An evaluation of continuous cover forestry in Ireland

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Introduction

A continuous forest is a forest so treated that the forest cover is continuously maintained and the soil never exposed (Troup 1927). Thus continuous cover forestry (CCF) includes all those silvicultural systems, which involve the continuous and uninterrupted maintenance of the forest (Troup 1928). These silvicultural systems tend to be associated with natural regeneration.

While the practice of CCF is not new, interest in this approach to forest management increased in Europe in the early 1980s when concerns about forest decline emerged. The occurrence of substantial windblow in forest stands throughout Europe in the 1990s further stimulated interest in CCF (Knoke and Plusczyk 2001). Coincident with these concerns, clearfelling has been subjected to increased criticism in recent years associated with its often negative impacts on many non-wood forest resources, such as scenic values, habitats, biodiversity and recreation (Jull and Stevenson 2001).

In CCF systems, only single or small groups of trees are removed at prescribed time intervals, allowing for the development of an understorey. This protects against soil erosion, improves aesthetics and reduces the negative effect of habitat fragmentation (Saunders et al. 1991; Guldin 1996; Mason 2002). However, continuous cover forestry does have drawbacks. It has been shown in some cases to result in greater harvesting costs per unit of volume (Kluender et al. 1998) and is considered to be more labour intensive and difficult to apply than the clearfell system (Hotvedt and Ward 1990 cited in Buongiorno 2001). Furthermore, continuous cover forestry requires an expert knowledge and is sometimes viewed as a very unpredictable method by which to achieve good financial return (Pommerening 2006). Nevertheless, increased public awareness and demand for multiple-use forestry suggests that the area of forest managed under continuous cover forestry is likely to increase (Buongiorno 2001).

In Ireland the majority of forests are non-native even-aged conifer monoculture plantations managed primarily under the clearfell system. Although the practice of continuous cover forestry has been used productively for the past 120 years in continental Europe it has yet to make an impact in Irish forestry. Yet indications are that pressure to introduce alternatives to clearfell systems in Ireland will increase.

Following a public consultation process conducted by Coillte as part of setting up a Sustainable Forest Management (SFM) initiative, biodiversity and clearfelling were the issues of greatest concern raised by the contributors (Pfeifer 1998). Following this consultation, Coillte adopted the principles of SFM as laid down by the Forest Stewardship Council including the commitment to consider continuous cover systems in windfirm conifer plantations. At the time the CONTINUCOVER project was initiated in 2002, CCF systems had not yet been introduced into any Coillte sites. By 2004, 34 sites (1062 ha) in the Coillte estate had varying CCF prescriptions drawn up for them, which were subsequently incorporated into the respective Forest Management Plans for these sites.

Initially the focus was on conifers, however, more recently, Coillte's Low Impact Silvicultural Systems (LISS) policy states that all Broadleaf High Forest will be managed under CCF. The policy further states that CCF will be the favoured silvicultural system in amenity areas - such as Gougane Forest.

Within the private sector, a number of large estate owners have decided to transform their forests to CCF. In addition, a number of smaller forest owners have either commenced transformation work or have expressed a commitment to do so when their forests are at an age to thin. Most of these private owners and their foresters are active members of Pro Silva Ireland which they use as a forum for discussion and informal training through field days and study tours (Paddy Purser, pers com).

The process of changing a stand that is even-aged, structurally homogenous, as is commonly the case with stands managed under the clearfell system, to one where the within-in stand structural diversity is greater, as is the case with stands managed under continuous cover forestry systems, is referred to as transformation (Mason and Kerr 2001). Although irregular structures may develop from a regular even-aged stand under a non-intervention regime as a consequence of natural disturbances, transformation can be viewed as an acceleration of such natural development to achieve the desired degree of irregularity (Malcolm et al. 2001). Transformation can be a gradual or a sudden change in forest structure depending on the required results and constraints imposed by the existing stand (Pommerening 2006).

The adoption of continuous cover forestry in Ireland will require greater knowledge and understanding of the processes involved in transformation. A key element of the transformation process is the ability to develop an understorey below an existing canopy using natural regeneration or underplanting. The presence of an overstorey will have direct effects on the levels of light, temperature, water availability and may also influence nitrogen dynamics, all of which will in turn influence the growth rates of understorey seedlings. Thus regardless of establishment methods, if seedlings are to survive beneath an existing canopy, the environment must be conducive to their growth and development.

Objectives of the research

The majority of the forest estate in Ireland is comprised of even-aged Sitka spruce (*Picea sitchensis* (Bong.) Carr.) plantations. In these plantations the process of transformation will involve opening up the canopy to encourage the emergence of an understorey through either natural regeneration or underplanting. However, little is known in Ireland about the process of opening up a canopy and how this influences the microclimate and soil dynamics in the understorey. Hence this project set out to:

1. examine the survival and associated growth rates of six tree species of varying shade tolerances when planted under three different levels of canopy openness in a 40-year old Sitka spruce stand;
2. quantify light levels in Sitka spruce stands under different levels of canopy openness;
3. develop models that could be used to predict light levels in the understorey using readily available and easy to measure stand variables;
4. assess how different levels of canopy openness affect the soil nitrogen dynamics; the processes involved in nitrogen transformations in the forest soil; soil temperature, water and pH;
5. establish demonstrations of methods to transform even-aged Sitka spruce stands to continuous cover forestry.

Crown thinned section of Brownhill site. Frame trees are identified by ribbons, plot boundaries are identified by X.

Methodology

This study consisted of a combination of field experiments, controlled experiments as well as demonstrations. A description of the sites selected and the methods used in the study areas now follows.

Ballinagappoge field experiment

In 2002, the field experiment was laid down in a 2.7 ha section of a Coillte-owned stand located within Ballinagappoge property in Aughrim Forest, Co Wicklow (13058L) (52°54' N; 06°23' W). The site has a slope of 5° to 10° with a southerly aspect and is at an elevation of 300 m above sea level. The soil type is an acid brown earth with associated brown podozols and the site is reasonably sheltered. In 1965 the site was afforested with a pure stand of Sitka spruce with an estimated yield class of 18 m^3 ha^{-1} an^{-1}. The stand was thinned in 1991, 1995 and 1999. The first thinning was a rack and selective thinning with both subsequent thinnings being selective thinnings from below.

Experimental layout

The experimental area was divided into three blocks (1-3). Each block was then divided into three plots measuring 50 x 60 m (Figure 1). The diameter at breast height (dbh) of every tree within each plot was measured with electronic callipers to yield the estimated basal area per hectare (Table 1). In February 2003, six plots (A, C, D, F, G and H) were thinned to different intensities. In plots C, F and G the basal area was reduced to 24 m^2 ha^{-1}, while in plots A, D and H it was reduced to 29 m^2 ha^{-1}. In the remaining plots, B, E and I, no thinning was carried out leaving the plots to act as a control with an average basal area of 34 m^2 ha^{-1}.

The allocation of the plots within the blocks was random constrained by the original basal area in the plots. The choice of trees to be removed during the thinning was influenced by the required basal area reduction and also by the constraint to have the remaining trees equally spread throughout the plots. Key characteristics of the stand prior to and post thinning are shown in Table 1.

In the spring of 2003, post-thinning, a deer fence was erected around the experimental area and the following six conifer and broadleaf species were planted in March and April: Sitka spruce, hybrid larch (*Larix* x *eurolepis* Henry), western red cedar (*Thuja plicata* Donn ex D. Don), European beech (*Fagus sylvatica*,L.), downy birch (*Betula pubescens* Ehrh.) and sessile oak (*Quercus petraea* (Matt, Liebl.).

Within each of the nine plots (A-I), two subplots of each species were laid down. Fifty-six containerised seedlings were planted in each subplot at the spacing recommended by the Forest Service (Anon 2000), conifers were planted at 2 x 2 m while the broadleaves were planted at 1.5 x 2 m spacing. The central 25 seedlings within each of the subplots were permanently marked as the experimental seedlings for annual measurement. A small area beside the experimental area was clearfelled and planted with a number of seedlings of each of the six species to give an indication of how the species might perform in full light. However, the clearfell area was not replicated due to concerns regarding windthrow risk.

Following planting, a combination of drought, hare damage and poor plant quality caused many of the seedlings to die. In September 2003 a hare fence was erected around the perimeter of the experiment and all seedlings were replaced in January 2004 (excluding western red cedar as mortality for this species was relatively low).

The experimental design was a split plot, with the three overstorey basal area treatments as main treatments and the tree species as subtreatments. As the clearfell plot was not replicated it did not form part of the experimental design.

In January 2008, the stand was marked for another thinning, with the aim of bringing the overstorey basal area down to the levels attained following the first thinning. Felling had taken place in Block 3 and part of Block 2, when it had to be stopped for operational reasons.

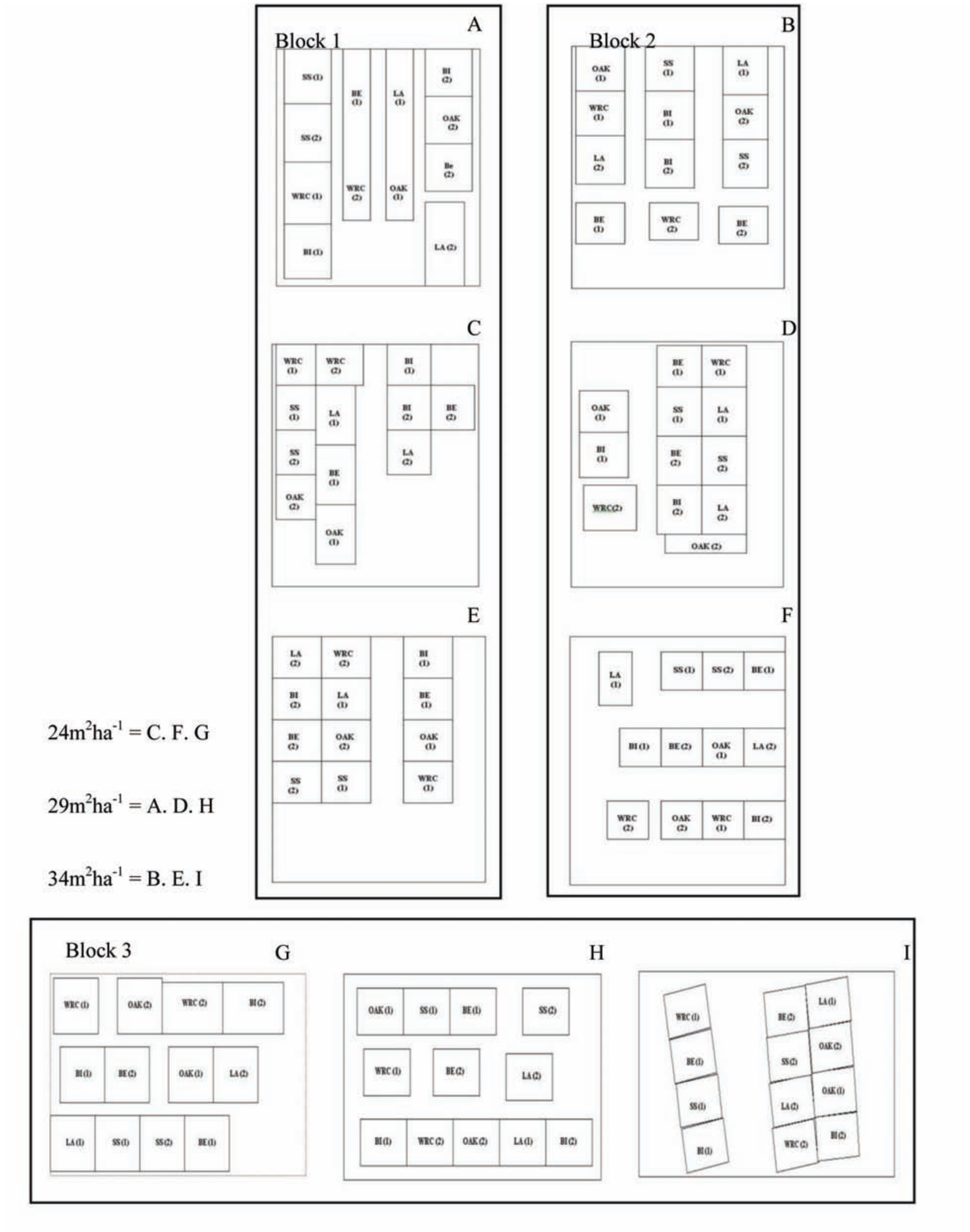

Figure 1: Experimental layout at Ballinagappoge, Co Wicklow.

Table 1: Key characteristics of the plots prior to and post thinning.

	Prior to thinning			Post thinning								
	2002			2003					2005			
Plot	Basal area (m^2 ha^{-1})	Stocking (trees ha^{-1})	Mean DBH (cm)	Basal area (m^2 ha^{-1})	Basal area removed (%)	Number of stems removed (trees ha^{-1})	Stocking (trees ha^{-1})	Mean DBH (cm)	Basal area (m^2 ha^{-1})	Basal area increase (%)	Stocking (trees ha^{-1})	Mean DBH (cm)
B	35.40	493	30	35.40	0.0	0	493	30	39.66	12.03	493	32
E	34.43	490	30	34.43	0.0	0	490	30	36.73	6.68	490	31
I	34.37	427	32	34.37	0.0	0	427	32	39.36	14.52	427	34
D	30.37	547	27	28.97	4.6	77	470	28	34.93	20.57	470	31
A	34.37	473	30	29.10	15.3	86	387	31	32.89	13.02	387	33
H	35.07	427	32	29.07	17.1	87	340	33	32.59	12.11	340	35
C	29.20	490	28	24.01	17.5	117	373	29	28.52	18.70	373	31
G	32.30	403	32	25.31	21.5	103	300	33	30.69	20.80	300	36
F	34.07	520	29	23.93	29.8	223	297	32	27.56	15.17	297	34

Morphological data collection

The height, root collar diameter and mortality of the planted seedlings were recorded in January 2004, December 2004 and December 2005. Mortality was recorded again in 2010. Heights were measured in cm to the highest live foliage or initiated bud with a measuring staff. Root collar diameters were measured in mm using a digital calliper at 5 cm above the ground. The height to diameter ratio was calculated for each seedling. Mortality was judged on the absence of needles for conifers and the absence of initiated buds for broadleaves.

The morphological data were analysed using the ANOVA procedure on the GENSTAT statistical package (Payne 2002). The analysis was limited to only four species; the data from western red cedar were excluded as the species had been planted in spring 2003 while the remaining five were planted in 2004. Additionally, larch was omitted as within a short period of planting in spring 2004 all seedlings had died. This may have been due to a combination of poor planting stock and very dry conditions.

Hemispherical photography

Altering the canopy can influence the amount of light available to understorey species. While understorey light levels can be measured directly using instruments such as quantum sensors, these must be place in the forest for a considerable period of time to capture the variability in light. Instead, indirect measures which measure canopy cover or canopy closure are often used. In this study hemispherical photography was used to assess canopy closure. Using this approach photographs are taken at particular points in the forest, looking upwards from beneath a canopy through a 180° 'fisheye' lens (Evans and Coombe 1959) (Figure 2). With a 180° field of view, hemispherical photography provides the most complete measure of canopy closure (Jennings et al. 1999). The advantage of this approach is that it is a quick and relatively inexpensive method that provides a permanent record of the overstorey canopy geometry relative to an understorey position (Lieffers et al. 1999). It is possible to superimpose the annual solar track on the pictures taken, using specialised computer software, and to estimate light penetration for different times of the year or the whole year (Cannell and Grace 1993).

In this study, hemispherical photographs were taken in eight positions (known as photo-points) in each of the nine plots in Ballinagappoge. Each photo-point was permanently marked with a wooden stake. Photos were taken in June 2002 before thinning and post-thinning in June 2003 and June 2005. The photographs were captured using a 180° fisheye lens (Sigma 8 mm F4, Sigma cooperation, Tokyo, Japan). The fisheye lens was used in conjunction with a self-levelling mount (Type SLM©, Delta-T Devices Ltd, Burwell, UK) and a digital camera (Nikon Coolpix 995©, Nikon Cooperation, Tokyo Japan). When assembled, these units were mounted on a commercial tripod. Photographs were captured on dry calm days with uniform overcast conditions. Using the cardinal alignment marker on the lens all

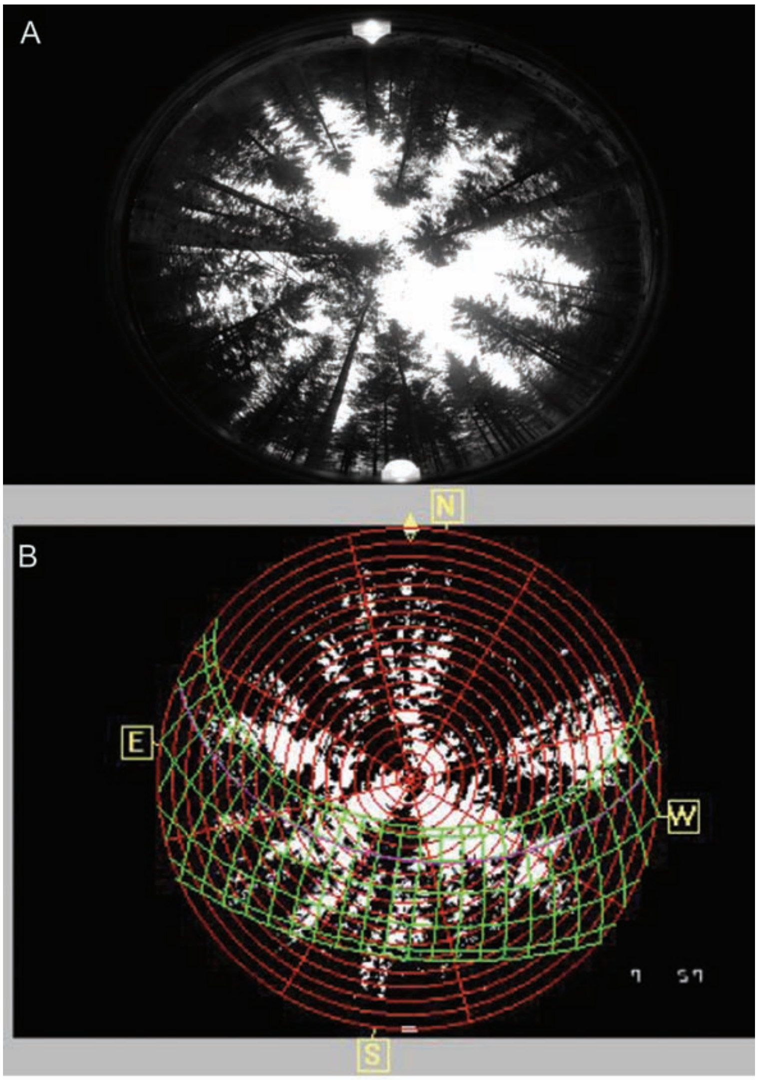

Figure 2: Hemispherical photograph of canopy (A); hemispherical photograph overlain with solar path (B).

photographs were taken so that the top of the image was aligned with the north at 1.3 m above ground level (Figure 2). Three photographs were taken at each position; overexposed, underexposed and automatic exposure. The image with the best sky/canopy contrast was selected for analysis.

The photographs taken in 2002 and 2003 were analysed by Dr Sophie Hale, Forestry Commission UK. Thereafter the photographs were analysed by Denis Coghlan (UCD), following training. HemiView (© Delta-T Devices, Cambridge, UK) software was used to analyse all the photographs. This software evaluated the digital images pixel by pixel, and classified each pixel as either unobstructed sky, or as canopy (including foliage, branches and stems). This classification was done by setting a brightness threshold, above which a pixel was classified as unobstructed sky, and below which it was classified as canopy. The output from the analysis of the hemispherical photos includes a measure of canopy openness (i.e. the complement of canopy closure, called VisSky or gap fraction in Hemiview software), as well as measures of direct (direct site factor) and indirect radiation (indirect site factor).

Gap fraction is the proportion of the hemisphere that is not obscured by the forest canopy, i.e. a measure of canopy openness. It is also a permanent photographic record of the appearance of the forest canopy observed by visual sighting.

The direct site factor (DSF) is the level of direct radiation that penetrates below the canopy for a unique location. DSF for a given location varies with time of day and time of year and was calculated by superimposing the annual solar track (of a given latitude) (Figure 2) over the hemispherical photograph and summing the level of direct solar light (sun beams) to the given location.

The indirect site factor (ISF) is the proportion of indirect radiation of the solar beam that has penetrated the canopy, i.e. the proportion of diffuse light that is transmitted through the canopy. In contrast to the direct site factor, the indirect site factor does not vary with time of year, and is independent of latitude. On completely overcast days, the indirect site factor equals the total radiation through the canopy. In the remainder of this report, ISF is referred to as transmittance.

The relationships between gap fraction, transmittance and certain characteristics of the overstorey recorded in the plots at Ballinagappoge were examined. The characteristics of the overstorey included;

i. Basal area per ha (m^2);
ii. Mean dbh per ha (cm);
iii. Basal area within a 7.5 m radius of each photo-point (m^2);
iv. Basal area within a 4.0 m radius of each photo-point (m^2);
v. Stems per ha;
vi. Basal areas of each of the four nearest trees to the photo-point (m^2);
vii. Total basal area of the four nearest trees to the photo-point (m^2);
viii. Crown projections of the two nearest trees to the photo-point (m^2).

Nitrogen mineralisation and nitrification

To estimate the rates of nitrogen mineralisation and nitrification in the plots (A to I) in Ballinagappoge an area of 100 m^2 was selected within each plot and a 2 m grid was marked to give 36 sample points per plot. The buried bag method was used (Eno 1960), which involved incubating samples of the organic layer in polyethylene bags, which were reburied at the point from which they were sampled. The bags allow exchange of O_2 and CO_2 with the outside but prevent loss of water, ammonium or nitrate. At the time the bags were buried, a second soil core was collected at each sample point and returned to the laboratory where it was stored at 4°C until processing. The incubated samples were collected after approximately one month. Upon return to the laboratory the concentrations of ammonium (NH_4^+-N) and nitrate (NO_3^--N) in the organic horizon soil cores were determined in both the incubated soil and the soil collected at the start of the incubation and rates of mineralisation and nitrification were determined by the difference between the concentrations at the beginning and end of the incubations. The first incubation period was during June 2003. The three plots in Block 2 were sampled at the 36 points in the sampling grid in each plot giving 108 samples in total. The second and third incubation periods were during September 2003 and June 2004 during which the grids in all nine plots from the three blocks were sampled giving 324 samples in total for each sampling period. The full details of the methodology used are outlined in Freeman (2008).

Temperature measurements

Soil temperatures were measured at the Ballinagappoge site using dataloggers, which are electronic devices that record information at intervals over a period of time. Miniature data loggers called Tinytags (Gemini Data Loggers, UK) which are compact, battery operated and waterproof were used. Three Tinytags were buried in each of six plots (A-F) in the organic soil horizon at selected sampling points (18 tags in total). Soil temperatures were recorded every half hour over periods from November 2003 to April 2005. The data were downloaded and analysed using OTLM Software, Version 2.8 (Copyright© Gemini Data Loggers, UK). Soil temperature was also recorded using a Delta-T DL2e datalogger (Delta-T Devices, UK). This datalogger records the temperature measured by soil probes connected to it via cables. Soil probes were inserted into the organic soil horizon at 5 cm depth, at 30 sample points. The datalogger and probes were moved between the six plots in Blocks 1 and 2 and soil temperature was recorded every 30 minutes at the 30 sample points in each of the plots for approximately two weeks. The data were downloaded and analysed using Ls2WIN Software, (Copyright© Delta-T Devices, UK).

The temperatures recorded provided two types of data sets: readings from the Tinytags, which were continuously recorded over long periods of time (months) simultaneously in six plots, and readings from the Delta-T logger which were continuously recorded for short periods (weeks) at each of the 30 sampling points in one plot at a time. This allowed estimation of these unknown temperatures at each point in the sampling grids by creating a temperature model. This was developed for each plot using the

Delta-T data and the Tinytag data from the same periods in the same plot. The Delta-T data were modelled against the Tinytag data using regression analysis to produce a model equation for each sample point. These equations were then used to provide estimates of the soil temperature at the 30 sample points using known temperatures for the period from the Tinytag data. The temperature models for each plot were created using regression analysis with SAS System Version 8 (Copyright© 1999-2001, SAS Institute, Inc.). The temperature models were tested by comparing model generated temperature data with recorded temperature data from the Delta-T datalogger. The estimates provided by the models were used to obtain daily, weekly and monthly maximum, minimum and average soil temperatures for each of the six plots.

Soil water content and soil pH

The soil water content was determined for all soil samples (324 samples for each sampling period) taken in Ballinagappoge. The pH of each soil sample was measured for the first sampling period only (324 samples) according to the method outlined in Freeman (2008).

Tree distance and canopy cover

The distances from each sample point, on the 36 point sampling grid, to the centre of the nearest tree bole were measured and recorded in each of the nine plots in Ballinagappoge. Furthermore, canopy cover at each sample point in each plot, was estimated using a densitometer (Geographic Resource Solutions, USA)[1]. This instrument uses a mirror to project a view of the canopy directly above the sample point on the ground. This provides an exact vertical line-of-sight into the canopy from which canopy cover can be estimated. Usually a densitometer is used in conjunction with some form of sampling to determine canopy cover in plots by noting at a number of sample points whether or not canopy is visible; the proportion of points that have cover expressed as a percentage of the total number of points is used to estimate canopy cover. In this study a subjective assessment of canopy cover (canopy uncover = 1-canopy cover) was made at each sample point by estimating the proportion of the view at each point that was canopy.

Path analysis

Multiple regression analysis can be used to provide explanations for relationships among a number of variables typically using a single dependent variable and several explanatory variables. However, multiple regressions do not provide direct paths between the predictor variables.

A method known as path analysis developed by Wright (1921) is an extension of the regression model and provides standardized partial regression coefficients from the multiple regression equations. These regression coefficients are called path coefficients, also known as beta weights and direct effects. Indirect effects are the path coefficients from one predictor variable through the intervening predictor variables to the dependent variable. This method can be used when causal relationships are known to develop a path model.

The path model is a diagram that represents the model and causal relationships graphically. Variables that have no causal factors in the model are termed exogenous variables and intervening variables are caused by another variable in the model and are called endogenous variables. Single arrows indicate causation between the exogenous variables and intervening variables. Variables not observed but have causal roles in the model are termed latent variables, directly observed variables are termed manifest variables (in this study all the variables were directly observed).

All endogenous variables have a residual error term associated with them which reflects the unexplained variance and measurement error. Path coefficients can be used to calculate direct, indirect and total causal effects. The direct effect of one variable on another is the regression weight from one variable along a single path to another. Indirect effects are calculated as the product of all the path coefficients of the intervening variables along the path. These indirect paths are calculated along all the possible paths and the sum of all the indirect effects is called the total indirect effect. The total causal effect is the sum of the direct effect and the total indirect effects.

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1 Canopy cover differs from canopy closure as estimated by hemispherical photography in that the latter integrates information over a segment of the sky hemisphere at one point on the ground while the former relates to the presence or absence of canopy directly above a point (Jennings et al. 1999).

It is possible to estimate and test these causal models based on maximum likelihood techniques using structural equation modelling software packages. A model was created to examine the causal relationships between the 18 variables measured in this study and the model fit was tested using Amos Version 6 (Copyright© 1983-2005, Amos Development Corp). The model was tested using a ratio chi-square test which assesses the overall fit of the model and also the Tucker-Lewis Index (TLI) and the Root Mean Square Error of Approximation (RMSEA).

Vegetation monitoring

A survey of the vegetation on the Ballinagappoge site was undertaken in 2006 by Marie-Christine Fléchard. The record of species was done through a walkover survey and did not involve the use of systematic quadrats. Both ground (< 0.20 m) and field layer (0.2-2 m) vegetation were recorded. An evaluation of the natural regeneration was also included.

The species presence was measured by the use of the frequency scale known as the DAFOR scale. DAFOR refers to the abundance of the species with the following decreasing order:

- D: Dominant
- A: Abundant
- F: Frequent
- O: Occasional
- R: Rare

The prefix 'locally' and 'very' were used where appropriate. The results of this survey can be found in Appendix A.

Belfield shadehouse experiment

The objective of the shadehouse experiment was to examine, under controlled conditions, the impact of shade on morphology, growth and biomass allocation in Sitka spruce, hybrid larch and western red cedar. In these controlled conditions seedlings of the three species were exposed to different shade levels but other resources such as water and nutrients were kept at almost the same levels for all treatments. In a forest understorey the response to changing light levels is influenced by the availability of other resources (Kimmins 1987). In this study the aim was to separate the effects of these confounding factors and focus only on the response to changing light conditions.

The shadehouses

Twelve shadehouses [2 m(h) x 2.5 m(w) x 5 m(l)] were constructed on a 0.2 ha section of an open field at the Thornfield Research Complex, located on the Belfield Campus of University College Dublin. The shadehouses were made from green polypropylene shade fabrics of different mesh gauges erected on frames to simulate three shade treatments: 25%, 50% and 75%. Frames without shade fabric served as controls (i.e. 0% shade). The shadehouses were placed on Mypex ground cover in the open, 2.0 m apart to prevent treatment overlap (Figure 3).

Figure 3: Shadehouse trial at Thornfield, UCD.

The plants

In April 2003, containerised Sitka spruce, hybrid larch and western red cedar seedlings were purchased from a nursery in Aughrim, Co Wicklow. The mean seedling heights were 42 cm for hybrid larch, 30 cm for Sitka spruce and 39 cm for western red cedar. The mean root collar diameters were 5.8 mm for hybrid larch, 4.5 mm for Sitka spruce and 5.2 mm for western red cedar. On arrival to the experimental site the seedlings were put into 3 litre pots with potting compost. They were then placed in a glasshouse and watered for one month.

In May 2003, 1008 (336 x 3 species) seedlings were taken from the glasshouse and placed in the shadehouses. A total of 28 potted seedlings of each species were placed in each level of shade. The inner 10 seedlings served as sample seedlings while the outer 18 acted as buffer seedlings. The total number of trees in each block was 336. The hybrid larch, which tends to have soft shoots, was staked with 0.5 m split canes to reduce overlapping and shoot breakage. This support was removed when the seedlings were repotted for the second growing season. The pot sizes used allowed the roots to grow freely at all stages during the experiment. All seedlings were watered to field capacity on a twice-weekly basis during the summer months and on a weekly basis otherwise. One litre of Kemira Feed (167 mg/l N; 46 mg/l P; 291 mg/l K; 140 mg/l Ca; 35 mg/l Mg; 64 mg/l S; 0.5 mg/l B; 0.6 mg/l Mn; 0.2 mg/l Cu; 0.4 mg/l Zn; 0.05 mg/l Mo) was applied to each pot every 8 weeks to ensure that lack of nutrients did not become a confounding factor over the duration of the study. Weeding was carried out when required.

Morphological measurements

At the beginning and the end of the first growing season, the heights (cm) and the root collar diameters (mm) of all sample seedlings in the Belfield shadehouse trial were measured. A detailed outline of the methodology used and the results obtained are given in Kennedy et al. (2007).

Chlorophyll fluorescence measurements

At the start of the shadehouse experiment a sample tree seedling of each species under each shade treatment within each block was selected at random and tagged. Chlorophyll *a* fluorescence measurements were taken on these sample plants. Chlorophyll fluorescence measurement is a practical non-intrusive method of assessing photosynthetic performance in plant physiological experiments (Govindjee, 1995). Fluorescence parameters can be used to show how efficient photochemistry is. Furthermore, characterisation of PSII photochemistry using chlorophyll fluorescence measurements can help to distinguish between photoprotective mechanisms and photoinhibition (Muller et al. 2001). A detailed outline of the methodology used and the results obtained are given in Kennedy (2007).

Carbon isotope discrimination

Conventional classification of shade tolerance in tree species has been based on a species ability to withstand low light conditions using indirect field observations (Daniel et al. 1979; Carter and Klinka 1992). Direct assessments of plant performance, based on growth increment under shaded conditions, are often time consuming and require complex factorial experimental approaches (Carter and Klinka 1992; Fownes and Harrington 2004). In contrast, indirect non-destructive assessments of seedling performance allow for the identification of individuals with desired traits over a range of selection stages and environmental conditions.

In this study the potential use of leaf carbon isotope discrimination for the selection of shade tolerant species was explored. Leaves of C_3 plants exhibit substantial inter- and intra-specific variations in stable carbon isotope composition ($^{13}C/^{12}C$) due to differences in fractionation during photosynthetic and other metabolic processes (Farquhar et al. 1982; Damesin and Lelarge 2003; Ghasghaire et al. 2003). The two main discriminating steps against ^{13}C in autotrophic tissue include CO_2 diffusion into the leaf air spaces (stomatal resistance) and carboxylation of ribulose-1,5-bisphosphate. Instantaneous ($^{13}C\Delta_i$, based on on-line gas exchange) or net long-term discrimination against ^{13}C ($^{13}C\Delta_n$, in organic material) is usually positively correlated with intracellular to ambient CO_2 concentration ratio (C_i:C_a) and is indirectly indicative of differences in water- and nitrogen-use (Farquhar et al. 1982; Griffiths 1996; Fownes and Harrington 2004). Therefore, relationships among photosynthesis, biomass increment and long term leaf $^{13}C\Delta_n$ may provide the basis for the development of physiological indices for the selection of species or provenances under conditions where growth is limited by light, water or nitrogen availability (Griffiths 1996; Fownes and Harrington 2004).

The inter- and intra-specific variations in leaf $^{13}C\Delta_n$ in the three species that formed the shadehouse trial were assessed in order to determine the possibility of using leaf $^{13}C\Delta_n$ as a marker for identifying the physiologically-based characteristics associated with shade tolerance. The methods used and the results found are outlined in Kennedy et al. (2006).

Mount Callan demonstration forest

Mount Callan is a 398.4 ha forest estate in Co Clare, which is currently owned by the Tottenham family. The estate ranges in elevation from 120 to 380 m above sea level, with a wide range of site types. The dominant species is Sitka spruce, which was first planted on the site in 1958. At the start of this study, the then owner, Robert Tottenham was a partner in this study, and an advocate for continuous cover forestry. As part of this project Mount Callan was established as a demonstration forest for continuous cover forestry. An inventory and a management plan with the aim of transforming the forest to CCF were drawn up as part of this project.

In 2002 a small regeneration experiment was established in Mount Callan forest. Four 20 m diameter coupes were created in two mature Sitka spruce stands. In each of these coupes, some sections were seeded in spring 2003 with Sitka spruce seed provided from the Coillte Seed Centre, Ballintemple, while other sections were left unseeded. Scarifying using a rake was also carried out in parts as was fencing using chicken wire. Eight plots were laid down in each of these gaps consisting of a combination of the above treatments (Table 2). The coupes were monitored and the level of germination as well as any natural regeneration recorded. In March 2005 the numbers of seedlings in five 20 x 20 cm plots within each of the treatments and groups (yielding a total of 160 sub-plots) were assessed.

Brownhill demonstration forest

A section of a pure Sitka spruce stand (planted 1975) in Brownhill property, adjacent to the Ballinagappoge site, was selected to demonstrate how silvicultural management for continuous cover forestry differs from that for the clear cutting system. Specifically, the objective of this demonstration was to show different approaches to thinning in a stand managed for continuous cover. This 20.8 ha stand with a yield class of 16 $m^3ha^{-1}an^{-1}$ had been thinned once (rack and selective thinning) in 1996. A small section (approx. 0.5 ha) was unthinned. In 2002, a one ha section of the thinned stand was marked for a crown thinning while the remainder of the thinned stand received a standard selective thinning. The unthinned section was not touched (Figure 4). The aim in marking trees for the crown thinning was to promote crown development on future parent trees (also referred to as frame trees) so as to encourage natural regeneration. Approximately 250 trees equally distributed throughout the plot were selected as future parent trees. Trees competing with these future parent trees were marked and removed during the thinning. All thinning (within and outside the plot) was carried out mechanically by harvester.

In August 2005, the crown thinned area (Block B) was divided into three sections. In section 1 all trees competing with the frame trees were removed. In section 2 all 'non-frame trees' of dbh 20 cm or greater were removed, while in section 3 all the 'non-frame trees' of dbh 17 cm or greater were removed. The three thinning intensities were chosen to mimic light, medium and heavy thinnings. To minimise the risk of windblow the sections were organised in the form of a strip shelterwood with the lightest thinning on

Table 2: Treatments included in Mount Callan trial.

Treatment Number	Treatments		
111	Scarify	Seed	Fenced
121	Scarify	No Seed	Fenced
112	Scarify	Seed	No Fenced
122	Scarify	No Seed	No Fenced
211	No Scarify	Seed	Fenced
221	No Scarify	No Seed	Fenced
212	No Scarify	Seed	No Fenced
222	No Scarify	No Seed	No Fenced

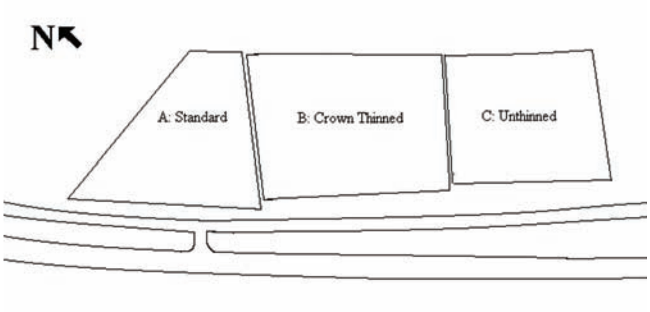

Figure 4: Layout of the three thinning demonstration blocks at Brownhill.

the western edge of block B and the heaviest, section 3, on the eastern edge (Appendix B).

A deer fence was erected in April 2007. In April 2007 and April 2009 canopy openness in the various thinning sections was assessed using hemispherical photography. In addition, estimates of the basal area of the trees surrounding the photo-points were made by measuring the dbh of each tree in a 7 m radius plot around each point. The emergence of natural regeneration was monitored.

A survey of the vegetation on the Brownhill site was undertaken in 2007 using similar methods to those outlined for the Ballinagappoge site. The results of this survey can be found in Appendix A.

Establishment of marteloscopes

Marteloscopes are 1 ha plots where all the trees are marked and plotted in a stand chosen to demonstrate a particular irregular structure or a stage in transformation to irregularity. They are training tools for continuous cover forestry and they provide a mechanism by which trainees can determine the consequences of theoretical removals from a plot of trees. A number of marteloscopes were set up as part of this study[2]. These were located in Curraghchase forest in Co Limerick (Coillte-owned), while a further two were laid down in Mount Callan forest. In setting up the martelscopes a detailed inventory of the trees was recorded and each tree was marked with an individual number tag and its location mapped and recorded. This information was inputted into specialised software. In 2007, a group of foresters and forestry students took part in a training exercise based in the Curraghchase marteloscope. The trainees selected trees for felling by inputting the corresponding tree number into the software which provided a summary of the consequences (including financial, silvicultural and ecological) of the marking exercise.

The Marteloscope is at once a practical demonstration and a sophisticated modelling tool that shows the mechanisms of transforming to irregularity set against both negative and positive management. Very few foresters nowadays have the marking skills required for continuous cover or an understanding of the financial and environmental benefits of transformation. The Marteloscope gives the trainee the means to practice alone and to see the immediate consequences of an approach to selection and therefore learn first hand without trailing an experienced practitioner. It also quantifies the financial and environmental and the carbon management benefits of irregular forestry putting into context the whole approach to management.

2 SelectFor, a Welsh-based forestry company specialising in continuous cover forestry, established the marteloscopes.

Results

Light in the forest stand

Prior to thinning, canopy openness ranged from 4.5% to 7.1% in the Ballinagappoge site. Following thinning it increased to 11.3%, on average, in the 24 $m^2 ha^{-1}$ plots and 8.3% in the 29 m^2 ha^{-1} plots. However, canopy openness dropped in the two-year period following thinning between 2003 and 2005. Trends in the response of transmittance to thinning were similar to those of canopy openness (Table 3).

The data on each of the stand characteristics were plotted against the canopy openness and transmittance data. Two single-variable models were derived using the variables that explained the greatest amount of variation:

canopy openness = 0.1341 – 0.00012079 (*stems per ha*) (r^2=14.5%) (Figure 5);

transmittance = 0.264 – 0.0047 (*basal area per ha*) (r^2=27.7%) (Figure 6).

The canopy openness values recorded at eight points within the Brownhill demonstration area in 2007 and 2009 ranged from 4% to 22% in 2007 (Table 4), with the latter value recorded in the area that had been crown thinned. Two years later the canopy had closed again and the highest canopy openness value was 17%.

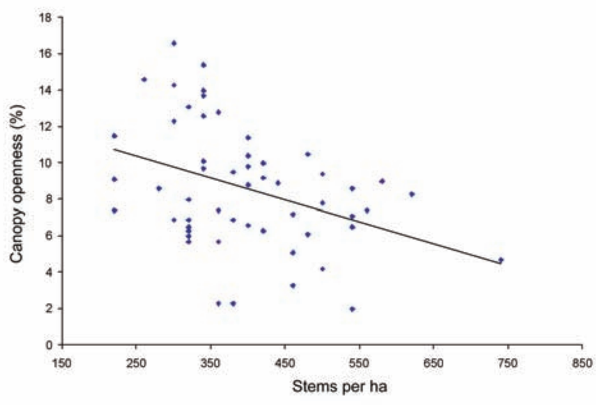

Figure 5: Canopy openness and stems per ha data.

Table 3: Mean canopy openness and transmittance values for each plot prior to and post thinning.

		Prior to thinning		Post thinning			
		2002		2003		2005	
Treatment	Plot	Canopy openness[2]	Transmittance[3]	Canopy openness	Transmittance	Canopy openness	Transmittance
(m^2 ha^{-1})		(%)	(%)	(%)	(%)	(%)	(%)
	B	6.3	10.2	6.3	10.2	3.7	5.8
34	E	5.8	9.5	5.8	9.5	4.4	7.2
	I	4.8	7.7	4.8	7.7	3.9	6.0
Mean[1]		5.6	9.1	5.6[b]	9.1[b]	4.0[b]	6.3[b]
	A	7.1	11.9	9.9	16.0	7.2	11.6
29	D	5.2	8.3	5.4	8.5	3.9	6.5
	H	5.4	8.3	9.7	15.5	5.3	8.5
Mean[1]		5.9	9.5	8.3[ab]	13.4[ab]	5.5[ab]	8.9[ab]
	C	6.6	10.9	10.7	16.4	7.3	11.6
24	F	4.7	7.6	12.9	20.1	7.8	12.4
	G	4.5	7.3	10.3	16.5	6.7	11.0
Mean[1]		5.3	8.6	11.3[a]	17.7[a]	7.2[a]	11.7[a]

1 The results of the pair-wise comparison of treatment means for 2003 and 2005 are shown. Means followed by different letters are significantly different.
2 The proportion of the hemisphere that is not obscured by the forest canopy.
3 The proportion of diffuse light that is transmitted through the canopy.

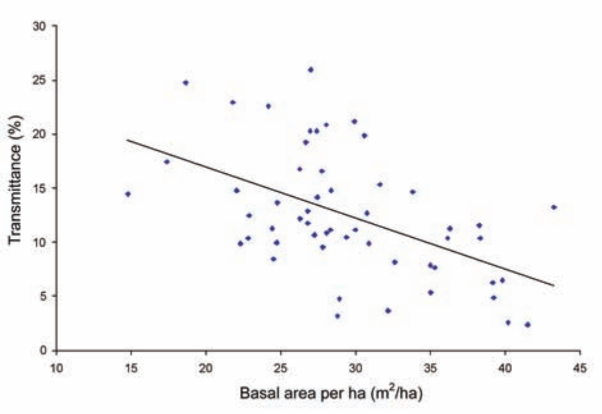

Figure 6: Transmittance and basal area per ha data

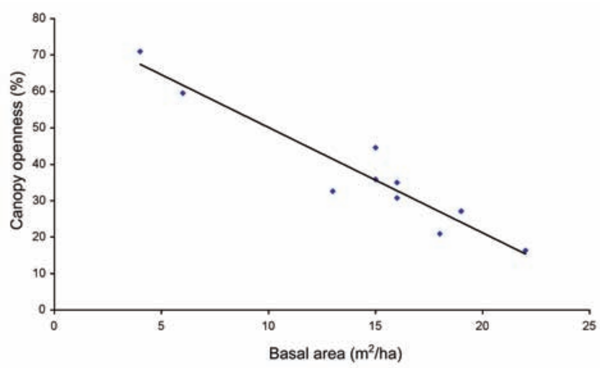

Figure 7: Canopy openness and basal area per ha data (Brownhill).

A strong linear relationship was found between the canopy openness and basal area using the 2007 data (r^2 =0.87) (Figure 7). Two years later the relationship between the two sets of data gathered at the same photopoints was not as strong (i.e. r^2 =0.57).

Underplanting experiment in Ballinagappoge

Mortality

As highlighted earlier all larch seedlings died within a short period of planting in spring 2004. For the species that remained and that had been planted in 2004[3], mortality rates varied from 0.3% to 10% after one growing season with no significant effect of overstorey basal area; by the end of the second growing season mortality rates increased significantly, with a clear increase in mortality with increasing overstorey basal area. Sitka spruce exhibited 44% mortality in the areas with the lowest overstorey basal area and 91% in the areas where the overstorey basal area was highest (Figure 8). In these latter plots, oak showed the lowest mortality (22 %).

Mortality rates continued to increase in subsequent growing seasons across all species and all treatments. An overview of the status of the experiment in early 2010 showed almost 100% mortality in all but one section of plot F where most of the species continued to flourish. Within this plot there is a substantial gap in the canopy, which was allowing a considerable amount of light to reach the understorey. Furthermore this plot was closest to the adjacent larch stand, and hence was benefitting from side light. In contrast in the clearfelled area, mortality rates remained low, with the exception of the larch.

Table 4: Canopy openness values recorded in Brownhill.

Plot	Canopy openness (%) 2007	Canopy openness (%) 2009	Thinning regime	Basal area per ha (2007)	Basal area per ha (2009)
1	4	8	unthinned	70.97	89.92
2	6	10	unthinned	59.54	71.32
3	22	17	crown	16.35	15.45
4	18	13	crown	20.89	25.34
5	19	15	crown	27.13	31.35
6	15	11	crown	44.56	56.21
7	16	11	crown	34.98	44.13
8	16	11	standard	30.77	36.40
9	15	9	standard	35.85	36.59
10	13	9	standard	32.59	46.95

3 The data on western red cedar are not included as this species was planted in 2003 while those included here were planted in 2004.

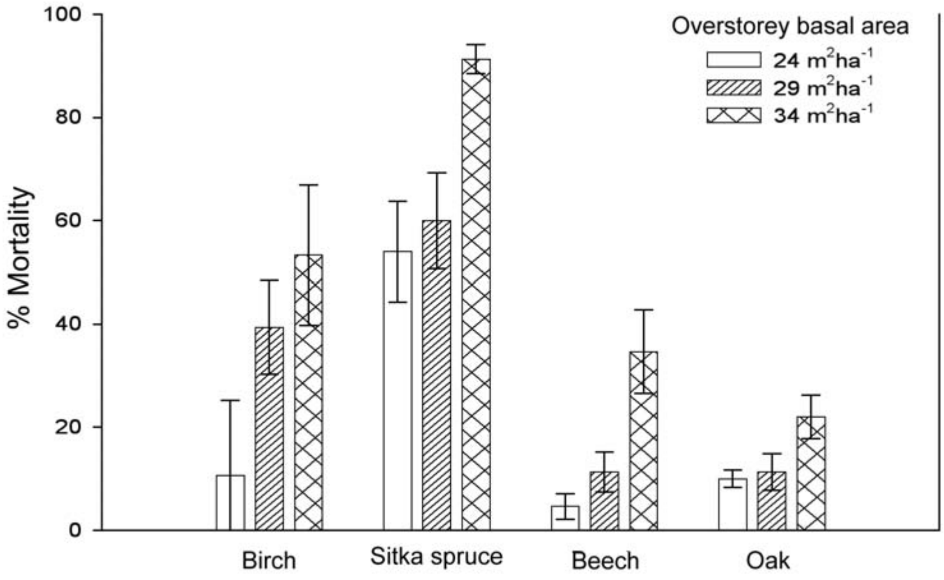

Figure 8: Seedling mortality after two growing seasons (error bars represent standard errors).

Seedling heights

Oak had the greatest increase in height growth after one growing season yet this increase in growth did not appear to be influenced by the basal area of the overstorey. In contrast, height growth in the other three species was influenced, with height growth declining as the overstorey basal area increased, with Sitka spruce exhibiting the lowest increase in height of 4.5%. The rate of height growth in the second growing season was smaller for all species than in the first growing season. Oak continued to perform the best with an increase in height of 20% in the plots where the overstorey basal area was lowest. It was also the only species to record a positive increase in height (1%) in the plots where the overstorey basal area was 34 $m^2 ha^{-1}$ (Figure 9). Sitka spruce continued to show the lowest level of growth with negative growth observed where the overstorey basal area was high and moderate, while in the plots where the overstorey basal area was lowest it exhibited only a 1.3% increase in height. In many plots, negative growth was observed. The negative growth was a

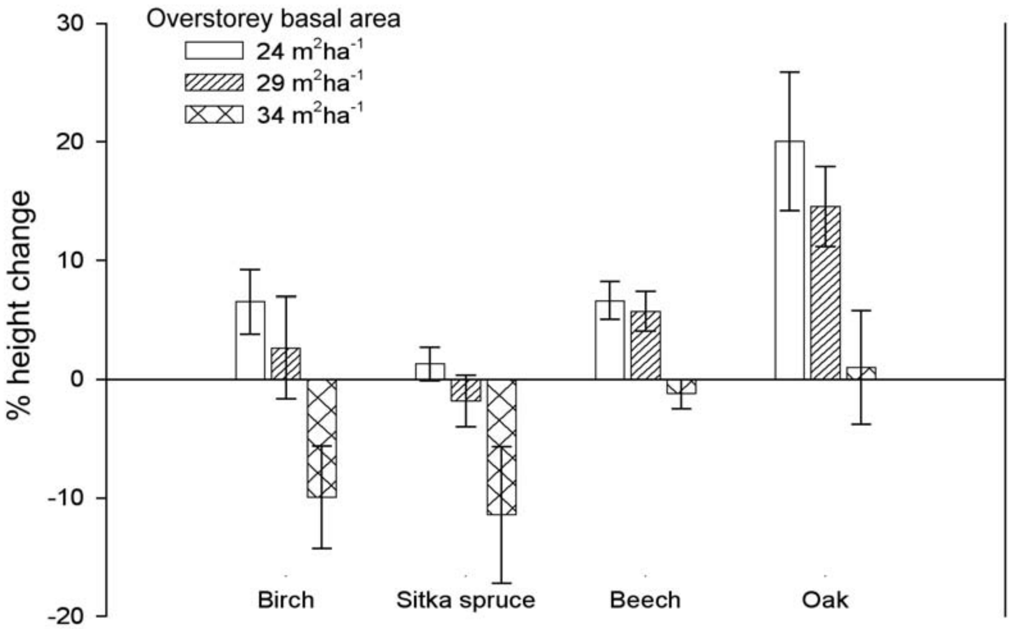

Figure 9: Percentage change in height growth after two growing seasons (error bars represent standard errors).

result of die-back of the terminal leader since the 2003-2004 assessment. By spring 2010 the western red cedar in the clearfelled area of the stand had reached 2 m in height.

Root collar diameter of seedlings

In general, root collar diameter increment decreased as the overstorey basal area increased, however the differences between treatments were not statistically significant after one growing season. While beech showed the greatest initial increase in root collar diameter, the differences between species were also not significant. After two growing seasons, beech exhibited the greatest decline in root collar diameter with increasing overstorey basal area (Figure 10). Oak showed a similar response. In contrast, there was little difference in the root collar diameter growth of birch or Sitka spruce following the thinning of the overstorey.

Height:diameter ratios of planted seedlings

The extent of the overstorey basal area did not significantly influence the H:D ratio after one growing season. However, significant differences between species were noted with Sitka spruce exhibiting the greatest H:D ratio. After two growing seasons, the H:D ratio of the beech seedlings in the plots where the overstorey basal area was lowest was significantly lower than that in the high overstorey basal area treatment (Figure 11). Similarly birch seedlings in the 34 m^2 ha^{-1} treatments had significantly lower H:D ratios than those in the 24 and 29 m^2 ha^{-1} plots.

Nitrogen concentrations

Total mineral N concentrations in the organic soil horizon decreased as basal area increased in both the summer and autumn sampling period. Similar trends were noted for the ammomium-N concentrations for the autumn sampling period (Table 5).

Nitrate-N concentrations decreased from 7.42 µg NO_3^--N g^{-1} dry soil in the 24 m^2 ha^{-1} plots to 5.78 (34 m^2 ha^{-1}) for the autumn sampling period. In the summer, concentrations were also highest under 24 m^2 ha^{-1} plots (Table 5).

Ammonium-N concentrations were higher than nitrate-N concentrations in all treatments for autumn and summer. The ratio of ammonium-N: nitrate-N in the 29 m^2 ha^{-1} plots was 4:1 and 3:1 in the 34 m^2 ha^{-1} plots in both autumn and summer. However, in the 24 m^2 ha^{-1} plots, the ratio was 7:1 in autumn but decreased to 4:1 in summer (Table 5).

In both the summer and autumn, nitrogen mineralisation rates decreased non-significantly as basal area increased. Nitrification rates were similar in all treatments in both seasons (Table 5).

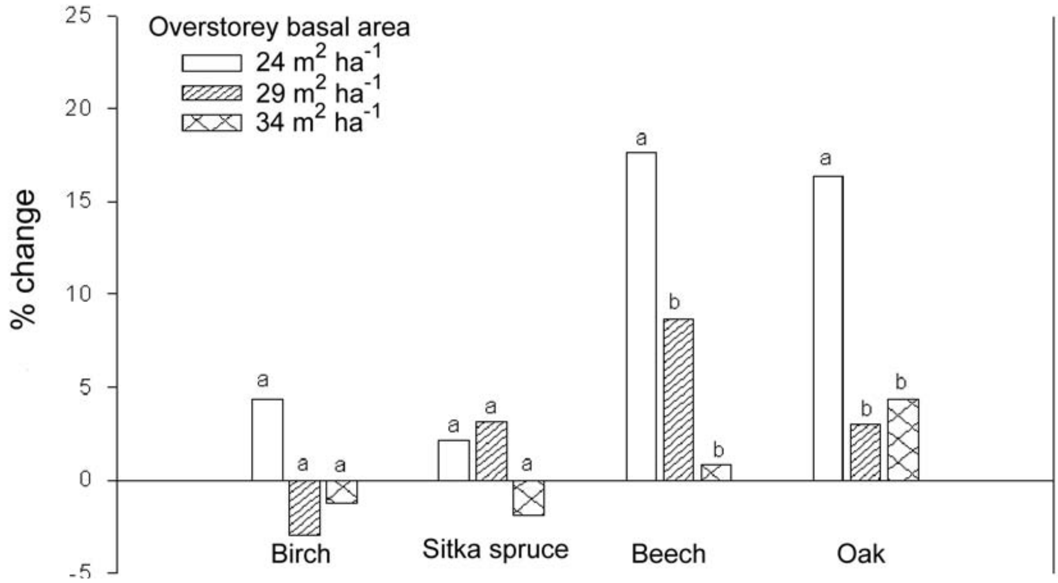

Figure 10: Percentage change in root collar diameter after two growing seasons (means followed by different letters are significantly different at the α ≤ 0.05 level for within-species comparisons)[4].

[4] Only where a significant shade-species interaction was noted in the analysis are within species treatment comparisons made, otherwise the graphs are presented with standard error bars.

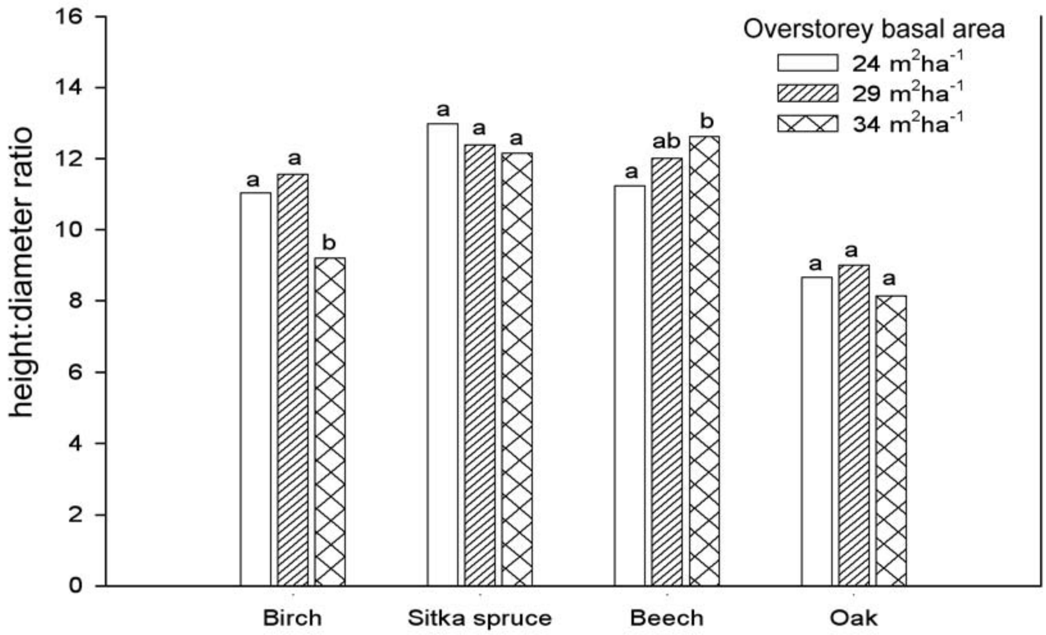

Figure 11 H:D ratios (cm:mm) after two growing seasons (means followed by different letters are significantly different at the α ≤ 0.05 level for within-species comparisons).

Table 5: Nitrogen concentrations (µg per g^{-1} dry soil), mineralisation and nitrification rates (µg per g^{-1} dry soil day^{-1}) by treatment and sampling period.

Sampling period*	Autumn			Summer		
Treatment	24 m^2 ha^{-1}	29 m^2 ha^{-1}	34 m^2 ha^{-1}	24 m^2 ha^{-1}	29 m^2 ha^{-1}	34 m^2 ha^{-1}
Total mineral-N	61.50 ^{a}	27.33 ^{ab}	23.44 ^{b}	65.00 ^{a}	44.98 ^{ab}	26.39 ^{b}
Ammonium-N	53.27 ^{a}	21.37 ^{ab}	17.66 ^{b}	51.40 ^{a}	35.78 ^{a}	26.52 a ^{a}
Nitrate-N	7.42 ^{a}	5.96 ^{a}	5.78 ^{a}	13.65 ^{a}	9.20 ^{a}	9.77 ^{a}
Mineralisation	3.14 ^{a}	3.07 ^{a}	2.88 ^{a}	3.73 ^{a}	3.45 ^{a}	3.38 ^{a}
Nitrification	0.08 ^{a}	0.07 ^{a}	0.06 ^{a}	0.06 ^{a}	0.05 ^{a}	0.06 ^{a}

* means followed by different letters are significantly different at the α ≤ 0.05 level for within overstorey basal area comparisons.

Soil temperature

The mean temperature in the organic soil horizon increased by 0.1°C with an increase in basal area in the three consecutive months of December, January and February 2003/2004 (Table 6). In March 2004 the mean temperature was the same for all treatments. In the months of June, July, August, September and October 2004, temperatures were lower as basal area increased and were significantly higher in the 24 m^2 ha^{-1} plots in July and August 2004. In the period June to October the range in temperatures was greatest in these plots and decreased with increasing basal area.

Soil water content and pH

In the autumn, the water content (% fresh weight) of the organic soil horizon decreased non-significantly as basal area increased from 60.2% water content (24 m^2 ha^{-1} plots) to 59.94% (29 m^2 ha^{-1} plots) and 55.26% (34 m^2 ha^{-1} plots). In the summer sampling period the water content in the 24 m^2 ha^{-1} plots (69.6%) was non-significantly higher than 67.31% in the 29 m^2 ha^{-1} plots and 67.32% in the 34 m^2 ha^{-1} plots.

The pH of the organic soil horizon was similar for all treatments (i.e. 3.90, 24 m^2 ha^{-1} plots; 3.88, 29 m^2 ha^{-1} plots and 3.94, 34 m^2 ha^{-1} plots).

Path analysis

The analysis showed that distance from the nearest tree had a large positive total effect on canopy uncover (.55) (Figure 12). Canopy uncover had a large positive total effect on maximum soil

Table 6: Monthly mean temperatures (°C) of the organic soil horizon (5cm depth). Temperature recorded continuously at 30 minutes intervals with Tinytag dataloggers.

Basal area		Nov ‘03	Dec ‘03	Jan ‘04	Feb ‘04	Mar ‘04	Jun ‘04	Jul ‘04	Aug ‘04	Sep ‘04	Oct ‘04	Nov ‘04	Dec ‘04	Jan ‘05	Feb ‘05	Mar ‘05
24 m^2 ha^{-1}	Ave	6.8	5.3	4.0	3.9	4.1	11.7	12.4	13.6	11.8	7.4	7.0	5.2	4.9	3.3	5.0
	Max	10.6	9.6	7.9	9.9	8.5	20.4	17.6	18.1	18.1	10.1	9.5	8.8	8.6	8.6	12.0
	Min	2.5	1.2	0.2	0.2	0.5	7.5	8.3	8.6	7.1	3.9	1.6	1.3	1.7	0.7	0.5
29 m^2 ha^{-1}	Ave	6.9	5.4	4.1	4.0	4.1	11.3	12.0	13.4	11.7	7.2	7.2	5.4	5.1	3.5	5.1
	Max	10.7	9.7	8.0	10.0	8.7	18.0	16.5	17.0	17.4	10.0	9.4	9.1	9.0	9.5	11.9
	Min	2.6	1.0	0.2	0.1	0.6	6.8	8.4	8.8	7.9	4.0	1.9	1.5	1.5	1.3	1.7
34 m^2 ha^{-1}	Ave	6.9	5.5	4.2	4.1	4.1	11.1	11.8	13.2	11.6	8.3	7.0	5.3	5.0	3.5	5.0
	Max	10.6	9.5	7.8	9.8	8.3	16.3	14.7	16.3	16.3	9.7	9.2	8.8	8.5	8.5	10.5
	Min	2.8	1.4	0.1	0.0	0.6	7.7	8.6	8.9	7.9	4.0	1.7	1.4	1.8	0.7	0.6

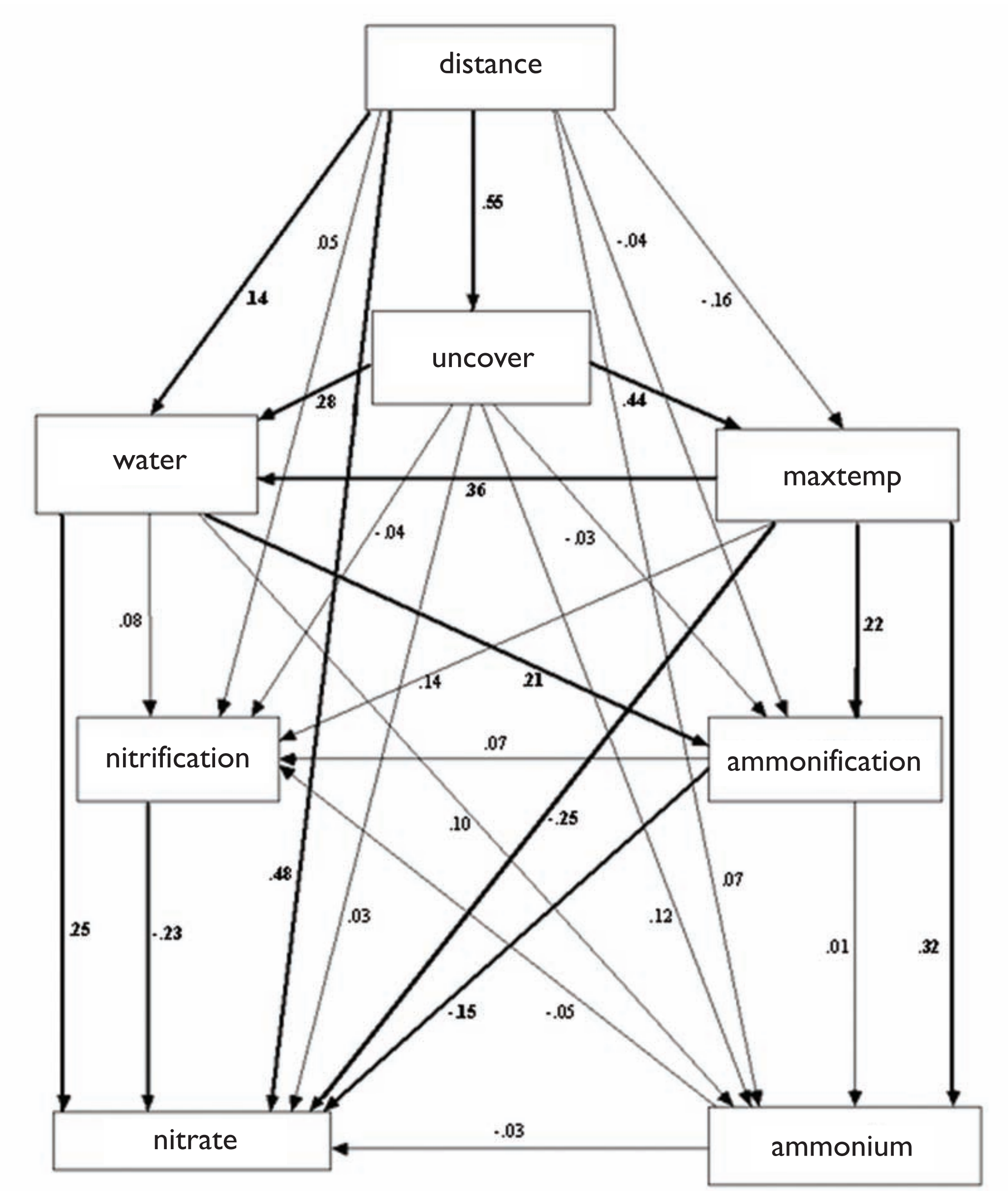

Figure 12: Path diagram with standardised regression weights displayed. Significant weights and paths indicated in bold. Variables included are, distance from the nearest tree (distance), % canopy uncovered (uncover), maximum soil temperature (maxtemp.), soil water content (water), ammonification rate (ammonification), soil ammonium-N concentration (ammonium), nitrification rate (nitrification) and soil nitrate-N concentration (nitrate).

temperature (.44) which was greater than the total effect of tree distance (.08). Canopy uncover also had a large positive total effect on soil water content (.44) which was greater than the total affect of tree distance and also soil temperature. Soil maximum temperature had the greatest direct (.22) and total effect (.30) on the ammonification rates and on ammonium concentrations (.32 and .36).

Soil maximum temperature had the largest direct and total effect on nitrification rates although this effect was small (.17). Soil water content had a large positive effect on nitrate-N concentrations, which also had the greatest total effect (.42) most of which was due to its own direct effect (.48). Distance from the nearest tree also had a small positive direct effect (.25) on nitrate-N concentrations and with the indirect effects increased the total effect to a modest effect (.38). Soil maximum temperature ammonification and nitrification rates all had negative direct effects on nitrate concentrations.

Regeneration in Mount Callan

The weather in the two-month period following the setting up of the regeneration experiment in Mount Callan in March 2003 was very dry; hence overall the number of seedlings found in the plots was low when assessed two years later. The greatest numbers, i.e. 1.5 seedlings per 400 cm^2 , were found in plots that had been seeded. In comparable plots that were not seeded this number fell to 0.01. It was also noted that the plots with the highest seedling density had a high percentage cover of moss (*Sphagnum* spp.). The high regeneration rates here were likely to be due to the ability of the moss to retain water thus making it a good seed bed for Sitka regeneration. Fencing and scarification did not have an effect on seedling densities.

Volume removed in the Brownhill demonstration area

A comparison of the volume removed during the setting up of the Brownhill demonstration area showed that the total number of trees removed (per ha) was lower in the crown thinned area compared to the number removed in a contiguous 1 ha plot, thinned using a rack and selective thinning. However, there was a greater amount of box and stake material in the crown thinned area which meant that overall the total volume removed in both areas was similar.

In addition, it was noted that the amount of brash on the forest floor in the crown thinned plot was substantially less than that in the section that had received a standard thinning.

Setting up the hemispherical camera at Brownhill.

Discussion

This study was a continuation of a process of research, initiated in the late 1990s, to explore how even-aged coniferous stands might be transformed into continuous forest systems in Ireland. This transformation process involves the manipulation of the existing stand in such a way that a successor stand is initiated and then develops (Kerr et al. 2003). In most situations the next generation will arise from natural regeneration, though planting may be necessary, e.g. where a different provenance or species is desired. In this study it was assumed that the latter applied, i.e. that one of the aims of introducing continuous cover systems in Ireland (and the transformation process that precedes it) would be to move from even-aged pure Sitka spruce stands to unevenaged mixed species stands.

The two main silvicultural systems used to provide structural and species diversity while maintaining a certain level of the existing canopy are shelterwood and selection systems. Both systems encapsulate a number of different methods to achieve specific irregularity and multi-storied forest structures (Nixon and Worrell 1999). In this study the shelterwood approach to transformation was used in a mature Sitka spruce stand while a mix of shelterwood/selection was used in a younger Sitka spruce stand. The species underplanted were primarily chosen to represent a range of shade tolerances and are not (with perhaps the exception of beech) species typically associated with underplanting. However, in the context of using underplanting as a transformation tool (and ensuring the canopy cover is maintained during the transformation process), and a means to increase species and structural diversity in a stand, it may be necessary to use species that are not typically underplanted. Furthermore the aim of underplanting species with a range of shade tolerances was to try to determine the limits, in terms of shade or overstorey basal area, for each of the species.

Irrespective of whether a shelterwood or selection system approach to transformation is used, transformation will involve thinning and regeneration fellings that allow increasing amounts of light into the understorey. Effectively these fellings involve the management of the forest canopy so as to provide the adequate light, temperature and water to encourage the growth of the understorey tree seedlings while at the same time ensuring that competing vegetation is kept under control. Changing the levels of canopy cover not only modifies light levels but also a number of environmental variables including temperature, throughfall and potential evapotranspiration. Forest cover buffers the daily and seasonal temperature difference compared to open ground (Aussenac 2000). In addition, soil temperatures are higher in the winter under forest cover and colder in the summer than they are in the open (Liechty et al. 1992). The results from this study confirmed these trends with higher temperatures found in the winter in plots where the overstorey basal area was greatest than where it was smallest, while the opposite was true for the summer months. Furthermore, forest canopies can intercept up to 40% of annual rainfall in coniferous forests and up to 25% in deciduous forests (Bruijnzeel 2001). Potential evapotranspiration is also lower under a forest canopy than in the open (Aussenac 2000). Thus in shaded conditions that prevail under a forest canopy, light may not be the only limiting factor. In an effort to distinguish the confounding effects of climate, edaphic factors and competition, two experiments were conducted. One was conducted out in the forest where the underplanted seedlings were exposed to varying light levels as well as varying water temperature and nutrients. The second main experiment was carried out using shadehouses where light levels varied while other resources such as water and nutrients were kept at almost the same levels for all treatments. This allowed the effects of these confounding factors to be separated from those of light.

One of the key aims of this study was to quantify light levels under different canopy levels in a Sitka spruce stand. Prior to thinning, canopy openness in the subplots ranged from 2% to 12%, while transmittance ranged from 1% to 13%. These values indicate how dark the understorey of a Sitka spruce stand of this age can be despite the fact that the stand had been thinned three times prior to this study. Hale (2001) similarly found that canopy openness ranged from 5% to 12% in a number of Sitka spruce stands of different ages in northern Britain. Even after what would be considered a heavy thinning for this stand (i.e. a reduction of initial basal area by 30% from 34 m^2 ha^{-1} to 24 m^2 ha^{-1} in one plot), light levels measured immediately after thinning remained low; the maximum canopy openness recorded after thinning was 17% while transmittance was 26%. This level of light was insufficient for the successful establishment of many of the species. Although mortality rates were low after one growing season (except for larch); after two growing seasons almost half the seedlings in the 34 m^2 ha^{-1} plots had died. Sitka spruce experienced particularly high levels of mortality with over 65% of species dying while over one third of the birch died. There was an unexpectedly high level of mortality for beech seedlings in the areas where the overstorey basal area was greatest. This may have partly been due to the presence of swift moth larva in isolated areas within this part of the research site. Mortality rates have continued to increase each year and currently there is almost 100% mortality in all species, with the exception of one light-filled section of a plot.

During the course of this study Sitka spruce regeneration appeared amidst the underplanted seedlings in Ballinagappoge but would then fail to become successfully established. Hale (2001) observed no natural regeneration of Sitka spruce in stands with canopy opennesss between 5 and 7% but did observe natural regeneration in stands where the canopy openness exceeded 10%. Nixon and Worrell (1999) estimated that Sitka spruce requires 50% of full sunlight for the establishment and growth of natural regeneration. The same authors also indicated that only very shade tolerant species such as western hemlock (*Tsuga heterophylla* (Raf.) Sarg.) could become established under a forest canopy transmitting 10–15% light.

Hybrid larch exhibited one hundred percent mortality in all basal area treatments shortly after planting. Mason et al. (2004) found similarly high levels of mortality in European larch (*Larix decidua* Mill.), after four growing seasons, in an underplanting experiment where the residual basal area of the overstorey Sitka spruce stand was 41 m^2 ha^{-1}. However, in the same experiment 40% of the larch seedlings survived where the basal area was 27 m^2 ha^{-1}. This would suggest that the 100% mortality rates recorded for larch in this study were in excess of what might be attributed to lack of light and it is unlikely that limited light resources would have caused such a severe die-off so quickly. The most likely cause of the mortality in the larch was a combination of drought, late planting and poor planting stock. Rainfall was measured in a clearfell area adjacent to the research site for the first three months following planting (April-June 2003) and was found to be negligible. Horgan et al. (2004) noted that moisture is vital for larch seedlings, especially when the species is planted on very dry soils.

In contrast to the underplanting experiment, survival rates of the three species used in the shadehouse trial were not influenced by shade. The fact that seedlings had access to equal and what seemed adequate levels of water and nutrients and were not subject to competition goes some way to explain these high survival rates. In addition, the highest shade level used in the controlled experiment was 75% (similar to 25% canopy openness) whereas within the forest understorey canopy openness never exceeded 11%. Thus the controlled experiment would have benefited from a more extreme shade level of perhaps 5% or lower reflecting the greater shade exerted in closed canopies.

Greater canopy openness and light transmission in a mature Sitka spruce stand can be achieved through heavier thinning than was conducted in this study. Under Irish conditions however, such heavy thinning in a mature stand would substantially increase the risk of windthrow, as other work has shown (Ni Dhubhain et al. 1996). The Brownhill site was used to demonstrate how heavier thinning in a relatively young stand might achieve the desired light levels. However, the results from that site show that even with a heavy thinning and a substantial reduction in overstorey basal area, canopy openness only reached a maximum value of 22%. Nevertheless there is a small number of naturally regenerated Sitka spruce on site. However, there is also other vegetation (see Appendix A) emerging which is beginning to swamp this spruce. This illustrates the challenge foresters face in trying to provide sufficient light for the understorey tree species, while ensuring that other vegetation is controlled.

In setting up the underplanting experiment the aim was to simulate three different lights levels with the canopy. The overstorey basal area was used as a surrogate for light. This seemed a reasonable approach as others had found a close relationship between understorey light levels and basal area of the overstorey (Bunnell and Vales 1990; Hale 2001). The particular levels of basal area chosen in this study were influenced by the structure of the stand and its location. Furthermore, concerns about the risk of windthrow following thinning in this site resulted in the local forest manager recommending the maximum reduction of basal area of 10 m^2 per hectare. This then corresponded to the heaviest level of thinning, while the intermediate thinning lay half way between this and the unthinned treatment. While the approach used served to produce a 'wind-firm' experiment it was less successful in generating different light levels. The limited reduction in overstorey basal area meant that the basal area treatments did not result in the creation of three appreciably different light levels. The narrow range of values may also have accounted for the poor predictive power of the models generated (r^2 values of 14.5% for canopy openness and 27.7% for transmittance) from the Ballinagappoge site. Using the data from the Brownhill site, where the range in overstorey basal areas was greater, a much stronger model was generated. The time since thinning is also a factor influencing the strength of the relationship between light values and stand characteristics. Where others have found a strong relationship between light and stand characteristics, the light values were recorded some time after thinning; hence the canopy had time to adjust to the changes in basal area and stand density that had occurred (Comeau 2001). In the Ballinagappoge site, canopy openness and transmittance were recorded shortly after thinning, while in Brownhill the photographs were taken approximately one year after thinning.

The monitoring of the understorey characteristics such as the nitrogen dynamics, nitrogen concentrations as well as the soil water, temperature and pH was undertaken in an effort to explain the trends in mortality and morphology. A further objective was to determine whether the understorey characteristics were affected by canopy cover. The results showed that the extent of canopy cover did affect the soils nitrogen transformations. Opening the canopy positively affected the soil temperature and water contents, both of which in turn affected the nitrogen transformations. Temperature was the most important factor affecting ammonification rates and ammonium concentrations.

Section of Brownhill site where all non-frame trees with dbh>20 cm were removed.

Conclusions

The following are the main conclusions from this study:

- Using a shelterwood approach to transforming a mature Sitka spruce stand results in inadequate levels of light being transmitted for the successful establishment of even the most shade-tolerant of species.
- A more severe intervention would be required in Sitka spruce stands of this age to achieve high enough levels of canopy openness to support the growth and survival of understorey species. However, if stands are thinned too heavily, wind damage will occur.
- Another means of encouraging regeneration within a mature Sitka spruce stand would be to plant within any existing gaps. The size of the various gaps would influence the choice of species to be planted. Creating new gaps in these stands would, however, compromise stability.
- Following a thinning, such as was carried out in this stand, the overstorey basal area returned very quickly (i.e. three years or so) to the pre-thinning value. This suggests that, in similar stands, thinning operations to maintain or increase the light levels would have to occur at intervals of three years or less. Once again this may pose a threat to stability.
- Overall the results of the study highlight the difficulties of initiating the transformation process in a mature Sitka spruce stand. If transformation of Sitka spruces stands is required the options are either to:
    - Start the transformation process earlier, perhaps at the time of first thinning. In younger stands much heavier thinnings can be carried out, increasing the light levels without jeopardising the stand stability. Additionally, providing more growing space at an early age will increase the overall stability of the stand by encouraging the development of greater root structures and deeper crowns.
    - Another approach would be to open existing gaps at a young age similar to the approach used in a group shelterwood.

Section of Brownhill site where all trees competing with frame trees had been removed.

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Project outputs

Theses:

Holzmann, M. 2004. Modelling the relationship between below-canopy light levels and stand variables in a mature spruce stand in Ireland. MSc(Agr), University College Dublin.

Coghlan, D. 2007. Survival and growth of five commercial tree species planted under various levels of canopy cover in a 40 year-old Sitka spruce stand. MAgrSc, University College Dublin.

Kennedy, J[5]. 2007. The impact of shade on the physiology and photochemistry of *Picea sitchensis, Larix x eurolepis* and *Thuja plicata.* PhD. National University of Ireland.

Freeman, N. 2008. The effects of canopy cover on soil nitrogen dynamics in a *Picea sitchensis* forest plantation. PhD. National University of Ireland.

Conferences organised:

Continuous Cover Forestry: Conversion Processes from a European Perspective - A knowledge transfer of the experiences gained though the application of conversion principles in European forests. International conference held in UCD. Dublin, June 29 – July 1, 2009.

Published papers:

Kennedy, S., Ní Dhubháin, Á., Ferguson, J., Schmidt, O., Dyckmans, J., Osborne, B and Black, K. (2006). Potential use of carbon isotope discrimination for the selection of shade-tolerant species. *For Ecol Management* 237: 394-403.

Kennedy, S., Black, K., O'Reilly, C. and Ní Dhubháin, Á. (2007). The impact of shade on morphology, growth and biomass allocation in *Picea sitchensis, Larix* x *eurolepis* and *Thuja plicata. New Forests* 33: 139-153.

Posters:

- "The effect of Canopy Cover on Soil Nitrogen Dynamics" poster by Nuala Freeman and Tom Bolger presented at the joint EFI/IUFRO conference on Transformation to Continuous Cover Forestry in a Changing Environment held in Bangor Wales in September, 2004.
- A poster on the project was presented by Nuala Freeman at the Environ 2005 conference in Sligo in February 2005.

Presentations:

- "Continuous Cover Forestry in Ireland" presentation by Áine Ní Dhubháin, 2003, to the Society of Irish Foresters' Annual Symposium.
- Presentation on the project was made by Áine Ní Dhubháin, Matthias Holzmann and Donal O'Hare at a Society of Irish Foresters' field day, September 2003.
- "The Impact of Shade on the Morphology and Photochemical Efficiency of Three Conifer Species" presentation by Seamus Kennedy at the joint EFI/IUFRO conference on *Transformation to Continuous Cover Forestry in a Changing Environment* held in Bangor, Wales in September, 2004.
- Áine Ní Dhubháin presented a paper on the project at the COFORD conference in Tullamore in September, 2004. A poster on the project was also presented.

[5] J. Kennedy, i.e. James Kennedy is also known as S. Kennedy, i.e. Séamus Kennedy

Appendix A: Results of vegetation surveys

Table A.1 Results of vegetation monitoring in Ballinagappouge (D: Dominant;A: Abundant;F: Frequent;O: Occasional; R:Rare).

Plot number / Species list	Clearfell Plot												PLOT A							
	SP1	SP2	SP3	SP4	SP5	SP6	SP7	SP8	SP9	SP10	SP11	SP12	SPA0	SPA1	SPA2	SPA3	SPA4	SPA5	SPA6	SPA7
Agrostis stolonifera																	F		F	A
Blechnum spicant				O																R
Calluna vulgaris		D	O	O	F	D	F	O	A	F			O							
Carex spp.					R	A														
Deschampsia flexuosa		A	A	D	D		A	A	A	F	A	F								
Dicranum scorparium		O											O	O	O	O			F	O
Dryopteris dilatata			R			R		R										R		
Erica cinerea			R				A	O	A			O								R
Festuca ovina				O						O										
Fissidens taxifolius																O		A		
Galium saxatile					F	F	F		O		F									
Grimmia pulvinata												O								
Hypnum cupressiforme		F	F	A	A	A	A	A	O			O	D	D	D	F	A	A	A	A
Juncus effusus			F				O			O										
Luzula spp.								O						R					F	F
Molinia caerulea												A								
Polytrichum commune			O	F		F	F		O	F	F	O	F	F			F	A	A	R
Pseudoscleropodium purum		O																		
Rubus spp.							O													
Rumex spp.			O					F				O								
Salix aurita				R																
Sphagnum spp.																	R			
Thuidium tamariscinum													O		R	F				
Ulex europaeus		F	O	O	O	O	O	O	A	D	R	O								
Vaccinium myrtillus				O					R							R				

Table A.1 (continued): Results of vegetation monitoring in Ballinagappouge (D: Dominant;A: Abundant;F: Frequent;O: Occasional R:Rare).

Plot number / Species list	PLOT B								PLOT C							
	SPB0	SPB1	SPB2	SPB3	SPB4	SPB5	SPB6	SPB7	SPC0	SPC1	SPC2	SPC4	SPC5	SPC6	SPC7	
Agrostis stolonifera														A		
Calluna vulgaris															R	
Carex spp.												R	O			
Dicranella heteromalla	O	O		F	R											
Dicranum scorparium		O			O	O	O				O					
Digitalis purpurea																
Dryopteris dilatata	R					R										
Hypnum cupressiforme	D	D	F	F	F	C	F	O	F	A	A	A	F		A	
Juncus effusus														R		
Polytrichum commune		A		O		O	O	R	O	F	F	A	F	A	A	
Rhytidiadelphus loreus													O			
Thuidium tamariscinum	O		A						O	F		O	O		F	
Vaccinium myrtillus	R									R						
	PLOT D								PLOT E							
	SPD0	SPD1	SPD2	SPD3	SPD4	SPD5	SPD6	SPD7	SPE0	SPE1	SPE2	SPE3	SPE4	SPE5	SPE6	SPE7
Blechnum spicant												R				
Carex spp.							R	O								
Deschampsia flexuosa	F															
Dicranella heteromalla		F						F								
Dicranum scorparium				O		R	O	O			F			O		
Dryopteris dilatata																
Erica cinerea		R						R								
Hypnum cupressiforme	D	F	F	O	O	O	F	D	F	O	F		A	F	A	F
Nardia spp.									F							
Polytrichum commune							F	F	O	R	O	A	F		F	A
Rhytidiadelphus loreus							R									
Thuidium tamariscinum					O						R				A	R
Vaccinium myrtillus									R							R

Table A.1 (continued): Results of vegetation monitoring in Ballinagappouge (D: Dominant; A: Abundant; F: Frequent; O: Occasional; R:Rare).

Plot number / Species list	PLOT F								PLOT G							
	SPF0	SPF1	SPF2	SPF3	SPF4	SPF5	SPF6	SPF7	SPG0	SPG1	SPG2	SPG3	SPG4	SPG5	SPG6	SPG7
Blechnum spicant											R					
Carex spp.		O	O	R				O		F			R			
Deschampsia flexuosa								F								
Dicranella heteromalla		O	O					R			A			O		
Dicranum scorparium		O				R	O	R	R				O		O	
Digitalis purpurea									R		R					
Dryopteris dilatata										R						
Erica cinerea		O	R													
Fissidens taxifolius										O		O				
Hypnum cupressiforme	A	A	A	D	D	D	D	D	A	A	D	D	A	A	D	D
Polytrichum commune		F	O				F	A	O	F	A	R		O	O	
Rhytidiadelphus loreus							O									
Thuidium tamariscinum		R	O						O					O		
Ulex europaeus		R														
Vaccinium myrtillus		R														R
	PLOT H								PLOT I							
	SPH0	SPH1	SPH2	SPH3	SPH4	SPH5	SPH6	SPH7	SPI0	SPI1	SPI2	SPI3	SPI4	SPI5	SPI6	SPI7
Agrostis stolonifera	F															
Carex spp.		O	F	R				R								
Dicranella heteromalla							O			O						
Dicranum scorparium		O	R	F	R	F	O	F	F	O	O	O	O		F	O
Dryopteris dilatata	R		R													
Fissidens taxifolius											R					
Hypnum cupressiforme	A	F	D	D	A	D	D	D	F	F	F	O	O	O	A	F
Mnium hornum					R										O	
Polytrichum commune	F	F	F	R					F	O					O	R
Rhytidiadelphus loreus				R		R				O						O
Thuidium tamariscinum	O	O			O	O					R	F			O	O
Ulex europaeus								R								
Vaccinium myrtillus											R					

Table A.2: Results of vegetation monitoring at Brownhill (D: Dominant; A: Abundant; F: Frequent; O: Occasional; R:Rare).

Plot / Species list	1	2	3	4	5	6	7	8	9	10	11	12	13
Calluna vulgaris		R											
Dicranella heteromalla				O	R	O	O		R	O		O	
Dicranum scorparium		O	F										
Erychnum praelongum					O	O							
Festuca ovina			O										
Hypnum cupressiforme	O	D	F	A	F	A	F	O	R	F	F	D	A
Polytrichum commune		O	O	F			O		R				R
Pseudoscleropodium purum			O	O								O	
Rhytidiadelphus loreus		R											
Thuidium tamariscinum	O					A	F	R		O	O		

Appendix B: Brownhill inventory

Complete inventory of the three blocks before and after marking and thinning operations carried out in August 2005.

Block	A	B			C
Thinning Type	Standard Thinning	<20 dbh and F-trees	Comp Crowns and F-trees	<17 dbh and F-trees	No Thinning
Area m^2	9089	1370	3990	3320	800[1]
No. tagged	0	175	373	194	0
Mean ht (m)	17.15	16.38	17.8	17.29	17.68
Total Ba m^2	37.94	7.38	20.95	17.42	5.35
Ba m^2 removed	10.15	2.2	6.03	10.09	0
Ba m^2 remaining	27.79	5.18	14.92	7.34	5.35
Total stems prior 05	1002	241	548	454	132
Removed stems	358	52	156	245	0
Stems remaining	644	189	377	199	132
Vol 05 m^3	308.24	57.11	177.81	142.75	45.03
Vol removed m^3	83.63	16.9	54.74	83.75	0
Vol remaining m^3	224.61	40.21	123.06	58.99	45.03
Ave st/vol m^3 remaining	0.349	0.229	0.330	0.304	0.341
Ave st/vol m^3 removed	0.234	0.325	0.351	0.342	0.000
Mean dbh 05	21	20	21	21	22
Mean dbh removed	19	23	23	23	0
Mean dbh remaining	23	19	22	21	0
Mean dbh F-trees	0	25	26	26	0
Per ha inventory					
Stems/ha prior 05	1102	1757	1376	1367	1650
Stems /ha removed	394	481	392	738	0
Stems /ha remaining	709	1276	937	630	1650
Ba/ha prior 05 m^2	41.75	53.85	52.63	52.48	66.98
Ba/ha removed m^2	11.17	16.09	15.14	30.39	0
Ba/ha remaining m^2	30.57	37.76	37.48	22.09	66.98
Vol/ha pre 05 m^3	339.14	416.27	446.54	429.97	562.87
Vol/ha removed 05 m^3	92.01	123.17	137.48	252.27	0
Vol/ha remaining 05 m^3	247.12	293.09	309.06	177.71	562.87
F-trees per ha	0	327	309	304	0