HARVEST RESIDUE EFFECT ON MICRO-CLIMATE, NUTRITION, AND EARLY GROWTH OF SITKA SPRUCE (*PICEA SITCHENSIS*) SEEDLINGS ON A RESTOCK SITE

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ABSTRACT

The mechanisms by which whole-tree harvesting affect growth of second-rotation Sitka spruce (*Picea sitchensis* (Bong.) Carr.) were studied for 2 years on a stagnohumic gley soil in Kielder Forest, Northumberland. The full factorial experiment included treatments with harvest residues (±R), fertiliser additions (±F), and herbicide (±H), giving a total of eight treatments in three replicate blocks.

Fertiliser and herbicide treatments increased foliage nutrient concentrations which were above those expected to limit growth of young Sitka spruce. The removal of harvest residues decreased height growth in both years ($p<0.05$). Soil temperature fluctuations at 10 cm depth increased during the year in whole-tree harvested plots. Soils were warmer in spring and summer and cooler in autumn where residues had been removed and this response was considered most likely to favour tree growth. However, the removal of harvest residues increased mean annual windspeed at 30 cm above ground-level by 40%. The sheltering effect of residues increased with increasing windspeed ($r^2=0.87$). The most likely cause of reduced growth after whole-tree harvesting on this exposed upland site was considered to be the removal of shelter from around the newly planted seedlings.

Keywords: whole-tree harvesting; micro-climate; temperature; windspeed; *Picea sitchensis*.

INTRODUCTION

Whole-tree harvesting (WTH) comprises the removal of branch and foliage material normally left on site as harvest residues after conventional harvesting (CH) of stems only. Interest in WTH within the U.K. has increased recently owing to perceived reductions in establishment costs associated with cleaner sites after residue removal (Nelson & Dutch 1991). Markets for harvest residues are being developed to feed large-scale power generating plants in an effort to reduce fossil fuel carbon emissions.

There are, however, concerns over WTH, both in terms of the nutrient export from the forest site (Martin 1988; Kimmins 1985; Hendrickson *et al.* 1989) and the potential for soil damage during the harvesting operation (Skinner *et al.* 1989; Senyk & Smith 1991). While WTH may increase biomass removal by 10–40%, it can lead to much greater increases in the quantity of nutrients removed (Carey 1980; Anderson 1985; Maliondo 1988; Stevens *et al.* 1989; Compton & Cole 1991). Computer simulation studies have suggested that such increases in nutrient removal associated with WTH may affect long-term site productivity (Waide & Swank 1975; Aber *et al.* 1979; Rolff 1986). Experimental evidence to support these predictions is sparse and that which does exist is equivocal.

Studies on successive rotations of Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) have shown reductions of up to 24% in tree growth after WTH, with differences increasing over time (Compton & Cole 1991). Other investigations have reported enhanced regrowth after WTH (Hendrickson 1988; Dyck *et al.* 1991), although both cautioned against drawing conclusions over short time periods. Mann *et al.* (1988) observed a reduction in tree growth after WTH but an increase in regrowth of herbaceous plants, suggesting that the observed growth reduction in trees was attributable to increased weed competition rather than to any decline in site fertility. Lundkvist (1986) reported an initial positive response in Scots pine (*Pinus sylvestris* L.) after WTH; this lasted for 10 years before becoming negative over the following 10 years, so that no net effect could be detected after 20 years. A recent study of Sitka spruce in northern England has shown a 20% decline in growth after 10 years associated with WTH and no evidence of the effect diminishing with time (Proe & Dutch 1994). The authors suggested that the mechanisms causing the observed growth reduction may change with time, being largely due to micro-climatic sheltering effects shortly after replanting but with nutrition becoming increasingly important. Clearly, the mechanisms by which trees respond to WTH are complex and it is unwise to draw conclusions too early or to extrapolate from one site to another without understanding the cause of any observed growth response.

The aim of the current experiment was to determine the causes of growth reductions after WTH and, in the longer term, to assess whether these will change over time. Particular attention was paid to the effect of residues on modifying the micro-climate, as shelter is an important feature in the exposed upland forest sites common in the U.K.

MATERIALS AND METHODS

Site Description

The experimental site was located in Kielder Forest, in northern England (55°10′N, 2°30′W) at an elevation of 300 m and with a gently sloping westerly aspect. The area has a temperate oceanic climate with a mean annual rainfall of 1300 mm and mean monthly air temperatures ranging between 0° and 15°C. The soil is a cambic stagnohumic gley (Avery

1980) developed on Scremerston Coal Group Sandstones overlying Carboniferous Limestone. The first-rotation stand of Sitka spruce was planted in 1940, and was felled by mechanical harvester in the autumn of 1991 when the top height of the crop was approximately 23.5 m. The stand had not been thinned and basal area at felling was 67 m^2/ha, of which approximately 13% comprised dead trees. The general yield class of the stand (maximum mean annual volume increment) was estimated to be 14 m^3/ha/year (Edwards & Christie 1981).

Experimental Design

The experiment was designed as a full factorial, with three factors, each at two levels (absent or present):

- +R residues retained and spread evenly across each plot
- +H herbicide to be applied annually from planting
- +F NPK fertiliser to be applied every 3 years from planting.

The herbicide glyphosate was applied in September 1992 and August 1993. Any Sitka spruce regenerating naturally within the +H plots and which was not killed by the glyphosate was removed by hand. In the F treatments, nitrogen was applied as ammonium nitrate at 470 kg/ha (160 kg N/ha), phosphorus as unground rock phosphate at 450 kg/ha (60 kg P/ha), and potassium as muriate of potash at 200 kg/ha (100 kg K/ha). Fertilisers were broadcast by hand in August 1992. Each treatment combination was randomised between eight plots and replicated three times to give a total of 24 plots.

The site was planted in May 1992 with Sitka spruce of Queen Charlotte Island origin. No site cultivation was carried out, although on plots where residues were retained, it was sometimes necessary to cut a hole in the residue mat using a chainsaw to allow access for planting. Treatment plots were 20 × 20 m with an internal assessment plot of 10 × 10 m. Trees were planted at approximately 2 m spacing, with the density being doubled in the assessment plots to allow for destructive sampling. All trees were treated with permetheron prior to planting and again during the first and second growing seasons in an effort to prevent damage by weevils (*Hylobius abietis* L.).

Micrometeorological Instrumentation

Air temperature was recorded at 10 cm above ground-level using screened thermistors in the –R–H–F and +R–H–F plots. Soil temperature was recorded at 10 cm depth using Skye Instruments SKTS 200-10K thermistors, scanned every 10 minutes and averaged over 2 hours prior to logging on a Campbell Scientific CR10 logger. Temperature recording started in April 1992.

Windspeed was measured at 30 cm above ground-level using Vector Instruments A100R or A101M cup anemometers. This height was chosen as being just above the height of the trees at planting. From April to December 1992, measurements were recorded in two replicate blocks for the –R–H–F and +R–H–F treatments only. Throughout 1993, all three replicate blocks were instrumented and –R+H+F and +R+H+F treatments included to give a total of 12 plots. In each plot, the anemometers were moved around five randomly assigned locations in each quadrant every month to cover plot variability. Windspeed was scanned every 5 seconds and averaged over 2 hours before being recorded on the Campbell logger.

Tree Assessments

Total tree height and root collar diameter (10 cm above ground-level) were measured at time of planting, at the end of the first growing season, and annually thereafter.

Standard foliage samples (Taylor 1991) were taken in the autumn of 1992 and 1993 from current growth on top whorl branches from 10 trees per plot and bulked for each plot prior to chemical analysis for total nitrogen, phosphorus, and potassium. Dried and milled samples were analysed using a semi-micro Kjeldahl method (Wall *et al.* 1975). Ammonium from the digests was measured colorimetrically (Crooke & Simpson 1971) whilst phosphorus and potassium were analysed using Inductively Coupled Plasma Spectroscopy.

Statistical Analysis

Results were analysed using analysis of variance for a randomised block design (Genstat 5 Committee 1987). For tree growth data, initial height and initial diameter at planting were used as covariates in each analysis. Temperature data were analysed using fourier transformation for time series data (Box & Jenkins 1970).

RESULTS

Tree Growth

During the first two growing seasons there was no indication of significant herbicide or fertiliser treatment effects upon tree growth. The initial heights and diameters of trees planted in +R plots were smaller than those planted where residues had been removed (Table 1). However, this difference was significant ($p<0.05$) only for diameters. Results from the end of both the first and the second growing seasons indicated a negative response to the removal of residues for mean tree height ($p<0.05$) but no significant effect on diameter (Table 1).

TABLE 1–Effect of residues on mean tree height (cm) and diameter (cm); 1992 and 1993 values adjusted for initial height and diameter at planting.

	Height (cm)			Diameter (cm)		
	–R	+R	5% LSD*	–R	+R	5% LSD*
Initial	25.6	23.6	2.8	0.50	0.47	0.03
1992	34.1	35.4	1.3	0.58	0.59	0.04
1993	57.9	62.2	3.9	1.17	1.13	0.09

* Least significant difference ($p<0.05$; n=12)

Foliage Analysis

The retention of residues decreased the mean needle dry weight ($p<0.1$) of foliage sampled during October 1992 (Table 2). There was similar weak evidence ($p<0.1$) of an increase in foliage nitrogen and phosphorus concentrations and strong evidence ($p<0.001$) of increased potassium concentrations in foliage where residues had been retained. Herbicide had no significant effect upon needle weights or nutrient concentrations whereas fertiliser applications increased foliage nitrogen and phosphorus concentrations ($p<0.01$) but had no significant effect upon mean needle weight or potassium concentration. Mean needle

TABLE 2–Treatment effects on 1992 mean needle dry weight (mg) and foliage nitrogen, phosphorus, and potassium concentrations (% oven dry weight).

Treatment	Weight	N	P	K
–R	1.77	2.27	0.21	0.74
+R	1.56	2.38	0.22	0.84
–H	1.58	2.33	0.22	0.78
+H	1.75	2.32	0.21	0.79
–F	1.59	2.10	0.20	0.78
+F	1.74	2.55	0.23	0.80
5% LSD*	0.22	0.17	0.02	0.04

*Least significant difference for each main effect ($p<0.05$; $n=12$).

nutrient contents increased with fertiliser application ($p<0.001$, $p<0.01$, and $p<0.1$ for nitrogen, phosphorus, and potassium, respectively) whilst herbicide increased potassium content per needle ($p<0.1$).

In samples collected during October 1993, retention of residues had no significant effect upon mean needle weight, nutrient concentrations, or nutrient contents per needle (Table 3). There was weak evidence ($p<0.1$) that application of herbicide increased mean needle dry weight but had no significant effect upon nutrient concentrations. Consequently, nutrient contents per needle increased significantly for nitrogen ($p<0.1$), phosphorus ($p<0.01$), and potassium ($p<0.01$). Fertiliser application significantly reduced mean needle dry weight ($p<0.01$) with no evidence of any change in nutrient concentration. Consequently, nutrient contents per needle decreased for phosphorus ($p<0.01$) and potassium ($p<0.01$) although the difference in nitrogen content was not significant.

TABLE 3–Treatment effects on 1993 mean needle dry weight (mg) and foliage nitrogen, phosphorus, and potassium concentrations (% oven dry weight).

Treatment	Weight	N	P	K
–R	3.61	2.59	0.22	0.90
+R	3.58	2.57	0.23	0.89
–H	3.48	2.56	0.22	0.87
+H	3.71	2.60	0.23	0.92
–F	3.80	2.53	0.22	0.89
+F	3.39	2.63	0.23	0.90
5% LSD*	0.25	0.17	0.02	0.08

*Least significant difference for each main effect ($p<0.05$; $n=12$).

Temperature

The retention of harvest residues reduced the amplitude of soil temperature fluctuation throughout the year (Fig. 1). From April to September 1992 soil temperature beneath residues was reduced, whereas from October to December 1992 it increased (Table 4). A similar pattern was observed during 1993, although the difference in soil temperature between treatments from October to December was not significant (Table 4). The removal

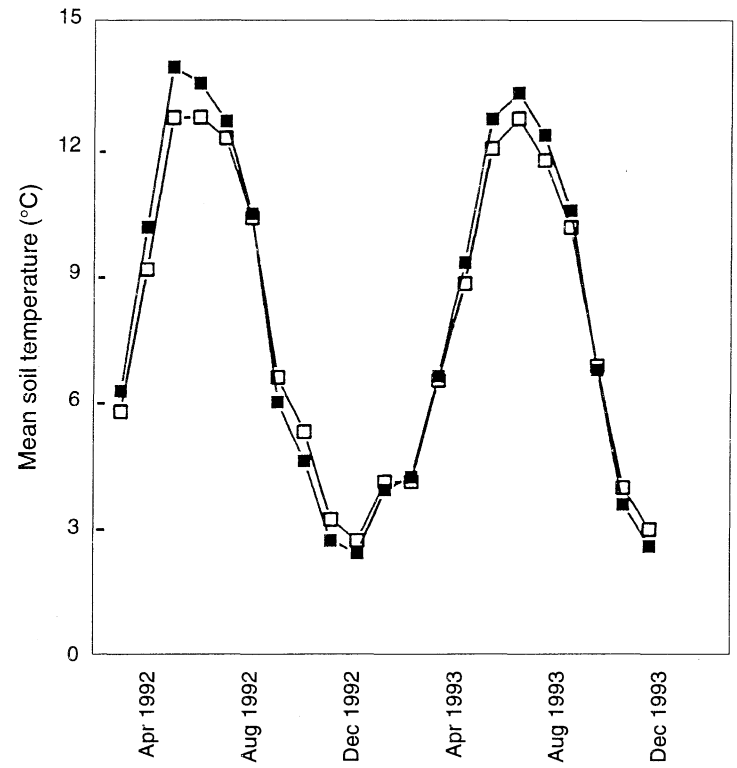

FIG. 1–Effect of harvest residues on mean soil temperature (°C) measured at 10 cm depth. ■-■ = – residues; □-□ = + residues

TABLE 4–Effect of residues on soil temperature (°C) at 10 cm depth. Overall air temperature (°C) also shown averaged across treatments.

	–R	+R	5% LSD*	Air
Apr–Jun 1992	10.2	9.2	0.20	11.2
Jul–Sep 1992	12.3	11.8	0.30	12.2
Oct–Dec 1992	4.4	5.0	0.60	3.4
Jan–Mar 1993	3.5	3.7	0.25	3.3
Apr–Jun 1993	9.5	9.1	0.20	9.7
Jul–Sep 1993	12.1	11.5	0.37	11.4
Oct–Dec 1993	4.2	4.5	0.47	2.7

*Least significant difference for soil temperatures ($p<0.05$; $n=9$).

of harvest residues increased the cumulative soil temperature (above 5.6°C) by 122 day °C (13.5%) during the growing period from April to September 1992. An increase of 91 day °C (10.5%) was observed during the same period in 1993. The removal of harvest residues had no significant effect upon mean air temperature during either year. Fertiliser and herbicide treatments had no significant effect on soil or air temperatures (data not presented).

Wind

Removal of harvest residues increased mean windspeed at 30 cm above ground-level (Fig. 2). During 1992, mean monthly windspeed increased from 1.2 to 1.7 m/s where residues had been removed. A similar increase of 40% was observed in 1993, with the removal of residues increasing mean monthly windspeed from 1.0 to 1.4 m/s ($p<0.001$). Reductions in windspeed due to sheltering by residues were observed in every month. The decrease in windspeed due to sheltering from residues increased with increasing windspeed (Fig. 3). Fertiliser and herbicide treatments had no significant effect on windspeeds (data not presented).

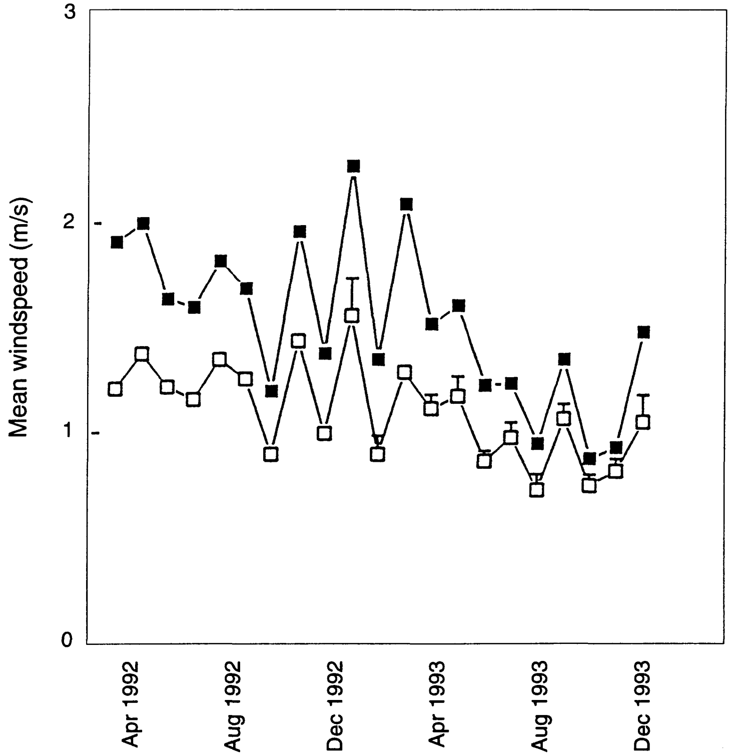

FIG. 2–Effect of harvest residues on mean windspeed (m/s) measured at 30 cm above ground-level.
■-■ = – residues; □-□ = + residues
Vertical bar represents least significant difference ($p<0.05$)

DISCUSSION

Clearfelling of forest stands has been shown to increase nutrient availability because of accelerated decomposition of the forest floor (Likens *et al.* 1970; Vitousek & Matson 1985). During the period of this "assart effect" (Tamm & Pettersson 1969) it is unlikely that a growth response to added fertilisers will be obtained. Although substantial fertiliser treatment effects were observed in the present study with respect to foliage nutrient concentrations, all values measured were well above those considered to be limiting to the growth of young Sitka spruce (Binns *et al.* 1980). In a whole-tree harvesting experiment within 1 km of the

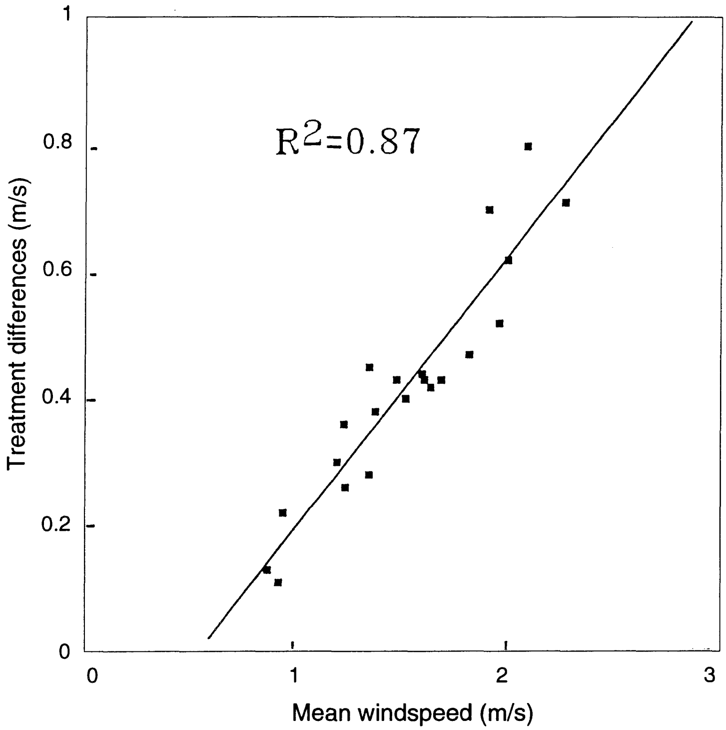

FIG. 3–Effect of mean windspeed upon reduction in windspeed associated with harvest residues (m/s).

present study site, foliage analyses indicated that nutrients were unlikely to be limiting tree growth for at least 4 years after replanting of Sitka spruce (Proe & Dutch 1994). Similar conclusions were reached by Titus & Malcolm (1987).

The lack of response in tree growth to weed control may be due to a lack of competition for nutrients during the period of rapid mineralisation after clearfelling. No detectable effects of herbicide upon microclimate were observed and this was probably due to the slow invasion by weed species after removal of the very dense spruce canopy, and a lack of aggressive weed species on this site. Care should be taken when extrapolating to other, more productive sites. Other studies have shown that weed control and fertiliser application can produce similar increases in tree growth during establishment of plantations in areas where competition for nutrients may be more severe (Colbert *et al.* 1990). In the present study, weed competition may become increasingly important as the "assart" flush of nutrients declines and weed growth continues.

Observed differences between tree growth in +R and –R plots confirm results from a nearby study which reported a significant reduction in tree growth of 0.08 m 3 years after whole-tree harvesting compared to conventional stem-only removal (Proe & Dutch 1994). This initially small response had increased to 0.8 m by age 10 years (Proe & Dutch 1994).

Evidence from other studies would suggest that the observed treatment effects upon soil temperatures should favour growth of trees on whole-tree harvested plots. Tabbush (1986) has shown that the number of new roots per plant increased with increasing soil temperature in young Sitka spruce. Root tip diameter and length of main lateral roots also increase with increasing soil temperatures between 5° and 25°C in young Sitka spruce (Coutts & Philipson 1987). Such increases in soil temperature have been, at least in part, responsible for improved tree growth when Sitka spruce has been planted on mounds to provide a raised planting position in cold wet soils similar to those in the present study (Tabbush & Ray 1989; Nelson & Ray 1990). The present site has a high water-table and roots are likely to be subjected to frequent water-logging. Coutts & Philipson (1987) have shown that Sitka spruce fine roots are susceptible to water-logging and that the level of damage may increase with increasing soil temperature. It is possible, therefore, that in the current experiment where no raised planting position was used, enhanced root growth associated with warmer soils may be offset by a greater predisposition towards damage by water-logging. A critical period for such damage is late autumn, when roots may still be active as the water-table rises (Coutts & Philipson 1987). In the present study, the insulating properties of harvest residues during this period maintained the soil temperature at levels higher than whole-tree harvested plots. The potential interactions between soil temperature, soil moisture, and harvest treatments are complex and further studies are required.

Wind is an important factor limiting tree growth in Britain (Dixon & Grace 1984; Worrell & Malcolm 1987). Boundary layer resistances are lowered by wind, and may lead to reduced needle temperatures and lower reaction rates for chemical processes associated with plant growth (van Gardingen & Grace 1991). Transpiration rates increase in windy conditions, particularly in warm temperatures (Dixon & Grace 1984; van Gardingen *et al.* 1991). Wind can reduce growth through stunting associated with mechanical stimulation (Jaffe 1973) and by abrasion of cuticular waxes (Wilson 1984; Pitcairn & Grace 1985). Under extreme conditions, abrasion of the cuticle may lead to breaching of the epidermis and a very large increase in cuticular conductance (Pitcairn *et al.* 1986). Windspeeds of 11 m/s have been shown to double epidermal conductance after 1 week, whilst rubbing of needles caused an 8-fold increase (van Gardingen *et al.* 1991). The large difference in mean windspeed, at 30 cm above ground-level, induced by the removal of harvest residues appears to be the most likely cause of the observed reduction in tree growth associated with whole-tree harvesting in the current experiment. The increasing level of shelter afforded by harvest residues as windspeed increases may be an important feature of the improved early growth of young Sitka spruce on these exposed upland sites where residues are left on site.

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REFERENCES

ABER, J.D.; BOTKIN, D.M.; MELILLO, J.M. 1979: Predicting the effects of different harvesting regimes on productivity and yield in northern hardwoods. *Canadian Journal of Forest Research* 9: 10–14.

ANDERSON, M. 1985: The impact of whole-tree harvesting in British forests. *Quarterly Journal of Forestry 79*: 33–9.

AVERY, B.W. 1980: Soil classification for England and Wales. Soil Survey of England and Wales, Harpenden. *Technical Monograph No. 14*. 67 p.

BINNS, W.O.; MAYHEAD, G.J.; MACKENZIE, J.M. 1980: Nutrient deficiencies of conifers in British forests. HMSO, London, *Forestry Commission Leaflet No. 76*.

BOX, G.E.P.; JENKINS, G.M. 1970: "Time Series Analysis, Forecasting and Control". Holden-Day, San Francisco.

CAREY, M.L. 1980: Whole-tree harvesting in Sitka spruce. Possibilities and implications. *Irish Forestry 37*: 48–63.

COLBERT, S.R.; JOKELA, E.J.F.; NEARY, D.G. 1990: Effects of annual fertilization and sustained weed control on dry matter partitioning, leaf area, and growth efficiency of juvenile loblolly and slash pine. *Forest Science 36*: 995–1014.

COMPTON, J.E.; COLE, D.W. 1991: Impact of harvest intensity on growth and nutrition of successive rotations of Douglas-fir. Pp. 151–61 *in* Dyck, W.J.; Mees, C.A. (Ed.) "Long-term Field Trials to Assess Environmental Impacts of Harvesting". Proceedings, IEA/BE T6/A9 Workshop, Florida, USA, February 1990. IEA/BE T9/A6 Report No. 5. Forest Research Institute, Rotorua, New Zealand, *FRI Bulletin No. 161*.

COUTTS, M.P.; PHILIPSON, J.J. 1987: Structure and physiology of Sitka spruce roots. *Proceedings of the Royal Society of Edinburgh 93B*: 131–44.

CROOKE, W.M.; SIMPSON, W.E. 1971: Determination of ammonium in Kjeldahl digests of crops by an automated procedure. *Journal of Science of Food and Agriculture 22*: 9–10.

DIXON, M.; GRACE, J. 1984: The effect of wind on the transpiration of young trees. *Annals of Botany 53*: 811–9.

DYCK, W.J.; HODGKISS, P.D.; OLIVER, G.R.; MEES, C.A. 1991: Harvesting sand-dune forests: Impacts on second-rotation productivity. Pp. 163–76 *in* Dyck, W.J.; Mees, C.A. (Ed.) "Long-term Field Trials to Assess Environmental Impacts of Harvesting". Proceedings, IEA/BE T6/A9 Workshop, Florida, USA, February 1990. IEA/BE T9/A6 Report No. 5. Forest Research Institute, Rotorua, New Zealand, *FRI Bulletin No. 161*.

EDWARDS, P.N.; CHRISTIE, J.M. 1981: Yield models for forest management. H.M.S.O., London, *Forestry Commission Booklet No. 48*.

GENSTAT 5 COMMITTEE 1987: "Genstat 5 Reference Manual". Clarendon Press, Oxford, U.K. 749 p.

HENDRICKSON, O.Q. 1988: Biomass and nutrients in regenerating woody vegetation following whole-tree and conventional harvest in a northern mixed forest. *Canadian Journal of Forest Research 18*: 1427–36.

HENDRICKSON, O.Q.; CHATARPAUL, L.; BURGRESS, D. 1989: Nutrient cycling following whole-tree and conventional harvest in northern mixed forest. *Canadian Journal of Forest Research 19*: 725–35.

JAFFE, M.J. 1973: Thigmomorphogenesis: The response of plant growth and development to mechanical stimulation. *Planta 114*: 143–57.

KIMMINS, J.P. 1985: Future shock in forest yield forecasting: the need for a new approach. *Forestry Chronicle 61*: 503–12.

LIKENS, G.E.; BORMANN, F.H.; JOHNSON, N.M.; FISHER, D.W.; PIERCE, R.S. 1970: Effects of forest cutting and herbicide treatment on nutrient budgets in the Hubbard-Brook watershed ecosystem. *Ecological Monographs 40*: 23–47.

LUNDKVIST, H. 1986: Ecological effects of whole tree harvesting—Some results from Swedish field experiments. Pp. 131–40 *in* Williams, T.M.; Gresham, C.A. (Ed.) "Predicting Consequences of Intensive Forest Harvesting on Long-term Site Productivity by Site Classification". Proceedings IEA/BE Project CPC-10 Workshop, Baruch Forest Science Institute of Clemson University, Georgetown, S. Carolina, U.S.A.

MALIONDO, S.M. 1988: Possible effects of intensive harvesting on continuous productivity of forest lands. Forestry Canada—Maritimes, Fredericton, New Brunswick, *Information Report M-X-171*. 26 p.

MANN, L.K.; JOHNSON, D.W.; WEST, D.C.; COLE, D.W.; HORNBECK, J.W.; MARTIN, C.W.; RIEKERK, H.; SMITH, C.T.; SWANK, W.T.; TRITTON, L.M.; VAN LEAR, D.H. 1988: Effects of whole-tree and stem-only clearcutting on post-harvest hydrologic losses, nutrient capital and regrowth. *Forest Science 34*: 412–28.

MARTIN, C.W. 1988: Soil disturbance by logging in New England—Review and management recommendations. *Northern Journal of Applied Forestry 5*: 30–4.

NELSON, D.G.; DUTCH, J.C. 1991: The silvicultural implications of harvesting residues for energy etc. Pp. 148–59 *in* Aldhous, J.R. (Ed.) "Wood for Energy: The Implications for Harvesting, Utilisation and Marketing". Proceedings of a Discussion Meeting, Institute of Chartered Foresters, Edinburgh, U.K.

NELSON, D.G.; RAY, D. 1990: Establishment of Sitka spruce in relation to mound size, plant handling and soil temperature. Forestry Commission, Edinburgh, U.K., *Research Information Note 167*.

PITCAIRN, C.E.R.; GRACE, J. 1985: Wind and surface damage. *Progress in Biometeorology 2*: 115–26.

PITCAIRN, C.E.R.; JAFFE, C.E.; GRACE, J. 1986: The influence of polishing and abrasion on the diffusive conductance of the leaf surface of *Festuca arundinacea* Shreb. *Plant, Cell and Environment 9*: 191–6.

PROE, M.F.; DUTCH, J. 1994: Impact of whole-tree harvesting on second-rotation growth of Sitka spruce: The first 10 years. *Forest Ecology and Management 66*: 39–54.

ROLFF, C. 1986: Some model aspects of whole tree harvesting and site classification. Pp. 121–9 *in* Williams, T.M.; Gresham, C.A. (Ed.) "Predicting Consequences of Intensive Forest Harvesting on Long-term Site Productivity by Site Classification". Proceedings IEA/BE Project CPC-10 Workshop, Baruch Forest Science Institute of Clemson University, Georgetown, S. Carolina, U.S.A.

SENYK, J.P.; SMITH, R.B. 1991: Estimating impacts of forest harvesting and mechanical site preparation practices on productivity in British Columbia. Pp. 199–211 *in* Dyck, W.J.; Mees, C.A. (Ed.) "Long-term Field Trials to Assess Environmental Impacts of Harvesting". Proceedings, IEA/BE T6/A9 Workshop, Florida, USA, February 1990. IEA/BE T9/A6 Report No. 5. Forest Research Institute, Rotorua, New Zealand, *FRI Bulletin No. 161*.

SKINNER, M.F.; MURPHY, G.; ROBERTSON, E.D.; FIRTH, J.G. 1989: Deleterious effects of soil disturbance on soil properties and the subsequent early growth of second-rotation radiata pine. Pp.201–11 *in* Dyck, W.J.; Mees, C.A. (Ed.) "Research Strategies for Long-Term Site Productivity". Proceedings of IEA/BE A3 workshop, Seattle, WA. August 1988. IEA/BE A3 Report No. 3. Forest Research Institute, New Zealand, *FRI Bulletin No. 152*.

STEVENS, P.A.; HORNUNG, M.; HUGHES, S. 1989: Solute concentrations, fluxes and major nutrient cycles in a mature Sitka-spruce plantation in Beddgelert Forest, North Wales. *Forest Ecology and Management 27*: 1–20.

TABBUSH, P.M. 1986: Rough handling, soil temperature and root development in outplanted Sitka spruce and Douglas-fir. *Canadian Journal of Forest Research 16*: 1385–8.

TABBUSH, P.M.; RAY, D. 1989: Effects of rough handling and microsite on the establishment of Sitka spruce on clearfelled sites in upland Britain. *Forestry Supplement 62*: 289–96.

TAMM, C.O.; PETTERSSON, A. 1969: Studies on nitrogen mobilisation in forest soils. *Studia Forestalia Suecica 75*. 39 p.

TAYLOR, C.M.A. 1991: Forest fertilisation. HMSO, London, *Forestry Commission Bulletin No. 95*.

TITUS, B.D.; ad MALCOLM, D.C. 1987: The effect of fertilization on litter decomposition in clearfelled spruce stands. *Plant and Soil 100*: 297–322.

VAN GARDINGEN, P.R.; GRACE, J. 1991: Plants and wind. *Advances in Botanical Research 18*: 189–253.

VAN GARDINGEN, P.R.; GRACE, J.; JAFFE, C.E. 1991: Abrasive damage by wind to the needle surfaces of *Picea sitchensis* (Bong.) Carr. and *Pinus sylvestris* L. *Plant, Cell and Environment 14*: 185–93.

VITOUSEK, P.M.; MATSON, P.A. 1985: Causes of delayed nitrate production in two Indiana forests. *Forest Science 31*: 122–31.

WAIDE, J.B.; SWANK, W.T. 1975: Nutrient recycling and the stability of ecosystems: Implications for forest management in the southeastern U.S. *Society of American Foresters Proceedings 1975*: 404–24.

WALL, L.L.; GEHRKE, C.W.; NEUNER, T.E.; CATHEY, R.D.; REXROAD, P.R. 1975: Total protein nitrogen: Evaluation and comparison of four different methods. *Journal of Association of Official Agricultural Chemists 58*: 807–11.

WILSON, J. 1984: Microscopic features of wind damage to leaves of *Acer pseudoplatanus* L. *Annals of Botany 53*: 73–82.

WORRELL, R.; MALCOLM, D.C. 1987: Productivity of Sitka spruce in northern Britain 1. The effects of elevation and climate. *Forestry 63*: 105–18.