IRISH FORESTRY

JOURNAL of THE SOCIETY OF IRISH FORESTERS

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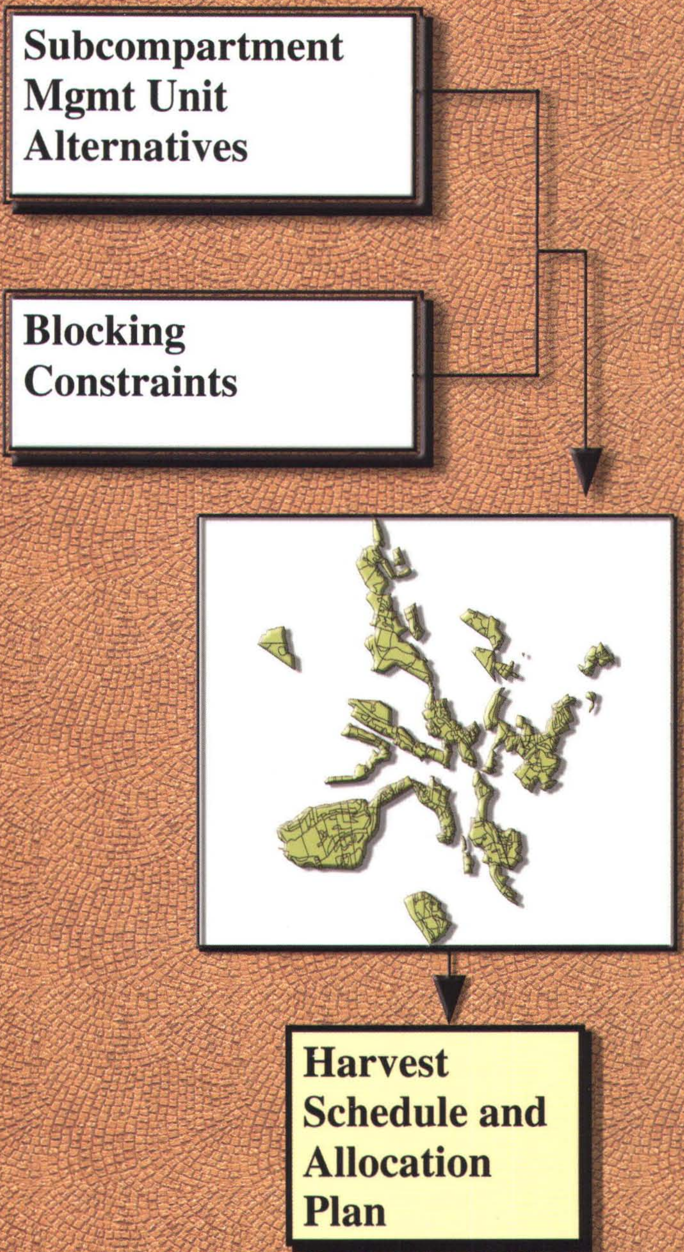

Vol. 56 No. 2, 1999

IRISH FORESTRY

JOURNAL OF THE SOCIETY OF IRISH FORESTERS

Volume 56, No. 2, 1999

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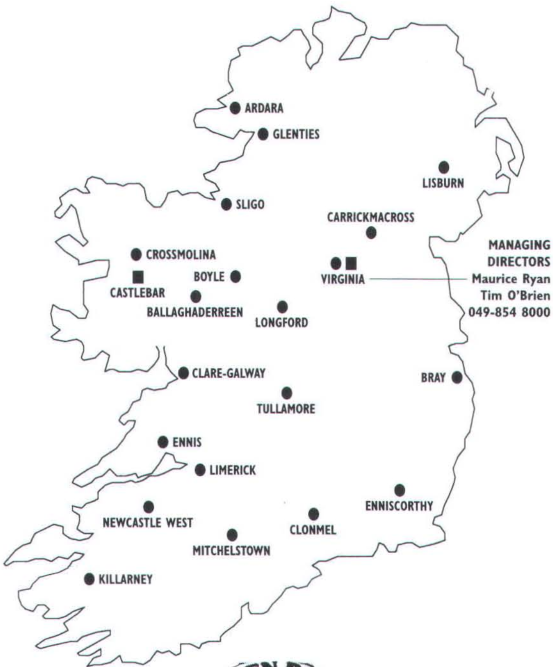

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The main activities of the Society include the organisation of symposia, field meetings and study tours on forestry topics, and the publication of *Irish Forestry*, the Society's journal, and *The Irish Forester*, its quarterly newsletter. The Society also organises forestry shows and exhibitions, and has published *The Forests of Ireland* and *Forest Images – Father Browne's Woodland Photographs*.

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Guidelines for Submissions
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Authors should use the following guidelines when submitting material for publication in *Irish Forestry*.

1. Scientific papers will be peer reviewed. Papers must include an abstract (max. 150 words) and a list of up to six key words before the main body of text. For general papers, a summary (max. 250 words) is required.
2. Papers must be original, unpublished and not being considered for publication elsewhere.
3. Two complete hard copies must be submitted. A computer disc copy must also be submitted, preferably in MS Word format. Correct spelling, grammar and punctuation are expected. Nomenclature, symbols and abbreviations should follow established conventions, with the metric system used throughout. Dimensions should follow units with a space, as in 10 kg.
4. Figures should be appended to the document as a hard copy and as separate computer files. The software used to create the Figure should be stated. The preferred format is eps or wmf graphic files. Avoid tif, bmp and MS Word picture formats. MS Excel format is acceptable but Figures using this format should appended to the text and not embedded.
5. Tables should be created using tabs. They should not be created using MS Word Table Editor. See this issue for other Table formatting features.
6. References should follow the following format:

   Kerruish, C.M. and Shepherd, K.R. 1983. Thinning practices in Australia. *New Zealand Journal of Forest Science* 47:140-167.

   Lavender, D.P. 1984. Plant physiology and the nursery environment: interactions affecting seedling growth. In *Forest nursery manual: production of bareroot seedlings*. Eds. Duryea, M.L. and Landis, T.D., Martinus Nijhoff/Dr W Junk Publ., The Hague/Boston/Lancaster, pp 133-141.

   Gallagher, G. and Gillespie, J. 1984. The economics of peatland afforestation. In Proc. 7th Int. Peat Conf., Dublin. Vol. 3:271-285.

   In the text they should appear as (Kerruish and Shepherd 1983), (Lavender 1984) and (Gallagher and Gillespie 1984). Forestry Abstracts may be used as a guide in the abbreviation of journal titles.

7. Communication will be with the senior author. Before printing, a draft will be returned to the senior author for final proofing. Authors are requested to confine alterations at that stage to the correction of typing errors.
8. The above guidelines are designed to facilitate the speedy processing of material submitted for publication in *Irish Forestry*. Inadequate adherence to these guidelines may result in material being returned to the author for redrafting.

EDITORIAL

For over a decade now afforestation by the private sector, mainly by farmers, has exceeded state planting. Today, close on 10,000 farmers are forest owners. These new forests are scattered over the length and breadth of the country, some in locations that will be difficult and expensive to harvest. Despite the best efforts of agencies such as the Forest Service and Teagasc, and growers groups such as the IFA and the Irish Timber Growers Association, many new forest owners are only vaguely aware of the most basic management requirements. Once a plantation has been established and is growing reasonably well and, of course, there is an annual premium, many growers will be content to leave things as they are. The wake up call will come when the annual premium stops or is about to stop. Growers will be forced to seek ways to generate alternative income. At present Coillte and the small number of growers with older plantations rely mainly on conifer thinnings to provide income before the crop matures. However in most cases they are forced to delay thinning until the pole size is sufficient to at least cover harvesting costs and overheads. The beneficial effects of early thinning, combined with pruning, on wood quality and financial return, in the long run, are well known from extensive research but these are rarely justified if one makes a loss on first thinning.

Looking at the market situation there is general agreement that the increase in wood supply that is forecast to come on stream over the next decade, from both the public and private sectors, will, in the main, have to be processed and sold in export markets, mainly the UK, and mainly as commodity products. Price sells as far as commodity products are concerned. There is an obvious need therefore for cost competitiveness and innovation to control the delivered-in price of wood for processing, as well as a need for streamlining and scaling-up on the processing side. Harvesting and transport are significant factors affecting wood price; innovation in systems and sales methods will lead to significant savings, given Ireland's disperse private forest resource. The harvest scheduling approach outlined in this issue of the journal is one such area - it needs to be seriously considered by processors and growers' organisations.

However not all wood will be processed and sold as commodity products. We loose sight of wood quality at our peril. Flexibility to respond to new standards, markets and market demands will be greatly facilitated by maintaining and improving resource quality. With increasing supply it is likely that processors will be more discerning and demanding. But to grow quality wood in the private sector we need a radical review of where we are going. Broadleaf crops are now rapidly entering the stage where they require tending (removal of poor quality stems). How many growers are aware of this need? Very few, one suspects. For conifers the issues are also quite immediate. Many crops are now reaching a stage where they could and should be thinned. Again the indications are that many private forest owners are at best, very faintly aware of the need for, and benefit of thinning. We should immediately look to ways of encouraging early thinning, and pruning by growers. There are grants for pruning and these should be vigorously promoted by state agencies, as should the concept of thinning. Supply contracts between growers-groups and processors should now be considered to facilitate thinning and wood flow from private forests. These will have to be supported by harvest scheduling and related informatics to maintain competitiveness. There is no doubt that the use of these approaches will result in the necessary economies of scale that will allow growers to thin early, at a profit and develop resource quality.

Submissions to *Irish Forestry* are welcomed and will be considered for publication.
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Influence of physiological status at the time of lifting on cold storage tolerance and field performance of Douglas fir and Sitka spruce

Conor O'Reilly[1], Charles P. Harper[1] and Michael Keane[2]

Abstract

The physiological status of Douglas fir (*Pseudotsuga menziesii* (Mirb.) Franco) and Washington origin Sitka spruce (*Picea sitchensis* (Bong.) Carr.) seedlings was assessed at the time of lifting. Seedlings of both species were sampled periodically from October to May and after cold storage in 1995/96 and 1996/97. Douglas fir only was sampled also in 1997/98. The field performance of seedlings that were planted in a field trial concurrently with the physiology work was evaluated. Shoot cold hardiness showed a clear seasonal pattern and was a good indicator of readiness of seedlings for lifting for planting or cold storage. Seedlings can be safely lifted for field planting when their shoots have hardened to -10 °C in Douglas fir (November to March) and -20 °C in Sitka spruce (late November/early December to March). Equivalent values for judging long-term (more than three months) cold storage tolerance are -20 and -30 °C, respectively. Root electrolyte leakage (REL) values should be considered to augment this information and to assess post-storage vitality. REL values should be <25% for cold storing Douglas fir, but the test is not reliable for judging its readiness-to-lift for field planting. In Sitka spruce, REL values of <20% and <15% indicate readiness for lifting for field planting and cold storage, respectively. Although more resistant to handling stresses later in the season, Douglas fir performs best in the field when freshly planted early in the lifting season (November to December), but Sitka spruce performs best when planted during the period of highest stress resistance (late November/early December to early March).

Keywords: cold hardiness, root electrolyte leakage, dormancy, stress resistance.

Introduction

The role of planting stock quality in ensuring good establishment success has come into clearer focus in Ireland in recent years. While the morphological (or visual) characteristics of plant quality (for example root collar diameter, height and shoot:root ratio) are of key importance (Thompson 1985), it is often the physiological (or non-visual) attributes of the stock that have the greatest impact upon field performance (Ritchie 1984). Physiological quality is, in turn, affected by many factors, including cultural practices used in the nursery. However, plant handling and storage practices probably have the greatest effect on quality (McKay 1997).

In Ireland, most planting stock is lifted in the nursery from about November to March, packed in co-extruded polyurethane bags and dispatched for field planting. In addition, the

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plants may be stored under ambient conditions for some weeks before planting, either at the nursery, in transit, at sorting depots, or at the planting sites. The seedlings[1] may be subjected to a variety of stresses during this chain of events, including desiccation, rough handling, and lack of light (see Tabbush 1988, McKay 1997). Plant condition also may deteriorate because of the depletion of stored food reserves during storage under ambient conditions, prior to planting (Puttonen 1986). In addition, a significant proportion of seedlings is currently placed in cold or freezer storage for a period before planting. The use of such storage allows flexibility in carrying out lifting operations; the stock is ready for dispatch for field planting when field conditions are favourable. However, the quality of the seedlings may deteriorate while in cold storage. Some plantation establishment failures have been attributed to this factor. While steps should be taken to minimise or avoid the potential stresses outlined above, in practice some stresses will always occur. The ability of seedlings to withstand these stresses varies with dormancy status and associated cold hardiness levels (Ritchie 1986).

The results of previous studies provided useful information on the annual cycle of physiological development in Douglas fir (O'Reilly *et al.* 1999) and Sitka spruce (O'Reilly *et al.* 2000) seedlings in Ireland. However, the effect of lift date on the ability to cold store and on subsequent field performance also required investigation, since field growth responses were not entirely consistent from year to year. The physiological status of seedlings at lifting and/or following cold storage was determined using shoot cold hardiness and root electrolyte leakage (REL). The survival and first-year height increment of the seedlings were evaluated in field trials established in tandem with the physiology work. The results are used to give guidelines on the best time to lift for planting or cold storage. In addition, recommendations are made on the best methods for assessing plant physiological quality.

Materials and methods

Plant material, sampling and cold storage

The Douglas fir were 1u1 (non-transplanted, undercut) seedlings {seed source: Darrington, Washington, US; seed description/seed zone 91(797) 403; 48° 15' N, 121° 36' W; <300 m elevation} from the None-so-Hardy Limited nursery at Ballymurn, Co Wexford (52° 27', 6° 29'; 70 m elevation) in 1995/96 and 1996/97, and 2+1 transplants {seed source: Chehalis/Centralia Washington, US; seed description/seed zone: (797) 241; 46° 43' N, 122° 58 W; <150 m elevation} from the Coillte nursery at Ballintemple, Co Carlow (52° 44' N, 6° 42' W, 100 m elevation). They were lifted at periodic intervals in 1997/98 from October to May each year and dispatched to University College Dublin (UCD) for analysis. Similarly, 2+1 Sitka spruce {seed source: seed description/seed zone (797) 030; 46° 58' N, 123° 53' W; <150 m elevation} from the Coillte Camolin nursery, Co Wexford (52° 38', 6° 26'; 65 m elevation) was lifted for analysis in 1995/96 and 1996/97, but not in 1997/98. Descriptions of the nursery soils are given in Table 1.

[1] Seedling is used in a generic sense to include all types of planting stock, including transplants.

Table 1. *Soil characteristics at study site nurseries.*

Nursery	*Ballymurn*	*Ballintemple*	*Camolin*
Soil type	*Sandy clay loam*	*Sandy loam*	*Clay loam*
pH	na[1]	5.7	5.5
Organic matter %	na	6-8	9
Sand %	na	66	35
Silt %	na	19	45
Clay %	na	15	20

[1] Information not available

The mean heights and diameters of the seedlings are shown in Table 2. Detailed descriptions of the cultural practices used at each nursery are not available, but they were similar to those described by Mason (1994a, 1994b).

Table 2. *Morphological characteristics of the Douglas fir and Sitka spruce seedlings used in the study.*

Species	*Douglas fir*			*Sitka spruce*	
Year	1995/96	1996/97	1997/98	1995/96	1996/97
Nursery	BN[1]	BN	BE	CN	CN
Height[3] cm	47.8 (0.48)[2]	44.8 (0.51)	47.4 (0.29)	41.2 (0.53)	48.9 (0.44)
Diameter[3] mm	6.7 (0.13)	6.7 (0.11)	8.6 (0.08)	6.7 (0.13)	6.7 (0.08))

[1]Nursery source abbreviations: Ballymurn (BN), Ballintemple (BE) and Camolin (CN).

[2]Values in parentheses are standard errors.

[3]Based on 20 plants from each of four lift dates (replicates) for each species in each year.

At each sampling date, 150 plants of each species were loosened by machine and lifted by hand, placed in polyurethane co-extruded bags (50 seedlings per bag) and dispatched the same day to UCD. In an identical manner, three bags containing 50 seedlings each (total 150) were dispatched for cold storage (1 - 2 °C) on each of four occasions in 1996/97, and on five occasions for Douglas fir in 1997/98. Upon removal from the cold store in May (after different duration of storage, depending on the lift date), 100 seedlings (two bags) were dispatched to the field trial, while 50 (one bag) were retained for the physiological assessments. Seedlings were also lifted and dispatched for field planting on most lifting occasions, as described below.

Observations and measurements of physiological parameters

All physiological tests/ assessments were carried out on plants just after lifting, but the REL test alone was performed on cold stored plants.

Shoot cold hardiness

Cold hardiness tests were carried out over a period of two to three days, commencing on the date of lifting. On each test occasion, one first-order excised lateral shoot (10 to 15 cm long, 2 to 4 mm base diameter) from the current year's growth, from each of 15 seedlings was subjected to one of a series of three to five target freezing temperatures in the range of -3 to -35 °C in a programmable freezer. The first test was carried out overnight starting on the day of lifting, while the remaining tests were carried out over the following two to three days. Air temperature was cooled from 5 °C at 5 °C h^{-1} until the desired target temperature was reached; it was held at this for three hours and then warmed at 10 °C h^{-1} to 5 °C. After treatment, the shoots were placed in beakers containing tap water and held in a heated (18 - 23 °C day/15 - 18 °C night; 16 h photoperiod) greenhouse for two to three weeks. Cold hardiness was determined by the extent needle tissue damage. Needle damage was scored (after Cannell *et al.* 1990) as: 0, no damage; 1, < 50% of needles killed; 2, > 50% killed but less than 100% killed; 3, all needles dead. The temperature at which 50% of the needles (LT_{50}) died was interpolated from these data, assuming that these scores represented 0, 33, 66, and 100 % damage, respectively.

Root electrolyte leakage

REL is used as an indicator of root vitality and potential field performance (McKay and Mason 1991). The principle of this test is that the movement of ions into and out of cells is largely controlled by the cell membrane. When root tissue is placed in distilled water (that has almost no ions) some ions will move through the membrane and surrounding tissue into the water through osmotic pressure. The amount of leakage depends on the level of damage to the membrane (McKay 1992). It is usually measured using a conductivity meter. However, active roots will leak more ions than inactive roots, making REL an indicator of root activity also. To determine if root damage has occurred however, REL values must be interpreted relative to the expected seasonal (baseline) values.

The REL tests were carried out at the time of lifting and following cold storage, using a method similar to that described by McKay and Mason (1991). (REL data are not available for Douglas fir removed from cold storage in February 1997/98 due to a processing error.) After washing the roots of the 15 seedlings to remove most of the soil, approximately 300 to 500 mg (fresh weight) of fine (< 2 mm diameter) roots were removed from the central portion of the root of each plant and placed in beakers containing tap water. The excised roots were washed thoroughly three times in tap water. The roots were then rinsed three further times in distilled water and placed in 28 ml universal vials with 17 ml distilled water. The vials were capped, agitated, and allowed to incubate at room temperature (18 - 20 °C) for 18 hours. After incubation, the conductivity of the bathing solution was measured using a conductivity meter with inbuilt temperature compensation (Delta Ohm, HD8706, Padova, Italy). All root samples were then killed by placing the vials in an oven at 90 °C for two hours. The samples were allowed to cool to room temperature (for four hours) before taking the second conductivity reading. The initial 18 hours conductivity reading was expressed as a percentage of the second reading.

Field performance

A separate trial was established each year in tandem with the physiology work. At approximately four to five week intervals each year, seedlings were dispatched for planting at a field site at the Coillte Tree Improvement Centre, Kilmacurra, Co Wicklow (52° 56' N, 6° 09' W, 120 m elevation). The soil at Kilmacurra had a pH of 5.7, 7% organic matter, and sand, silt and clay fractions of 40, 32 and 27%, respectively. Each year the field site was cleared of weeds prior to planting using Roundup at 2 l/ha (720 g glyphosate). Thereafter weeds were removed by hand at regular intervals.

The field trial was set down as spilt-plot with four blocks, comprising two storage treatments (freshly lifted and three to seven months cold storage) as the main treatments and six to eight lifting dates as the sub-treatments. Each of the four blocks contained one replicate of most of the storage treatment x lifting date combinations, as a row plot of 20 seedlings. Because plants were not placed in the cold store on all lifting dates, some plots were incomplete. Spacing was approximately 50 cm between rows and 30 cm within rows.

Survival (per subplot) and height increment were recorded at the end of the first growing season of each year. Because there was some variation in initial planting stock size, the height increment data were analysed as percent of initial height, measured before growth began in the spring. Subplot means were used in all of the data analyses.

Data analysis and presentation

Because the exact time of sampling varied from year to year, comparison of calendar date effects on response data were difficult to carry out. Therefore, the means and standard errors on each sample date for each year and 95% confidence intervals are presented. Unless otherwise stated, each seedling observation/value was treated as a single replicate.

Separate analyses were carried out on the root electrolyte leakage values (after arc sine square root transformation) for each year using an analysis of variance in SAS (1989) to test for the effects of lift date, storage treatment (no storage, or storage until May). In addition, the REL values recorded for seedlings from each lift date before and after cold storage until May were compared using a t test.

The field survival (after arc sine square root transformation) and percent height increment (plot mean) data for each year were subjected to an analysis of variance (SAS 1989) to test for block and lift date effects, separately for each storage (no storage, cold stored until May/June) treatment. The factorial split-plot model for the two factors was not tested because the cold storage treatments were not carried out at all lift dates. Means for each date were also compared using LSD tests. The performance of cold stored stock was compared with that of the freshly planted stock of same lift date using a t-test.

Meteorological data

Dormancy and cold hardiness development and growth are strongly influenced by weather (Lavender 1984). Because measurements were not taken at the nurseries, temperature data were obtained from weather stations closest to or most representative of the weather at the nurseries. Degree-days was calculated by accumulating temperature sums above each daily mean value (degree days = mean-5 °C; mean=maximum-minimum/2) for the April to October period of each year. Similarly, the cumulative chilling from September to March each year was calculated using temperature sums ≤5°C.

Air temperature data were obtained for Johnstown Castle, Co Wexford, approximately 17 and 35 km from Ballymurn and Camolin nurseries, respectively, for the 1995 to 1997 period. Temperature data from Kilkenny (data for Oakpark, Carlow, not available in late 1999) were used for 1997/98 (about 40 km from Ballintemple Nursery). Weather data were not available for the planting site. However, for months in which comparisons could be made between the each of the two stations and Kilmacurra, degree-day sums differed little between stations (Figure 1).

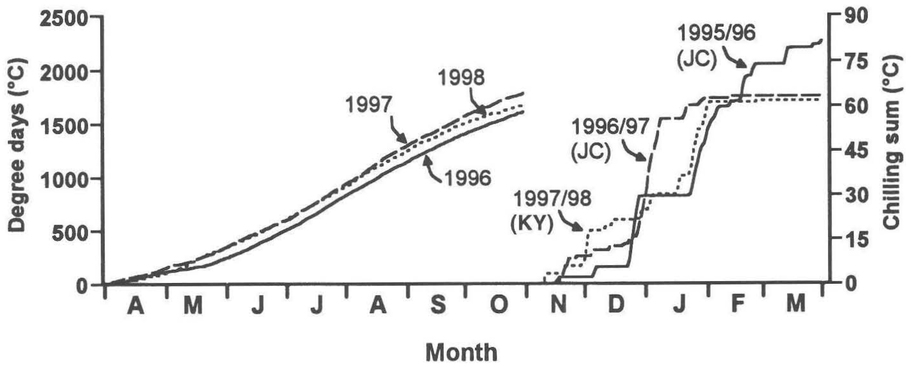

Figure 1. *Accumulated degree-days (>5 °C) from April to October and daily chilling sums (<5 °C) from November to March for Johnstown Castle (JC) and Kilkenny (KY).*

Results

Cold hardiness

Since cold hardiness is expressed as an LT_{50} value (temperature that kills 50% of the shoots), many shoots will be actually damaged by temperatures about 2 to 4 °C warmer than those shown (Figure 2).

The shoots were least hardy in early October (about -5 °C) in both species and became most hardy by December/February in each year (Figure 2). Interestingly, Douglas fir did not harden greatly after late November (ca. -15 °C) in 1997/98, whereas the shoots hardened greatly (ca. -25 °C) after this time in the other years (Sitka spruce was not sampled in 1997/98). The shoots hardened to about -25 °C in Douglas fir and -35 °C (lower limit of freezer) or lower in Sitka spruce by early January in 1995/96 and 1996/97. Thereafter, shoots maintained high hardiness levels until mid to late February, then dehardened rapidly during February and March, achieving similar hardiness levels to those attained in October. The seasonal pattern of change in cold hardiness was remarkably similar each year in Sitka spruce, but the shoots dehardened sooner in 1996/97 than in 1995/96 in Douglas fir. Douglas fir shoots were significantly less hardy from December to February in 1997/98 than in the other years ($p \leq 0.01$). Shoots were significantly ($p \leq 0.05$) hardier during deacclimation from January to April in 1995/96 than in 1996/97 (too few data were available for 1997/98 to assess significance), but differences were not significant between the latter two years.

Root electrolyte leakage

REL was significantly (all $p \leq 0.01$) influenced by lift date in both lifting seasons and date of cold storage in 1996/97 (both species) and 1997/98 (Douglas fir only, Figure 3). Root electrolyte leakage was much higher in 1997/98 than in other years in Douglas fir. REL also was generally higher in Douglas fir than in Sitka spruce.

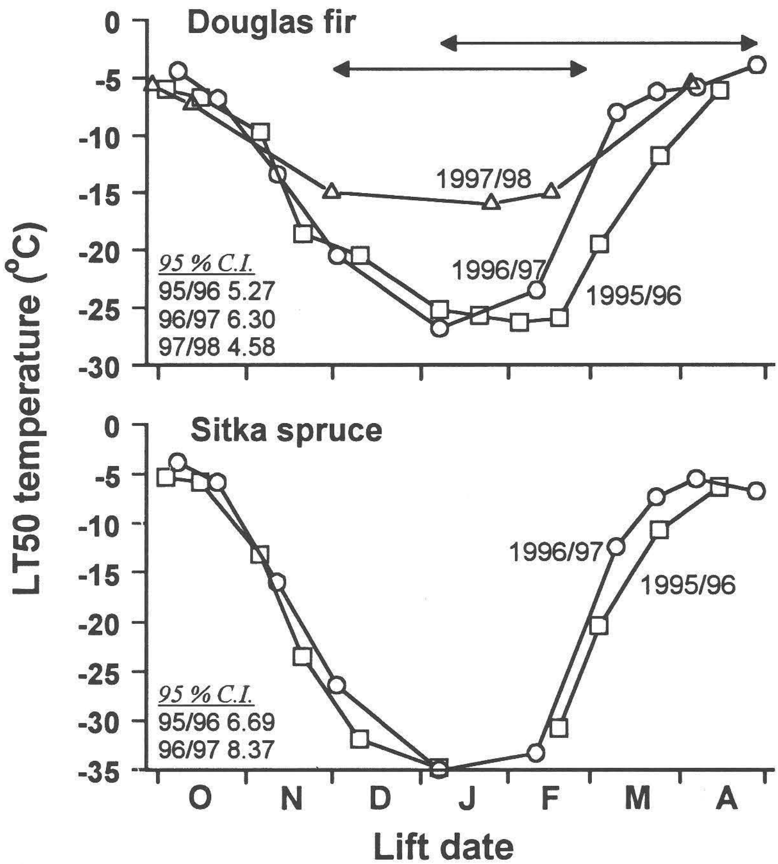

Figure 2. *Seasonal change in cold hardiness of Douglas fir and Sitka spruce.* Periods where cold hardiness differed significantly between lift dates are indicated by arrows. (C.I. is confidence interval).

In Douglas fir in 1995/96 and 1996/97, REL values were relatively high in October and early November (27-37%), then declined to low values (ca. 20%) by January to early February (Figure 3). Thereafter, REL remained relatively similar in 1995/96 (20-25%), but increased to high values (ca. 40%) by March in 1996/97. In 1997/98, REL decreased from 53% in September to about 38% in late November. Values ranged from 36-39% until early March. Thereafter, REL increased again, reaching 45% by early May.

In Sitka spruce, REL was generally low (12 - 21%) and showed no clear seasonal trend in 1995/96 (Figure 3). In 1996/97, REL decreased rapidly from a high (29%) in October to a low (ca.15%) from late November to early February. Thereafter, REL increased gradually to a high (20%) in May.

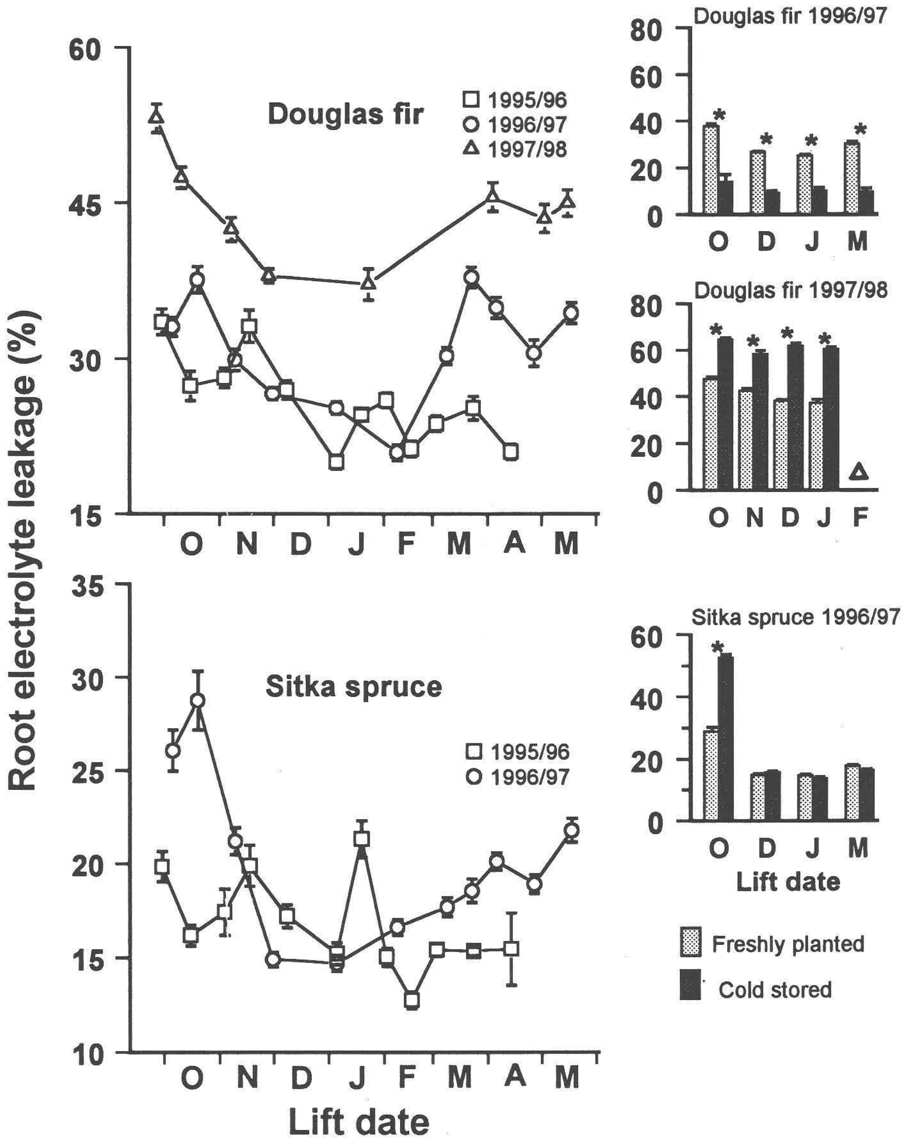

Figure 3. *Root electrolyte leakage of Douglas fir and Sitka spruce seedlings at time of lifting.* Insets show values for stock freshly lifted and following cold storage until May. Vertical bars on symbols indicate standard errors. Significant differences between cold stored and freshly lifted stock are indicted (*).

In Douglas fir, REL was lower ($p \leq 0.01$) following cold storage than at the time of lifting in 1996/97, whereas the reverse was the case in 1997/98 (Figure 3). Survival in the field was much higher in 1996/97 than in 1997/98, in agreement with this trend (Table 3a). In Sitka spruce in 1996/97, REL values after storage were similar to those at the time of lifting in December, January and March, but REL was higher ($p \leq 0.01$) after storage for stock lifted in October. Field mortality also was highest for Sitka spruce lifted to the store in October (Table 3b).

Table 3a. *Survival of Douglas fir seedlings freshly lifted or cold stored until May and planted three to four days later.*

1995/96		*1996/97*			*1997/98*		
Month	*Freshly lifted*	*Month*	*Freshly lifted*	*Cold stored*[2]	*Month*	*Freshly lifted*	*Cold stored*
Oct	99a[1]	Oct	98a	25b*	Oct	88bc	0b*
Nov	98a	Dec	96a	98a	Nov	98ab	0b*
Dec	99a	Jan	99a	98a	Dec	100a	14b*
Jan	100a	Mar	91a	97a	Jan	81c	11b*
Mar	99a	Apr	91a		Feb	96ab	79a
Apr	100a	May	55a		Mar	100a	
					Apr	93ab	
					May	89bc	
p≤	ns[3]		0.0001	0.0001		0.0005	0.0001

[1]Means followed by the same letter are not significantly different.

[2] Cold storage lift dates indicated (*) are significantly different from the freshly lifted stock of that date.

[3]Not significant.

Table 3b. *Survival of Sitka spruce seedlings freshly lifted or cold stored until May and planted three to four days later.*

1995/96		*1996/97*		
Month	*Freshly lifted*	*Month*	*Freshly lifted*	*Cold stored*[2]
Oct	100a[1]	Oct	100a	41.0b*
Nov	100a	Dec	100a	97.5a
Dec	100a	Jan	98.8a	100a
Jan	100a	Mar	100a	100a
Mar	100a	Apr	96.3a	
Apr	98.9a	May	92.5a	
p≤	ns[3]		0.0500	0.0001

[1]Means followed by the same letter are not significantly different.

[2] Cold storage lift dates indicated (*) are significantly different from the freshly lifted stock of that date.

[3]Not significant.

Field performance

The survival of freshly lifted seedlings was generally very high (>90%), except for those planted early or late in the season (Table 3). In both species, differences in survival among lift dates were significant (p≤0.05) in 1996/97 and 1997/98, but not in 1995/96. Height increment (as percent of initial height) of seedlings showed larger differences among planting dates (Figure 4). Height increment in Douglas fir was best for stock that was freshly planted early in the season, gradually declining to low values for those planted in April and May. Although similar to Douglas fir in the 1995/96 season, the effect of planting date on height increment of Sitka spruce was less clear in 1996/97.

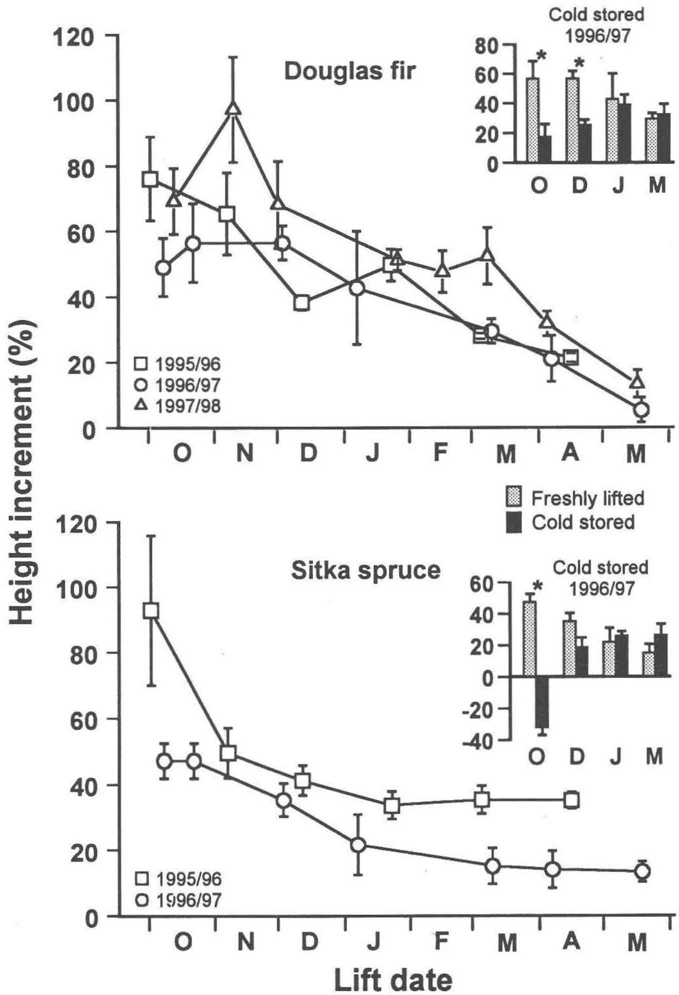

Figure 4. *End-of-season height increment as percent of initial height of seedlings freshly lifted or cold stored until May and planted three or four days later in 1995/96, 1996/97 and 1997/98 spruce (Douglas fir only).* Vertical bars on symbols indicate standard errors.

The survival (Table 3) and height increment (Figure 4) of Douglas fir and Sitka spruce seedlings that had been cold stored from January or March until the time of planting in May were similar to values for the freshly planted stock. However, there were significant differences ($p \leq 0.05$) between the storage treatments for other lift dates. Most of the Douglas fir seedlings that were cold stored in 1997/98 died. Sitka spruce cold stored from October had poor survival and many leading shoots died back, resulting in negative height increment overall

Discussion

The results reported in this paper are a continuation of earlier work (O'Reilly *et al.* 1999, 2000). For this reason, the recommendations on optimum lift/storage dates given here differ slightly than if they were based solely on the results shown in this paper.

Physiological status at the time of lifting

Cold hardiness displayed a clear seasonal trend each year in both species, as found in earlier studies carried out in Ireland (O'Reilly *et al.* 1999, 2000). Cold hardiness varies seasonally mainly in response to seasonal changes in photoperiod and chilling temperatures (normally considered those <5 °C) (Larcher 1995), but species may differ in their relative response to these factors. Cold hardiness acclimation and deacclimation was remarkably similar in 1995/96 and 1996/97 in Sitka spruce (Figure 2). However, shoots of Douglas fir deacclimated significantly earlier in 1996/97 than in the slightly cooler 1995/96. Hybrid larch (*Larix x eurolepsis* Henry) shoots sampled from seedlings lifted from the same nursery (Ballymurn) also dehardened sooner in 1996/97 than in 1995/96 (O'Reilly *et al.* 2001). While differences in cold hardiness acclimation were not significant for the two species in this study, such differences were evident in seedlings of both species sampled from Ballintemple Nursery in earlier studies (O'Reilly *et al.* 1999, 2000). The effect was pronounced in Douglas fir only, similar to the trend detected in this study for the deacclimation phase. Sitka spruce is a coastal species in its native habitat and therefore cold hardiness acclimation and deacclimation may be more heavily influenced by photoperiod than in Douglas fir, which covers a wider longitudinal range (Colombo *et al.* 2001).

Perhaps the most surprising outcome in this study was the observation that Douglas fir did not harden to temperatures colder than -17 °C in 1997/98 (Sitka spruce was not sampled that year). The reasons for this result are not fully clear, but some hypotheses may be advanced. First, a different provenance of Douglas fir was used in 1997/98 than in the two previous years, although all were from a similar part of the species range in Washington. Provenance can have a large impact on the cold hardiness of conifer seedlings (Cannell and Sheppard 1982, Nicoll *et al.* 1996, Colombo *et al.* 2001). Second, three-year-old transplanted seedlings were sampled in 1997/98 from Ballintemple Nursery, whereas two-year-old undercut stock from Ballymurn were used in the two previous years, which may have further confounded treatment effects. Cold hardiness of conifer seedlings is influenced greatly by nursery cultural practices and climatic differences between nurseries (Colombo *et al.* 2001). However, it is unlikely that these factors fully explain the cold hardiness differences. Chilling sum accumulations were similar in Ballymurn in 1996/97 as in Ballintemple in 1997/98 (Figure 1), yet cold hardiness levels differed between these years. Chilling temperatures have a major impact on cold hardiness development in

Douglas fir (Burr *et al.* 1989, O'Reilly *et al.* 1999). Furthermore, in previous research carried out on Douglas fir sampled from Ballintemple Nursery, seedlings became hardy to temperatures colder than -25 °C in three consecutive years, including the very mild 1994/95 (O'Reilly *et al.* 1999), whereas this did not happen in the relatively cool 1997/98. Another possible explanation is that nutrient levels were sub-optimal for cold hardiness development. Nutrient availability is known to have a large effect on the development of cold hardiness in conifer seedlings (Colombo *et al.* 2001). However, there is no evidence to support this claim since shoot tissues were not analysed to determine nutrient levels.

The seasonal course of root electrolyte leakage was less clear in both species, perhaps reflecting fluctuations in root activity. Providing soil temperatures are adequate, root growth may occur throughout much of the winter in Ireland (O'Reilly *et al.* 1999, 2000). Nevertheless, REL was generally lowest in the December/February period each year (except for high peak in January for Sitka spruce in 1995/96), and values increased later in the cooler spring of 1995/96 than in 1996/97. High REL values indicate root damage or high root activity levels (Harper and O'Reilly 2000). REL was exceptionally high in Douglas fir in 1997/98, probably because the roots were more active that year than in other years. The shoots of the seedlings were also less cold hardy during the winter of 1997/98, suggesting that the plants were generally more active then than in other years. The higher than expected REL for Sitka spruce stock lifted in January 1995/96 may have been the result of damage caused during lifting under wet conditions. Although O'Reilly *et al.* (2000) suggested that REL values <16% might indicate readiness for lifting in Sitka spruce, the high variation in REL values among lift dates in both species in this study indicates that the test is of limited value for this purpose. The results reinforce the view that no one test can be relied upon to determine plant quality (Puttonen 1997).

Lifting for field planting

Seedlings lifted for field planting should be sufficiently resistant to the stresses of normal lifting and handling operations; otherwise they will perform poorly after planting. However, post-planting field conditions may also be important. Seedlings of some species, for example, may benefit from planting at certain times of the year because warm soil temperatures allow new root growth. New roots are more efficient in supplying water for the plant's needs than nursery roots (Larcher 1995). Good quality plants may die if planted into a cold soil, probably due to the gradual loss of water during transpiration, water that the plant is unable to absorb through the old roots.

The results from this study showed that the date of planting was important for Douglas fir, but less so for Sitka spruce, which is largely in agreement with earlier findings (O'Reilly *et al.* 1999, 2000). Douglas fir performed best when planted between October and early December. The main reasons for the superior performance of Douglas fir planted at these times are (i) the higher root growth potential of the seedlings at this time (data on file), and (ii) soil temperatures are warm enough to permit root growth. Soil temperatures are unfavourable for root growth from about late December to February, although this is the period when the plants are most resistant to handling stresses. Although soil temperatures also may be favourable for root growth in March/April, root growth potential is very low (shoot activity appears to take precedence) and resistance to handling stresses is declining; poor performance can be expected from late planting. Therefore, it is recommended that Douglas fir should be planted in autumn and early winter, provided soil temperatures are >5 °C. For this reason, the planting season may vary with soil type and location of site in Ireland. In addition to their effects on competition for nutrients and water, the presence of competing vegetation may lower soil temperatures (Low and Greig 1973), thus reducing seedling field performance. Soil preparation and vegetation control seems to be more important in ensuring the successful establishment of Douglas fir than for most other conifers (Tabbush 1988).

The biggest risk in planting Douglas fir during the recommended period, especially in October, is that the plants are not highly stress resistant and may suffer from damage during handling, or while in temporary storage prior to planting. The seedlings will be most resistant to these handling stresses when the shoots have hardened to ≤-10 °C. Nevertheless, recent research results indicate that it should be possible to store Douglas fir stock (in the shade) for a period equivalent to 1,500 degree hours (base >5 °C) (Harper and O'Reilly 2000). This is equivalent to about 12-19 days during the October to December period, based upon 1997 temperatures at Ballintemple nursery. The period of safe storage may be much shorter in some years than in others (especially in October), and in milder coastal and southern locations than at this nursery, but may be longer during colder periods. For this reason, the use of both ambient air and soil temperature data in judging lifting windows is advocated, rather than relying solely on calendar date, especially for Douglas fir.

Planting date had little effect on the survival and height increment of Sitka spruce, but height increment was lowest for those planted late in lifting season. Although field performance was good for stock planted in October and November (especially since planting took place within two to four days of lifting), it is recommended that under operational conditions stock should not be lifted unless they are hardy to -20 °C, commencing about mid-November (Figure 2). Sitka spruce will withstand the stresses of lifting and handling when hardy to this or lower temperatures (O'Reilly *et al.* 2000). There is some evidence that the lifting of QCI Sitka spruce could commence about two to three weeks earlier than this, commencing in early November (O'Reilly and Keane 1996). Lifting should cease when the shoots have dehardened to temperatures warmer than -20 °C, in about early March (Figure 2). Sitka spruce of Washington provenance is less resistant to the stresses of lifting and handling during October and early November than Douglas fir, so planting should be avoided during this period. Unlike Douglas fir, the main criterion in deciding when to lift Sitka spruce is when stress resistance levels are sufficient to permit safe handling. The results of this study and earlier work (O'Reilly *et al.* 2000) indicate that the window of opportunity for lifting Sitka spruce may not change greatly from year to year, since hardiness levels appear to respond strongly to photoperiod. Nevertheless, lifting might be delayed until December in an exceptionally mild year, such as occurred in 1994/95 (O'Reilly *et al.* 2000).

Lifting for cold storage

A major focus of this research was to determine the effect of cold storage on plant quality, especially for Sitka spruce. Cold hardiness is a very useful indicator of readiness to lift stock for planting or cold storage (Tinus and Burr 1997). Field performance after planting was good following long-term (>three months) cold storage until May for Douglas fir and Sitka spruce seedlings; these had achieved cold hardiness levels of -20 and -30 °C, respectively. This confirms results from earlier studies (O'Reilly *et al.* 1999, 2000). The levels of cold hardiness were achieved by the period January to February in Douglas fir and December to early March in Sitka spruce. Shoots of Douglas fir did not harden below -17 °C in 1997/98, and stock was not highly storable that year, reinforcing the validity of the cold hardiness test. The reason why Douglas fir did not harden off and become storable in 1997/98 is unclear, as discussed earlier.

The results of this study confirm the view that long-term cold storage of Douglas fir is viable, despite the problems encountered in 1997/98. However, it is essential that hardiness levels be determined to confirm that the plants are 'storable', whereas this may not be necessary for lifting Sitka spruce for cold storage from January to March. In addition, the quality of the stored Douglas fir should be monitored more often while in cold storage than Sitka spruce, and all seedlings should be removed for planting by April or early May at the latest. The REL test is useful for monitoring quality in storage (McKay and Mason 1991). Although the post-storage performance of Douglas fir stock was poor in 1997/98, survival in the field was better for seedlings placed in storage in February than on other lift dates. Seedlings stored in December, January or February had similar cold hardiness levels, but the duration of cold storage was shortest for those lifted in February. The period of cold storage of Douglas fir should be kept as short as possible (preferably from February), perhaps until April or early May, but not until June (see also O'Reilly *et al.* 1999).

Although field survival was excellent, height increment was usually slightly less than that of the stock lifted freshly lifted on same date. The shorter growing season available to seedlings planted after cold storage is probably the main reason for this outcome. The buds of seedlings planted late (May/June) usually do not flush until four to five weeks later, thus limiting the period available for growth. In another study of hybrid larch carried out in Ireland, the growth of seedlings following cold storage was also reduced (O'Reilly *et al.* 2001). Foresters should be aware that additional vegetation management might be necessary for sites planted late with cold-stored stock. Furthermore, there may be a higher risk of drought stress shortly after planting (even leading to mortality) for cold stored stock, since new roots (which absorb most of the water required by the plant) may not have been initiated prior to the onset of the drought.

In general, REL was a good indicator of post-storage root vitality for Sitka spruce, as

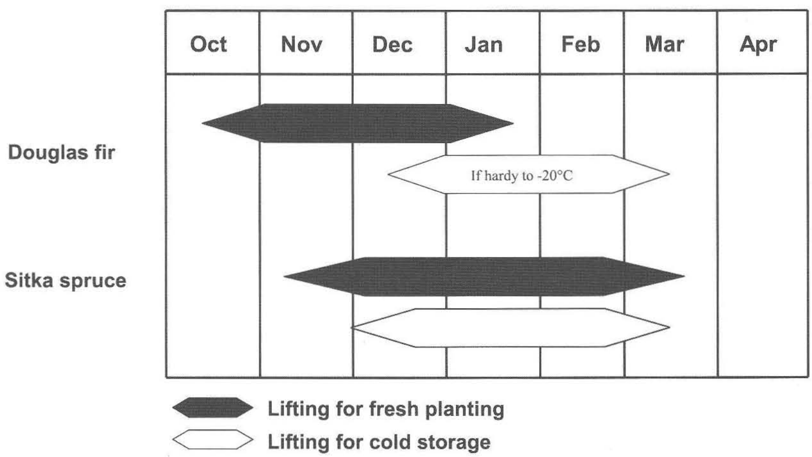

Figure 6. *Recommended lifting dates for Douglas fir and Sitka spruce.* Recommendations are less reliable where bars narrow - seedlings should be planted soon after lifting, or may not be ready for cold storage during these periods.

found previously in this and other species (McKay and Mason 1991, McKay 1992, 1993, 1998, O'Reilly *et al.* 2000). However, the relationship between REL and field performance was less clear for Douglas fir. For example, in 1996/97, post-storage REL values were generally low (indicating good quality), but performance was poor for stock lifted for cold storage in October. Nevertheless, the REL data corroborated the findings for the cold hardiness data in 1997/98; REL values were high at the time of lifting and were >60% after cold storage. Very high REL values were associated with high mortality in Douglas fir planted after cold storage that planting season.

Conclusions and implications for forestry practice

Seedlings can be safely lifted and handled when their shoots have hardened to -10 °C in Douglas fir (November to March) and -20 °C in Sitka spruce (late November/early December to March) (Figure 5). Equivalent values for judging cold storage tolerance are -20 and -30 °C, respectively. However, the height increment of freshly planted Douglas fir declines almost linearly with date of planting from November to May; early planting is recommended (Figure 5). Root electrolyte leakage values could be used to support this information and in assessing post-storage vitality, although the test was less useful for this purpose in Douglas fir. In Sitka spruce, REL values of <20% and <15% indicate readiness for lifting for field planting and cold storage, respectively. REL values should be <25% for cold storing Douglas fir, but the test is not reliable for judging readiness to lift for field planting. Sitka spruce appears to respond more strongly to seasonal changes in photoperiod than Douglas fir; the safe lifting windows may vary little from year to year in Sitka spruce.

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Ex-vitro growth studies of *Quercus robur* L.

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Abstract
Micropropagated oak trees (*Quercus robur* L.) were established in a replicated field trial together with conventional seedlings at Castlewellan Forest Park, Co Down. At the end of the first year (1994) the micropropagated trees were significantly smaller than the seedlings (49 v 65 cm). Five years later there was no significant height difference between the two planting stock types (218 and 220 cm respectively). No abnormal growth was observed in any micropropagated trees during the course of the experiment.

Keywords: *Quercus robur* L., micropropagation, *in-vitro*, *ex-vitro*.

Introduction
Quercus robur L. is one of the main forest species in the British Isles. Tree improvement in the species is difficult, due to its slow maturation and marked fluctuations in acorn production (Carmen *et al.* 1987). Consequently there is a considerable interest in short-circuiting traditional improvement methods by identifying elite oaks in the forest and propagating them vegetatively. Unfortunately the potential of *Q. robur* cuttings to form adventitious roots decreases rapidly with increasing plant age (Chalupa 1993). However, vegetative reproduction in the genus *Quercus* can occur through stump and rhizomatous sprouting (Muller 1951). During COST[3] Action 87 a propagation system was developed whereby *in-vitro* material was successfully established from adult trees, thus allowing the genotype to be micro-propagated (Evers *et al.* 1990). It was necessary, however, to examine the growth performance of the micro-propagated planting stock following field planting, in order to determine if there were *in-vitro* effects leading to abnormal growth.

Materials and methods
The *in-vitro* clone (NL 100) was established in culture from sprouted shoots supplied in the autumn of 1991. These were from trunk segments of a 100-year old *Q. robur* tree, which had been harvested in the forest of Oosterengh, near Wageningen, The Netherlands (Evers *et al.* 1995). Acorns were subsequently gathered from the same stand of trees in 1991.

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The clone was micro-propagated in Woody plant media (WPM) (Lloyd and McCown 1980) with 0.2 ppm BAP as described by Chalupa (1984). The shoots were rooted in 1/3 WPM containing 0.3 ppm IBA, 20 g l^{-1} sucrose, solidified with 7 g Difco Bacto agar. During the multiplication stage the shoots were grown under one of three different light regimes – Grolux (high red light component at λ 660 nm), Cool White (half the red light of Grolux at λ 660nm but twice the blue light at λ 430 nm) or a combination of both (two light tubes of each type as opposed to four tubes of one type). The stimulating effect of red light on the micropropagation of oak has already been reported (Mac An tSaoir and Kabrianis 1993). In the spring of 1992 the plantlets were established *ex-vitro* in a glasshouse with seedlings which had been germinated from the acorns sown in trays of sand during the winter of 1991/92. Thus the two planting stock types were of a similar age. In 1993 all plants were moved outside the glasshouse and grown-on in pots.

The following spring (1994) the seedlings and micro-propagated plants were planted in a field trial at Castlewellan Forest Park, Co Down, at 140 m elevation (Irish Grid reference: J 333364). The micro-propagated plants and seedlings were planted in alternate plots of 20 trees. Each plot measured 8 x 8 m with a tree spacing of 0.8 x 2.0 m. There were four rows of five oak trees in each plot (with a beech tree planted between each pair of oaks). The treatments were replicated five times in alternate blocks. The height of each tree was recorded at the end of each growing season and plot means calculated. The means were then used to compute an analysis of variance.

The heights of the micro-propagated trees were further analysed to determine if there was any carryover effect of the light treatments *ex-vitro* (each micro-propagated tree had been labelled *in-vitro* according to the light treatment it had been subjected to).

Results

In the first year plants grew taller when grown under the Grolux light regime than in the Cool White or combined treatment (Table 1). By the second year when the plants were moved *ex-vitro* there was no significant difference between any of the light treatments.

Table 1. *The effect of in-vitro light quality on tree height under glasshouse conditions.*

	Light treatment				
Year	*Cool White*	*Grolux*	*Cool White/ Grolux*	*Significance*	*Standard Error*
		cm			
1992	5.53	7.70	5.87	$p \leq 0.001$	0.358
1993	17.83	20.60	18.90	ns[1]	0.924

[1] Differences between means not statistically significant

While the micropropagated material was considerably smaller (17.5 cm or 2.73 times) than the seedlings at the start of the experiment (Table 2), this difference gradually decreased over time. By the end of the first growing season in the field the difference was no longer statistically significant.

Abnormal growth patterns were not observed in the micropropagated material during the course of the experiment.

Table 2. *Effect of propagation* method *on the* mean *height of Q robur micro-propagated (C) plants and seedlings (S).*

Year	*1992*	*1993*	*1994*	*1995*	*1996*	*1997*	*1998*	*1999*
	cm							
C	6.4	19.1	48.8	87.8	116.6	163.6	183.0	218.0
S	23.9	47.9	64.8	96.4	127.0	169.2	189.0	220.4
Significance	$p<0.001$	$p<0.001$	$p<0.001$	ns[1]	ns	ns	ns	ns
Standard error	0.84	1.27	1.40	2.59	3.37	4.49	5.92	8.39

[1] Differences between means not statistically significant

Discussion

Several laboratories in the COST group failed to establish field trials as the cultures of the NL 100 clones they received did not propagate very well. It subsequently transpired that the clones which were distributed to the different research partner organisations were derived from a range of trunk sprouts (the positions of origin of which had not been recorded). This raises the possibility that some vegetative shoots were more juvenile than others were. Thus, if a laboratory received material established from a lower (and therefore potentially more juvenile) trunk segment, propagation may have been easier in comparison to those who received material from further up the trunk.

Given that predominantly red light emitting tubes (Grolux) significantly increased the shoot multiplication rate over predominantly blue light emitting tubes (Cool White) *in-vitro*, there was always the risk that the plants grown under the former light regime would develop into bushier trees *ex-vitro*. However, the data show that while there was a significant height difference between the treatments at the end of the first growing season; by the end of the second year this difference was no longer significant.

The data show that the system developed by Evers *et al* (1990) can be used to propagate oak material *in-vitro* and that the clones grow normally when compared to seedlings of the same age. Given the food reserves that are present in acorns it was expected that the seedlings would initially grow faster than the clones. This proved to be the case. However, as the data clearly show (Table 2), this height difference quickly disappeared. Since the clone was selected from a proven elite tree and the acorns were of mixed genetic origin (albeit from a superior stand), it might be expected that the clone would demonstrate superior growth, as shown by the results (Table 2).

Comparison with data recorded between 1994 and 1997 from other field trials, which used the same genetic material, shows that the results presented here are typical. In two of the field trials where the clones were taller than the seedlings at establishment, the former remained taller (Hammatt and Jones 1997, Monney and Schmid 1998). In three other trials where the seedlings were significantly taller at the start, the difference persisted (Hunter and Moore 1998, Appelgren 1998, Wilhelm and Cachèe 1998). However, the increment after planting for both stock types remained about the same. This gradually reduced the relative height difference between the two and its statistical significance.

It is reasonable to conclude that in this instance planting stock produced from tissue culture, derived from vegetative juvenile sprouts removed from adult trees, grew normally *ex-vitro* and at the same rate as seedlings five years after planting.

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Modelling soil water fluxes in a Norway spruce {*Picea abies* (L.) Karst.} stand at Ballyhooly, Co Cork

Julian Aherne[1], Thomas Cummins[1] and Edward P. Farrell[1]

Abstract

Solute fluxes within the soil can contribute greatly to the understanding of biogeochemical processes. They are typically estimated from measured concentrations and simulated soil water fluxes. Models used to calculate soil water fluxes generally require water retention characteristics, hydraulic conductivity characteristics and root distribution as inputs.

Using measured precipitation and throughfall volume in combination with modelled soil water fluxes, estimated using the FORHYD model, the six-year (1989–1994) mean annual hydrological balance for a Norway spruce stand at Ballyhooly, Co Cork, has been estimated. Precipitation was 1141 mm yr^{-1} while evaporation from tree surfaces was 497 mm yr^{-1}. The vertical soil-water flux, estimated by simulation, was 322 mm yr^{-1} at 1 m depth.

Keywords: hydrological balance, soil water fluxes, FORHYD model, forest ecosystems.

Introduction

The Forest Ecosystem Research Group (FERG), at University College Dublin, operates four forest monitoring plots in Ireland with the aim of quantifying the effects of atmospheric deposition on forest ecosystems (Farrell *et al.* 1993). An important part of the research involves estimating water and element budgets within the ecosystem. Element transport is typically estimated from measured concentrations and simulated soil water fluxes. The hydrological study, which is presented here, describes the six-year mean annual hydrological balance for a forest ecosystem at Ballyhooly, Co Cork.

The Ballyhooly intensive forest monitoring plot is located in a mixed intensive farming area in the south of Ireland (8°25' W, 52°08' N). The altitude is 70 m, annual precipitation averages 1141 mm and the mean annual temperature is 9.9° C. The monitoring plot is located in a plantation of Norway spruce {*Picea abies* (L.) Karst.} established on a former oak woodland site, supporting a relatively rich woodland flora. The spruce was planted in 1939, with periodic thinning between 1950–1985 and was clearfelled in 1995. The dominant soil type is orthic podzol (Spodosol; Typic Haplorthod), developed from periglacial colluvium, which overlies Devonian sandstone till. It is deep and relatively free-draining, stones are common and fine roots occur throughout. A detailed site description is given in Farrell *et al.* (1996)

Methods

Precipitation was measured weekly at a treeless site near the forest plot using permanently open 10 cm diameter funnel collectors (three collectors). Throughfall was collected weekly in similar collectors located below the tree canopy but above the herb layer (nine

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collectors). Stemflow was collected in helical, silicon rubber gutters attached to tree stems (eight collectors). Canopy interception was calculated as the difference between precipitation and throughfall plus stemflow. Soil-water fluxes were estimated using a hydrological model developed for forest soils (Tiktak and Bouten 1992). Soil moisture tension, used for model calibration and validation, was measured weekly using Thies Clima type tubes with an unglazed ceramic cup sealed to a frost-resistant transparent hollow tube, with the upper end sealed by a rubber septum in a screw cap. Tensiometers were installed at two depths, 25 cm (ten tensiometers) and 75 cm below the organic horizon (16 tensiometers). Measurement methods are further described in Farrell *et al.* (1996).

The FORHYD model

Soil water fluxes were estimated using the computer simulation package FORHYD (FORest HYDrology), developed by the Laboratory of Physical Geography and Soil Science, University of Amsterdam (Tiktak and Bouten 1992). FORHYD contains several modules simulating the hydrological processes in forested ecosystems. SWIF (Soil Water In Forests) the soil water module, describes root-water uptake and vertical water flow in the unsaturated soil zone (m week^{-1}) as well as lateral drainage in the saturated zone. Essentially the model calculates the finite difference solution of the Richards equation (Richards 1931):

$$C(h)\cdot\frac{\delta h}{\delta t}=\frac{\delta\left[K(h)\left(\frac{\delta h}{\delta z+1}\right)\right]}{\delta z}-S(h)-D(h)$$

where:
C is differential water capacity (m^{-1}),
t is time (estimated weekly for the simulation scenario presented here),
z is height (m),
h is soil-water tension (m),
K(h) is unsaturated conductivity (m week^{-1}),
S is a sink term accounting for root water uptake and
D is a sink term accounting for net lateral drainage (m week^{-1}).

The energy available (W m^{-2}) for forest floor evaporation and root-water uptake is calculated as the Makkink reference evapotranspiration (de Bruin 1987) based simply on air temperature (K) and global solar radiation (W m^{-2}). The available energy is partitioned between potential transpiration and soil evaporation, using a canopy gap fraction (Von Röhle and Huber 1985). A crop factor is used to calculate the actual root water uptake from the potential transpiration.

Several of the system parameters that are used in the uptake and drainage functions were not, or cannot be, measured directly. They are either obtained from literature or need calibration. Details of the model, including the equations and underlying assumptions, are given in Tiktak *et al.* (1990).

Measurements and simulations

The physical soil properties required as inputs for the model were: (a) water retention characteristics—obtained using a sand/kaolinite box and pressure plates at higher tensions for the three depths: 0–30 cm, 31–60 cm and 61–100 cm, (b) hydraulic conductivity characteristics - calculated as described in van Genuchten (1980), and (c) distribution density of roots <2 mm, determined from a study of root numbers by depth (Jones 1990). The soil properties used in the model are shown in Figure 1.

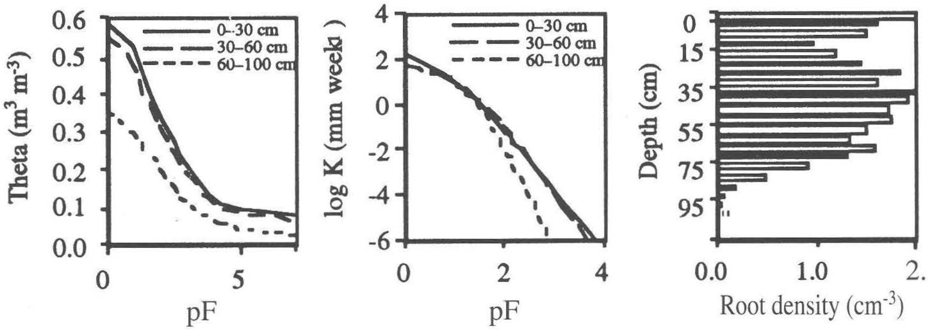

Figure 1. *Model inputs: (a) water content, theta, as a function of soil tension (after Hall 1990), (b) hydraulic conductivity as a function of soil moisture tension (after Hall 1990) and (c) average root distribution, 150 cm from the trees, as a function of depth (after Jones 1990).*

Global solar radiation, used in the calculation of Makkink evapotranspiration, was obtained using an Ångström-type relationship solved for Ireland as described by Connaughton (1967).

The model was validated by comparing simulated with measured soil water tensions. There was a close correlation (r = 0.731) between the two. This gave some reassurance that the model was accurate, especially as tensiometers are known to be sensitive to minor changes in water uptake and rainfall, which would not be predicted from the model. A plot (Figure 2) of measured (average of ten tensiometers, sampled weekly) and simulated soil water tensions for 1989–1994 at 25 cm depth shows the closeness of the correlation.

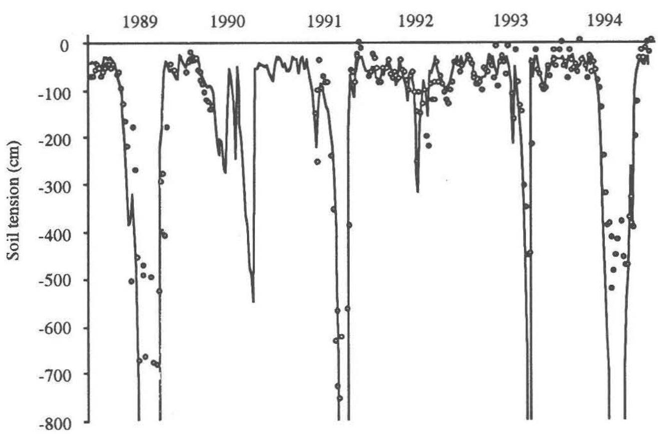

Figure 2. *Measured (•) and simulated (–) soil water tensions at 25 cm depth, 1989–1994.*

Results

The six-year mean annual water budget for the measured and modelled water fluxes are presented in Table 1. Precipitation at Ballyhooly (1141 mm yr^{-1}) was close to the mean for the whole of Ireland (Rohan 1975). The amount of evaporation from the tree surfaces, 497 mm yr^{-1}, is typical for coniferous plantations in this climate. Stemflow volumes were insignificant at Ballyhooly. Tree transpiration, via soil-water uptake, removed a further 291 mm yr^{-1}. The vertical soil-water flux, estimated by simulation, was 570 mm yr^{-1} between the organic and mineral soil horizon (humus water: 0 cm below mineral soil); 472 mm yr^{-1} at 25 cm depth (soil-water shallow); 331 mm yr^{-1} at 75 cm depth (soil-water deep); and 322 mm yr^{-1} at 100 cm depth.

Table 1. *Six-year annual mean water budget at Ballyhooly, 1989–1994.*

Water flux layer	*Volume mm*	*Calculation method*
Precipitation	1141	Measured
Throughfall	632	Measured
Stemflow	12	Measured
Interception	497	By difference
Humus water (0 cm depth)[1]	570	FORHYD
Soil water shallow (25 cm depth)[1]	472	FORHYD
Soil water deep (75 cm depth)[1]	331	FORHYD
Transpiration	291	FORHYD

[1] Depths correspond to solute concentration measurement depths, see Farrell *et al.* (1996) for details.

The water balance is shown graphically in Figure 3.

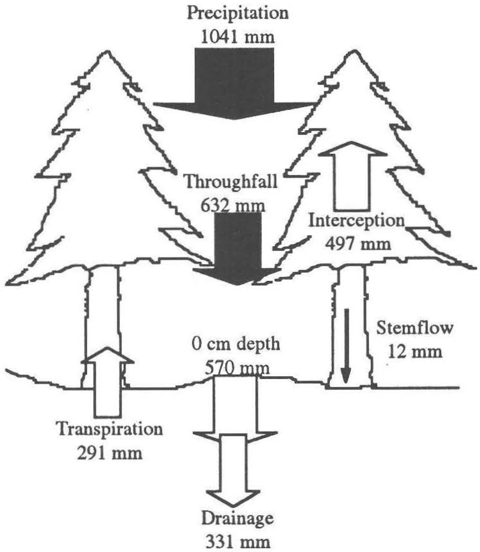

Figure 3. *Six-year mean annual measured (shaded arrows) and simulated (white arrows) water fluxes, at Ballyhooly 1989–1994.*

The water flux estimates, in combination with solute concentrations, can be used to compute solute fluxes {in cases where the solute concentrations over the time intervals (C_i) are assigned to the recharges (q_i) estimated for the same time periods}. Such a computation has been carried out on the Ballyhooly data which has allowed the forest biogeochemical cycles to be described (Farrell *et al.* 1996, 1997).

Limitations

There are a number of limitations to the accurate application of the hydrological balance to Ballyhooly. Open-funnel collectors are designed for chemical analysis of rain water and do not match standard rain gauge design. Long-term comparison suggests an underestimation of 10–15% by the smaller funnels used in this study. Therefore, the water flux entering the soil was probably underestimated. Large, dead root channels in the forest soil and other macropores may allow significant bypass flow, which was not assessed, nor was it taken into account by FORHYD. This may be especially important during heavy rainfall. A further limitation concerns lateral soil-water flow, which was evident occasionally at Ballyhooly. FORHYD does not take this into account in the unsaturated zone. Several of the model parameters and inputs were based on literature or preliminary measurements and may not adequately describe the soil properties. This may cause inaccurate distributions of simulated water through the simulated soil profile.

Conclusions

A thorough knowledge of the hydrological behaviour of ecosystems can greatly contribute to the understanding of biogeochemical processes. Using water fluxes together with measured ion concentrations, solute fluxes can be estimated for forested ecosystems. This allows biogeochemical cycling and turnover of elements to be quantified. Using measured water fluxes and simulated soil-water fluxes the hydrological budget for a Norway spruce stand at Ballyhooly has been described. Using these water fluxes in combination with measured solute concentrations, solute fluxes through the forest ecosystem have been described (Farrell *et al.*, 1996)

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Country-wide and regional wood volume regulation with a harvest scheduling decision-support system

Maarten Nieuwenhuis[1] and Caroline Nugent[2]

Abstract

As part of the development of a decision-support system for integrated harvest scheduling and wood allocation in Coillte (The Irish Forestry Board), a number of studies were carried out with the objective of evaluating the capabilities and flexibility of a prototype system, the Harvest Scheduling System (HSS), developed by Williamson (1991). Of a total of five studies carried out, two are reported in this paper. The first was used to analyse periodic, fluctuating volume constraints. The results indicated that the demand by management for regulated regional harvest volumes had a significant negative impact on overall profits. Hence, the need for regional volume regulation should be assessed. The second of the two studies indicated that it was possible to produce a periodic, increasing supply of wood in each region. However, this resulted in a large reduction in profits, irrespective of the level of annual increase imposed. The relevance of this type of regulation in relation to sustainability and to the expanding wood processing sector should therefore be carefully examined. The results of the two studies illustrated that the HSS can provide valuable decision-support to Coillte managers at national and regional levels.

Keywords: harvest scheduling, volume regulation, decision-support system, constrained optimisation.

Introduction

Coillte (The Irish Forestry Board) is the largest forest landowner in Ireland. By the end of 1995, the Board owned 390,000 ha of forest estate (Department of Agriculture, Food and Forestry 1996). The estate is scattered in nature and comprises 117 forests, 5,600 different properties and 125,000 sub-compartments or stands. It has an unbalanced age class distribution due to large planting programmes over the past 20 years (Carey 1997). The Coillte wood supply is forecasted to grow from 2.2 million m^3 in 1997 to 3.8 million m^3 by 2010. If target planting levels (Department of Agriculture, Food and Forestry 1996) are achieved national wood production (including Coillte and the private sector) is predicted to grow to about 10 million m^3 by 2030. This increased wood volume and the more wide-ranging requirements of the expanding processing sector of the Irish forest industry have made current planning procedures inadequate. Traditionally harvest scheduling has been conducted in isolation from wood allocation and optimisation techniques have not been used. The production of an efficient and cost effective harvest schedule that takes into account forest management constraints, processing sector requirements and the location of the demand and supply, has become an extremely difficult task.

To facilitate the management of these increased and more complex wood flows efficiently and effectively, new integrated management procedures such as a Harvest Scheduling System are required. Currently a Harvest Scheduling System (HSS), incorpo-

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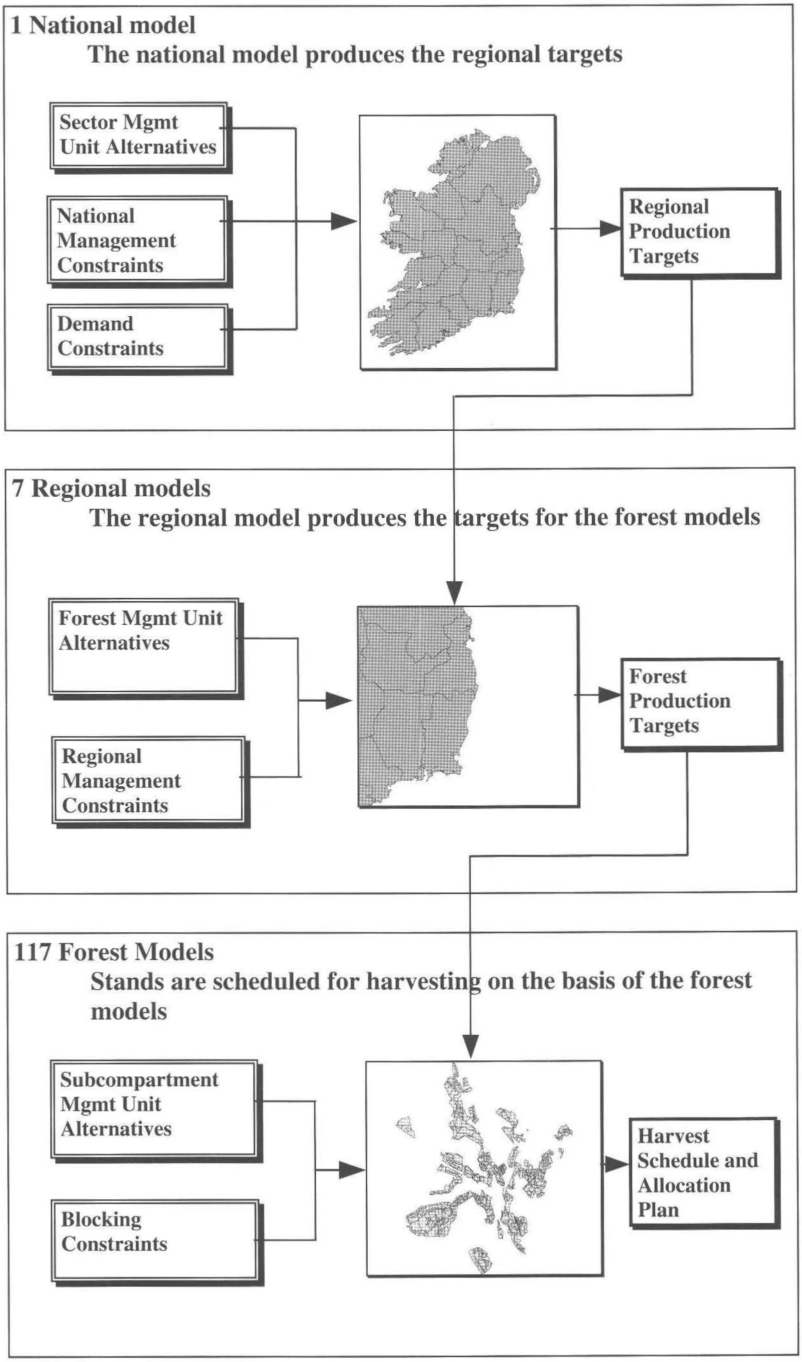

Figure 1. *Schematic diagram of the hierarchical model structure.*

rating wood allocation procedures, is being evaluated as a decision-support tool. To improve Coillte's current methods of determining wood production targets and their subsequent allocation, a number of problems were addressed in the developed HSS. First, the processing sector demand was included, to change the emphasis from a production- to a demand-driven approach. Second, the spatial distribution of market demand and wood supply, and the associated haulage cost was included in the production target determination process. Third, the economic consequences of selecting a particular production year for a particular stand were evaluated with respect to value increment and harvesting and transport costs. In addition, the HSS provided the manager with an optimal solution, whereas, in the past, the production of a stand harvest schedule was a 'trial and error' process.

The full operational procedures of the HSS can be divided into five modules. These are: management option production, growth simulation, data aggregation, optimisation and report generation modules. A three-level hierarchical model was used in the development of the present wood harvest scheduling system (Williamson 1991). It consisted of a national level model, seven regional level models and 117 forest level models (Figure 1). The national model determined optimal regional production targets, which satisfied both the requirements of the processing industry and national, regional and forest management constraints. The targets that were produced in the national model were used to run the seven regional models. (Coillte reduced the number of regions from seven to six at end of 1997. The HSS was developed prior this reorganisation. However, the model can easily be modified to incorporate this change.) Each region produced optimal production targets for each forest within that region. A forest level model was produced for each of the 117 forests. The targets that were produced in the regional models were used to produce a stand (sub-compartment) harvest schedule for each forest.

Examples of operational optimisation-based forest management decision-support systems

A large number of planning models have been developed internationally over the past twenty years to aid decision making in forest management. While many of these are of interest, only a few such as 'MELA', 'FOLPI', 'LOGPLAN' and 'REGRAM' have found widespread use. Each of the models uses linear programming (LP) techniques. LP models consist of a (linear) objective function, expressing the alternative courses of action, and a set of (linear) constraints, expressing limitations on resources and on acceptable scenarios. As a result of the increased computing power, LP models can be constructed and solved at almost any scale and level of precision. The most important restriction on size and complexity is the capability of the modeller to visualise the complex interactions embedded in the models (Nieuwenhuis 1989).

MELA is a forestry model and an operational decision support system that integrates stand management planning and forest wide production planning into a single hierarchical optimisation problem (Siitonen 1995). MELA was originally designed in the 1970s for regional and national analysis of wood production potentials in Finland (Siitonen *et al.* 1996). Large-scale applications of MELA include two rounds of national wood production analysis in Finland since the middle of the 1980s (Siitonen 1993).

FOLPI (Forestry Oriented Linear Programming Interpreter) is an LP based forest estate modelling system developed by Garcia (1984). FOLPI was designed to be compatible with the Interactive Forest Simulator (IFS), as it was considered that growth simulation and LP are complementary. The IFS (Garcia 1981) was widely used by the New Zealand Forest Service. FOLPI is an optimising, forest estate modelling system that allows a forest manager to evaluate alternative management strategies for the forest estate (Manley and Wakelin 1990). Applications of FOLPI include yield regulation, forest management and investment evaluation, forest valuation and log allocation (Manley and Threadgill 1990, 1991).

LOGPLAN is an LP model that was developed to aid in the construction and evaluation of one year logging plans (Newnham 1975). The objective of the model is to obtain a plan that will satisfy mill demand throughout the year at a minimum cost, while satisfying constraints on available wood and machine resources. Newnham (1991) also developed LOGPLAN II, which can be used to formulate annual operating plans for companies.

In New Zealand REGRAM I (Regional Resource Allocation Model) uses a combination of LP and simulation techniques. Tasman Forestry Ltd. have used REGRAM I since 1991 as the company's principal resource planning tool (McGuigan and Scott 1995). The system is capable of being run as a simulator, an optimiser or a combination of both. Tasman Forestry have used REGRAM I to optimise thinning and clearfelling in a number of forests in a given region, to determine the availability of resources from external suppliers, to allocate resources between processing plants and to define planting and regeneration strategies (McGuigan 1992).

Williamson (1991) developed the HSS prototype that is used in this study. The HSS has been formulated within the framework of LP and mixed integer programming (MIP) to optimise solutions. The national and regional level models are based on linear programming, while the forest level models use mixed integer programming. The HSS is linked to ARCINFO (Geographic Information System) which extends the analysis and interpretation capabilities of the HSS and combines the output with existing information systems. The system was initially developed to help optimise the allocation and transportation of Coillte's annual wood supply of 1.4 million m^3 in 1990. The actual wood allocation and haulage routes were compared with the optimal routes suggested by the study (Williamson and Nieuwenhuis 1991, Nieuwenhuis *et al.* 1991, Nieuwenhuis *et al.* 1992). The programme indicated that a 38% reduction in overall transport costs was possible (Williamson 1991). The HSS was further developed using inventory and forecast data for a time span ranging from 1994 to 1998 (Williamson and Nieuwenhuis 1994, Nieuwenhuis and Williamson 2000).

Evaluation of the HSS

The evaluation process of the HSS began in January 1997. Coillte supplied up-to-date inventory data and a forecast of wood production for the period 1998-2002. This forecast was used to compile the management constraint files. Constraints were used to control the level of production. These can be applied at national, regional or forest level. Within each level, constraints can be applied to volume, revenue and area. For the purpose of this study only volume constraints were used. Volume constraints can be applied to total volume, to products (pulp, pallet and sawlog), harvest type (first, second and subsequent thinning, clearfell) or species. The introduction of (additional) constraints or making existing constraints more restrictive will always result in an optimal solution with a value less than or equal to the original. The HSS optimises the Net Present Value (NPV) of harvest revenues, using a discount rate of 5%.

The following studies have been carried out with a view to evaluate the HSS (Nugent 1998):

1. A 'no constraints' study: the objective was to see what the maximum NPV and the associated NPV/m^3 was that could be attained where no management constraints were applied.
2. Models that conform to Coillte's harvest forecast: the objective was to see if the HSS could produce a forecast in line with Coillte's harvest forecast and to determine the associated decrease in NPV and NPV/m^3 as compared with the 'no constraints' study.
3. Periodic fluctuating volume constraints: the objective was to produce an even supply of volume from year to year within each region and to determine the associated decrease in NPV and NPV/m^3 as compared with the 'no constraints' study.
4. Periodic increasing volume production models: the objective was to create an increasing supply of volume from year to year, within each region and to determine the cost of imposing these constraints when compared with the 'no constraints' study.
5. Regional study: The objective was to produce a harvest schedule for Coillte's southern region.

Studies 1 and 2 have been reported in Nieuwenhuis and Nugent (2000). The main conclusion was that Coillte's production smoothing process resulted in harvesting schedules that were not feasible, as no adjustments for volume were included. In this paper, studies 3 and 4 are presented. For each study, a comparison with the output of study 1 is also included.

Methods

Periodic fluctuating volume constraints (study 3)

In this study the objective was to produce an even supply of volume over the planning period within each region and to determine the associated impact on net revenue as compared with the 'no constraints' study. Constraint files were added to the 'no constraints' study. Explicit constraints were compiled whereby the maximum fluctuation of the HSS volumes from Coillte's harvest forecast was set at ± 10%, ± 5%, ± 3%, ± 2% and ± 1% (as in study 2). These constraints were applied at national level only and ensured that a steady supply of wood was achieved while meeting Coillte's targets. Implicit constraints were used to limit the maximum volume fluctuation from year to year within each region to ± 10%, ± 5%, ± 3%, ± 2% and ± 1%. For example, the volume produced in 2000 could fluctuate by ± 10%, ± 5%, ± 3%, ± 2% and ± 1% on the volume produced in 1999. These constraints were applied at a regional level and ensured managed regional total supply patterns. For each constraint file a national model, seven regional models and some forest models were solved and analysed.

Periodic increasing volume production models (study 4)
Constraint files were compiled and added to the 'no constraint' model. Explicit constraints were compiled, whereby the maximum fluctuation of the HSS volumes, compared to Coillte's harvest forecast, was set at ± 5% and ± 1% (as in study 2). These constraints were applied at national level only, i.e. total volume constraints. Implicit constraints were used to specify that the harvest volumes in each region should increase by a minimum of 1% or 5% in each year of the planning period, depending on the constraint file used. These constraints were applied at a regional level only.

Results

Periodic fluctuating volume constraints (study 3)

The ± 10% fluctuation model

The periodic volumes harvested within each region were set to vary by a maximum of ± 10%. In addition, the fluctuation of the HSS national-harvest volumes from Coillte's forecast was set at ± 10%. A relatively even volume production was achieved within each region in this case (Table 1). The NPV obtained from this national model was IR£303.1 million. The cost of applying these constraints represented a decrease of 10.1% by comparison with the NPV obtained in the 'no constraints' study (see Table 6 for a summary of the results). The volume harvested decreased from 15.5 million m^3 to 15.2 million m^3 and the NPV/m^3 was reduced from £21.72 to £19.98, a decrease of 8.0%.

Table 1. *Regional production volumes which are within the annual volume fluctuation of ± 10%.*

				Region				
Year	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*Total*
				m^3				
1998	418,005	455,395	532,699	349,802	376,204	498,297	369,604	3,000,006
1999	459,802	409,865	479,429	384,775	413,820	457,303	395,006	3,000,000
2000	505,783	378,908	431,487	423,257	416,669	411,567	432,324	2,999,995
2001	556,357	416,804	388,341	465,585	375,000	370,418	471,908	3,044,413
2002	611,994	458,477	349,503	512,141	357,722	333,371	503,988	3,127,196
Total	2,551,941	2,119,449	2,181,459	2,135,560	1,939,415	2,070,956	2,172,830	15,171,610

The periodic percentage changes in volume production that occurred varied within each region (Table 2). Regions 1, 3 and 4 were limited at each interval by the ± 10% constraints used in this model. For example, the periodic volume produced for region 1

Table 2. *Periodic change in volume within each region for the ± 10% fluctuation model.*

				Region			
Period	*1*	*2*	*3*	*4*	*5*	*6*	*7*
				%			
1998-1999	10.0	-10.0	-10.0	10.0	10.0	-8.2	6.9
1999-2000	10.0	-7.6	-10.0	10.0	0.7	-10.0	9.4
2000-2001	10.0	10.0	-10.0	10.0	-10.0	-10.0	9.2
2001-2002	10.0	10.0	-10.0	10.0	-4.6	-10.0	6.8

increased by 10% each year which was the maximum volume increase allowed for by the model.

The ± 5% fluctuation model

In this scenario, the difference between the HSS and Coillte's national harvest volumes, and the periodic volumes harvested within each region were set to vary by a maximum of ± 5%. This resulted in a more even supply of wood for each region (Table 3). A comparison of the preceding model and the ± 5% fluctuation model showed that the NPV and the NPV/m^3 were reduced (Table 6). The total volume harvested decreased from 15.2 million m^3 to 15.0 million m^3 when compared with the previous model.

Table 3. *Regional production volumes which are within the annual volume fluctuation of ± 5%.*

				Region				
Year	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*Total*
				m^3				
1998	399,004	434,696	536,549	333,899	359,102	475,648	352,805	2,891,703
1999	418,949	456,437	527,089	350,590	377,055	499,433	370,436	2,999,989
2000	439,904	433,612	500,741	368,127	395,907	474,455	388,962	3,001,708
2001	461,889	419,393	475,700	386,531	415,704	450,739	408,412	3,018,368
2002	484,987	440,361	451,916	405,859	436,492	456,009	428,831	3,104,455
Total	2,204,733	2,184,499	2,491,995	1,845,006	1,984,260	2,356,284	1,949,446	15,016,223

It was evident that the regional fluctuations within each period were reduced. This resulted in a more uniform wood harvest forecast. For example, the difference in the volume to be produced in region 1 between 1998 and 1999 was forecast at 19,945 m^3 or 5% of the 1998 volume (as compared with 10% volume fluctuation in the previous model). The periodic percentage change in volume production that occurred within each region was quite uniform except for regions 2, 3 and 6 (Table 4). Regions 1, 4, 5 and 7 were limited at each interval by the ± 5% constraints.

Table 4. *Periodic change in volume within each region for the ± 5% fluctuation model.*

				Region			
Period	*1*	*2*	*3*	*4*	*5*	*6*	*7*
				%			
1998-1999	5.0	5.0	-1.8	5.0	5.0	5.0	5.0
1999-2000	5.0	-5.0	-5.0	5.0	5.0	-5.0	5.0
2000-2001	5.0	-3.3	-5.0	5.0	5.0	-5.0	5.0
2001-2002	5.0	5.0	-5.0	5.0	5.0	1.2	5.0

The ± 3% fluctuation model

Subsequently the ± 3% fluctuation model was solved and analysed. As in the case of the ± 5% model, the results showed a further reduction in the NPV and the NPV/m^3 (Table 6). The total forecast volume available for harvest was reduced from 15.0 million m^3 in the ± 5% model to 14.8 million m³, as a result of the more restrictive fluctuation constraints in this model. It is evident that the regional volume fluctuations within each period have been reduced, and a smoother forecasted wood harvest over time resulted. The resulting periodic percentage changes in the volume production forecast (Table 5) for regions 1, 4, 5 and 7 were limited at each interval by the ± 3% constraints.

Table 5. *Periodic change in volume within each region for the ± 3% fluctuation model.*

Period	*1*	*2*	*3*	*Region* *4* %	*5*	*6*	*7*
1998-1999	3.0	3.0	3.0	3.0	3.0	3.0	3.0
1999-2000	3.0	3.0	1.3	3.0	3.0	3.0	3.0
2000-2001	3.0	0.8	-3.0	3.0	3.0	-0.6	3.0
2001-2002	3.0	3.0	-1.5	3.0	3.0	3.0	3.0

The ± 2% and ± 1% fluctuation model

As in study 2, the system was unable to produce a valid solution when the level of constraints (i.e. regional, periodic and national HSS/Coillte fluctuations) was set at ± 2% and ± 1%. The reason was that the constraints, especially Coillte's production targets constraints, were too restrictive and the HSS could not find a feasible solution. This is an indication that Coillte's current production smoothing process may result in unrealistic and infeasible harvest volume estimates (Nugent 1998).

Summary of the results of study 3

A summary of the results obtained in this study highlights the percentage decrease in the total NPV and the NPV/m³ by comparison with the 'no constraints' study (Table 6). For example, a total NPV of £303.1 million was obtained from the ± 10% fluctuation model. The cost of applying these constraints represents a decrease of 10.1% from the NPV obtained in the 'no constraints' study. The volume harvested decreased from 15.5 million m³ to 15.2 million m³ and the NPV/m³ was reduced to £19.98. This reduction represents a decrease of 8.0% in the NPV/m³ from the 'no constraints' study.

Table 6. *Summary of the results from study 3 ('periodic fluctuating volume constraints').*

Model	*NPV* Million £	*Decrease in NPV from the 'no constraints' study* %	*Total volume* Million m³	*NPV* £/m³	*Decrease in NPV/m³ from the 'no constraints' study* %
The 'no constraints' study	337.0	-	15.5	21.72	-
The ± 10% fluctuation model	303.1	10.1	15.2	19.98	8.0
The ± 5% fluctuation model	294.0	12.7	15.0	19.58	9.8
The ± 3% fluctuation model	289.1	14.2	14.9	19.43	10.5
The ± 2% fluctuation model	–	–	–	–	–
The ± 1% fluctuation model	–	–	–	–	–

Periodic increasing volume production models (study 4)

In the second study, two scenarios were analysed which included volume constraints to ensure a non-declining wood supply, with annual regional volume production increases of at least 1% or 5%, depending on the constraint files used. As outlined previously, national (total) volume constraints were included, whereby the maximum fluctuations of the HSS volumes from Coillte's harvest forecast volumes were set at ± 1% and ± 5% of the forecast volumes.

The + 1% production model

As stated, the periodic volume harvested was set to increase by a minimum of 1% each year within each region. The output from this non-declining wood supply resulted in an NPV of £286.7 million (Table 7). Thus a cost penalty was incurred which represented a decrease of 14.9% from the NPV obtained in the 'no constraints' study (see Table 8 for a summary of the results). The results also showed that the volume harvested decreased from 15.5 million m^3 to 14.8 million m^3 and the NPV/m^3 reduced to £19.33. This change represents a decrease of 11.0 % in the NPV/m^3 from the 'no constraints' study.

Further analysis of the regional production values showed that each region, with the exception of region 4, produced volume increases of exactly 1% at each given interval. In the case of region 4, an increase of 50.9% in the volume harvested between 1998 and 1999 was forecast. Similarly, an increase of 12.2% was forecast between 2001 and 2002.

Table 7. *Regional production volumes with a minimum increase of 1% each year.*

				Region				
Year	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*Total*
				m^3				
1998	383,802	418,137	505,890	321,178	345,423	454,709	339,363	2,768,502
1999	387,640	422,320	510,950	484,638	348,875	459,257	342,749	2,956,429
2000	391,517	426,541	516,064	489,492	352,363	463,847	346,180	2,986,004
2001	395,430	430,814	521,222	494,387	355,887	468,496	349,648	3,015,884
2002	399,386	435,118	526,435	554,875	359,447	473,170	353,138	3,101,569
Total	1,957,775	2,132,930	2,580,561	2,344,570	1,761,995	2,319,479	1,731,078	14,828,388

The + 5% production model

A further scenario in this case study was examined whereby the regional volumes harvested in each period over the time span 1998-2002 were set to increase by a minimum of 5%. Similar results to those obtained in the previous scenario were achieved. The total NPV obtained was further reduced, as was the NPV/m^3 (Table 8). This was a direct result of applying more restrictive constraints. The volume harvested also decreased from 14.8 million m^3 to 14.7 million m^3 by comparison with the + 1% model. Furthermore, it became evident that each region produced exactly the minimum volume increases (5%) that were set out in the regional volume constraints.

Summary of the results of study 4

A summary of the results obtained in this study (Table 8) showed that an NPV of £286.7 million was obtained from the + 1% production model and that the cost of applying these constraints represented a decrease of 14.9% from the NPV obtained in the 'no constraints' study. The volume harvested also decreased from 15.5 million m^3 to 14.8 million m^3 and the NPV/m^3 was reduced to £19.33. This represents a decrease of 11.0% in the NPV/m^3 obtained in the 'no constraints' study. In the + 5% production model the NPV and the NPV/m^3 were further reduced to £283.3 million and £19.26 respectively, however the additional reductions were small in comparison to the ones associated with the +1% production model.

Table 8. *Summary of the results from study 4 ('periodic increasing volume production').*

Model	*NPV*	*Decrease in NPV from the 'no constraints' study*	*Total volume*	*NPV*	*Decrease in NPV/m³ from the 'no constraints' study*
	Million £	*%*	*Million m³*	*£/m³*	*%*
The 'no constraints' study	337.0	–	15.5	21.72	-
The + 1% production model	286.7	14.9	14.8	19.33	11.0
The + 5% production model	283.3	15.9	14.7	19.26	11.3

Even though species constraints were not included in these + 1% and + 5% increasing volume production models, a comparison of the volumes of Sitka spruce produced with those in the 'no constraints' study showed that a smoothed species wood supply was achieved as an indirect result of the total volume regulation constraints (Figure 2). For example, the difference between the 1999 and 2000 volumes in the 'no constraints' study was –406,000 m^3. This was reduced to –60,000m^3 in the + 1% production model and to +8,000 m^3 in the + 5% model.

Discussion

Periodic fluctuating volume constraints (study 3)

The purpose of this study was to evaluate the capability of the HSS to produce a harvest schedule consisting of regulated volume supplies for each period within each region and to determine the associated decrease in net present revenue as compared with the 'no constraints' study. A summary of the results obtained in the study is presented in Table 6. A similar pattern of 'exponential' decrease in NPV was achieved in this study (Figure 3) as reported previously for study 2 (Nieuwenhuis and Nugent 2000). The reason was, that as constraints became more restrictive, the number of management options to choose from rapidly decreased and more and more financially unattractive options had to be included in the solution in order to continue to satisfy the model specifications.

This study resulted in a number of conclusions. First, regional targets that reduce annual fluctuations in the level of production but are still compliant with the company forecast can be produced by the HSS. The results show that the demand of management for regulated periodic regional production volumes has a significant negative impact on overall profits. Hence, careful evaluation of regional volume regulation requirements is essential.

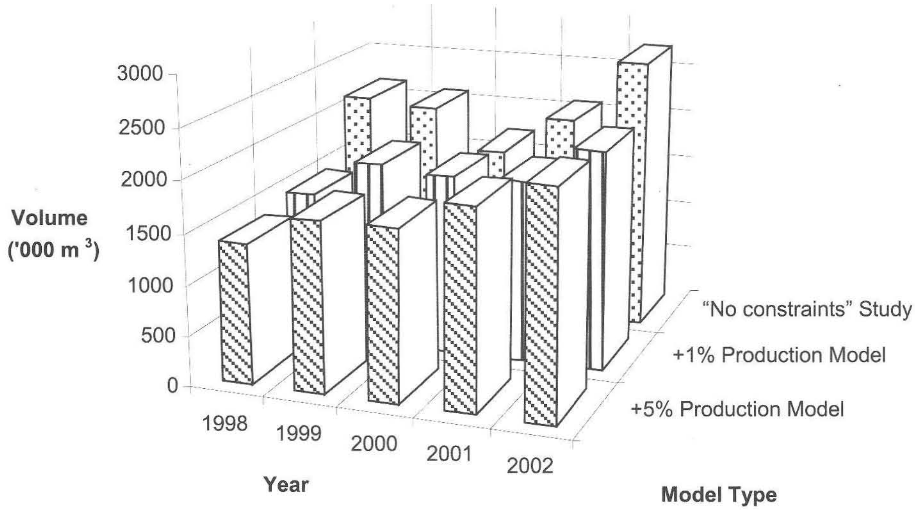

Figure 2. *Comparison of the production volumes for Sitka spruce by period for different models.*

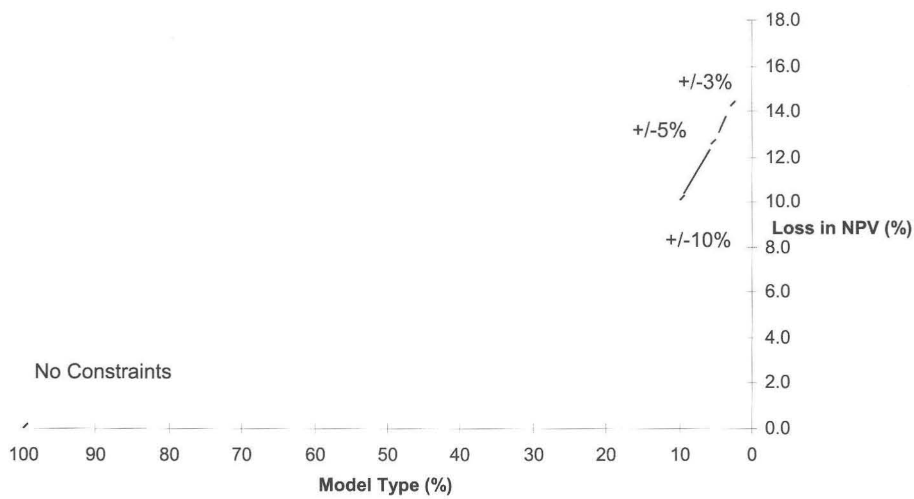

Figure 3. *Percentage reduction in NPV where production fluctuation constraints have been applied.*

Finally, the costs of various levels of smoothing were determined. For example, a comparison between the 'no constraints' study and the ± 3% fluctuation model shows a loss of £47.92 million in NPV over the five year period (Table 6).

Periodic increasing volume production models (study 4)

The aim of this case study was to examine the suitability of the HSS to produce a harvest schedule consisting of an increasing supply of wood year on year for each region and to ascertain the impact on NPV of implementing such a harvest schedule. An increasing supply of wood is desirable so as to cope with anticipated growth in demand from the processing sector. This aim was achieved using two constraint sets: the volume produced within each region was set to increase by a minimum of 1% or 5% per year (Table 8). However, a considerable cost penalty was incurred in this study (Figure 4).

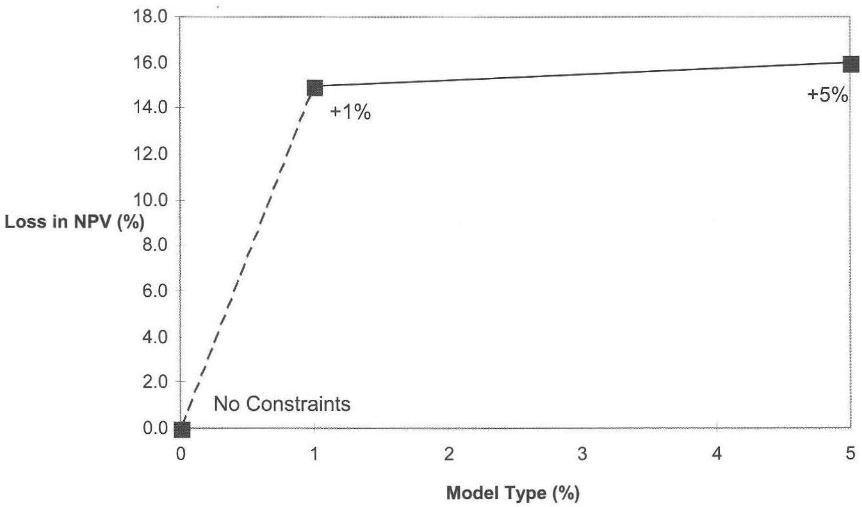

Figure 4. *Percentage decrease in NPV where periodic increasing volume constraints were applied.*

Analysis showed that it was possible to produce a periodic increasing supply of wood from each region. However, while the periodic increase in regional harvest volumes may be feasible (due to the general age-class structure of Irish forests), it is clearly inadvisable for economic reasons to implement it rigidly. Results presented in this study indicate that the cost, in terms of reduced NPV, is high, irrespective of the level of annual increase imposed. The reason for imposing this type of constraint on the production levels has to be carefully evaluated in order to be able to weigh the costs and benefits to Coillte. The relevance in relation to the requirements of the processing industry should also be examined.

It is interesting to note that each region produced volume increases of exactly + 1% or + 5% for both scenarios (the models with annual volume production increases of at least 1% and 5%) with the exception of region 4 in the + 1% production model. In this case an increase of 50.9% (Table 8) in the volume harvested between 1998-1999 was produced. Similarly, an increase of 12.2 % was achieved between 2001-2002. A possible explanation is that the forest age class structure in region 4 is the most flexible in relation to harvest scheduling, and is used to 'allow' the other regions to achieve the required periodic volume increases.

Sustainability

The current model is designed for short-term operational planning. However, the basic model structure is also very suitable for more long-term strategic planning, for analysis of long-term supply commitments and for investigations of sustainable wood harvest management practices.

Presently, the model does not use ending constraints that would ensure that the level of harvesting would not exceed the increment of the Coillte forest estate. This control is currently achieved by the definition of allowable management options and by specifying constraints that either control the level of production for the entire planning period or for each year within the planning period. The result of introducing ending constraints would be a model that could be used to determine the appropriate level of production compatible with long-term sustained yield. However, this would require significant model modification and was outside the scope of the investigations reported here.

Another method of investigating the sustainability of the wood harvest would be to use the five-year model in a stepwise fashion. This would necessitate running the model from 1999 to 2003, then from 2000 to 2004 and so on, and to use the results from each run as production constraints in the following run. The forecast in its present form allows for a maximum planning horizon of 20 years. To allow for long-term planning, the forecast would require a certain amount of development work (i.e. felled stands would have to be reintroduced as young regenerated stands).

Conclusions

The HSS prototype is a complex decision-support tool. As a result a degree of specialisation is required to operate the system. It is not designed to replace forest management decision making but should be used as a planning tool to assist in the efficient scheduling of Coillte's harvest programme. The main benefits are the integration of spatial and temporal harvest scheduling, the production of optimal feasible harvest schedules, and the efficiency with which these are produced. This study has illustrated that the HSS can provide decision-support for Coillte managers at nation-wide and regional levels.

The HSS was successfully used to design forest management strategies that satisfied a range of detailed management and processing industry demand requirements. The resulting detailed national and regional harvest schedules, combined with the associated NPV and NPV/m^3 values, provides forest managers with the type of information necessary to make decisions that balance conflicting demands on the forest estate. As a result, the use of the HSS has the potential to generate significant savings in terms of time and money. The precise quantification of the monetary savings obtainable through the implementation of the HSS with Coillte's harvest scheduling procedures is difficult, but indicators from the analyses carried out in this study are that potential savings of several million pounds over a five year period can be expected. In a study carried out by Williamson (1991), Coillte's wood production scheduling, allocation and haulage routes were compared with the optimal solution as suggested by the HSS, and a possible saving of up to £1.0 million per year was indicated. The savings in terms of time are impossible to estimate, as these are dependent on the level of integration of the HSS with current planning procedures.

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A preliminary investigation of the operational use of a laser dendrometer for tree height measurement

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Abstract
The accuracy of tree height measurements using a laser dendrometer and a Suunto clinometer were compared for a small sample of eight Sitka spruce (*Picea sitchensis* (Bong.) Carr.) trees between 20 and 25 m in height. Measurements were taken at 15 and 30 m from the tree, and these were compared to the actual tree height measured after felling. Both the laser dendrometer and the Suunto produced estimates significantly lower than the actual height for measurements taken at 15 m from the tree, but at 30 m distance the actual and estimated heights (using both instruments) were not significantly different. Given the comparably high accuracy of the laser dendrometer and the traditional instrument, the gain in productivity from using the former which results from their being able to be used at any distance from the tree (without the need for a tape or range finder), as long as the tip and foot of the tree are in view, is a strong argument for recommending their use. However, further testing over a wider range of tree heights and species should be carried out.

Keywords: laser dendrometer, Suunto clinometer, tree height measurements

Introduction
Carrying out standing volume assessment and forest inventory can be time-consuming and expensive. As part of a research project on the development of a pre-harvest, wood procurement inventory procedure for a sawmill, the methodology and equipment used in tree height measurements were investigated. An aspect of the investigation was the comparison between a traditional tree height measurement instrument and one of the new laser based tools that have come on the market in recent years. This paper reports on a preliminary comparison of the two.

Testing of tree height measurement instruments
The accuracy of a full pre-harvest measurement system is dependent on the accuracy of each component within it (McHugh 1999). One of the basic components of a pre-harvest inventory procedure which was developed in he course of a larger research project (Malone 1998) is a stand-specific dbh/height model. This requires the height measurement of a number of standing trees in each stand by the sawmill wood procurement manager. In order to minimise the amount of time spent on inventory work, the actual number of heights to be measured was reduced to the minimum required to produce a sufficiently accurate dbh/height model (Nieuwenhuis and Malone 1999). Therefore, it is of utmost importance that the height measurements of the small number of sample trees produce

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accurate estimates. With this in mind, a test of height measuring instruments was carried out. Controlled tests of a wider range of similar equipment were carried out by Skovsgaard *et al.* (1998) and Williams *et al.* (1999).

Materials and methods

The height measurement instruments tested were the Suunto clinometer and the Impulse 200 (Laser Technology™) instrument. The latter is a new height measurement instrument that allows the user to measure tree heights at any distance from the tree (without the need for a tape) as long as the top and bottom of the tree are visible. Ten trees were chosen randomly for the test at a Sitka spruce clearfell site near Newcastle West, Co Limerick. Each tree was measured by two observers, each using both instruments at 15 and 30 m from the trees. Each height measurement was based on the mean of two readings. The trees were subsequently felled and the stem length was measured. The stump height was added to the stem length to determine the full total stem length. Two of the ten trees were subsequently omitted from the analysis as they had suffered stem breakage during the felling process.

The first step in the analysis was a comparison of the measurements obtained by the two people. No statistically significant difference was found between the two measurements so the data were pooled and the analysis was carried out on the mean of the two observations on each tree. In order to determine the accuracy of each height instrument/distance from the tree combination, a pair-wise comparison between actual height and estimated height was carried out using the 95% confidence interval. The objective was to compare the instruments and to determine the optimal distance from the tree at which to use them.

Results

The actual heights of the eight trees (measured after felling) and the values of the estimates based on the means of the two observations ranged from 20 to 28 m (Table 1). In most cases the estimates were consistently lower than the actual heights, especially for the measurements taken at 15 m.

Table 1. *Actual tree height and as estimated by the two instruments.*

Actual Height	*Impulse @15 m*	*Suunto @15 m m*	*Impulse @30 m*	*Suunto @30 m*
23.90	22.80	23.25	23.52	23.70
20.07	20.21	20.15	20.45	20.10
25.40	23.63	23.55	24.80	24.90
25.70	25.36	24.75	25.42	25.80
24.10	24.02	23.85	24.23	24.40
25.30	24.90	24.60	25.40	25.80
23.02	21.71	21.67	22.10	21.90
24.91	24.08	27.60	24.73	24.30

The results of the pair-wise comparison of the height measurement instrument /distance from the tree combinations (Table 2) showed that there was little difference in accuracy between the two height measuring instruments. However the results did show that at the greater of the two distances (30 m) from the tree, the accuracy of height estimation was higher than at the shorter distance. For trees between 20 and 25 m in height, it was clearly necessary to move more than 15 m away from the tree to get an accurate height measurement.

Table 2. *Comparison of actual tree height and estimated tree height for different combinations of instrument and distance from tree.*

Instrument & Distance		*Bias* *m*	*SEE*[1]	*Difference from actual height (@ 95%)*
Impulse	15 m	-0.7075	.230549	Significant
Suunto	15 m	-0.8100	.244703	Significant
Impulse	30 m	-0.2150	.147793	Not significant
Suunto	30 m	-0.1775	.180573	Not significant

[1] SEE: standard error of estimate

An estimation of the residuals of each combination of distance and instrument (Figure 1, a & b) showed that both instruments under-estimated tree height almost every time when height was measured from a distance of 15 m from the tree. For measurements taken by both instruments at a distance of 30 m, the residuals were much closer to the actual

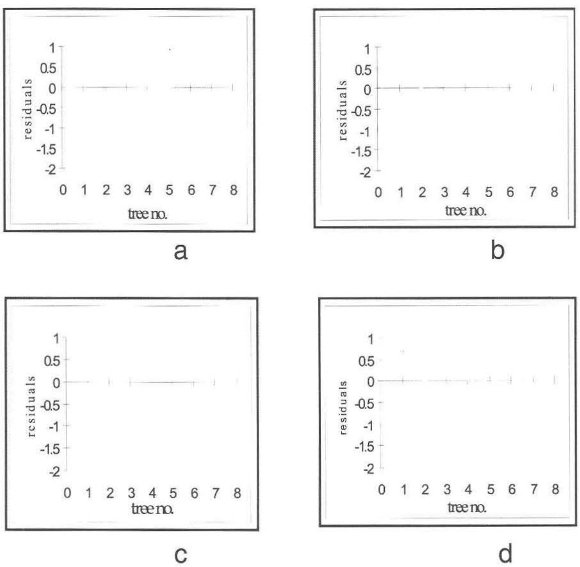

Figure 1. *Residuals (the difference between actual tree heights and height estimates) using (a) Impulse and (b) Suunto @ a distance of 15 m from the tree and (c) Impulse and (d) Suunto @ a distance of 30 m.*

measurements (Figure 1, c &d). These figures confirmed that the measurements from both instruments resulted in an under-estimation of height.

Discussion and conclusions

Laser dendrometers first became commercially available in 1991. Two manufacturers, Laser Technology Inc. (USA) and Jenoptik (Germany), dominate the market at the present (Skovsgaard *et al.* 1998). Although these instruments are expensive, they offer considerable potential to improve the efficiency of forest surveys (Hellström 1997).

Although only eight trees were included in this preliminary study, the results indicated clear, statistically significant differences. For this reason it was felt that, notwithstanding the small sample size, important conclusions could be drawn from the analysis and that reporting these to a wider audience was worthwhile.

The results showed that both instruments, under the right conditions, produced very accurate estimates of tree height. When the height estimates from the two instruments were compared with the actual heights, the height estimates taken with the Impulse 200 produced a slightly lower standard error than those taken with the Suunto. The distance from the tree significantly influenced the accuracy of the height estimates produced by both instruments. Significant differences were found between the actual and estimated heights taken at a distance of 15 m using either instrument. No such differences were found when heights were measured at a distance of 30 m from the trees. This is not surprising, for a number of reasons. First, as at the shorter distance it will be more difficult to see the actual tip of the tree. Second, small errors in pointing the instruments to the top and foot of the tree will result in larger differences in height estimates at closer distances as a result of the geometry involved. Third, the instruments were hand-held and not positioned on a support, resulting in a pivot axis that did not coincide with the axis of the instruments. This 'incorrect' operational use resulted in greater inaccuracies in the measurements at the 15 m distance because of the greater pivot angles involved.

It should be noted that measurements obtained with both instruments were for the vertical distance from the tip of the trees to the ground. The measurements obtained after felling the tree were for the distance along the bole. In the case of leaning trees, these two measurements are not expected to be equal and should not be compared to evaluate the accuracy of the instruments used. The standing trees selected for this study were however considered vertical for all intent and purposes.

In a controlled test carried out by Skovsgaard *et al.* (1998), two laser dendrometers and the Suunto were tested. Both laser dendrometers were found to give very precise readings but they did show some bias. The authors made the point however that this bias was statistically significant only because of the precision of the instruments, whereas a similar bias produced by traditional hypsometers might not be significant in a statistical sense because of the lower precision and so would remain undetected. In a study by Williams *et al.* (1999), of two dendrometers capable of measuring upper stem diameters and tree heights, it was found that increasing the distance from the tree at which the measurements were taken had a negative impact on the accuracy of the diameter measurement but no influence on the accuracy of the height measurements.

The main advantage of the laser instruments is the possibility to take the height measurement from any point where both the base and tip of the tree are visible, without the need to walk to the stem to establish the distance. Given the similar high accuracy compared to the traditional instruments, this gain in productivity, in itself, is a strong argument for recommending the use of these new instruments. However, in this project only one laser dendrometer could be tested on a small number of trees with a limited range of heights between 20m and 25m. It would be interesting and useful to test this and other laser instruments (including those with the added capability to measure upper tree diameters) on a larger sample of trees with a wider range of heights.

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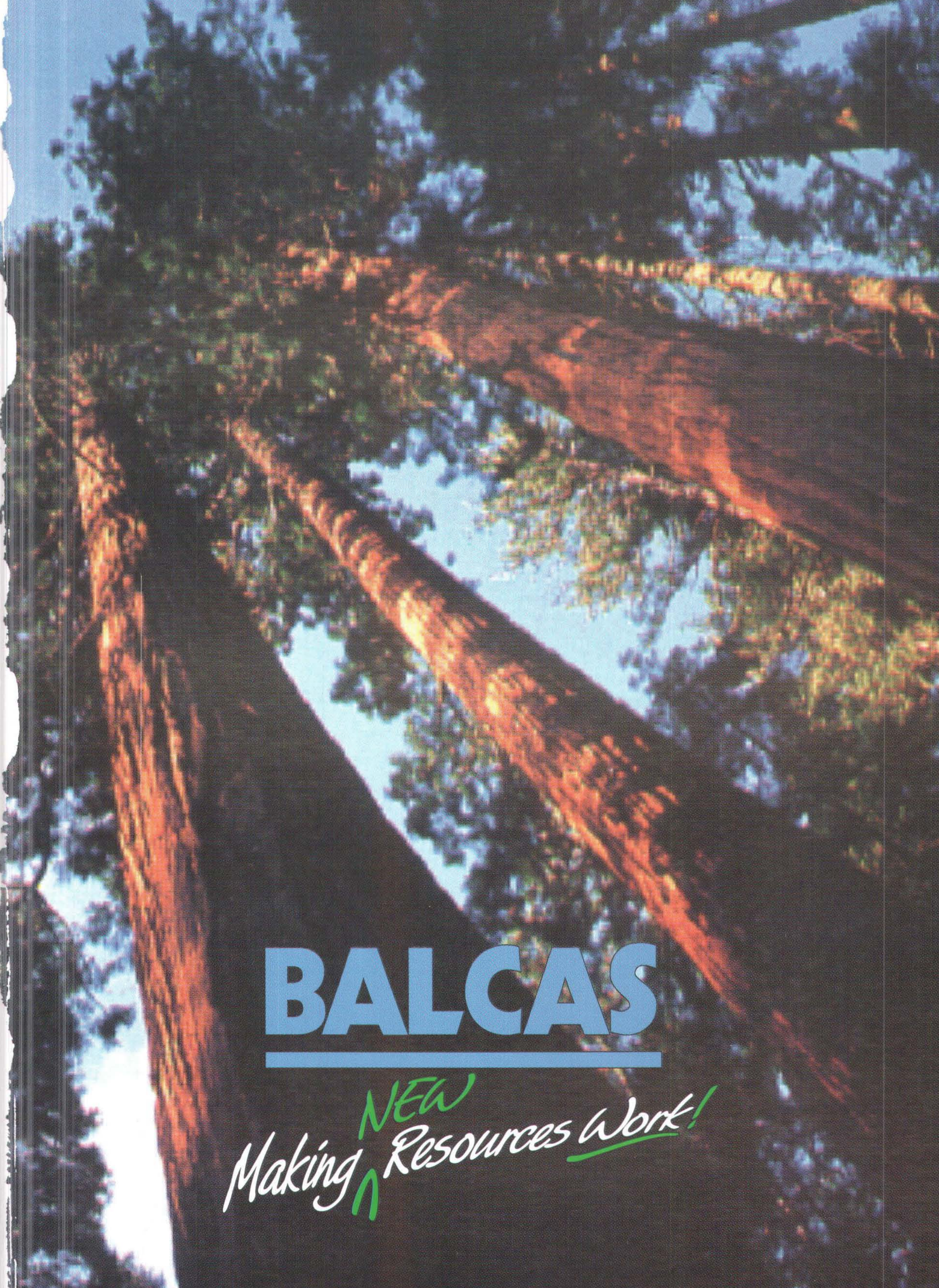
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