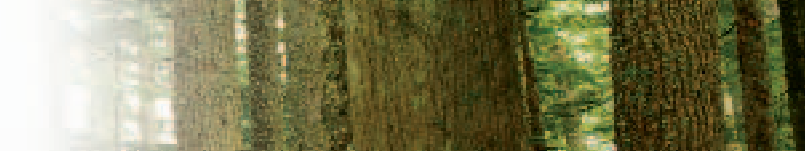


Further impetus to these changes was provided by the Scottish and Welsh forestry strategies (Anon., 2000; Anon., 2001) which both contain aspirations to increase the area under CCF management. The Welsh Woodland Strategy contains the strongest commitment, aiming for 50 per cent of public forests to be transformed to CCF by 2020, where feasible.

Achieving these aspirations represents a major challenge for forest managers in Britain, given that there were probably less than 5000 ha of forest under CCF management at the beginning of the 1990s. As a consequence, there is little experience of appropriate stand management strategies to favour CCF (Hart, 1995) and of a range of operational aspects (e.g. harvesting techniques, modelling growth of stands) which could affect the outturn. Research programmes were started in the late 1990s at Forest Research and the School of Agricultural and Forest Sciences (SAFS) of the University of Wales, Bangor to provide knowledge that would help overcome these difficulties. For example SAFS and Forestry Commission Wales started the ‘Tyfiant Coed’ project in September 2001; the Welsh phrase means forest or tree growth: see more details at http://tyfcoed.bangor.ac.uk

The following sections provide a brief overview of findings from our research. An earlier report (Kerr, 2001) discussed alternative methods of developing irregular structures in broadleaved and conifer stands in lowland Britain. The focus here is on the use of CCF in conifer plantation forests in upland Britain since this is where the challenge of transformation to irregular stand structures is the greatest.

Management demonstration sites

A number of trial areas have been established in different forests in Britain to support this research (see Table 1). It is critical to install demonstration sites relevant to CCF to illustrate best practice and to convey an impression of what particular forest types on particular sites could look like (Gadow, 2001). The sites can also provide data for modelling transformation to CCF (Pommerening, 2002), since the growth information from mixed uneven-aged stands subjected to modern CCF management complements existing knowledge. Besides standard mensuration procedures, the data are also spatially explicit which means that all trees are mapped and can be identified by their three-dimensional coordinates, enabling a wide range of follow-up research involving spatial statistics. Subsequent re-measurement every five years will establish an excellent database of forests in transition from even-aged management.

A mixed 34-year-old Sitka spruce–birch stand at Coed y Brenin (see Figure 1) at an elevation of 210 m asl on a site formerly dominated by oak may serve as an example. The parent rock is Cambrian sandstone and the predominant soil types are brown earths; the yield class of Sitka spruce ranges between 16 and 18. Although birch readily seeds itself on Sitka spruce restock sites (Humphrey *et al.*, 1998) it is eventually outcompeted by the spruce and is shaded out, which in Wales generally occurs at a stand age of about 30 years. Maintaining the birch in mixture for longer would enhance the diversification of coniferous plantations. In this plot the competitors of 75 birch and 66 Sitka spruce ‘frame’ trees (per hectare) were removed in a crown thinning in May 2003. Most competitors were Sitka spruces; birches were only removed when accidentally damaged by falling trees.

Table 1

Main experimental sites, species and aspects for the investigation of CCF in Great Britain.

Forest	Main species	Approximate age (years)	Main aspects under investigation
Aberfoyle[a]	European larch	70	Thinning, seed fall, light regime
Glasfynydd	Sitka spruce	50	Thinning, light regime, *Hylobius* damage
Wykeham[a]	Scots pine/others	70/50	Thinning, stand development
Gwydyr	Douglas fir/others	80	Thinning, stand development
Gwydyr	Scots pine/others	80/70	Natural succession, mycorrhizal ecology
Clocaenog[a]	Sitka spruce	50	Thinning, natural regeneration, stand stability
Clocaenog[a]	Japanese larch and Norway spruce/others	75	Natural succession
Mortimer	Douglas fir	35	Thinning
Glen More	Scots pine	75	Thinning, light regime, seed fall
Coed y Brenin	Sitka spruce/birch	30/20	Stand development
Cardrona[a]	Scots pine	65	Natural regeneration, cultivation
Trawllm[a]	Sitka spruce	40	Thinning, operational aspects

[a] Denotes that the experiment is located within a national CCF demonstration site.

Figure 1 gives a visual impression of the spatial impact of the intervention. As a consequence of the crown thinning the proportion of birch trees per hectare (ha) increased from 40% to 43% while the Sitka spruce trees decreased from 41% to 38%. The SG ratio, an index to assess thinning types (Gadow and Hui, 1999), shows that the intervention clearly fell into the crown thinning category.

Figure 2 depicts the so-called mark connection function (Pommerening *et al.*, 2000; Stoyan and Penttinen, 2000) applied to the main two tree species and the situation before and after thinning. In this case a particular tree species is given a discrete mark.

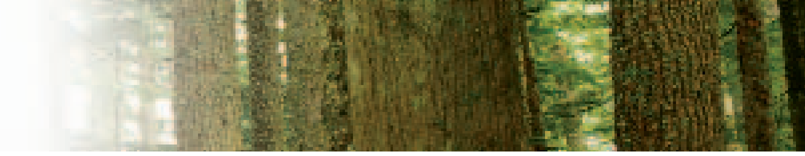
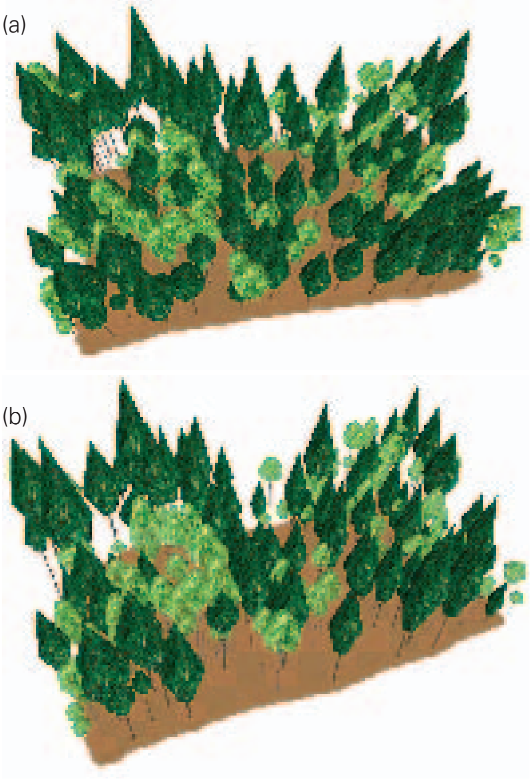


Figure 1

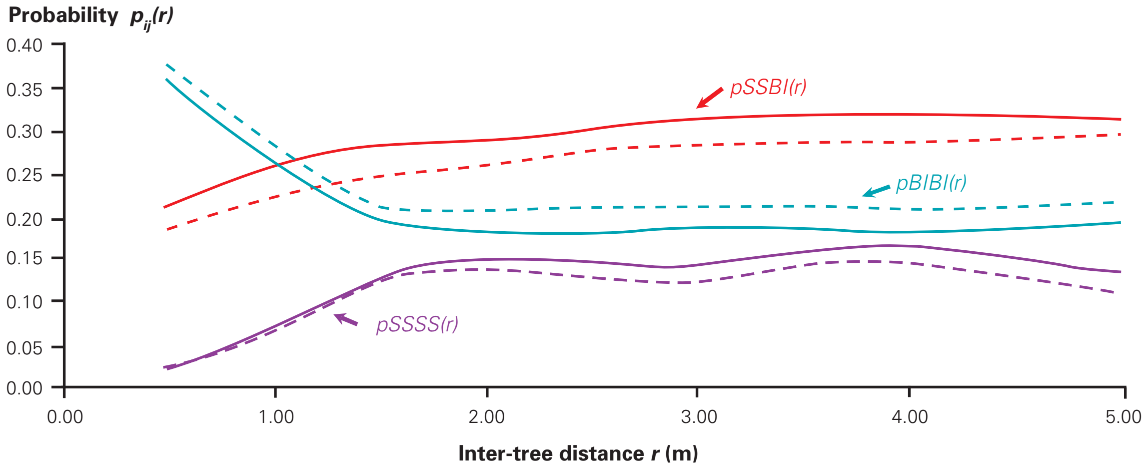
Computer visualitions of a 34-year-old mixed Sitka spruce and birch stand at Coed y Brenin Forest: (a) pre-thinning, (b) post-thinning. Dark green: Sitka spruce, light green: birch.

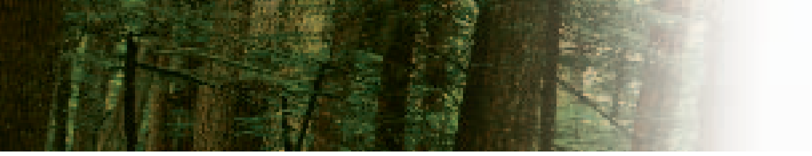


The value $p_{ij}(r)$ of this function is the conditional probability that one of two trees considered has mark i (e.g. Sitka spruce) and the other has mark j (e.g. birch). On average the combination Sitka spruce–birch is the most likely pairing. However, at distances of less than 1.0 m, there is a high probability of birch–birch combinations occurring.

Also, when considering tree distances from 0.5 m to 1.5 m it becomes clear that the probability of Sitka spruce–birch pairings occurring has been reduced following the thinning. The probability of Sitka spruces having Sitka spruce neighbours at these distances remained virtually the same and the probability of birch trees having birch trees in their immediate vicinity has slightly increased. The results show that the thinning has released birch trees from Sitka spruce competition by consolidating birch clusters and reducing mixed species pairs of nearest neighbours. However the general character of a mixed Sitka spruce–birch woodland has remained unchanged.

The mark connection functions showing the probability of different species combinations occurring (solid curves: pre-thinning, dashed curves: post-thinning) when applied to the Sitka spruce–birch stand at Coed y Brenin (see Figure 1).





Natural regeneration

The promotion of natural regeneration is generally a precondition for wider use of CCF. To encourage the establishment and growth of natural regeneration, five fundamental requirements, outlined in Box 1, must be met (see also Nixon and Worrell, 1999).

Box 1

Fundamental requirements for natural regeneration.

There must be:

- a sufficient seed supply
- a suitable seedbed for germination
- an adequate light environment for seedling growth
- protection from browsing damage
- freedom from vegetation competition.

Seed supply

There is considerable year-to-year variation in seed production in conifers, with good seed years occurring at intervals of several years (Malcolm *et al.*, 2001). This is exemplified by 5-year results from the larch plots at Aberfoyle (Table 1) where monthly seed fall has been compared in two plots thinned to different intensities and on an adjacent clearfell (Figure 3). In the one very good seed year (2001) the seedfall under the more heavily thinned plot was almost twice as high (16.3 million ha^{-1}) as on the plot given standard thinning (9.0 million ha^{-1}), with even fewer seeds on the clearfell area. These results indicate the potential interaction between thinning and seed production as well as the limited potential for colonisation of relatively small (1.0 ha) clearfelled coupes.

Seedling growth and light environment

Tree species vary in their ability to survive and grow at different light levels. Thus species which are considered 'shade tolerant' such as western hemlock and beech can survive at low light levels where 'light demanding' species such as Scots pine or birch would die. Implementing CCF requires an understanding of the critical levels of below canopy light for the survival and growth of different conifer species which, in turn, influences the choice of silvicultural system and the desired stand structure (Mason and Kerr, 2004).

In 1999 seedlings of European larch, Scots pine, Sitka spruce, Douglas fir and western hemlock were planted in a Sitka spruce spacing trial, which provided a range of light environments. After 4 years, there were clear differences in survival between species according to light intensity (Table 2). The highest survival of all species was found at the highest light intensity and declined with decreasing light. However, the more light demanding species such as larch and Scots pine were unable to survive at the lowest light intensity unlike more shade tolerant Douglas fir and western hemlock. Thus, everything else being equal, managers can manipulate the light environment within a stand to favour the growth of one species at the expense of another.

There are two main methods of increasing light levels to allow seedling growth: gap creation and thinning of the overstorey. Creating gaps within a forest stand will create areas which receive greatly increased light levels compared to the intact stand, with systematic variation in light across the gap. Seedling growth is likely to be uneven across the gap, and the greatly increased light levels may result in rapid colonisation by vegetation competing with seedling growth. The microclimate will be relatively harsh, with high daytime and low night-time temperatures causing risk of desiccation and frost damage, respectively.

Thinning a stand creates a light environment which is more variable at a small scale than in a gap. Increased light levels are not concentrated in any single location, allowing better control of vegetation competition. Microclimate is less severe than in gaps, with lower diurnal fluctuations. Measurements showed that even a

Figure 3

Cumulative seeds per hectare in three European larch plots at Aberfoyle; opening of the canopy in the thinned plot occurred in December 1998.

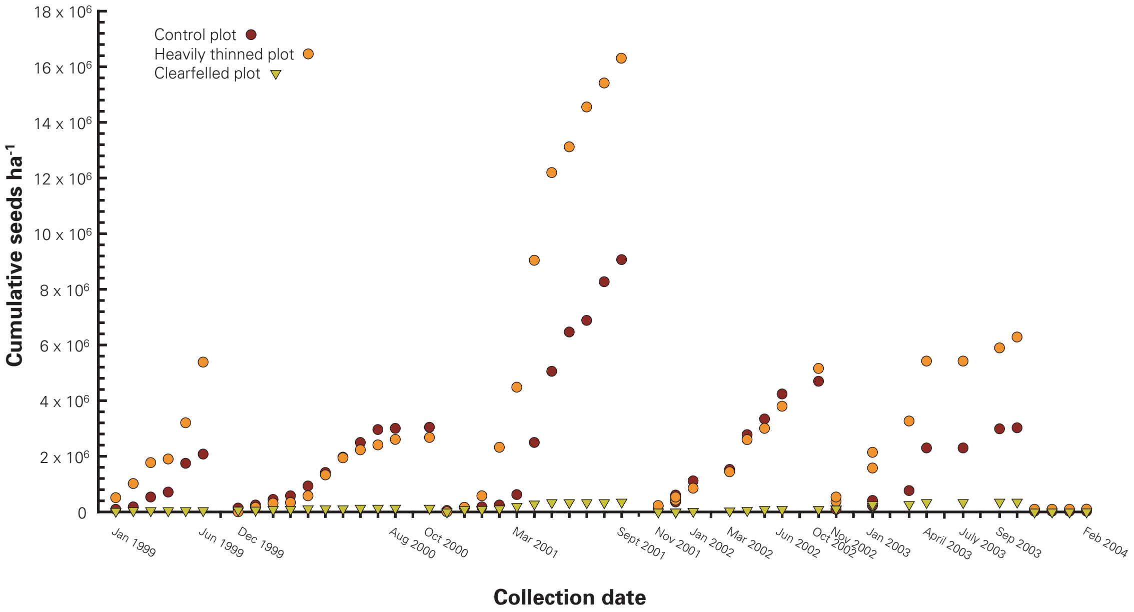


Table 2

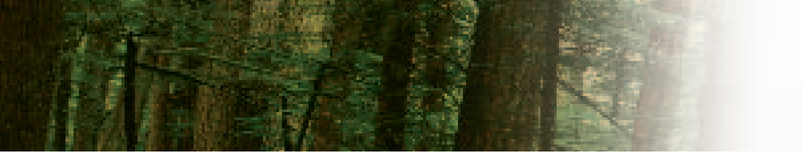
Survival (% : transformed) of seedlings of five conifer species 4 years after planting in a Sitka spruce spacing trial with different light environments (adapted from Mason *et al.*, 2004).

Species	**Spacing: 8 x 8 m**	**6 x 6 m**	**4 x 4 m**
Light intensity:	**61%**	**16%**	**3%**
European larch	78.1	39.9	-
Scots pine	90.0	34.2	-
Sitka spruce	78.3	53.7	-
Douglas fir	70.3	68.5	11.9
Western hemlock	79.2	60.9	25.6
Significance	**	*	**
5% LSD	10.1	21.7	9.9

*$p < 0.05$, ** $p < 0.01$.

relatively sparse tree canopy (trees at 8 m spacing) caused the night-time temperature to be up to 7 ˚C warmer than in adjacent open ground on a cold calm night (Sellars, 2004).

Figure 4 shows canopy transmittance (the proportion of incident radiation passing through the canopy) plotted against basal area for a range of Sitka spruce and Scots pine stands in Britain. These data are derived from hemispherical photographs and show excellent correlation with estimates of light transmittance from direct measurements (Hale, 2003). We have combined these results with studies of seedling survival and growth in different light regimes to produce guidelines for the critical basal area which should provide sufficient light for seedling growth beneath a canopy (Table 3). These critical basal area values tend to be lower than those recommended in management yield tables (Edwards and Christie, 1981), particularly for the more light demanding species, suggesting that heavier thinning should be employed to promote growth of advance regeneration.



Note that although basal area can be used as general guidance (Hale, 2001), light levels will also vary with stand structure: a more mature stand with fewer, larger trees will transmit more radiation than a less mature stand with many small stems, because there are larger gaps between the crowns and crowns themselves are sparser. Ongoing work to collect data from very open stands of Sitka spruce and other species should allow species-specific relationships to be developed to predict light regime from stand-level parameters such as basal area, stocking and top height.

Canopy transmittance plotted against basal area for stands of Sitka spruce and Scots pine in Britain.

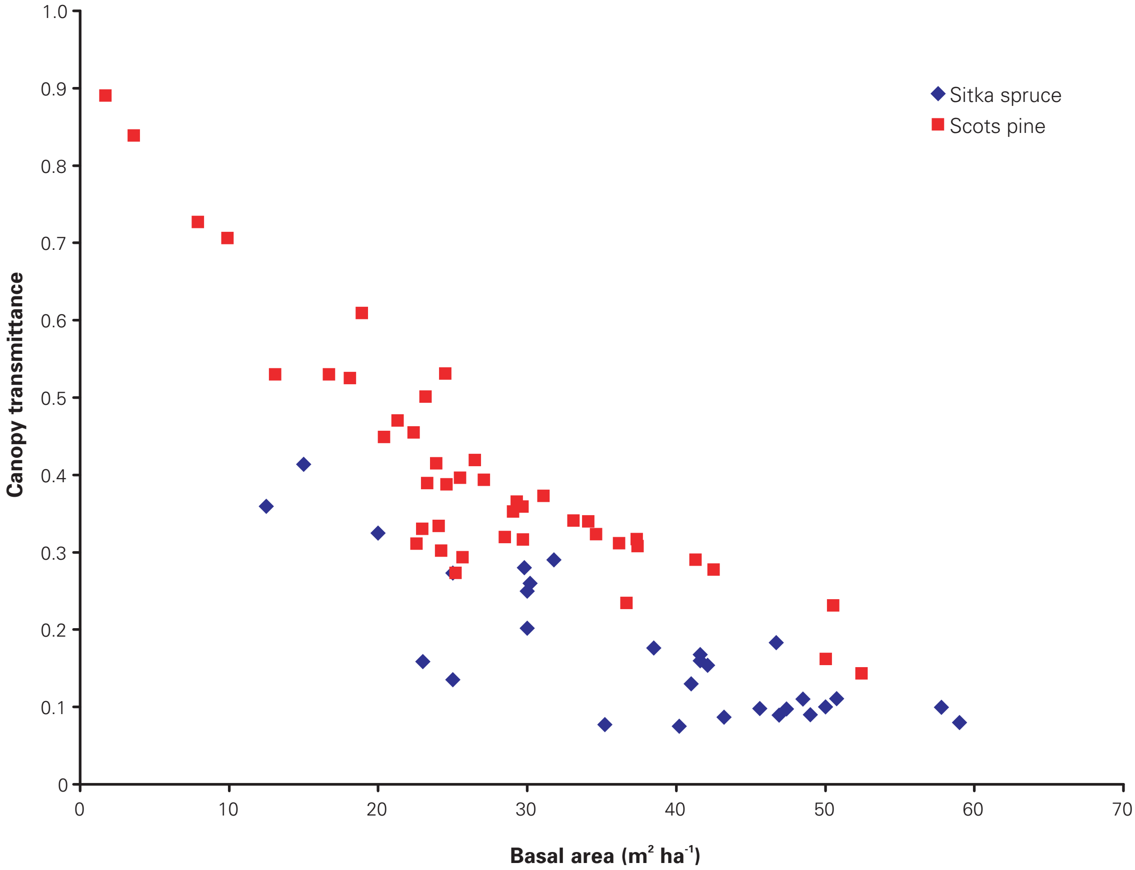


Table 3

Minimum percentage of incident light (transmittance) required for seedlings to achieve 50 % of the growth that would be achieved in full light, and the critical basal area required to achieve these light levels beneath an overstorey of the same species.

Species	Percentage light		Critical basal area (m² ha⁻¹)
Larch	Light-demanding	> 40 %	~20
Scots pine		~35 %	~25
Sitka spruce		~20 %	~30
Douglas fir		~15 %	~35
Western hemlock	Shade-tolerant	~10 %	~40

Hylobius damage

In 2002, an experiment was started at the Glasfynydd site (see Table 1) to investigate the effect of differential thinning in three Sitka spruce CCF stands upon *Hylobius* populations, and the damage to planted Sitka spruce seedlings. Comparison with a nearby clearfelled site was included. Description of the stands at the beginning of the experiment is given in Table 4.

Until July 2002, *Hylobius* population numbers were broadly similar in all treatments. Thereafter they were substantially higher on the clearfelled site than on any of the CCF stands, particularly during the autumn (Table 5). However, past experience suggests that the population density on the CCF sites in July and August would have been sufficient to have caused appreciable damage on a clearfelled site. At the end of 2002 mortality due to Hylobius exceeded 60% on the clearfelled site (Figure 5) but was negligible in the CCF treatments. These trends were also apparent in 2003 (data not shown) by which time mortality on the clearfelled plot exceeded 90%.

These early results are encouraging since they suggest that a possible benefit of a move to CCF could be a reduction in the risk of Hylobius damage to planted or regenerating seedlings. This might also result in a reduction in pesticide inputs to the forest ecosystem in line with UKWAS requirements.

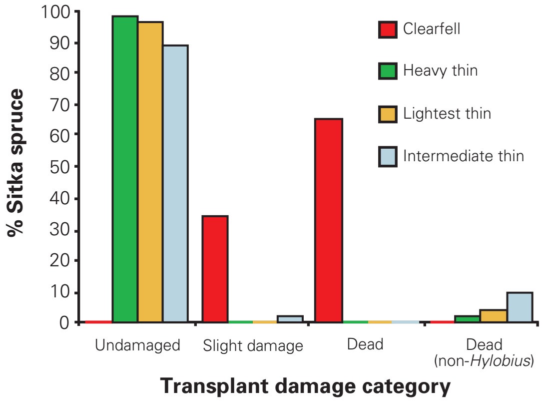
Details of the 3 CCF Sitka spruce stands in Glasfynydd in 2002 at the beginning of the study of *Hylobius* damage.

Treatment	**Trees ha^{-1}**	**Top height (m)**	**Basal area (m^2 ha^{-1})**	**GYC**	**% Light transmittance**
GNT	519	23.8	40.9	16	15
GLT	348	28.3	41.3	20	14
GHT	287	29.0	38.1	22	14

The total numbers of *Hylobius abietis* that were caught at billets on 1.0 ha plots at Glasfynydd between 29 May and 30 October 2002.

Treatment	**Total *H.abietis* captured**
Clearfell (CF)	1230
Heavy thin (GHT)	355
Intermediate thin (GLT)	277
Lightest thin (GNT)	190

Levels of damage to Sitka spruce transplants on a clearfelled site and in three Sitka spruce CCF stands due to *Hylobius abietis* feeding.



Stability of CCF stands

As the discussion of critical basal area makes clear, thinning is critical in developing a stand structure and microclimate favourable for promotion of natural regeneration and achievement of CCF. When carrying out such a thinning, care must be taken not to increase the risk of wind damage to a stand in order to achieve light levels required for seedling growth. In general, previously unthinned stands will be less suitable for heavy thinning than those where previous thinnings have resulted in increased tree stability (Hale *et al.*, 2004).

Preliminary evaluation using the wind risk model ForestGALES suggests that sites of wind exposure of greater than DAMS 17 should not be considered for CCF management (Mason, 2003). The timing of early thinnings may be critical in ensuring that the trees within a stand develop more stable (i.e. lower) height:diameter ratios and root architectures to withstand the increased wind loading experienced by the dominant trees in CCF stands. Since the interaction between thinning, stand structure and wind risk will largely determine the extent of use of CCF in upland Britain, a new research project starts in 2004 to investigate wind forces upon trees in irregular stands using the Clocaenog site as a test bed.

Modelling CCF scenarios

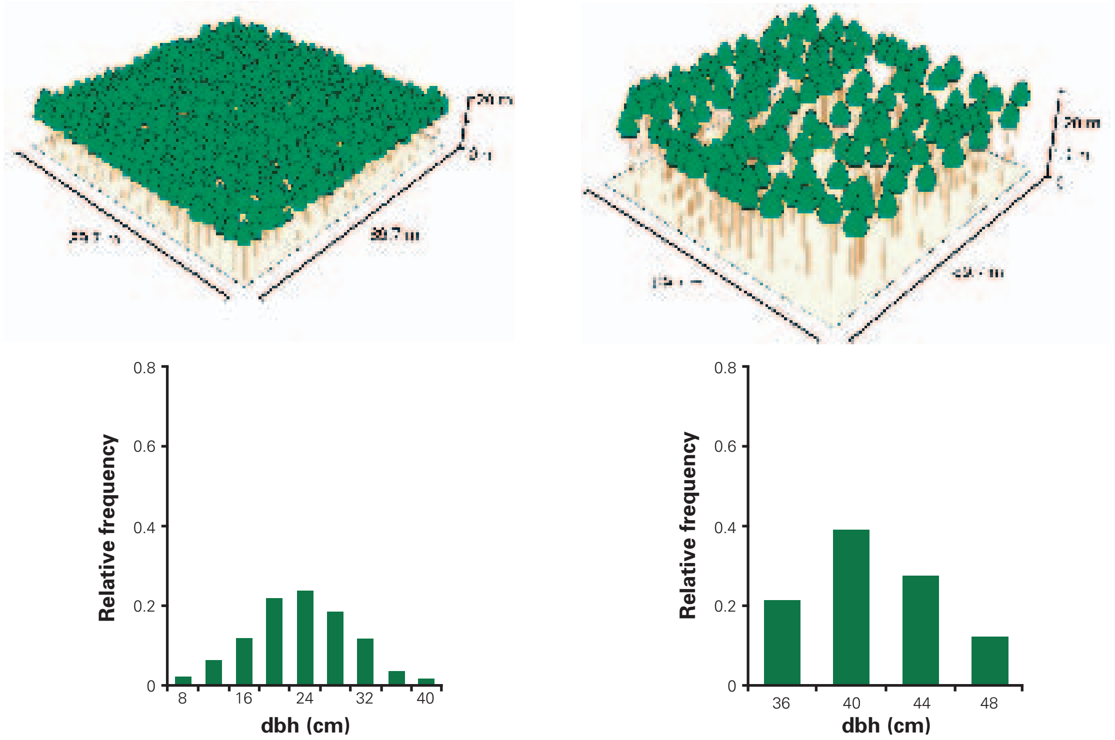
Silviculturists have recognised the need to compensate for the lack of practical experience with scientific tools, producing management guidelines and corresponding financial scenarios (for example, see O'Hara and Valappil, 1999; Twery *et al.*, 2000; Lexer *et al.*, 2000). Therefore part of the Tyfiant Coed project is the modelling of CCF scenarios. According to Pretzsch (1992) existing yield models based on even-aged management are inadequate for use with CCF for at least three reasons:

1. The development of mixed stands cannot be predicted reliability from models of single species stands.
2. The transition to new thinning and harvesting strategies based on the selection of individual trees requires more flexibility and better quality of information from growth models. The demand for information has shifted from mean stand values to individual tree dimensions of specific parts of a forest stand.
3. Since the 1970s it has been realised that, for example, steadily increasing uptake of carbon dioxide and nitrogen results in a better and faster growth than is indicated by the yield models currently in use.

Research is under way at SAFS to develop a spatially explicit individual tree model capable of simulating different management scenarios for CCF (Pommerening and Wenk, 2002; Pommerening, 2002). The results can then be assessed in the light of management, ecological and other objectives. Forest managers should be able to use this model to compare and identify suitable silvicultural options without relying on lengthy experiments. Figure 6 gives the visual impression of such a simulation which shows the transformation of a Scots pine plantation to a mixed uneven-aged Scots pine–oak forest. The simulation assumes a planted stand with no thinning before year 40. Phase 1, beginning at year 40, involves a selective crown thinning to favour 'future' trees at about 6 m centres. In phase 2 there is light thinning from below, complemented by pine regeneration and some underplanting of oak. Finally, in phase 3, the majority of the overstorey trees are removed in target diameter fellings. The simulation also demonstrates the length of time required to achieve transformation from regular stands to CCF.

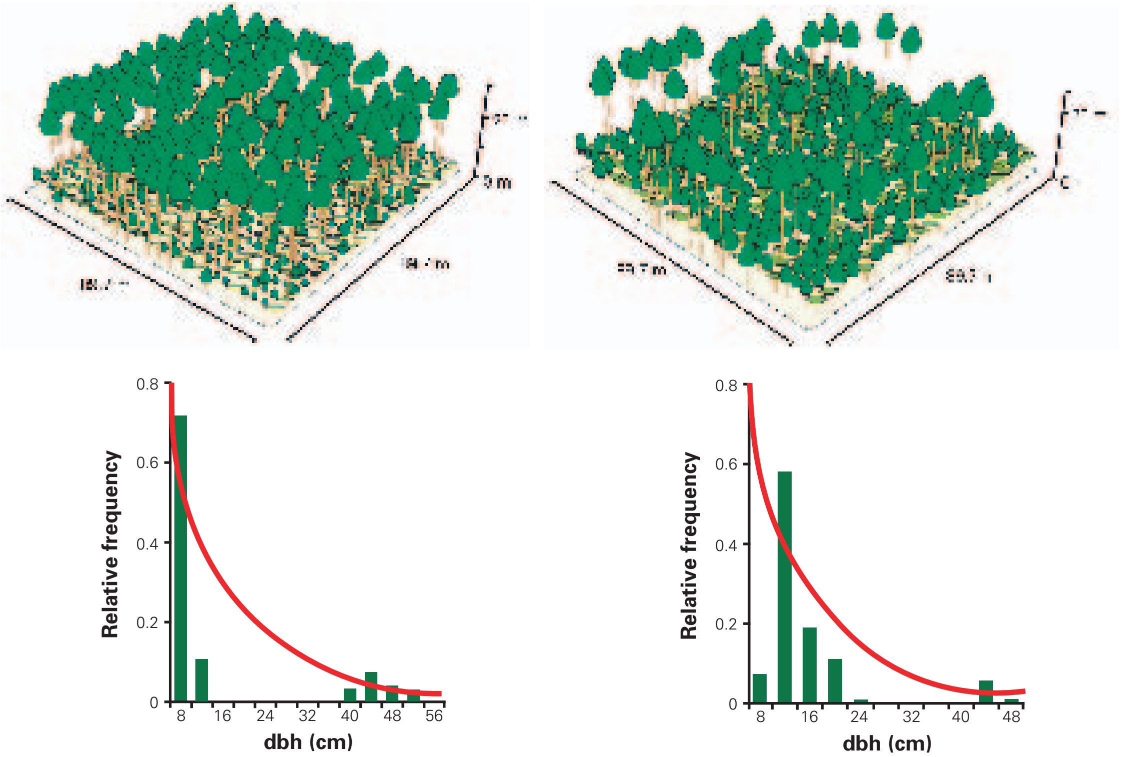
Figure 6

Visualisation of a sample simulation run for the transformation of a Scots pine plantation from a 40-year-old even-aged stand to a 135-year-old irregular stand. Upper graph shows the spatial pattern while the lower graph illustrates diameter distribution over time.



40 years, top height=18 m

95 years, top height=28.7 m
phase 1



120 years, top height=31.0 m
phase 2

135 years, top height=19.14 m
phase 3

Harvesting requirements and access tracks

With an increasing number of foresters attempting to transform even-aged stands to CCF there is a need for guidance on operational aspects including methods of timber extraction and appropriate provision of forest access tracks.

Selection of extraction system and machinery

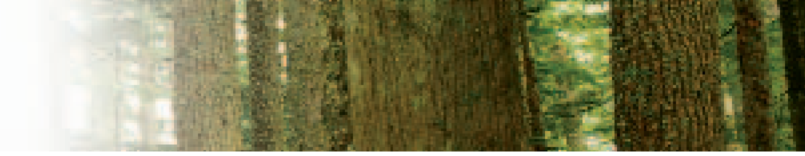
A decision support system has been developed to identify the most appropriate selection of timber extraction methods and machinery for a given site (Ireland and Jones, 2004). This starts by carrying out a preliminary site assessment to identify the site and crop constraints on extraction systems and machinery. Significant variation in site and crop will require stratification of the site into homogeneous management blocks. A decision matrix (Figure 7) is used to guide the user through the criteria influencing the choice of extraction machinery, and suggests a range of appropriate extraction methods, given the specific site constraints. These criteria include slope, terrain, extraction distances and environmental site constraints as well as crop factors such as the size and end use of the felled timber.

For example, if a transformation thinning is to be carried out on a site with a gradient in excess of 30˚, and extraction distances more than 250 m, then the only feasible extraction options will be cable crane or helicopter. Given the prohibitive cost of helicopter hire for forestry operations, it is likely that cable crane extraction will be the most practical option in this example. Examination of Figure 7 indicates that the harvesting systems suited to cable crane extraction are: *pole-length* where felled, snedded poles are extracted; *part pole-length* which is a variation where the sawlog component of the pole is removed at stump and extracted separately allowing for easier product sorting; and *whole-tree* where all the above ground parts of the tree including crown and branch wood are extracted. The selection of appropriate timber extraction equipment and machinery is important to ensure cost-effective timber extraction. Additionally, equipment and methods of extraction should be appropriate to the site conditions, so as not to cause excessive disturbance to the site or standing crop.

Suitability of extraction machines for different harvesting systems.

		Extraction machine option									
		Forwarder/ mini-forwarder	**Skidder**	**Portable winch**	**Log chute**	**Cablecrane/ highlead**	**Horse**	**Wire loader**	**Specialised terrain chipper**	**Helicopter**	**Fell to waste/ chemical thin**
Suitable harvesting system	**Terrain chipping**								▨		**Alternatives to extraction**
	Shortwood	▨	▨	▨	▨		▨	▨		▨	
	Pole-length	▨	▨	▨		▨	▨			▨	
	Part pole-length	▨	▨	▨		▨	▨	▨		▨	
	Whole-tree		▨	▨		▨	▨			▨	

▨ Harvesting system is suitable for the given extraction machine option.



Access track planning

Appropriate planning and construction of access tracks and racks is essential to allow sustainable timber harvesting and extraction (Ireland, 2004). Appropriately specified tracks can reduce harvesting and extraction costs and enable all weather access through the stand, with minimal environmental and landscape impacts. As well as allowing for sustainable timber harvesting, tracks also provide for a range of additional benefits including access for forest management, conservation and recreation.

CCF management requires ongoing access to the stand for thinning both during the transformation phase and the subsequent implementation of the chosen silvicultural system. The need to establish natural regeneration within a stand is likely to restrict location of machinery access routes. One option is to construct a permanent track infrastructure. Alternatively, a network of permanent access routes may be supplemented by temporary or semi-permanent access tracks that will allow the same level of machine access as permanent tracks but at a lower construction cost and offer increased flexibility in relocating tracks in the future. Racks (i.e. unsurfaced corridors through the standing crop) are likely to require some level of brash cover to achieve machine flotation and avoid excessive compaction and soil disturbance when harvesting. The amount required will depend upon soil type. The appropriate specification and location of access through the forest must be carefully planned to enable sustainable long-term use to an appropriate standard.

Monitoring

One way of increasing success in transformation to CCF is to practise 'adaptive management', i.e. to base silvicultural interventions on stand level information (Mason and Kerr, 2004). A system of monitoring has been designed to collect useful stand data at low cost. This procedure aims to (1) quantify changes in the diameter distribution and species composition of a stand over time and (2) ensure that regeneration fulfills stocking requirements.

The first step is to stratify the area into blocks with common site factors that are to be managed as a single unit (for more information see Kerr *et al.*, 2002, 2003). Within each block, data are collected from fixed-area plots where the plot area is selected to assess a minimum number of trees. To avoid the problem of clustering associated with random sampling, plots are located on a systematic grid covering the whole area (Figure 8); this has the added benefit that systematic sampling is easier to implement. The plots can be permanent or temporary depending on the data required by the forest manager and the resources available. The main assessments are: species, number and diameter of trees; species and number of saplings; species and number of seedlings; and vegetation type and cover.

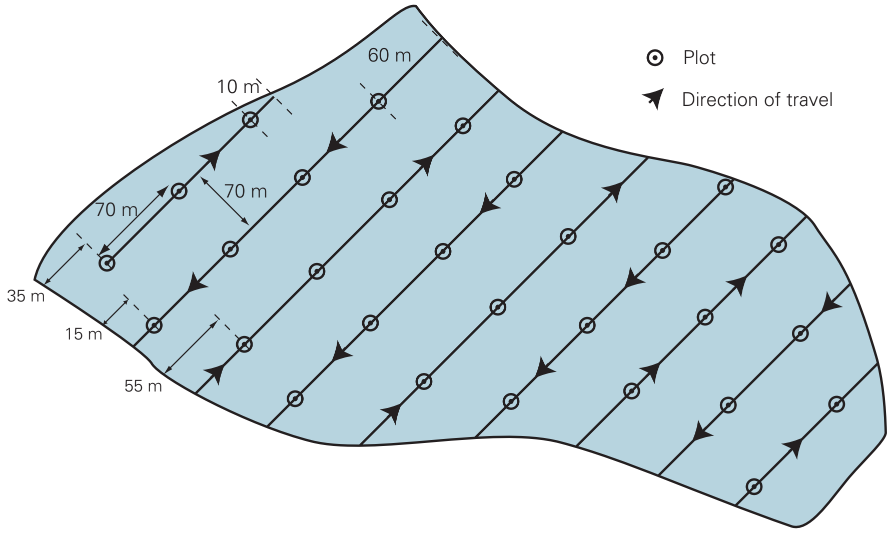
To help forest managers, we have developed software that processes the data into a useful format. The opportunity has also been taken to allow other information about the transformation of an area to be recorded alongside the monitoring data. Hence the system allows storage of the transformation plan, diary notes, fixed-point photographs and information on stand location. The following information is displayed:

- Species, number and size of trees
- Basal area per species
- Diameter distribution
- Sapling and seedling regeneration
- Vegetation type and cover.

The software was released in 2004 (contact gary.kerr@forestry.gsi.gov.uk).

Figure 8

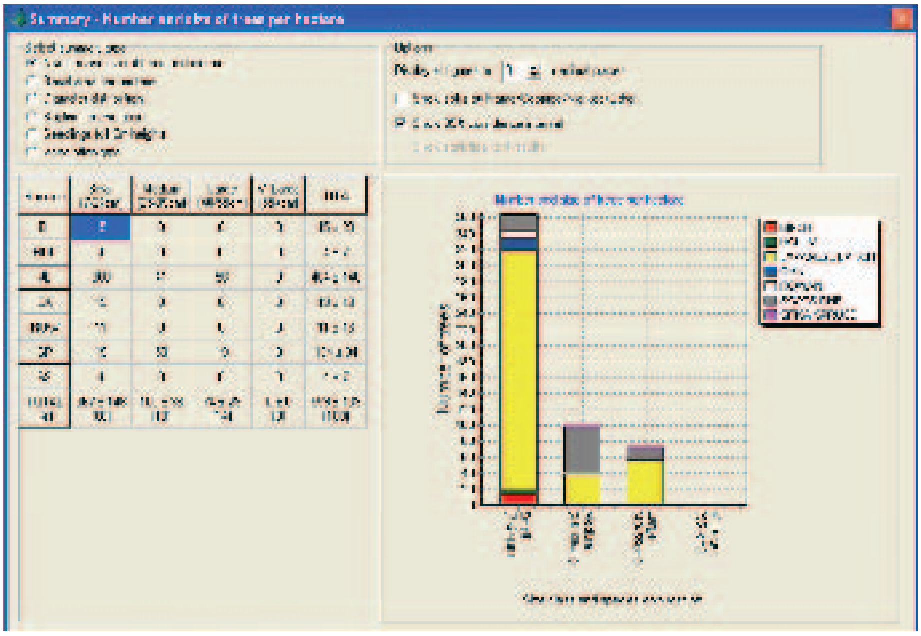
Plots are located on a systematic grid to ensure data is collected from the whole stand.

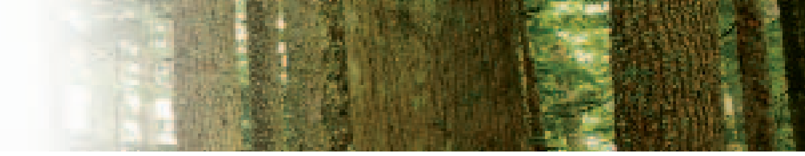


Examples of the way the software presents data are shown in Figures 9 and 10, using data from a mixed stand dominated by Scots pine and Japanese larch in Wykeham Forest, Yorkshire. Figure 9 shows the number and size of trees presented by species; Figure 10 shows the diameter distribution of the stand. A statistical test can be performed on the diameter distributions to determine if the distribution is 'symmetric' (similar to a normal distribution) or 'skewed'.A skewed distribution would have a large number of small trees, a moderate number of medium trees and a low number of large trees, and is similar to the 'reverse-j' distribution much discussed as an option for managing continuous cover forests (O' Hara, 1996 and 1998). This information can be used when thinning the stand, especially if the aim is to develop a complex structure, i.e. one with three or more canopy strata and a skewed diameter distribution.

Figure 9

Number and size of trees per hectare presented by species.





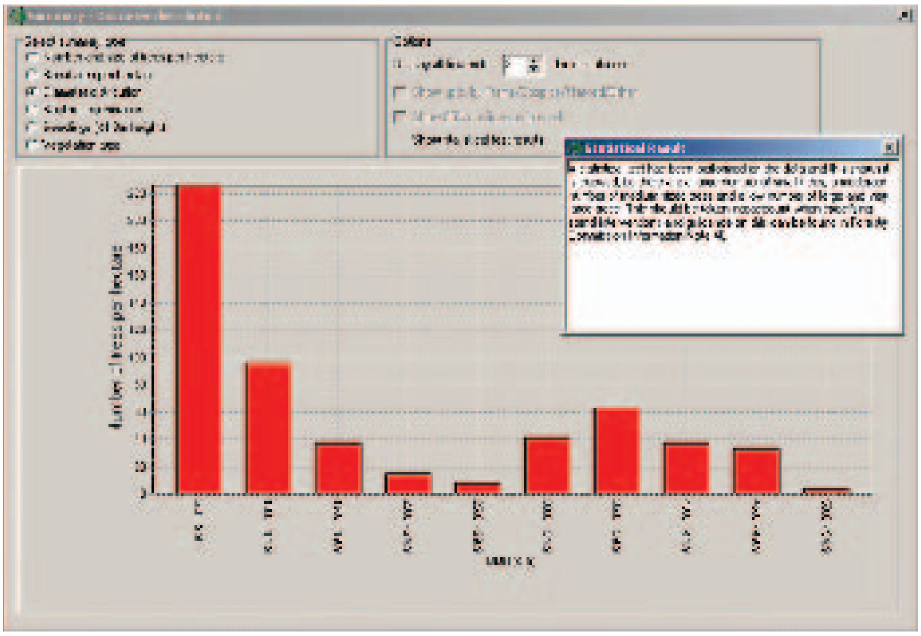


Figure 10

Diameter distribution of the stand.

Data on sapling numbers can also be examined, including testing whether the distribution of saplings is even, clustered or distinctly clustered. The quantity and spatial distribution of sapling regeneration is one of the factors to consider when transforming a stand to continuous cover (Mason and Kerr, 2004).

Conclusion

The breadth of research activity outlined above indicates how widespread adoption of CCF could affect a wide range of conventional forestry practices and outputs. Other aspects that may need to be considered include effects upon wood properties (where a preliminary study is being sponsored by the Scottish Forestry Trust), on biodiversity, on amenity and recreational benefits, and upon soil properties and quality. Given that transformation to irregular forest structures can take 50-100 years, successful implementation of these desired changes will only be achieved through an 'adaptive management' approach involving shared experience between field foresters, forest scientists, policymakers and other stakeholders.

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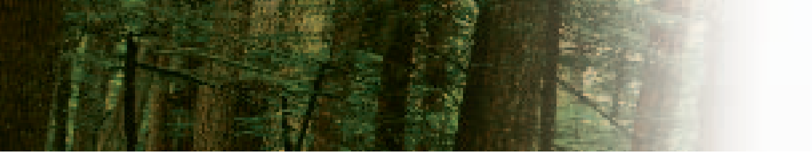

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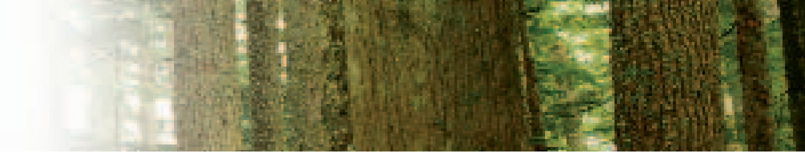

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