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Seedling height and the impact of harvesting operations on advance regeneration of conifer species in upland Britain

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Summary

Extensive damage to and mortality of understorey seedlings during overstorey thinning could prevent the use of natural regeneration as a method of restocking. Experiments carried out on three upland conifer sites in Britain assessed the short-term impact of thinning operations on survival and damage to advance regeneration seedlings of different heights. At two sites dominated by Sitka spruce, the number of small-sized (<50 cm) and medium-sized (50–200 cm) seedlings lost during harvesting was significantly higher than the number of large seedlings (>200 cm) which tended to be damaged rather than lost. At the Scots pine/Japanese larch site, damage and loss were not related to seedling size. Survival or damage was significantly related to the distance from the nearest extraction rack (striproad). At two of the sites, survival or damage was related to distance to the nearest felled tree stumps. The seedlings in 25–30 per cent of the area were lost due to clearing the extraction racks prior to harvesting. In the stand matrix, 40–80 per cent of the regeneration survived and was not severely damaged; the remaining regeneration was likely to be sufficient to restock at all three sites, although distributions were clumped. There were no marked differences between motor-manual and harvester felling.

Introduction

In some British upland (>250 m above sea level), conifer plantations that have been thinned or felled, extensive natural regeneration has been observed with seedling densities as high as 300 000 ha^{-1} (Clarke, 1992; von Ow *et al.*, 1996; Mason, 2008). Until recently, it was thought that many foresters would not welcome natural regeneration as it can be very uneven and increase the cost of silvicultural operations (Nelson, 1991). However, the use of alternative silvicultural systems to clearfelling is being increasingly adopted in Britain (Mason *et al.*, 1999) with a move away from the predominant silvicultural practices in which even-aged stands of a few species are managed using the clearfelling system. Under this alternative management approach, natural regeneration represents an opportunity to both increase the species and structural diversity of the forest (O' Hara, 1998) and minimize restocking costs (Pommerening and Murphy, 2004).

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Although factors influencing the regeneration and survival of coniferous seedlings in Britain have been studied (e.g. McNeill and Thomson, 1982; Mason and Quine, 1995; Malcolm *et al.*, 2001), little work has been done on the effects of felling and extraction of the overstorey on survival of advance regeneration (seedlings and saplings already present on the site). Managers implementing alternative silvicultural systems such as Continuous Cover Forestry (CCF) have expressed concern that damage to regeneration may hinder their attempts at transformation, i.e. the process of increasing within-stand structural diversity in even-aged forests (Mason and Kerr, 2004).

Vorob *et al.* (1994) found that overstorey thinning using harvesters killed 52–56 per cent of coniferous advance regeneration. These concerns are also partially supported by work in other countries using other felling and extraction methods, such as manual or motor-manual felling (Andersson and Fries, 1979), the Kostroma method (in which trees are felled in a fan pattern onto a lying tree before being de-limbed and skidded root-end first as described by Jeansson and Laestadius, 1981) and narrow-strip methods (trees are felled with their crowns towards the extraction rack, or striproad, before being skidded top-end first as described by Jeansson and Laestadius, 1981). Glöde and Sikström (2001) reported on a method of felling known as 'tossing the caber' in which trees are felled top-end first into an extraction rack with the lower end then lifted over the regeneration. Tesch *et al.* (1986) and Youngblood (1990) reported the effects of skyline logging and of ground skidding and cable yarding, respectively, on regeneration. However, with all of these, overstorey thinning and particularly final overstorey removal has been found to kill or damage a large proportion of coniferous advance regeneration, e.g. 48–54 per cent (Westerberg and Berg, 1994), 38–65 per cent (Sikström and Glöde, 2000) and 17–76 per cent (Granhus and Fjeld, 2001). Work in the US has shown that overstorey thinning caused up to 83 per cent mortality in under-planted red oak (*Quercus rubra* L.) seedlings but that the thinning intensity had no significant effect on mortality (Olson *et al.*, 2003). Coniferous seedlings planted under Douglas-fir (*Pseudotsuga menziesii* (Mirbel) Franco) before thinning of the overstorey to different densities also showed severe harvesting damage (Newton and Cole, 2006). Overall 40 per cent of the seedlings were damaged with up to 30 per cent being removed or buried under debris. A further 16 per cent had significant damage, such as broken or dead tops or severe lean, and 2 years after the thinning, these damaged seedlings had grown 10 cm less than undamaged seedlings (Newton and Cole, 2006). Conversely, Douglas-fir seedlings and saplings were found to recover from most types of harvesting damage within 6 years (Tesch *et al.*, 1993) although taller trees at the time of thinning showed the poorest recovery.

It may be possible to minimize harvesting damage to regeneration by carrying out operations when seedlings are at their most resilient size. However, reviewing the published literature relating harvesting damage to seedling and sapling height does not reveal a clear relationship between the two. Table 1 summarizes the results of nine papers reporting on different conifer species and harvesting methods from which we have drawn tentative optimum harvesting heights. In some situations, smaller seedlings were more resilient to harvesting damage (e.g. Andersson and Fries, 1979, Preuhsler and Jakobi, 1996, Eliasson *et al.*, 2003), while in others, larger seedlings and saplings survived better (e.g. Gordon, 1973, Tesch *et al.*, 1993). These differences may be partly due to the species being studied and the site conditions and partly due to the harvesting and extraction methods used. Granhus and Fjeld (2001) reported that harvesting using a harvester and forwarder caused more injury to taller Norway spruce (*Picea abies* L.) H. Karst.) saplings while motor-manual felling and skidding with a farm tractor tended to damage smaller saplings, demonstrating the importance of the methods used. They hypothesized that this was due to a tendency to fell trees towards areas of shorter regeneration when using motor-manual felling, compared with harvester felling in which directional felling is less often practised. In Sweden, where the shelterwood system is commonly used to regenerate Norway spruce (Westerberg, 1995), tall saplings have been found to suffer more damage than short saplings and damage can be reduced by manually felling trees away from densely regenerating areas (Eliasson *et al.*, 2003).

The lack of information on the impact of harvesting on differently sized regeneration in British

Table 1: Summary of relationships found between seedling height and damage for a range of harvesting and extraction methods

Research paper	Regeneration species	Harvesting and extraction method	Relationship between height and damage	Least-damaged seedling height class (m)
Gordon (1973)	*Abies magnifica* A. Murray and *Abies concolor* (Gord. and Glend.) Lindl.	Overstorey removal by tractor logging	Seedlings <0.25 m had much higher mortality than taller seedlings, both immediately after harvesting and for the following 7 years.	>0.25
Andersson and Fries (1979)	*Pinus sylvestris* L.	Motor-manual seed tree cutting	No apparent relationship, although there appeared to be least damage on the smallest seedlings.	<0.5
Granhus and Fjeld (2001)	*Picea abies* L. (Karst.)	Motor manual with farm tractor and harvester/forwarder	Injury rates increased with sapling height for harvester–forwarder method but decreased with sapling height for the manual/farm tractor method.	<0.5 (harvester–forwarder), >3.0 (motor-manual/tractor)
Youngblood (1990)	*Picea glauca* (Moench) Voss	Various cable yarding methods	Seedlings of 0.4–1.0 m received less damage than both smaller and larger seedlings.	0.4–1.0
Tesch *et al.* (1986)	Planted *Pseudotsuga menziesii* (Mirbel) Franco and *Pinus ponderosa* Laws	Skyline logging	No apparent relationship between mortality and seedling height. However, small seedlings received more damage than 0.6–1.0 m seedlings. Seedlings >1.0 m suffered more stem snap and uprooting.	0.6–1.0
Tesch *et al.* (1993)	*P. menziesii* (Mirbel) Franco	Motor manual and skyline extraction	Mortality was predominantly in seedlings <0.75 m within 2–3 years of overstorey removal. Of the damaged trees, only those >1.5 m had reduced height growth in the following years.	>0.75
Eliasson *et al.* (2003)	*P. abies* L. (Karst.)	Simulated harvesting–bending of individual saplings	Taller saplings were significantly more likely to snap when pulled by a cable in a controlled experiment than shorter saplings.	<1.0
Sikström and Glöde (2000)	*P. abies* L. (Karst.)	Single-grip and double-grip harvesters with forwarder	No apparent relationship between damage severity and seedling height. The proportion of dead and seriously damaged seedlings was lowest in the 1.6–2.0 m height class. Breakages increased with height up to 2.5 m and thereafter decreased with height.	1.6–2.0
Preuhsler and Jakobi (1996)	*P. abies* L. (Karst.) and *Abies alba* L.	Motor-manual felling and skidding	50–80% loss of saplings 2.5–4.5 m tall, almost complete loss of saplings >4.5 m.	<4.5

The seedling height associated with least harvesting damage were estimated and papers ordered by least-damaged height class.

conditions has lead to an understandable reluctance on the part of forest managers to intervene. There is no clear guidance on whether smaller seedlings, with their lower chance of being hit, or taller seedlings, with larger inflexible stems, are more at risk. Recent work (S.E. Hale and G. Kerr, unpublished data) has shown that there is also very little guidance on acceptable stocking densities for coniferous natural regeneration. The target density for British restock or new planting sites is 2500 plants per hectare 5 years after planting (Anonymous, 2004), usually achieved by planting 2700 seedlings per hectare. Based on this, Kerr *et al.* (2002) suggest that >2000 regeneration saplings >1.3 m tall per hectare may be sufficient to restock a CCF site, reflecting the fact that the environment is more sheltered than a restock site and that there are also likely to be other seedlings less than 1.3 m tall present.

Work is needed to determine how and when to plan interventions in order to minimize damage and to establish whether the remaining regeneration is likely to be sufficient to restock the site. In this study, we examined the hypotheses that:

1 Smaller seedlings would be more likely to survive harvesting operations than taller seedlings.
2 Taller seedlings would be more likely to be severely damaged by overstorey harvesting than smaller seedlings.

Figure 1. Map showing locations of the three field sites.

Methods and materials

The experiment was carried out on three sites with similar management objectives, all situated within CCF pilot sites established by the Forestry Commission (McIntosh, 2000). The locations of the three sites are given in Figure 1 and details are given in Table 2.

Stand parameters Basal Area (BA) per hectare and top height) were assessed using standard procedures as described by Matthews and Mackie (2006). The initial overstorey characteristics of the three stands were very different (Table 3). The two Sitka spruce (*Picea sitchensis* (Bong.) Carr.) stands, Fernworthy and Clocaenog, had a lower number of trees per hectare and higher BA than the Scots pine (*Pinus sylvestris* L.)/Japanese larch (*Larix kaempferi* (Lamb.) Carrière) stand at Wykeham. At Fernworthy, the very high basal area of 77 m^2 ha^{-1} reflected delayed thinning due to reluctance to damage the well-developed regeneration across the site; this contrasts with a BA of 42 m^2 ha^{-1} at Clocaenog, despite similar top heights (33.3 and 30.4 m, respectively). BA and top height at Wykeham were much lower at 28.2 m^2 ha^{-1} and 21 m, respectively. All sites had ground vegetation dominated by ericaceous shrubs, ferns and regenerating seedlings.

All sites were being managed as a simple system, i.e. one in which there will be one or two canopy layers, and thinning was carried out according to Mason and Kerr (2004). Thinning of the mature crop trees took place in winter 2005 (Fernworthy) and winter 2006 (Wykeham and Clocaenog) using the standard local operational practices as described below.

At Fernworthy, previously used extraction racks were still apparent. These were designated as permanent racks and cleared with chainsaws

Table 2: Characteristics of the three experiment sites

Characteristics	Fernworthy	Wykeham	Clocaenog
Location	Dartmoor National Park, Devon	North York Moors, Yorkshire	Clocaenog Forest, Denbighshire
Latitude and longitude	50° 38.5′ N and 3° 52.9′ W	54° 16.7′ N and 0°, 33.0′ W	53° 4.3′ N and 3° 27.2′ W
Description	Extensive moorland Sitka spruce plantation	High plateau planted with Scots pine and Japanese larch	Extensive upland Sitka spruce plantation
Overstorey	Planted 1922 Sitka spruce, occasional Norway spruce	Planted 1931 Scots pine and Japanese larch	Planted 1949 Sitka spruce
Elevation	360 m a.s.l.	170 m a.s.l.	435 m a.s.l.
Topography	Gently sloping to the north-west	A level plateau with the sea 10 km to the east	Sloping to the north-west
Geological formation	Permian granite	Carboniferous and Jurassic sandstone	Drift from Palaeozoic sandstone, mudstone and shale
Soil	Well drained, humose, gritty, loamy soils. Occasionally with thin iron pan	Coarse loamy, very acid, upland soils over rock with a wet, peaty surface horizon and thin iron pan. Some shallow peaty soils	Slowly permeable, seasonally waterlogged, loamy, upland soils with a peaty surface horizon. Some very acid peat soils
Avery soil classification (1980)	6.12 (podzolic soils: humic brown podzolic soil)	6.51 (podzolic soils: iron pan stagnopodzol)	7.21 (surface-water gley soils: cambic stagnohumic gley soils)
Mean annual rainfall (mm)	1622	800	1174
Vegetation	Moss, grasses, *Vaccinium*, ferns, dense Sitka spruce regeneration	Grasses, *Vaccinium*, ferns, Scots pine and Japanese larch regeneration, birch	Heather, *Vaccinium*, bramble, ferns, extensive Sitka spruce regeneration

prior to harvesting. Where there was no previous rack and access was required, the areas with the lowest regeneration density were used. The spacing between racks was ~20 m, although there were some areas where the spacing increased to 30 m. Due to the large tree size, trees were felled with chainsaws using feller selection, i.e. trees were not marked and operators selected trees according to a felling prescription as they worked. Trees were felled towards the racks and then the first one or two timber lengths were cut before processing the remainder of the stem with a CAT-318 excavator base and Logset harvesting head, reducing the need to drag long timber lengths out. The bulk of the top (harvesting residue) was processed in the rack and was used as a brash (slash) mat. The weather had been dry in the preceding weeks but was cold and wet during felling, although not below freezing.

At Wykeham, existing racks with a spacing of ~20 m were cleared and used. Trees were felled using operator selection with a Valmet 921 harvester with tracks and steel rollers. Logs were extracted using a Valmet 840.1 forwarder with a 6 m reach and 10 tonne bunk capacity. No tracks or chains were used and conditions were mainly dry during the operations.

At Clocaenog, the intention was to use the existing rack system, but the machine operator found that in the dense regeneration and low light conditions these were not visible from the cab and therefore a new rack system was established. Racks were not pre-cleared as the harvester was large enough to drive over the regeneration. Trees were felled using a John Deere 1270D with standard metal feed rollers and Clarke tracks were fitted to the front bogie of the six-wheeled machine. Extraction was using

Table 3: Harvesting and assessment information

	Fernworthy	Wykeham	Clocaenog
Date of first assessment	September 2004	July 2006	August 2006
Date of harvesting	March 2006	November 2006	January 2007
Date of second assessment	April 2006	January 2007	February 2007
Overstorey tree species	Sitka spruce	Scots pine and Japanese larch	Sitka spruce
Number of plots	70	70	63
Compartment area (ha)	1.0	8.5	8.3
Distance between plots (m)	12	40	24
Mean pre-thinning DBH (cm)	52.7	19.2	nr
Pre-thinning top height* (m)	33.3	21.3	30.4
Pre-thinning trees per hectare*	345	640	283
Post-thinning trees per hectare*	153	370	113
Pre-thinning mean tree volume (m^3)	2.76	0.25	nr
Pre-thinning stand BA* (m^2 ha^{-1})	77.6	28.2	41.8
Post-thinning stand BA* (m^2 ha^{-1})	44	21.5	20.8

nr indicates data not recorded.
* Assessed using standard procedures as described by Matthews and Mackie (2006).

a John Deere 1110D with CF585 loader and 0.35 m^2 grab. The bunk capacity was 12 000 kg with Clarke tracks on the rear bogie. The thinning was carried out up and down the slope using operator selection. Weather conditions were sunny and dry during the work and snow on the ground was thawing.

The operators were all highly experienced in the harvesting methods used on each site and had many years experience of working in the local site conditions. They were aware that the intention was to utilize the regeneration to restock the site but were not informed that the sites were being used for a harvesting damage study. No special precautions were taken to protect the regeneration in the experiment plots which were marked as discretely as possible.

Approximately 70 regeneration assessment plots were laid out across each study area prior to thinning, positioned systematically on a grid, as described by Kerr *et al.* (2002). Plots were 2 × 2 m quadrats with the distance between plot centres calculated as described by Kerr *et al.* (2002), see Table 3. Quadrats were aligned north–south and were permanently marked with discrete wooden marker pegs with 5 cm above ground in opposite corners. The distance and bearing from the nearest canopy tree was recorded to aid relocation, and the plot number was painted discretely on the tree.

Prior to harvesting, the regeneration in each quadrat was counted by species and it was noted whether they were alive or dead. Seedlings with no green leaf or needle tissues (and for broadleaves, no fresh, healthy buds) were assumed to be dead. For the purposes of this study, all regenerating stems have been termed 'seedlings', recorded on the basis of height as small (<50 cm), medium (50–200 cm) or large (>200 cm). Presence or absence of deer browsing damage was also recorded for each seedling.

The second assessment of the plots took place within 2 months of completion of the thinning. The plots were relocated and number of seedlings by species, height class and whether they were alive or dead was recorded. An assessment of harvesting damage to each seedling was also made using the scale: no damage, low damage (central axis not snapped and likely to recover) and high damage (central axis snapped and unlikely to recover). At Clocaenog, the level of damage was not recorded; seedlings were recorded as damaged or undamaged. The number of seedlings lost from each quadrat was calculated by subtracting the number after harvesting from the number before harvesting for each height class. The distance from the centre of each plot to the closest edge of the two nearest extraction racks and to the two nearest recently felled stumps was also recorded.

Statistical analyses

The pre-harvest seedling numbers were first tested for a random distribution by testing the goodness of fit of a Poisson distribution (the distribution that would be observed if the seedlings were randomly distributed). Then a negative binomial distribution was fitted to give a measure of aggregation, $1/k$, where k is the exponent parameter of the negative binomial distribution (GenStat, 2005).

Pearson's chi-squared tests were applied to tables of before and after counts in order to determine whether seedling fate was related to height.

The principal model used to relate the damage to the explanatory variables of the distance to the nearest racks and nearest stumps was an ordinal logistic model for the three classes: undamaged, low damage and high damage. Data were pooled across size classes when numbers of seedlings were too low for analysis. In some cases, the numbers in the three damage classes were too low for a successful fit with an ordinal logistic model and a simpler logistic regression model regression (binomial generalized linear model (GLM) with logit link) was fitted (GenStat, 2005). For this model, the numbers in a particular damage category were the response and the initial numbers of seedlings were the binomial denominator.

For the Fernworthy data, occasional increases in post-harvesting numbers of seedlings occurred which could be due to misclassification. This precluded the use of the logistic type models and instead a Poisson GLM was used with the log of the pre-harvesting number of seedlings included as an offset (GenStat, 2005).

Results

Regeneration characteristics before harvesting

The regeneration at the three sites was markedly different before the harvesting took place (Table 4).

At Fernworthy, the vast majority (94.5 per cent) of the regeneration was Sitka spruce while the remainder (all species pooled) were 82 per cent rowan (*Sorbus aucuparia* L.), 15 per cent holly (*Ilex aquifolium* L.) and 3 per cent western hemlock (*Tsuga heterophylla* (Raf.) Sarg.).

Table 4: Number of seedlings per hectare in the three stands before harvesting (actual number of seedlings in all sample plots shown in brackets)

		Live seedlings			Total no. of live seedlings per hectare	Dead seedlings			Total no. of dead seedlings per hectare
Site	Species	<50cm	50–200cm	>200 cm		<50cm	50–200cm	>200 cm	
Fernworthy	Sitka spruce	26 071 (730)	38 250 (1071)	4536 (127)	68 857$^{0.325}$	11 000 (308)	11 393 (319)	36 (1)	22 429
	Other	4750 (133)	250 (7)	0	5000$^{1.971}$	321 (9)	36 (1)	0	357
	Total	30 821	38 500	4536	73 857	11 321	11 429	36	22 786
Wykeham	Sitka spruce	410 (11)	1903 (51)	2238 (60)	4551$^{4.138}$	1231 (33)	3769 (101)	187 (5)	5187
	Japanese larch	75 (2)	149 (4)	821 (22)	1045$^{n/a}$	75 (2)	560 (15)	75 (2)	710
	Birch	2276 (61)	1306 (35)	1343 (36)	4925$^{2.796}$	261 (7)	485 (13)	75 (2)	821
	Other	635 (17)	336 (9)	896 (24)	1867$^{n/a}$	149 (4)	336 (9)	261 (7)	746
	Total	3396	3694	5298	12 388	1716	5177	598	7464
Clocaenog	Sitka spruce	11 825 (298)	33 016 (832)	4881 (123)	49 722$^{1.325}$	0	3333 (84)	0	3333
	Other	0	238 (6)	159 (4)	397$^{n/a}$	0	0	0	0
	Total	11 825	33 254	5040	50 119	0	3333	0	3333

Superscript values are Poisson indices (value of 0 indicates a random distribution). n/a indicates number of seedlings was too low to draw any conclusions from Poisson indices.

Of the total number of Sitka spruce seedlings, 25 per cent were dead and a further 5 per cent were browsed. The majority of live, unbrowsed Sitka spruce seedlings were in the medium size class, although there were also many small seedlings; fewer unbrowsed Sitka spruce seedlings had reached the large class.

At Wykeham, there was a wider range of species regenerating, reflecting the mixed overstorey, but the overall density of seedlings was much lower. The commonest seedlings were Sitka spruce and birch (*Betula pendula* L.), with similar numbers, but while there were few dead birch, more than half of the Sitka spruce seedlings recorded were dead. The numbers of Japanese larch and 'other' seedlings were lower. Other seedlings were 34 per cent western hemlock, 22 per cent rowan, 18 per cent lodgepole pine (*Pinus contorta* Dougl. ex. Loud), 11 per cent Norway spruce, 10 per cent Scots pine, 4 per cent holly and 1 per cent grand fir (*Abies grandis* Dougl. ex. D. Don). Despite a large number of small dead Sitka seedlings, there were a few small live Sitka; the most common size class was the largest. The opposite was true for birch with the majority of live seedlings being small and a high number of dead seedlings in the medium class. Most live Japanese larch seedlings were large.

At Clocaenog, the total regeneration density was intermediate between the other sites. As at Fernworthy, the large majority (>99 per cent) of the seedlings were Sitka spruce, due to the single species overstorey. The two other species present were rowan (90 per cent of the remainder) and larch (10 per cent of the remainder) and were all small. The proportion of dead Sitka seedlings was 6 per cent (much lower than at Fernworthy) and these were exclusively in the medium class. This was also the most common height class for the live seedlings at Clocaenog with only 10 per cent being large. At all sites, the distribution of the seedlings among the quadrats was not random, with high Poisson indices (Table 4) due to the occurrence of quadrats with zero seedlings, showing the distributions to be clumped.

Harvesting damage

Regeneration in the plots positioned on extraction racks was usually completely destroyed; in many cases, the plot could not be located due to heavy brash or wheel ruts (data not shown). At Fernworthy, 14 of 70 plots fell on a rack and a further three were less than 1 m from the rack and lost all regeneration, totalling 24 per cent of the plots. At Clocaenog, 15 of 63 plots were on racks and suffered very severe or complete seedling loss, again representing 24 per cent of the plots. At Wykeham, the number was slightly higher, as 20 of 70 plots were on racks, representing 29 per cent of the plots.

Within the matrix plots, the percentage of seedlings surviving the thinning with no damage or low damage (i.e. still potential canopy trees) was variable. The highest percentages were seen at Wykeham, where 81.9 per cent of Sitka spruce seedlings (Figure 2) and 69.4 per cent of birch seedlings (data not shown) were not severely damaged, compared with 44.6 per cent of Sitka spruce seedlings at Fernworthy (Figure 2). At Clocaenog (where level of damage was not recorded), 40.6 per cent of the Sitka spruce seedlings in the matrix survived with no damage and a further 23.4 per cent survived with damage (Figure 2). The fate of matrix Sitka spruce seedlings is summarized in Figure 2.

There was no indication that harvesting method significantly affected survival; at the two similar

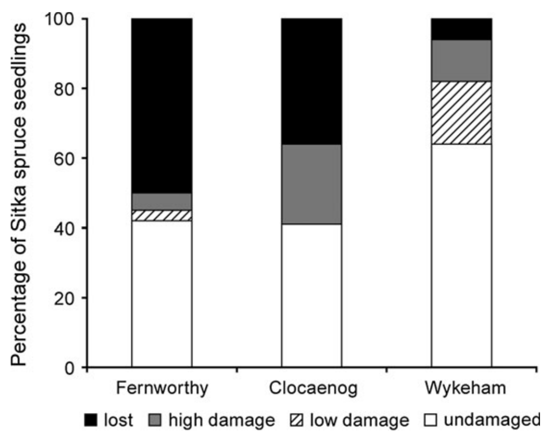

Figure 2. Fate of matrix Sitka spruce seedlings (all size classes) at the three sites expressed as a percentage of total pre-harvesting number of live Sitka spruce seedlings. At Clocaenog, damage classes were not differentiated; damaged seedlings have been shown as high damage.

sites, Fernworthy and Clocaenog, motor-manual felling and harvester felling both resulted in heavy loss of small seedlings and heavy damage to tall seedlings (Table 5). The percentage of undamaged Sitka spruce seedlings at these two sites was almost identical (Figure 2) indicating that the harvesting method used had little influence.

Damage related to seedling size

Throughout the stand as a whole (matrix and racks) at Fernworthy and Clocaenog, high numbers of small and medium Sitka spruce seedlings were lost (Pearson's chi-square, $P < 0.001$ for both sites) while much lower numbers of large seedlings were lost, as the large seedlings tended to sustain high levels of damage instead (Table 5). At both of these sites, there were too few seedlings of other species to carry out statistical analysis.

No significant difference in damage or loss was found between size classes for birch, Sitka spruce or other seedlings (analysed together) at Wykeham (Table 5). For the large height class, a comparison of numbers of undamaged Sitka spruce and birch seedlings at Wykeham was significant (Sitka spruce 70 per cent undamaged, birch 42 per cent, $P < 0.01$). At Wykeham, large birch were more likely to be damaged than large Sitka spruce.

Seedling fate and proximity to harvesting disturbance

At Fernworthy, both the number of Sitka spruce seedlings remaining and the number undamaged were related to the distance to the closest rack (Table 6, both $P = 0.002$). No distance variables were significantly related to the number of seedlings recorded as damaged. For the other species at Fernworthy, there were no significant relationships between distance variables and the numbers of seedlings damaged, undamaged or total surviving.

At Clocaenog, the ordinal logistic model showed significant relationships between damage and distance parameters for all three size classes for Sitka spruce. For all classes, the distance to the closest rack was significant (Table 6, $P = 0.035$, $P < 0.001$ and $P = 0.022$ for small, medium and large classes, respectively). For the middle height class, the distances to the two nearest stumps were also significant ($P = 0.024$ and $P = 0.008$ for the first and second stump, respectively). The alternative binomial GLM showed that for medium seedlings only the distance to the closest rack significantly influenced the numbers of seedlings surviving ($P < 0.001$). The numbers of other species were too low to analyse.

At Wykeham, the binomial GLM showed a weak relationship between the number of undamaged, medium-sized Sitka spruce seedlings and the distance to the closest rack but there was no relationship for small or large seedlings. Combining the lost and heavily damaged categories and using the ordinal logistic model, the distance to the first and second closest cut stumps were significant ($P = 0.03$ and $P = 0.021$, respectively). For birch, no significant distance effects were found for the small- or medium-sized seedlings but for large seedlings the ordinal logistic model showed a significant relationship between damage and distance to the closest rack ($P = 0.020$). There were too few seedlings of other species to analyse.

Discussion and practical implications

The first hypothesis that smaller seedlings would be more likely to survive harvesting than taller seedlings was not supported for the species, harvesting methods and sites studied; despite the lower likelihood of being hit, smaller seedlings tended to be lost on all three of the sites. The second hypothesis that taller seedlings would be more likely to be severely damaged than smaller seedlings was supported. This agrees with some of the literature, e.g. Gordon (1973) and Tesch *et al.* (1993), both of whom found that mortality was highest for the smallest seedlings, but contradicts results reported by Preuhsler and Jakobi (1996) in which almost all of the regeneration in the tallest class died. This may be due to tall seedlings having better developed root structures compared with smaller seedlings which are more likely to be dragged out of the ground or crushed (as reported for Norway spruce by Skoklefald, 1967). If the regeneration is still growing strongly prior to harvesting, it may be worth considering delaying the harvesting for a short while to allow seedlings to become better established before harvesting. Although tall seedlings did not have such high mortality as expected, there was a higher incidence of stem snap than in

Table 5: Impact of harvesting on seedlings at the three sites

Site	Species	Size class (cm)	Pre-harvesting total number in all plots	% Undamaged	% Low damage	% High damage	% Lost
Fernworthy	Sitka spruce	<50	730	34.0	0.8	0.0	65.2
		50–200	1071	33.1	3.2	1.4	62.3
		>200	127	43.3	5.5	46.5	4.7
	Other	<50	133	15.0	n/a	n/a	85.0
		50–200*	7	28.6	n/a	n/a	71.4
		>200	0	n/a	n/a	n/a	n/a
Wykeham	Sitka spruce	<50	11	54.5	0.0	36.4	9.1
		50–200	51	51.0	25.5	11.8	11.8
		>200	60	70.0	13.3	10.0	6.7
	Japanese larch	<50*	2	0.0	0.0	100	0.0
		50–200*	4	0.0	0.0	100	0.0
		>200	22	27.3	4.5	68.2	0.0
	Birch	<50	61	49.2	3.3	47.5	0.0
		50–200	35	54.3	20.0	45.7	−20.0†
		>200	36	41.7	13.9	41.7	2.8
	Other	<50	17	23.5	5.9	58.8	11.8
		50–200*	9	11.1	0.0	77.8	11.1
		>200	24	25.0	4.2	45.8	25.0
Clocaenog	Sitka spruce	<50	298	27.9	15.1‡		57.0
		50–200	832	35.0	19.7‡		45.3
		>200	123	38.2	53.7‡		8.1
	Other*	<50	0	n/a	n/a‡		n/a
		50–200*	6	33.3	0.0‡		66.7
		>200*	4	25.0	0.0‡		75.0

Values are percentages of the pre-harvesting numbers of seedlings.
* Based on a very low number of seedlings.
† Some plot corner markers were damaged during harvesting and it was not possible to relocate the plot position exactly and seven more birch seedlings 50–200 cm were recorded in the post-harvesting assessment than the pre-harvesting assessment.
‡ Low- and high-damage scores were not distinguished.

Table 6: Significant relationships between seedling fate and disturbance parameters

Site	Species	Model	Parameter	Size class	Distance parameter	*P*-value	Coefficient
Fernworthy	Sitka spruce	Poisson GLM	Numbers remaining	All pooled	R1	0.002	0.0769
	Sitka spruce	Poisson GLM	Numbers undamaged	All pooled	R1	0.002	0.0905
Clocaenog	Sitka spruce	Ordinal logistic	Damage category	<50 cm	R1	0.035	−0.431
	Sitka spruce	Ordinal logistic	Damage category	50–200 cm	R1	<0.001	−0.322
	Sitka spruce	Ordinal logistic	Damage category	50–200 cm	S1	0.024	−0.2272
	Sitka spruce	Ordinal logistic	Damage category	50–200 cm	S2	0.008	−0.2268
	Sitka spruce	Ordinal logistic	Damage category	>200 cm	R1	0.022	−0.1964
Wykeham	Sitka spruce	Ordinal logistic*	Damage category	All pooled	S1	0.030	−0.279
	Sitka spruce	Ordinal logistic*	Damage category	All pooled	S2	0.021	−0.2167
	Birch	Ordinal logistic	Damage category	>200 cm	R1	0.020	−0.249

R1, S1 and S2 are the disturbance parameters of distance to the closest rack and the closest and second closest stumps, respectively.
* Loss and heavy damage categories combined.

the smaller seedlings, probably due to the greater chance of being hit and inflexibility of the main stem; this has also been reported by Tesch *et al.* (1986), Sikström and Glöde (2000) and Eliasson *et al.* (2003).

Despite the high losses, seedling density is likely to be sufficient to restock all three sites. At Fernworthy and Clocaenog, the two similar Sitka-dominated sites, the percentage of initial seedlings surviving undamaged was remarkably similar; 27–43 per cent across the three size classes, despite the different harvesting techniques used on the two sites. The high density of the regeneration at these two sites means that even at the lowest survival rates seedling densities would be close to 10 000 ha^{-1}. At Wykeham, although the seedling densities were lower, they were still clumped and the operator was able to protect the regeneration better while carrying out the work; between 51 and 70 per cent of the Sitka seedlings and between 41 and 54 per cent of birch seedlings were undamaged. As the survival of smaller seedlings can be unpredictable (as demonstrated by the large number of small and medium seedlings that were dead before harvesting, Table 4), Kerr *et al.* (2002) recommend >2000 saplings per hectare (>1.3 m tall; broadly comparable with our large seedling size class) as being sufficient to restock a site. Post-harvesting numbers of undamaged or slightly damaged large seedlings were in excess of this at 2214 Sitka spruce per hectare at Fernworthy and 2090 Sitka spruce and Japanese larch per hectare at Wykeham. At Clocaenog, where damage scores were not differentiated, there were 4444 surviving large Sitka spruce per hectare after harvesting, 1825 ha^{-1} of which were undamaged. The quality of trees developing from damaged seedlings may be poor; hence, it may be preferable to base assessment of sufficient seedling density on the number of undamaged seedlings. However, Tesch *et al.* (1993) reported that surviving Douglas-fir seedlings and saplings recovered from almost all logging damage within 6 years of overstorey removal, to the extent that 62 per cent of those initially classified as non-crop trees were reclassified as crop trees, indicating that some of the severely damaged regeneration on our sites may also recover.

In comparison to Fernworthy, the proportion of Sitka spruce seedlings lost was much lower at Wykeham, although a higher proportion was damaged (Figure 2). The high Poisson index of Sitka spruce at Wykeham (4.138, compared with 0.325 at Fernworthy) indicates that the seedlings were highly aggregated or clumped, perhaps enabling operators to avoid crushing the Wykeham seedlings during felling. However, it is surprising that the proportion of seedlings receiving damage was higher at Wykeham than at Fernworthy. The practice used at Fernworthy, of cutting the first one or two timber lengths from the felled tree before processing the remainder, may have minimized damage rates by reducing the need to drag long timber lengths out of the stand.

The distribution and species composition of the seedlings should be considered. Both before and after harvesting, distributions at all sites were clumped with areas of no regeneration and areas with very dense regeneration. Virtually all of the seedlings at Fernworthy and Clocaenog were Sitka spruce, reflecting the overstorey composition, while at Wykeham, although there had been successful regeneration of Japanese larch at some point in the past, there was little new larch regeneration and very little Scots pine regeneration on the site. Therefore, if only the existing seedlings are used to restock these sites, the future stands at all three will remain clumped and at Wykeham, the stand will become more heavily dominated by Sitka spruce and birch, as these species tended to be more resilient.

Although the relationship varied between the sites, species and size classes, there was considerable evidence that loss and damage to seedlings were related to proximity to extraction racks. Granhus and Fjeld (2001) also reported that distance to the extraction rack had a significant effect on sapling damage. They noted that although the rack spacing was at the maximum allowing the harvester access to all trees, increasing the rack spacing when using motor-manual felling could potentially reduce damage rates as a large proportion of damage was in the rack plots. As it is now the intention at all three sites to maintain and reuse the existing racks, it is unlikely that a similar level of damage would be sustained in subsequent thinnings or final overstorey removal. Distance to the nearest stump was less commonly related to the damage or losses, regardless of the harvesting method used. This indicates that once a good rack system is in place, the harvesting disturbance caused by the felling of the tree is unlikely to cause much further regeneration to be lost. This probably partly reflected the skill of the operators in directing the tree away from particularly dense areas of regeneration but also suggests that the seedlings were more resilient than expected.

The high numbers of seedlings lost on racks highlights the importance of maintaining a strict rack system while working and using the same racks in subsequent operations as this will result in very little impact of the thinning on the rest of the matrix. The racks should be well protected with brash (Moffat *et al.*, 2006) to protect them for future operations. Rack spacing should be optimized to minimize the destruction of seedlings in the racks while allowing the large majority of the matrix to be accessed without leaving the rack. If new racks are created in each operation, the regeneration will be lost over a larger area. However, the operators at Clocaenog commented that the previously existing racks were difficult to see due to dense regeneration, particularly when working in low light. Investing some time in motor-manual clearing of the racks prior to the harvesting (as was done at Fernworthy) or marking the rack position with painted arrows beforehand may be beneficial in the long run and reduce wandering in the stand. However, it should be noted that higher disturbance rates in the extraction racks may cause a change in vegetation type, possibly promoting vigorous or woody weed growth, as was reported by Harvey and Brais (2002). This could potentially increase time and cost, particularly for motor-manual operations, and may result in the need for costly control of invasive woody weeds.

Although not tested on sufficient sites to draw firm conclusions, there was no indication that motor-manual felling resulted in higher survival than harvester felling. Despite the similar species composition of the Clocaenog and Fernworthy sites in this study, both the motor-manual felling method used at Fernworthy and the harvester felling at Clocaenog resulted in heavy loss of small seedlings and heavy damage to tall seedlings. This is in contrast to Granhus and Fjeld (2001) who showed that motor-manual felling reduced injury rates to tall regeneration while harvester felling caused lower injury rates to small regeneration. As our data indicate that smaller seedlings are less likely to survive the operation, use of motor-manual felling may enable operators to increase survival rates by felling trees into the areas of smaller regeneration, rather than into areas of less-dense, but larger regeneration. However, further studies designed to examine the effects of different operational methods would be required to confirm this. Across all three sites, the damage rates sustained were comparable with those quoted in other studies on the impact of overstorey thinning on coniferous advance regeneration (Vorob *et al.*, 1994; Westerberg and Berg, 1994; Sikström and Glöde, 2000).

In summary, the recommendations are as follows:

1 Create and maintain a permanent rack system, with distance between racks appropriate to the intended harvesting method. This is likely to kill ~25–30 per cent of the regeneration on the site as a whole.
2 Allow for a further loss of 20–60 per cent of the regeneration in the stand matrix due to damage caused by thinning operations.
3 Clear and/or mark the racks before harvesting to ensure machinery stays on the rack.
4 Protect the taller regeneration, e.g. by felling trees away from these areas. Taller regeneration is more likely to survive undamaged and develop to become a future crop tree.

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Conflict of Interest Statement

None declared.

References

Andersson, O. and Fries, J. 1979 Pilot study on plant damage in a seed tree cutting. *Sver. Skogsvårdsförb. Tidskr.* **2**, 123–129. (in Swedish, English summary).

Anonymous 2004 *Plant Density: Right First Time. Operational Guidance Booklet* No. 4. Forestry Commission, Edinburgh.

Clarke, G.C. 1992 The natural regeneration of spruce. *Scott. For.* **46**, 107–129.

Eliasson, L., Lageson, H. and Valinger, E. 2003 Influence of sapling height and temperature on damage to advance regeneration. *For. Ecol. Manage.* **175**, 217–222.

GenStat, 2005 The Guide to GenStat Release 8.1. Part 2: Statistics. R.W. Payne (ed). *Lawes Agricultural Trust (Rothamsted Experimental Station)*. VSN International, Oxford.

Glöde, D. and Sikström, U. 2001 Two felling methods in final cutting of shelterwood, single-grip harvester productivity, and damage to the regeneration. *Silva Fenn.* **35**, 71–83.

Gordon, D.T. 1973 *Released Advance Reproduction of White and Red Fir: Growth, Damage, Mortality. USDA Forest Service Research Paper* PSW-95. US Department of Agriculture, Berkley, CA.

Granhus, A. and Fjeld, D. 2001 Spatial distribution of injuries to Norway spruce advance growth after selection harvesting. *Can. J. For. Res.* **31**, 1903–1913.

Harvey, B. and Brais, S. 2002 Effects of mechanized careful logging on natural regeneration and vegetation competition in the southeastern Canadian boreal forest. *Can. J. For. Res.* **32**, 653–666.

Jeansson, E. and Laestadius, L. 1981 *Reforestation by Site Preparation, Natural Regeneration and Understorey Regeneration in the Soviet Union*. Department of Silviculture, The Swedish University of Agricultural Sciences, Umeå. *Rapporter* 6:65 p. (in Swedish, English summary).

Kerr, G., Mason, B., Boswel, R. and Pommerening, A. 2002 *Monitoring the Transformation to Continuous Cover Management. Forestry Commission Information Note* 45. Forestry Commission, Edinburgh.

Malcolm, D.C., Mason, W.L. and Clarke, G.C. 2001 The transformation of conifer forests in Britain—Regeneration, gap size and silvicultural systems. *For. Ecol. Manage.* **151**, 7–23.

Mason, W.L. 2008 Natural regeneration of Sitka spruce in the forest of Ae: development over 25 years. *Scott. For.* **62**, 2–8.

Mason, W.L. and Kerr, G. 2004 Transforming of even-aged conifer stands to continuous cover management. *Forestry Commission Information Note* 40. Forestry Commission, Edinburgh.

Mason, W.L. and Quine, C.P. 1995 Silvicultural possibilities for increasing structural diversity in British spruce forests: the case of Kielder forest. *For. Ecol. Manage.* **79**, 13–28.

Mason, W.L., Kerr, G. and Simpson, J.M.S. 1999 What is continuous cover forestry? *Forestry Commission Information Note* 29. Forestry Commission, Edinburgh.

Matthews, R.W. and Mackie, E.D. 2006 *Forest Mensuration: A Handbook for Practitioners*. Forestry Commission, Edinburgh.

McIntosh, B. 2000 Role of continuous cover silvicultural systems in the management of the Forestry Commission estate. *CCFG Newsletter*. **16**, 5–9. Continuous Cover Forestry Group, Bellever, May Road, Turvey, Bedford, MK43 8DT.

McNeill, J.D. and Thompson, D.A. 1982 Natural regeneration of Sitka spruce in the Forest of Ae. *Scott. For.* **36**, 269–282.

Moffat, A., Jones, B.M. and Mason, B. 2006 Managing brash on conifer clearfell sites. *Forestry Commission Practice Note* 13. Forestry Commission, Edinburgh.

Nelson, D.G. 1991 Management of Sitka spruce natural regeneration. *Forestry Commission Research Information Note* 204. Forestry Commission, Edinburgh.

Newton, M. and Cole, E.C. 2006 Harvesting impacts on understory regeneration in two-storied Douglas-fir stands. *West. J. Appl. For.* **21**, 14–18.

O' Hara, K.L. 1998 Silviculture for structural diversity: a new look at multi-aged stands. *J. For.* **96**, 4–10.

Olson, M.G., Clatterbuck, W.K. and Schlarbaum, S.E. 2003 . *Mechanical damage incurred by underplanted northern red oak following six overstorey treatments: first-year results. General technical Report—Southern Research Station, USDA Forest Service* (No. SRS-71). *554–551.*

Pommerening, A. and Murphy, S.T. 2004 A review of the history, definitions and methods of continuous cover forestry with special attention to afforestation and restocking. *Forestry*. **77**, 27–44.

Preuhsler, T. and Jakobi, K.-P. 1996 Effects of a shelterwood felling on the natural regeneration. *Forst Holz*. **51**, 205–211. (in German, English summary).

Sikström, U. and Glöde, D. 2000 Damage to *Picea abies* regeneration after final cutting of shelterwood with single- and double-grip harvester systems. *Scand. J. For. Res.* **15**, 274–283.

Skoklefald, S. 1967 Release of natural Norway spruce regeneration. *Medd. Nor. Skogforsoksves.* **23**, 381–409. (in Norwegian, English summary).

Tesch, S.D., Lysne, D.H., Mann, J.W. and Helgerson, O.T. 1986 Mortality of regeneration during skyline logging of a shelterwood overstorey. *J. For.* **84**, 49–50.

Tesch, S.D., Baker-Katz, K., Korpela, E.J. and Mann, J.W. 1993 Recovery of Douglas fir seedlings and saplings wounded during overstorey removal. *Can. J. For. Res.* **23**, 1684–1694.

von Ow, F., Joyce, P. and Keane, M. 1996 Factors affecting the establishment of natural regeneration Sitka spruce (*Picea sitchensis* (Bong.) Carr.) in Ireland. *Ir. For.* **53**, 2–18.

Vorob, V.N., Danchenko, A.M., Bekh, I.A., Panevin, V.S. and Burkov, V.P. 1994 Is it possible to preserve advance growth when using harvesters. *Lesn. Khoz.* **6**, 33–34. (in Russian, English abstract).

Westerberg, D. 1995 Profitable forestry methods—maintaining biodiversity as an integral part of Swedish forestry. In *Innovative Silviculture Systems in Boreal Forests*. C.R. Bamsey (ed). Clear Lake Ltd, Edmonton, Alberta, Canada, pp. 61–65.

Westerberg, D. and Berg, S. 1994 Felling of standards: trial method for determining productivity, costs and damage to advance growth The Forestry Research Institute of Sweden, Uppsala, *Redogörelse* 10:26 p.

Youngblood, A.P. 1990 Effects of shelterwood removal on established regeneration in an Alaska white spruce stand. *Can. J. For. Res.* **20**, 1378–1381.

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