ANEXOS

INFORME TECNICO Y DIFUSION FINAL

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KILMUN ARBORETUM

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Introduction

The Kilmun Arboretum was established in 1930 in the former Benmore Forest (now part of Cowal and Trossachs Forest District, Forest Enterprise, South Scotland Region) and since inception, some 190 species have been planted. It is the largest 'Forest Garden' in Scotland

In 1948, the Forestry Commission's Research Division assumed responsibility for the arboretum. It was charged with the aim of extending the range of species within the arboretum, carrying out a range of assessments on those species and recording regular observations of climatic, insect and fungal damage.

In 1962, a revision of the 1950 Working Plan stipulated that only species that had grown well in arboreta in Scotland should be included in 0.1 ha Plots. (Although many of the plots are in excess of 0.1 ha, in many cases the internal assessment plot is smaller, typically 0.05 ha to 0.075 ha often due to topographical limitations.) Untested species would initially be trialed in smaller Groups. For amenity, small trees and shrubs would be planted where appropriate.

Between 1930 and 1981, 318 Plots were planted. Severe gales (particularly in 1968) and frosts1 (1981/82) destroyed many Plots whilst others were reduced to Group status leaving 117 Plots and 227 Groups. Subsequent changes has produced current figures of 116 Plots and 204 Groups. There are 195 and 67 closed Plots and Groups. Details of these Plots and Groups are kept with reasons for closure.

In 1986 overall responsibility for the Arboretum was returned to Forest Enterprise whilst Research Division (now Forest Research) retained control over the management of 39 Plots and 28 Groups. This has now changed to 46 Plots and 3 Groups. (all the *Eucalyptus* groups were returned to FE in 1994.) Since 1986 the Arboretum has been managed primarily as a forest recreational facility. Maintenance of footpaths and bridges is restricted to way marked visitor routes but many other paths still continue to be used by regular visitors and the keen dendrologist will find that these give easier access to the more out of the way areas of the Arboretum. The presence of the Forestry Commission Research Division's outstation at Kilmun meant that regular maintenance of the plots and groups were possible. However, in 1987 the Outstation was closed and staff transferred to the new Outstation at Cairnbaan, Argyll, some 100 km distant. Since then Plots have been assessed only when funds permit whilst local Forest enterprise staff are currently seeking additional funding to allow improved access, way marking and labelling of Plots and Groups.

Efforts are currently being made to improve the state of the arboretum, which had fallen into decline over the past 20 years. In 2004, a steering group, comprising members from the Forestry Commission, Edinburgh Royal Botanic Gardens, the Area Tourist Board and other local authorities, was set up to monitor and advise on improvements to the arboretum. This recognises the value of Kilmun as an

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1 -10°C recorded in January 1979
-14°C recorded in 1981/82

Thinning has been irregular and sporadic depending on finance and availability of staff. The main problem is slope steepness with the irregular plot layout preventing the easy timber extraction. In recent thinnings, timber has not been removed but simply ciut into manageable lengths and stacked neatly in the plots. This provides shelter and deadwood for improving biodiversity.

Access

Kilmun can be easily reached from the central belt. There are two main routes into the Cowal Peninsula. From Glasgow via the M8 to Gourock where there are two ferry services to Dunoon. Gourock to Dunoon via Calmac and Ashton to Hunters Quay via Western Isles Ferries. Alternatively it is possible to drive via the A82 Loch Lomond, the A83 from Tarbet and the A815 to Benmore.

Once at Kilmun the Arboretum entrance lies 200 m south of Cowal Forest District office and is sign posted. Access is via a narrow tarmac road to the car park. From the car park there are three walks laid out, with timings of between ½ and 2 hours. There are however many minor paths and it is possible to range widely throughout the Arboretum on the trail of interesting species.

Results And Discussion

A total of 582 Plots/Groups of different species or provenances have been established in the arboretum since 1930. Current plots can be found in Table 1 while Table 2 lists those plots and groups which have failed.

The majority of the plots contain conifers which is understandable given the emphasis placed upon such species for forestry in Scotland during the first 50 years of this century.While one has to be careful in reading too much into the assessment data (given the generally small size of the plots), the most recent data from those plots which are managed by the Forestry Commission Research Agency provide a useful guide to those species which have the potential to be high volume producers. The data, for both conifers and broadleaves, is given in Table 3.

The **conifers**, particularly those which are suited to the wet moist climatic conditions, have done particularly well. For example *Abies amabalis, Abies grandis, Abies procera, Cryptomeria japonica, Cupressocyparus leylandii, Sequoia sempervirens and Psuedostsuga menziesii* have all attained basal areas .>75m² and Top heights > 22m leading to GYC's in excess of 20. One of the most interesting plots is that of *Sequoiadenron giganteum* which has an amazing basal area of 108m² yet only has a GYC of 12 due to the surprisingly small top height (17m) As this plot is at the bottom of the slope and generally fairly sheltered, one might have expected better height growth.
Those species more suited to the drier climates, like the *pinus* species and the *Tsugas* have generally grown less well with the exception of *Pinus peuce* with a basal area > 70m², a top height of c 17m giving a GYC of 10 .

Of the **broadleaved** species, only the *Nothofagus obliqua* has grown well, an indication that is could have a place in British Forestry. All of the other broadleaves have, in timber terms, generally grown poorly, there values probably seen as amenity trees.

of these plots will be a helpful reminder of the need to select species that are adapted to the differing climatic regions in Scotland and Britain. If global warming does proceed as predicted, then these plots may serve to make possible changes to the species composition of our forest easier and more accurate.

nitens	1969	New South Wales	All trees dead - severe winter 1981/82 (temp -14C)
perriniana	1949	Tasmania	2 trees. Poor height and diameter, multi stemmed.
simmondsii	1950	Tasmania	Very poor form,multi stemmed, healthy. 1 tree good height.
urnigera	1953	Crarae, Argyll	Now dead - various storms and frosts.
vernicosa	1949	Tasmania	4 trees - 2 poor form and diameter. Healthy.
vernicosa spp columnaris	1949	Tasmania	Poor height and form. Multi stemmed.
viminalis	1969	Crarae, Argyll	All dead - winter 1981/82
Fagus			
orientalis	1962	Bulgaria	Good plot. Healthy but variable growth. Dense stems.
sylvatica	1933 / 1953	Benmore own collection / Sussex and Moray	1993 plot total loss. 1953 good healthy plot.
Fraxinus			
americana	1934	S. France Vilmorin-Andrie	Relegated to group
excelsior	1934 / 1935 /1953	Home forest / home seed / Dean, Glos	1934 and 1935 plots total loss. 1953 relegated to group in 1962.
Juglans			
cinerea	1935	Home nursery	2 trees left - relegated to group. Small and not healthy looking.

GENUS/SPECIES	PYEAR	ORIGIN	CURRENT HEALTH STATUS
Populus			
trichocarpa	1930	Home nursery cuttings	Diseased (Bacterial Canker?). Felled
Prunus			
avium	1953	Scotland	Variable quality - but healthy and growing well.
Pseudotsuga C			
macrocarpa			
menziesii	1933 / 1953	Oregon USA/ Manning Seed Co (Washington) / Herbst Bros B.C	1933 poor plot for species and age. Very variable. 1953 Good plot. 1953 Var Caesia. Poor form. Variable growth and health.
Pyrus			
communis			
Quercus			
petraea	1932 / 1959	Brandenburg, Germany / Hell's Glen & Deer Prk,Benmore	1932 plot total loss - vole damage. 1959 reasonable plot. Slow growth.
robur	1957	Kirkudbright	Reasonable plot. Recently thinned.
rubra	1934 / 1953/1956	USA /Arnhem Holland	1934 plot total loss. 1953 poor survival. Possibly hybridised. Some butt rot in a few inches.
Rhamnus			
frangula	1954	N. Italy, Ansaloni	Cedrus deodara. Generally poor health and vigour.
Robinia			
pseudoacacia	1934 / 1950	France / B.C.	1934 plot - 1 tree remains (honey fungus damaged / killed others). 1950 plot closed - 100% vole damage
Salix			
triandra			Trees removed - ground required.
Sorbus			
aria	1955	Benmore Garden	A good plot. Both health and form good.
Thujopsis			
dolabrata	1957	Bagley Wood	Healthy but multi stemmed.
Tilia			
cordata	1935	Czechoslovakia	Form is only fair.
Ulmus			
montana	1953	Yorkshire	

pensylvanicum	1935	USA,Blue Ridge Mts,N Carolina	Poor form and colour - relegated to group status.
platanoides	1933 / 1935 /1953	Hursley, Hants	1933 and 1935 plots total loss. 1953 plot - good health.
pseudoplatanus	1951	South Scotland	Large plot, requires thinning. Good health.
rubrum	1934	USA, Philadelphia	Total loss by 1950.
saccharum	1934	USA Rockingham CO.	Poor form.
Ailanthus glandulosa	1953 /1955	N Italy	Both written off - mice damage and road line.
laricina	1960	Ontario	Generally poor health and vigour. Some dieback.
occidentalis	1933 / 1967	Fraser River, Canada/ Shuswap Lake, British Columbia	1933 plot written off / 1967 Very poor health. Dead and dying.
sibirica	1961	USSR	Written off - poorplot.
x eurolepis	1959	East & Central Scotland	Excellent plot - health, form and vigour.
Metasequoia			
glyptostroboides	1951 / 1955	Unknown / cuttings Kew	1951 - Very mixed growth and form. 1955 plot cleared.
Picea			
albertiana	1954	Montana USA	Variable plot. Moderate health. Albertiana?
abies	1930 / 1953	Switzerland	1930 - small, growing amongst exotic rhododendron. 1953 plot requires thinning, otherwise healthy.
asperata	1961	Glentanar	Variable growth in a dead and dying plot.
breweriana	1966	California, USA	Generally poor plot. Poor growth. Health reasonable.
engelmannii	1933 / 1953	Forestry Commission seed / Canada, Herbst Bros.	1933 plot total loss. 1953 very tall, slim stems and thinnish crowns. Thinned c 5 years ago.
glauca	1930 / 1937 /1956	U.S.A. / Cumloden, Argyll /Jutland	1930 Poor Plot. Poor slow growth for age. 1937 - most of plot felled (under power line) now Group 24. 1956 plot - moderate health. Not outstanding.
glauca	1930	U.S.A.	Poor slow growth for age
glauca	1956	Jutland	Moderate health. Not outstanding.
glehnii	1938 / 1963	Cumloden, Argyll /Hokkaido, Japan	1938 plot - poor height, good form and colour, heavy branched. 1963 - Good healthy plot. Not tall but dense crop. Colour good.
lutzii	1967	Moose Pass,Kenai Pen,Al	
jezoensis	1936		Written off - hurricane 1968.
mariana	1954	USA	Very poor health. Dieback, blowing. Dying?
obovata	1937	Russia 1930	Written off.
omorika	1930/1932/ 1953	Tullialian Nursery / gift from Sir J Stirling Maxwell / Germany, Rahte	1930 group poor height but good form and colour. 1932 group - very few trees, heavy branched, tall straight stems 1953 plot - good health and condition.
orientalis	1953	Carnwath Estate, Lanark	Very good healthy plot.
patula	1933	Mexico - RBG	Total loss at 5th year.

pungens	1959	Pennsylvania	Very small group but individuals healthy.
radiata	1933 - 34 / 1960	Dorset	1960 - Very variable. Some trees very thin crowned.
resinosa	1954	Canada	Complete failure
rigida	1951	Herbst Bros. USA	Mixed growth rates.
strobus	1964	Spessart, Bavaria, Germany	Windblow present. Health good.
sylvestris	1930 - 1933 / 1953 / 1970	Lapponica/Achachoich Estate, Scotland / Slattadale, Wester Ross	1930 - 1933 1 group of good quality and health. 1953 - reasonable growth and form. 1970 - Poor quality plot. Variable health and growth.
sylvestris scotica	1932	Glen Moriston, Inverness-shire	Written off
tabuliformis	1932/1933	Rock	written off
taeda	1933 / 1954	Georgia, USA	Complete failure
thunbergii	1958	Chila, Japan	Slow growth, wind damage - possibly too exposed.
uncinata	1930	France, Pyrenees,Mt Louis 1925	Very good growth and health.
Sequoia			
sempervirens	1933 / 1954	Europe /Northern California, USA	1933 relegated to group. 1954 very highly stocked. Good health.
Sequoiadendron			
giganteum	1961	California	Excellent plot. Good health and growth.
Thuja			
occidentalis	1954	Buriton, Hants	Poor plot. Snap, blow dying. Survivors - poor health.
plicata	1930	Lower Fraser Valley, B.C. 1923	Large plot. Trees in excellent health
plicata	1954	Caernarvonshire	Very good plot.
Tsuga			
heterophylla	1930 / 1956	1926 Canada, B.C./ Q. Charlotte Islands	1930 plot very good growth and health. 1956 plot - gGood growth. Heavy branching.
mertensiana	1959 / 1961	Estacada,Oregon / Juneau, Alaska	1959 plot appears good but top height low. 1961 plot - Very poor height,heavily branched,multistemmed. Colour good- 'blow.

GENUS/SPECIES		PYEAR	PLOT	CLREAS
Pinus nigra		1933	P77	Relegated to Group Status
Pinus peuce		1937	P150	Total loss
Pinus pinaster		1930	P34	Made into Group 8 - 1 tree
Pinus pinaster		1933	P73	No trace of plot.
Pinus pinaster		1933	P76	Relegated to Group status
Pinus pinaster		1954	P217	Relegated to Group status
Pinus ponderosa		1933	P67	Relegated to Group Status
Pinus ponderosa		1933	P78	Total loss
Pinus ponderosa		1949	P179	No trace of plot. 1 tree alive in 1952.
Pinus radiata		194	P178	Complete loss.
Pinus radiata		1933	P62	Relegated to Group status
Pinus radiata		1933	P64	Relegated to Group Status
Pinus radiata		1934	P120	Plot clear felled (outside Genus block)
Pinus resinosa		1954	P218	Written off - plants stripped of bark by mice
Pinus sylvestris		1930	P20	Relegated to Group status
Pinus sylvestris		1930	P25	Amalgamated with P24 and relagated to Group status
Pinus sylvestris		1930	P29	Felled. Area replanted & renumbered P288
Pinus sylvestris		1930	P30	Relegated to Group status
Pinus sylvestris		1930	P31	Total loss
Pinus sylvestris		1930	P32	Relegated to Group status
Pinus sylvestris		1932	P36	Diseased (Bacterial Canker?). Felled.
Pinus sylvestris		1932	P37	Relegated to Group status
Pinus sylvestris		1932	P38	Relegated to Group Status
Pinus sylvestris		1932	P39	Relegated to Group status
Pinus sylvestris		1932	P40	Relegated to Group status
Pinus sylvestris		1932	P41	Relegated to Group status
Pinus sylvestris		1932	P43	Total loss
Pinus sylvestris		1933	P69	Relegated to Group status
Pinus sylvestris			P168	Hurricane 1968. Clear felled January 1969
Pinus sylvestris	scotica	1932	P44	Relegated to Group status
Pinus tabuliformis		1932	P60	Relegated to Group status
Pinus tabuliformis		1933	P61	Relegated to Group status - poor survival
Pinus taeda		1933	P74	Relegated to Group status
Pinus taeda		1954	P221	Relegated to Group status
Populus trichocarpa		1930	P35	Felled - ground required for new plot

LIST OF FAILED GROUPS

GENUS/SPECIES	PYEAR	PLOT	CLREAS
Abies balsamea	1935	G175	2 remaining trees windblown 1980/82. Written off.
Acer	1969	G198	No survivors.
Acer saccharinum	1969	G201	No survivors - written off.
Ailanthus glandulosa	1960	G43	All plants dead
Betula albo-sinensis	1940	G117	Written off - ?1970
Catalpa bignonioides	1963	G121	Written off - no signs of life.
Cedrus libani	1962	G110	
Cupressus macrocarpa	1933	G171	Gales blew down last 2 survivors of this group
Eucalyptus	1955	G25	1 surving tree - badly leaning
Eucalyptus	1958	G112	The 1 survivor died severe winter 1978/79
Eucalyptus	1959	G182	All trees killed severe winter 1981/82 (temp -14)
Eucalyptus	1959	G183	Severe winter of 1981/82 (temp -14) - 1 survived
Eucalyptus	1960	G189	All trees dead after severe winter 1981/82.
Eucalyptus	1960	G190	Sole survivor killed winter 1981/82 (temp -14C)
Eucalyptus	1963	G118	all trees dead
Eucalyptus	1963	G119	Written off - no survivors
Eucalyptus	1963	G120	No survivors
Eucalyptus	1963	G123	Written off - year unknown - 1 survivor 1971
Eucalyptus	1964	G126	No survivors after winter 1981/82 - temp -14C
Eucalyptus	1965	G137	No survivors.
Eucalyptus	1966	G142	No survivors
Eucalyptus	1966	G145	No survivors
Eucalyptus	1966	G148	No survivors
Eucalyptus	1966	G149	All trees died winter 1978/79 - min temp -10C
Eucalyptus	1969	G211	Written off - winter 1981/82 temp -14C.
Eucalyptus	1969	G214	No survivors - windblow & windbreak winter 1976/77
Eucalyptus	1970	G217	No survivors.
Eucalyptus dalrympleana	1969	G207	Last survivor dies winter 1981/82 (temp -14C)
Eucalyptus nitens	1960	G188	All trees dead - winter 1981/82 (temp -14C)
Eucalyptus nitens	1969	G208	All trees killed winter 1981/82 (temp -14C)
Eucalyptus nitens	1969	G209	All trees killed winter 1981/82 (temp -14C)
Eucalyptus nitens	1969	G210	Written off - winter 1981/82 (temp -14C)
Eucalyptus pauciflora	1959	G34	None given

TABLE 3

TOP HEIGHT (m) CUMULATIVE BASAL AREA PRODUCTION (m^2ha^{-1}) AND ESTIMATED GENERAL YIELD CLASS OF RESEARCH DIVISION MANAGED PLOTS AT KILMUN ARBORETUM

SPECIES		AGE	BASAL AREA	GYC	TOP HEIGHT
Abies	alba	41	61.54	14	19.80
	amabalis	39	74.75	22	24.50
	cephalonica	48	79.20	14	21.50
	fraserii	37	64.82	14	17.50
	grandis	42	73.07	28	31.50
	lasiocarpa	38	18.29	12	16.00
	lasiocarpa var arimonica	27	18.72	10	7.50
	lowiana	39	59.98	18	23.20
	pinsapo	41	49.41	12	18.00
	procera	41	84.24	22	22.40
	sachalinensis	33	60.00	14	15.50
Acer	macrophyllum	63	58.67	12	28.00
	platanoides	44	30.62	2	13.00
Alnus	cordata	63	88.83	12	24.80
	glutinosa	28	31.05	4	12.90
	incana	28	48.71	4	10.20
Betula	lenta	46	26.47	2	8.20
	lutea	47	31.86	2	9.00
Cryptomeria	japonica	43	98.56	24	24.60
Cupressocyparis	leylandii	38	73.44	24	22.40
Fagus	orientalis	35	44.21	6	11.20
	sylvatica	44	52.52	10	23.50
Larix	kaempferi	63	79.38	12	27.00
Nothofagus	obliqua	41	30.41	18	26.40
	procera	25	78.11	14	18.00
Picea	albertiana	43	20.31	10	17.40
	engelmannii	44	36.60	12	17.50
	omorika	44	84.76	12	17.50
	orientalis	44	68.13	14	19.00

TABLE 4

SOME NOTABLE EUCALYPTS AND NOTHOFAGUS

SPECIES		YEAR PLANTED	PROVENANCE	NOTES	LARGEST IND HT X DBH
Eucalyptus	coccifera	P49	Tasmania	Poorly site. Good winter survival	21.5 m x 56 cm
	coccifera	P52	Tasmania	Good survival in severe winters	19 m x 59 cm
	dalrympleana	P52	Brind Abella	Severe dieback 1981 / 82 due to frost	19 m x 45 cm
	gigentea	P60	Victoria, Australia	Considerable dieback in 81/82 winter	25.5 m x 64 cm
	gunni x gigantea	P49	Tasmania	Poor form.	23.5 m x 73 cm
	mitchelliana	P50	Mt Buffalo, Australia	From subalpine zone	17.5 m x 50 cm
	simmondsii	P50	Mt Arrowsmith, Tasmania	44% survival after 81/81	22 m x 82 cm
	simmondsii	P52	Tasmania	55% survived winter 81/82	28 m x 68 cm
	urnigera	P52	Crarae	72% survived 81/82 winter	23.5 m x 57 cm
	vernicosa	P49	Lake Dobson, Tasmania	Only one tree died in 198/82. Poor form	31 m x 57 cm
Nothofagus	antartica	P61	Inveraray Estate	Group suffered from windblow	11 m x 32 cm
	betuloides	P79	Chile	Suffered severe dieback post planting	16 m x 33 cm
	betuloides	P79	Chile	Deer damage and dieback after winter 1981/82	11 m x 25 cm
	dombeyi	P61	North Korea	Suffered stem dessication from winter weather	19 m x 73 cm
	menziesii	P59	New Zealand	Winter 69/70 severely desscicated small trees but larger trees left undamaged.	12 m x 49 cm
	nervosa	P56	Chile	Frost scorch ruined the bottom metre of the butt.	28 m x 48 cm

Findlay's Seat Reserve, Teindland Forest

This area was chosen in 1925 for experimental work on sites that were considered unplantable using the techniques of the time. It has been a major centre for investigation of afforestation techniques until the 1970's. Further background, including photographs from the 1950's can be found in Zehetmayr (1960).

Site Details

Elevation c. 240 m asl; rainfall c. 890 mm; ESC climate zone: cool-moist; WHC IV.

Lithology

Middle Old Red Sandstone sandy conglomerate.

Soil Details

A podzolic ironpan soil with indurated material in the ericaceous phase (code 4zxe). There is c. 10 cm of surface peat. The hard ironpan generally lies at around 35 cm depth and lies immediately above a strong indurated layer some 40 cm thick.

The soils derived from these ORS sediments are inherently low in nitrogen and in phosphorous. As category D sites in nutritional terms (Taylor, 1991) establishing pure Sitka spruce would require N inputs every 3 years, and heather control would not be cost-effective.

The undisturbed soil would be classed as nutritionally very poor and moist to very moist in terms of soil moisture using the ESC classification.

Vegetation

Dominant heather (*Calluna vulgaris*) with *Cladonia, Trichophorum, Sphagnum* spp. and *Erica tetralix*.

a. Undisturbed reserve

An area of some 5 ha retained without management. The old Scots pine are around 150 years old and represent the survivors of early attempts to replant the Speyside heathlands (see photograph for conditions in 1951).

These early attempts may have used heather burning and limited hand site preparation to help establish trees. However no cultivation was employed. There now appears to be progressive colonisation of this reserve by lodgepole pine (*Pinus contorta*) which is more tolerant of the very moist soil conditions.

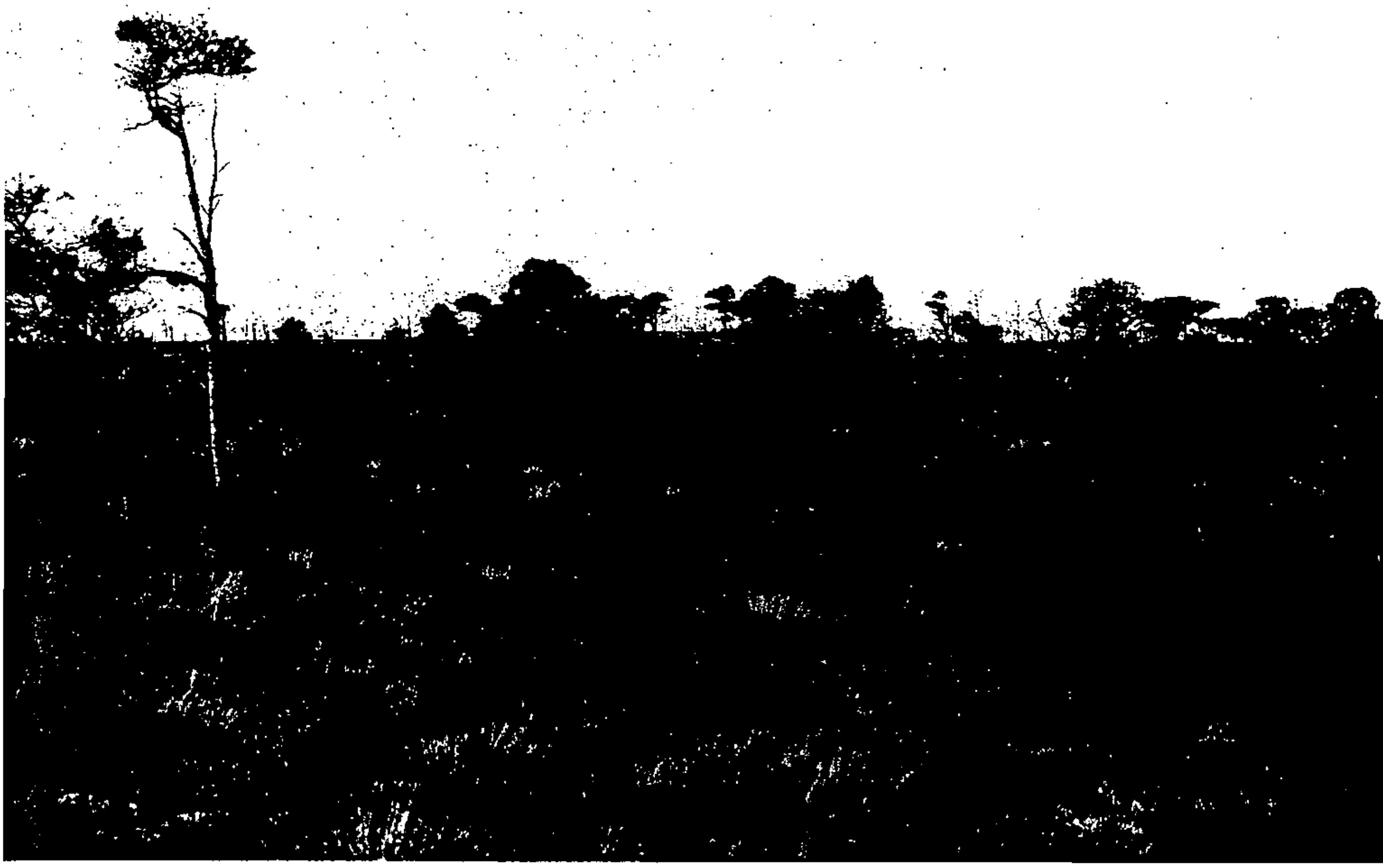

Plate 4. Findlay's Seat, Teindland, 1951. These survivors of the 100-year-old planting rarely exceed twelve feet in height; the trees in background were killed in the 1942 fire. *Calluna–Trichophorum* vegetation.

b. Soil Pit

This shows the undisturbed profile including the shallow peat layer, the strong ironpan and the indurated layer.

c. Cultivation experiment: Teindland 81 p52

Objective

This experiment examines the effect of 6 types and intensities of ploughing upon the growth of Scots pine and of a lodgepole pine/Japanese larch mixture. There are subsidiary plots of Sitka spruce, Norway spruce, Douglas fir and western hemlock, all planted in mixture with Japanese larch.

Background

When established, a review of earlier cultivation experiments at Teindland had concluded:

- the surface layer of peat must be broken to expose the mineral soil;
- each plant must be planted on broken soil or turf and early growth improves with more complete ploughing;
- deeper cultivation is beneficial.

Treatments (see also attached diagram)

Code	Description	Ploughing Depth (cm)	Subsoil Depth (cm)	% Breakage of Ironpan
A	Deep spaced furrow ploughing	30	-	10
B	Shallow spaced furrow tine ploughing	20	40	25
C	Shallow complete ploughing	18	-	0
D	Shallow complete ploughing and subsoiling	18	43	15
E	Deep complete ploughing	33	-	50
F	Deep complete ploughing plus rotovation	30	-	40

Supplementary basic treatments

1952 - P fertiliser to all treatments;
1970 - PK fertiliser to all treatments;
1978 - N Fertiliser to Sitka spruce plots;
1971, 1977, 1982, 1988 - Thinning of treatments A, D, F.

Figure 1.

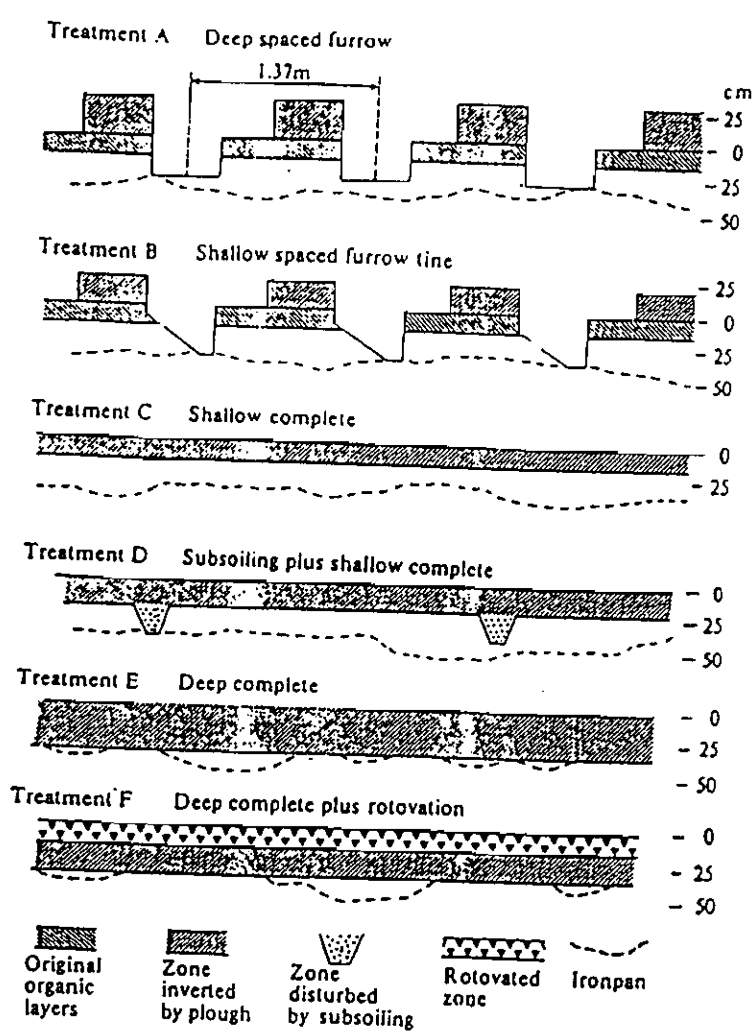

Fig. 1. Schematic diagram of ploughing treatments.

Plot Size

0.4 ha split for the major species. A randomised block design with 3 replications.

Results

This experiment has been studied over many years. Results at various stages are presented in Zehetmayr (1960), Thompson and Neustein (1973) and Wilson and Pyatt (1984).

In brief, early growth showed a major response to the more intensive cultivation treatments and was one of the causes of the move to intensive site preparation in upland Britain in the period 1960-1975. However, this benefit did not persist beyond the initial 15-20 years. Assessments at 30 years showed no significant differences between treatments in terms of volume or basal area. These results are confirmed by the more recent assessments of the Scots pine plots (see below). This transient early benefit of intensive cultivation has become known as the 'Teindland effect'.

Irrespective of cultivation treatments, the effect of the trees has been to reduce soil wetness sufficiently to remove the problems caused by the perched water table and promote soil aeration. In all treatments, rooting is limited by the indurated subsoil.

The good growth of the Sitka spruce planted in mixture with Japanese larch should be noted. This mixture has produced good stands of spruce saw logs in other experiments in the reserve.

Current cultivation recommendations (Paterson and Mason, 1999) for this site type are: either complete tine ploughing or spaced tine ploughing plus ripping in the afforestation phase; disc trench scarification at restocking (assuming the ironpan was broken during afforestation).

Table 1. Teindland 81 p52

Growth of Scots pine after 45 years

Ploughing Treatment	Thin	Standing Basal Area (m^2 ha^{-1})	Top Height (m)	GYC
A	✓	48.2	15.8	8
B		63.6	15.7	8
C		65.0	16.0	10
D	✓	47.3	16.2	10
E		65.2	15.9	10
F	✓	52.4	16.2	10
SED		2.7	-	-

Note: Analysis shows a major effect of thinning but no effect of cultivation. The effect of thinning is removed if cumulative basal production is considered.

Species Experiment – Speymouth 52 p85

Objective

To compare the growth of a range of alternative conifer species to Sitka spruce under restocking conditions.

Site Details

Location in the lower slopes of Teindland forest. Elevation c. 120 m asl; rainfall 800 mm; ESC climatic zone: cool-moist; WHC III.

Soil

A hard pan podzol (3m) with occasional pockets of podzolic gley (7z) overlying induration. Rooting depth is appreciably greater than at Teindland 81. However, other comments about soil nutrient status and soil moisture regime apply.

Vegetation

Calluna dominant.

History

Previous stand was a mixture of p30 Scots and lodgepole pine felled in 1983. Ploughed in 1985 with a spaced tine plough (S45/T60/m).

Treatments

Pure species plots: Scots pine, lodgepole pine (both Skeena and interior provenances), Sitka spruce (both Washington and Queen Charlotte Islands provenances), Japanese and hybrid larches, Douglas fir, grand fir, noble fir, Pacific silver fir, Englemann/White spruce.

Mixed plots: Sitka spruce with respectively Scots pine, Japanese larch and Alaskan lodgepole pine.

Plot size

0.06 ha. Randomised block design with 3 replications.

Supplementary Basic Treatments

1985 – P fertiliser at planting;
1990 – Heather control in pure plots (except pines, larches);
1991 – N fertiliser to all pure plots;
– P fertiliser to all plots.

Results

After 10 years, there are highly significant differences between treatments in height growth as shown below:

a. *Pure Plots*

Species	HL	JL	ILP	KLP	WSS	DF	GF	PSF	QSS	SP	NF	ESWS	SED
Height (m)	6.4	4.9	4.0	3.8	3.7	3.3	3.3	3.2	3.1	2.9	2.7	2.3	0.3

b. *Mixed Plots*

Species	QSS/SP	QSS/ALP	QSS/JL
Height (m)	2.5/2.7	2.1/3.1	2.3/4.8

Foliage analysis in 1995 indicates that all spruce plots (ie pure and in mixture) are deficient for N. However, we expect the nursing mixture effect to occur within the next 2-4 years. In brief, this effect is believed to be due to mycorrhizal fungi associated with the nurse species which enhance N availability (Ryan and Alexander, 1992) and greater phosphate retention (Williams, 1996) in the mixed stands.

Discussion

The results indicate the promising growth that can be obtained from a wider range of conifer species on this slightly deeper rooting soil. However, the very poor nutritional status of these soils is exemplified in the input of N and the requirement for heather control. It seems unlikely that pure stands of higher yielding species will be a feasible option on these nitrogen poor heathland soils.

Overall Conclusion

Sustainable silviculture on the heathlands of northereastern Scotland overlying Old Red Sandstone requires careful attention to site limitations. These are expressed primarily through nitrogen and phosphate status, but also by reduced rooting depth and increased soil moisture status as a result of iron pan formation. Cultivation can improve rooting depth by disrupting compacted horizons where these occur but there is no other justification for more intensive methods. Harvesting needs to pay particular concern to maintaining the nutrient capital of the site and whole tree harvesting may be risky on the poorest sites. Less demanding species such as pines and larches are the safest choice. Other species can provide satisfactory alternatives if planted in mixture so that they benefit from the nursing effect.

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Nutrient Cycling and Availability in Forest Soils after Harvesting

Background:

The 1998 UK Forestry Standard requires that forest soil condition is stable or improving and that harvesting should not result in a decline in soil quality. Such issues can be a particular concern following whole tree harvesting since the concentrations of nutrients in brash and foliage are higher than in the stem (Dutch, 1995). An experiment in the 1980's in Kielder showed a c. 40% decline in spruce biomass following whole tree harvesting. However, it was unclear whether this effect was due to nutrition, shelter or other factors. This experiment, along with two other sister experiments, Kielder 147 P1992 and Ae 79 P1996, was established in partnership with MLURI to quantify these effects. This series of three experiments lie on an ESC soil nutrient regime gradient with Moray very poor, Kielder poor and Ae on the upper part of poor.

Objectives:

1. To quantify the relative importance of nutrition, shelter and weed suppression in improving the growth of trees planted in the absence or presence of brash.
2. To quantify the effects of brash on microclimate.
3. To validate model predictions of tree growth.
4. To study the effect of brash on the development of ground flora.

Site description:

Location:	Teindland Forest, Moray FD. (NGR: NJ283542)
Soil type:	Podzolic ironpan.
Lithology:	Middle Old Red Sandstone.
Elevation:	240 m a.s.l.
Aspect:	Flat, open to N and NE.

Previously this site was a mixed species/cultivation experiment, Teindland 69 P1948. The new experiment was imposed upon the original blocks in such a way that any carry-over effect can be ignored.

Treatments:	**O**	Brash removed (completely removed from site)
	B	Brash retained (evenly spread across site)
	F	Fertiliser applied (NPK at planting, repeated every 3 years)
	H	Herbicide applied (glyphosate as required to retain weed free conditions)
Fertiliser applied as:	N	urea @ 350 kg/ha
	P	UPR @ 450 kg/ha
	K	muriate of potash @ 200 kg/ha

Last fertiliser application 2001, next 2004.

Design:

Fully factorial (2^3) replicated in 3 blocks. Plot size 9 x 9 (81) trees at ~2.0m spacing with an internal assessment plot of 7 x 6 (42) trees.

Summary of results:

Treatment	N	P	K
O			
OF	1.49		
OH			
OHF			
B			
BF			
BH		0.17	
BHF	1.45		

	Deficient
	Marginal
	Optimal

Table 1: Foliage analysis, 2002 (% DW).

Table 1 shows that all fertilised (+F) treatments have higher levels of N (>1.5), P (>0.18) and K (>0.7). All treatments without fertiliser are sub-optimal for N and P, those without brash (+O) being poorer than those with brash (+B). The only deficient treatment is the untreated control (O), deficient in N (<1.2). Herbicide treatment (+H) has the effect of increasing foliar N.

Treatment	Yr 4 (2001)		Yr 6 (2003)	
	Ht (m)	Dm (mm)	Ht (m)	Dm (cm)
O - brash removed	1.53 bc	34.7 b	2.58 ab	5.77 a
B - brash retained	1.94 a	41.4 a	3.51 d	7.07 c
OF - brash removed, NPK every 3 years	1.63 b	35.7 b	3.09 c	5.72 a
BF - brash retained, NPK every 3 years	1.64 b	32.1 b	2.97 c	7.10 c
OH - brash removed, weed free (herbicide)	1.38 c	34.2 b	2.48 a	6.96 c
BH - brash retained, weed free (herbicide)	1.56 bc	36.1 b	2.91 c	6.66 bc
OHF - brash removed, NPK every 3 years, weed free (herbicide)	1.43 bc	34.4 b	2.89 bc	6.38 b
BHF - brash retained, NPK every 3 years, weed free (herbicide)	1.54 bc	34.7 b	2.96 c	6.56 b

Table 2: Height and diameter (at 10cm) at years 4 and 6 years from planting. Figures within an assessment followed by the same letter are not significantly different (based upon 5% LSD).

The growth data in Table 2 show a consistent significant difference on both height and diameter between brash removal (O) and brash retention (B), with the B treatment giving greater growth. The effects of herbicide (+H) and fertiliser (+F) and their various interactions are less clear but in all cases give poorer growth than simple brash retention (B).

The sister experiment, Kielder 147, now 10 years since planting, also shows the benefits of brash retention and addition of fertiliser with both giving significant improvements in growth and foliar N and P levels. There is also an indication of a positive combination effect. Herbicide treatment has had no significant effects. These effects did not occur for the first 8 years after planting, conforming with trends reported from other restocking experiments with spruce (Smith & McKay, 2002) showing a progressive decline in N foliage levels in unfertilised trees up to 10 years after planting.

Conclusions:

1. Brash removal can lead to a reduction in yield of second rotation Sitka spruce, depending on site fertility.
2. The reduction in growth following brash removal is of the order of 10 – 20% in height and 20 – 30% in basal area (based upon Kielder 147).
3. Retention of brash alone may not be sufficient to maintain nutrient levels at the required level on nutritionally very poor/poor soils.
4. Herbicide treatment has little effect on either nutritional status or subsequent growth.
5. The long-term effect appears to be nutritional although shelter may provide some initial benefit, as shown at the Kielder experiment.

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The Potential for Tree Growth and Woodland Creation in the Western Isles of Scotland

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Summary

Despite the perception that the Western Isles is a treeless region of Britain there is ample evidence of successful tree growth throughout the islands. Results from experimental plots established by the Scottish Agricultural College and the Forestry Commission, together with information from many other woodlands demonstrate that woodlands can be created and achieve quite respectable growth rates. Exposure and grazing pressures are limiting factors but correct choice of species and sound silvicultural practices will ensure success. Commercial stands of timber can be grown on the more sheltered sites but the major benefits will be shelter for homes and livestock and creation of additional wildlife habitats. Extensive planting of the ecologically important machair lands should be avoided.

Introduction

The Western Isles of Scotland have been almost devoid of natural tree cover for so long that it is commonly asserted that trees cannot grow there. Indeed some early 18th and 19th century records refer to the complete absence of trees and the barrenness of the landscape. For example, Macgillivray in 1831 stated "Speaking generally one might pronounce these islands entirely destitute of wood. In fact, an incurious person might travel from one end of them to the other without seeing a single shrub." Early attempts by land proprietors to grow trees usually ended in failure. However, despite such assertions, there are numerous examples of natural woods and trees growing in favourable locations throughout the islands. These woods usually occupy sites inaccessible to grazing animals and are sheltered from the worst of the winter gales. More recently there have been examples of tree planting on a variety of sites throughout the Isles and lessons can be learned from both successful and unsuccessful schemes. The successes highlight the benefits of woods as shelter for homes and livestock and as habitats for plants and wildlife. Such successes have created a demand for more woodlands, and planting by both individuals and organisations (such as Achmore township on Lewis and the Stornoway Trust) has increased over the last 15 years.

The results presented here from Forestry Commission experiments and plantations, and Scottish Agricultural College trial plots, highlight suitable species (both tree and shrub) and indicate the timber, shelter and wildlife benefits of woodlands. The silvicultural principles recommended are similar to those used in other exposed areas of the British Isles.

The Environment for Tree Growth

1. CLIMATE

The islands lie in the path of frequent Atlantic depressions bringing rain and strong, salt-laden winds. Rainfall varies from 1200 mm, on the low lying western edge of the islands, to 1400 mm on Harris where the mountains are close to the sea (Boyd *et al.*, 1990). There is a potential water surplus in every month of the year, but severe water deficits can occur in early spring on the sandy machair soils when sunshine and warm south-westerly winds combine with low rainfall.

The Western Isles are situated in one of the windiest regions in Europe. The average windspeed on Benbecula is 7.5 m s^{-1} compared with 5.0 m s^{-1} in Edinburgh or 2.5 m s^{-1} in the relative shelter of the Great Glen at Fort Augustus (Bibby *et al.*, 1988). Gale force winds (windspeeds 17.2 m s^{-1} or greater) are a regular feature of the climate and on average occur on over 30 days a year compared with only 4 days in Glasgow (Meteorological Office, 1989). The winds are reflected in tatter flag measurements which provide an estimate of degree of exposure (Miller *et al.*, 1987). Tatter rates above 10 cm^2 day-1 are likely to result in poor stem form and a reduction in timber value, but this is less important if the main objectives are to provide shelter and wildlife habitats. Despite the prevalence of strong winds the average tatter rate (Table 1) on low level sites on the islands indicates that satisfactory tree growth is possible. However, at elevations greater than 100 m tree growth will be more limited.

The climate is a very temperate one and long spells of freezing weather are unusual except on the high hills of Harris and South Uist. Mean annual temperatures are similar to those found elsewhere in the British Isles but the seasonal range is much less (9 °C at Benbecula, 10.6 °C at Aberdeen, 11.6 °C in Glasgow and 13.5 °C in the London area). The diurnal range is also reduced by the maritime influence and is typically only 5 °C in July (Boyd *et al.*, 1990).

The length of the growing season (defined as the period when the soil temperature is above 6 °C at a depth of 30 cm) is similar to the central belt of Scotland. However, the cumulative warmth of the season which is defined as the accumulated day °C over 5.6 °C (Bibby *et al.*, 1988) is somewhat lower in the islands than in lowland Scotland (Stornoway - 1265, Aberdeen - 1364, Perth - 1540). On the islands the growing season is modified in a number of ways. The spring rise in temperature is more sluggish with a consequent slower drying-out of the soil and a delayed start to growth. Windblast, high rates of transpiration and low day-time temperatures all contribute to slow crop growing conditions. Lack of autumn frosts delay shoot hardening of the more actively growing trees and shrubs which leads to shoot dieback during the winter.

In summary, the Western Isles have a humid, generally cool, relatively frost free but extremely windy climate.

Table 1. Exposure flag tatter rates at sites in the Western Isles

Site	Elevation	Exposure Flags Tatter Rate cm2/day	Exposure Class
Benbecula (Airport)	11 m	8.9	Moderately exposed
Langass (North Uist)	1. 46 m	7.6	Moderately exposed
	2. 61 m	10.4	Very exposed
Marrival (North Uist)	1. 76 m	9.9	Moderately exposed
	2. 122 m	12.1	Very exposed
Barvas Moor (Lewis)	90 m	11.1	Very exposed

2. SOILS

Rock and blanket peat are the dominant features over most of the Western Isles. Good soils are in short supply and it is a noticeable feature of the landscape that in historical times much of the accessible land was cultivated by the formation of *feannagan* or 'lazy beds'. This method of cultivation provided drainage in an otherwise waterlogged soil and seaweed was added to provide the nutrients. In more recent times shell sand, the only locally occurring source of lime, was used to provide the nutrients and to 'sweeten' the soil as a land improver.

Along the western seaboard of Harris and the Uists machair soils form about 8% of the total land area but are extremely important as an agricultural resource. These soils are formed by wind-blown, lime rich shell sand with a calcium carbonate content as high as 80% in places (Dickinson *et al.*, 1979). The majority of the people of the islands live and work on the machair. Crofting and fishing are still the predominant ways of life.

3. SUITABILITY OF LAND

The capability of land to grow trees has been assessed by the Macaulay Land Use Research Institute, Aberdeen (Bibby *et al.*, 1988) and is based on the limitations imposed by soil factors, topography and climate. The whole of the Western Isles fall into the two lowest classifications F6 and F7 with the latter considered unplantable.
Class F6 represents about 15% of the total area of the islands and is almost entirely confined to sheltered areas on the east coast and in the high hills.
Exposure limits the area of blanket peat with potential to grow trees. In the more sheltered areas the main limitations are poor drainage and lack of nutrients. These problems can be overcome in much the same way as on the blanket peats of mainland Scotland so that reasonably good crops of trees can be grown where there is adequate shelter.

The machair has very limited forestry opportunities due to the high pH and seasonal waterlogging of the soil. In addition it is fully exposed to the west and deposition of salt can be very severe. The unique and varied plant and animal life of the machair must also be protected. In practical terms tree planting on the machair is likely to be used only to provide localised shelter for homes and livestock.

Other areas of land for planting trees are the so-called 'blacklands'. These are the transitional areas between the sandy machair soils and the hill peats which have been the traditional cultivated lands of the crofting townships. Seaweed and shellsand have been used in the past as soil improvers. In terms of benefits to homes and livestock these are the best situated soils and they also have the greatest potential for tree growth. The 'blacklands' are the typical enclosed lands under individual ownership as opposed to the unenclosed lands on the common grazings belonging to the whole crofting township.

Examples of Tree Growth

1. NATIVE WOODLANDS

There is evidence that woodlands existed on the Western Isles in post-glacial times. Human settlement, which commenced about 5000 BP, and a change to a less favourable climate about 3000 BP were responsible for the gradual demise of tree cover. The old Statistical Account (1791) refers to tree roots found in the peat below high water mark in Vallay, North Uist. There is also a reference to large trees still rooted to 'blackmoss' at low tide on the island of Pabbay. There are numerous references in the New Statistical Accounts (1845) to trunks, roots, and particularly, hazel nuts existing in the peat on Lewis, North and South Uist and Barra. Tree roots can still be found in cut-over peat at Laxay on Lewis (Figure 1). Tradition has it that the woods of Lewis were burned by the Norwegians and the Danes for strategic or commercial reasons.

All that remain today of these once extensive woodlands are small isolated pockets and individual trees which have escaped the predation of human husbandry and grazing animals. The most important of these woodlands is at Allt Volagir (Figure 1), a sheltered ravine near the north shore of Loch Eynort in South Uist. This narrow, steep defile has escaped the attention of grazing animals and has formed an interesting canopy of trees and shrubs with a varied associated ground flora.

The dominant woodland species are aspen (*Populus tremula* L.) and hazel (*Corylus avellana* L.). Downy birch (*Betula pubescens* Ehch.) is locally dominant. Other species include abundant growth of eared willow (*Salix aurita* Linn.) some rowan (*Sorbus aucuparia* L.) and juniper (*Juniperus communis* L.) and a single vigorous example of ash (*Fraxinus excelsior* L.).

Not far from Allt Volagir at the southern end of Sloc Dubh, an arm of Loch Eynort, lies another native woodland, Meall Mor (see Figure 1). This wood is more extensive than Allt Volagir (Bennett *et al.*, 1987) but is more accessible to grazing sheep, deer and rabbits. As a consequence the variety of tree and shrub species and ground flora is more impoverished. *Betula pubescens* is the dominant species here but the abundant natural regeneration is grazed and cannot develop. There are several individuals of *Sorbus aucuparia*, and *Salix aurita* is commonly found around the edges of the birch stand. Hazel and aspen are not present.

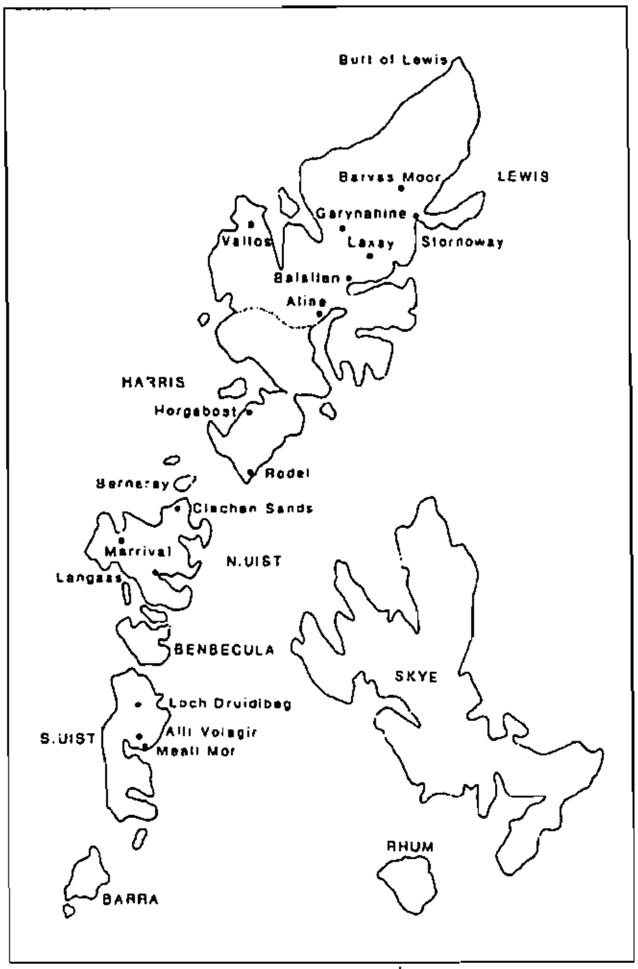

Fig 1 The Western Isles

Both Allt Volagir and Meall Mor are sheltered from the prevailing winds and it is grazing pressure rather than the strong winds which prevents the spread of natural woodland. The island woods of Loch Druidibeg (see Figure 1) on South Uist are examples of woods exposed to the prevailing winds but free of grazing pressure because of their inaccessibility. The largest of these woods consists mainly of a canopy of *Betula pubescens, Salix aurita* and *Sorbus aucuparia.* Hazel, aspen and juniper also occur on some of the islands as do some exotic *Abies* sp., Monkey puzzle and *Rhododendron* planted in the last century.

In inland lochs throughout the Outer Hebrides small wooded islands can be found which have survived grazing pressures. Aspen can be frequently found in steep valleys and on inaccessible cliffs at the edges of lochs particularly along the eastern side of the Uists.

2. VICTORIAN AND OTHER EARLY PLANTINGS

The old Statistical Account (1791) recorded that 'gentlemen' and 'proprietors' planted trees near their houses in an attempt to provide shelter and some relief to the barren landscape. Nearly all failed although it is recorded that in some cases alder and rowan survived.

The most successful early attempt to grow trees was by the Matheson family in Stornoway (Figure 1). James Matheson was a wealthy merchant of Sutherland stock who founded the Far East trading firm, Jardine, Matheson & Company. He purchased the island of Lewis from its previous owner in 1844 and proceeded to build Lews Castle and establish wooded policies which today could be considered to be among the finest woods in the west of Scotland.

Initially 12 ha of land were planted on the comparatively sheltered south shore of the loch opposite the town of Stornoway. The land was described as "risque pasture, butts, in-and-out-fields". The planting was later extended to 243 ha and it can be safely assumed that the bulk of the land was of very poor quality and probably unfit for the agriculture of the time.

The establishment of the present day woods must have been a colossal task requiring a great deal of trial and error. It is commonly believed that great quantities of soil were brought over from the mainland to enrich the peat. This was during the period of the great Victorian plant collectors and much encouragement and enthusiasm must have been engendered by their activities. Matheson's own company may well have been responsible for bringing back much exotic plant material.

Today the woods stand as a memorial to the foresight and endeavours of these early pioneers. A recent inventory by the Stornoway Trust (Cunningham, 1978) of tree species in the policies has detailed at least 28 conifer species, 39 broadleaved species of which 15 are native species, and 24 shrub species of which 9 are native species commonly found in woodlands on the mainland. There is also a very wide and varied range of woodland ground flora. Due to lack of maintenance during a long period before and after the Second World War some shrubs, particularly rhododendron and salmonberry, became very invasive and damaged a number of the more sensitive trees and shrubs. More recently the gales of February 1989 blew down a large number of the mature trees which included some huge, but splendid, Sitka spruce. Clearance operations are now in hand and restoration of the woods by new planting is taking place.

There is a wide variety of amenity trees in the gardens and streets of Stornoway, benefiting from the favourable location, shelter provided by houses and buildings and rather better garden soils. Trees and shrubs are nearly as abundant in Stornoway as they are in similar towns on the mainland.

Other policy woods planted by early pioneers include Horgabost (see Figure 1) and Borve, Harris; Grogarry, South Uist; Newton, North Uist; Rodel (see Figure 1) woods, Harris and Northbay, Barra. Most of these woods have grown in severe exposure and have survived to form interesting habitats for birds and other wildlife. Present day owners continue to develop and enrich the woods with a patience to admire. One interesting survivor planted at the turn of the century is a small stand of Corsican pine (*Pinus nigra var. maritima (Ait) Melville*) growing in a very sheltered position at the southern end of Little Loch Roag, Lewis. This must surely be one of the most northerly stands of the species in Europe.

3. POST 1945 PLANTING

The Forestry Commission established trial plantations at Balallan and Valtos (see Figure 1) on Lewis between 1945 and 1948. Both these relatively sheltered sites were planted with lodgepole pine (*Pinus contorta Dougl. var contorta*) and Sitka spruce in pure blocks and subsequently top dressed with phosphate. Growth has been good and the most recent inspections show the Sitka spruce to be growing at about General Yield Class 12; some of the larger trees have a diameter at breast height of 45 cm. The lodgepole pine are generally very poor form. The Balallan plot has now started to blow down and felling is in progress to clear the ground for replanting. A heronry which had established there has moved to a nearby experimental plot. The Valtos plot is on a much steeper slope with deeper, better drained soil and continues to grow vigorously. A varied woodland flora has begun to develop in the more open areas of the plantation and a large number of small birds have settled there.

Following the success of these early plantations the Forestry Commission made larger acquisitions at Garynahine and Aline (see Figure 1) on Lewis. Between 1968 and 1972 these areas were planted with mainly Alaskan provenances of lodgepole pine and some Sitka spruce. Both areas have grown well except for occasional trees of an inland provenance of lodgepole pine unsuited to the cool climate and poor soil. The Sitka spruce are now growing vigorously after going through a short period of check and are outstripping the pine. In the last 2 to 3 years native broadleaves have been introduced to increase species diversity and thus to improve both the general appearance of the stands and their conservation value. A recent attack by the Pine Beauty Moth (*Panolis flammea*) has caused serious damage and death of lodgepole pine trees in both areas. This casts doubt on the wisdom of growing large areas of pure lodgepole pine on deep peat with the risk of further attacks (Leather, 1992).

SAC trial at Clachan Sands, N Uist. Mixed conifer and broadleaved woodland. Age 29 years.

Over the last 30 years various individuals and local organisations have established plantations and small woods using sound silvicultural techniques and much enthusiasm. Notable examples are the work by the Stornoway Trust at Tolsta, Arnish and Barvas Moor (see Figure 1), Lewis; Achmore township, Lewis; Trumisgarry and Galtersay, North Uist; and Arinambane on South Uist. In very recent times large planting schemes have gone ahead at Sollas and Langass (see Figure 1) on North Uist. Both schemes have included a significant proportion of native broadleaved species as well as lodgepole pine and Sitka spruce.

Research on Tree Growth

1. NORTH OF SCOTLAND COLLEGE OF AGRICULTURE (NOSCA)

The earliest recorded trials were established by the North of Scotland College of Agriculture (now the Scottish Agricultural College, Aberdeen)in 1963 at Clachan Sands (see Figure 1), North Uist and at Laxay (see Figure 1), Lewis. The objective was to test a variety of tree and shrub species under the soil and climatic conditions of the Outer Hebrides in order to guide the establishment of shelterbelts for livestock (Sutherland, 1976).

Clachan Sands is on a drift type soil with a slight slope which provides good drainage except where rock sills occur. Vegetation was originally heather and grasses. The site is exposed to the north, south and west, lies about 2 km from the sea and within reach of salt laden gales. The site at Laxay is more sheltered and on an area of deep peat previously used as a College reseeding demonstration. It received 10 tons of shell sand per acre in 1963. A second site at Laxay was chosen in 1964; this was higher up the slope occupying an area of thin peat and slightly more exposed.

At Clachan Sands the trees were planted on an inverted turf at approximately 1.8 m x 1.2 m spacing. The Laxay sites were ploughed and the trees planted into the inverted plough ridge at similar spacing.

Each experiment was divided into two randomised blocks and individual species were planted in 6 plant plots. The plots were split so that 3 trees received 56 gm of ground mineral phosphate per tree and 3 trees received 38 gm of 10:20:10 compound fertiliser per tree. Shrub species were planted along the exposed edges and lodgepole pine and Sitka spruce were planted immediately inside the shrub rows to provide further protection to the more sensitive species planted behind.

Between 1963 and 1967 44 species of tree and 20 shrub species were planted. Measurements were taken in 1972 and 1975 and, subsequently, not repeated until 1990. In the intervening years there was no maintenance and many trees became suppressed because of the close spacing. In general only the most vigorous species have survived the intense competition but many, particularly broadleaved, species have struggled through and provide an added interest and diversity to the canopy.

The design and layout of the experiments and the problems created by close spacing make it difficult to interpret the results and one can only come to general conclusions about the performance of the majority of species. However, it does appear that once woodland conditions and mutual shelter have been established a number of more sensitive species including broadleaves will grow and flourish. The most successful species in terms of survival (>50% survival) and the ability to compete in the upper canopy are listed in Table 2.

At Clachan Sands there is a very pronounced Krumholz effect on the south west side. The height of the canopy rises from ground level at the plot edge at an angle of about 35%. Many of the conifers on the edge have died, but even when dead the branches provide shelter for the trees behind. This indicates how important it is for shelterbelts to have a width of at least 30 m. Narrower belts or single rows of trees will always grow poorly in comparison with those in a woodland.

Table 2: North of Scotland College of Agriculture (Scottish Agriculture College) Trials. Height of species with more than 50% survival (all sites combined).

Species	Common name	P Year	Height in1990 (m)
Picea sitchensis	Sitka spruce	1963	8.3
Pinus contorta	lodgepole pine	1963	7.0
Cupressocyparis leylandii	Leyland cypress	1966	8.2
Acer pseudoplatanus	sycamore	1963	8.0

Table 3: Scottish Agricultural College Trials - Species surviving on one or more trial sites (1990).

Conifers	Broadleaves
Abies grandis	*Alnus glutinosa*
Chamaecyparis lawsoniana	*Alnus incana*
Cupressus macrocarpa	*Aesculus hippocastanum*
Larix decidua	*Betula pendula*
Larix x eurolepis	*Castanea sativa*
Larix kaempferi	*Crataegus oxycantha*
Pinus nigra var. maritima	*Fagus sylvatica*
Pinus sylvestris	*Nothofagus procera*
Pinus uncinata	*Populus serotina*
Tsuga heterophylla	*Populus alba*
	Populus tremula
Shrubs	*Prunus padus*
Escallonia macrantha	*Quercus ilex*
Lonicera ledebourii	*Quercus borealis*
Olearia macrodonta	*Salix caprea*
Phormium tenax	*Salix daphnoides*
Ribes alpinum	*Sorbus aucuparia*
Senecio grayii	*Sorbus aria*
	Ulmus glabra

Within the plantation at Clachan there is a very definite and attractive woodland environment, calm even on a windy day and full of various bird species. Canopy height is very uniform, despite the range of species present. This appears to reflect the exposure and any individual tree or species that grows above the average canopy level will become more exposed, and growth will be limited.

Many other species have survived through the intense competition and may well have been more successful had they been planted in larger groups and managed more intensively. Other species still surviving on one or more sites are listed in Table 3.

Reports of growth and survival during the first ten years of the trials indicated a number of tree species which were easy to establish and survived despite repeated blast damage, shoot breakage and dieback. Some of these species later failed but this is due more to competition with vigorous species and lack of silvicultural management than for climatic reasons. In addition to the species listed in Table 3 *Alnus rubra* showed early promise. Species which have for various reasons failed include: *Thuja plicata; Larix griffithii; Ulmus stricta.* Voles and rabbits may have contributed to losses in later years.

Twenty different shrub species were planted along the exposed edges of the block to help lift the wind over the trees planted in the lee. Most of these failed but the following have survived on one or more sites (see also Table 3): *Escallonia macrantha; Olearia macrodonta; Lonicera ledebourii; Phormium tenax; Senecio grayii; Ribes alpinum.* Of these survivors *Lonicera ledebourii* has proved outstandingly successful at Clachan Sands where it has formed a dense wind-resistant screen along the windward edge of the block.

2. FORESTRY COMMISSION

In 1969 the Forestry Commission Research Branch established two experimental blocks on North Uist at Marrival (see Figure 1) and Langass. The objectives were to extend known planting limits and to test the establishment success rate of both Sitka spruce and lodgepole pine under extreme exposure conditions using the latest silvicultural techniques of the time.

Both sites are on a *Calluna/Trichophorum* unflushed peat varying between 30 cm and 120 cm deep overlying glacial till. The main rock type is Lewisian gneiss. The Marrival block is at an elevation of 100-150 m asl and extremely exposed to the south west, whereas the Langass block is at an elevation of 40-80 m asl and sheltered from the south west.

Cultivation was carried out using a Cuthbertson single mould board plough at 1.7 m spacing and plant spacing was 1.7 m along the plough ridge. Fertiliser was broadcast after planting at a rate of 50 kg P and 94 kg K per ha. The experiments compare pure plots of Sitka spruce of Alaskan and Queen Charlotte Islands origins with pure plots of lodgepole pine of South Coastal, Alaskan and Skeena River origins plus mixtures of both species. In the mixtures the Sitka spruce are planted in a 3 x 3 matrix within the line with alternate lines of pure pine *i.e.* 25% of the total crop.

In 1990 a small species trial was established on machair land on the island of Berneray (Harris) (see Figure 1) in a joint project between the local community and the Forestry Commission. The principal objective was to find suitable tree or shrub species for the formation of shelterwoods to protect livestock during the harsh winters. The site was cultivated and fenced by the local people and the experiment designed and planted by the Forestry Commission.

Results

MARRIVAL

Exposure has been the main problem in this experiment (although there is a marked difference in exposure levels between the top and bottom of the block with a rise in elevation of 50 m). All treatments suffered severe climatic needle browning and leader breakage in the early years although survival, in general, stood at more than 90%. During the early years the South Coastal (Washington) origin of lodgepole pine grew better than the other lodgepole pine origins but suffered badly from poor form. By their sixth year the heavier crowns of the South Coastal origins caused widespread socketing and further deterioration in form as the trees began to topple over. The Alaskan lodgepole pine grew more slowly but with a straight stem and a uniform bushy crown, and the Skeena origin lodgepole pine also grew slowly but with a sparse, poorly furnished crown.

Sitka spruce grew very slowly at first but improved with mutual shelter from the lodgepole pine. In 1975 nitrogen was applied at a rate of 190 kg N per ha to all pure and mixed plots of Sitka spruce to try and improve the poor appearance of the crop. This is unlikely to be recommended today in the mixtures where we would expect the nursing effect of lodgepole pine to eventually improve the nitrogen status of the spruce (Taylor, 1991). The Queen Charlotte Islands origin of Sitka spruce has always performed slightly better than the Alaskan origin but there is little to choose between them.

Phosphate and potash levels were maintained over the whole experiment with the addition of phosphate at 52 kg P per ha in 1975 and phosphate again plus potash at 95 kg K per ha in 1981. This regime closely follows the recommended rates for similar sites on the mainland.

The severe exposure has been very damaging to the form and commercial value of both species. Most trees are multi-stemmed and very heavily branched and leader breakage is still commonplace. These effects are most apparent in the outer four or five rows on the windward edge of the block. However, the trees inside the block now have the full benefit of mutual shelter and continue to grow vigorously.

It is unlikely that this experiment will form a crop of any commercial timber value, but it has demonstrated the feasibility of growing shelterwoods on very exposed sites on the islands. Table 4 gives the heights and yield achieved in this experiment.

Table 4: Marrival: Height and General Yield Class of Sitka spruce *(P. sitchensis)* and lodgepole pine *(P. contorta)* at 21 years of age.

Species	Height (m)	General Yield Class/ cubic metres/annum
Sitka spruce (Alaskan)	5.4	8
Sitka spruce (Queen Charlotte Islands)	6.3	8
Lodgepole pine (Skeena River)	3.9	4
Lodgepole pine (Alaskan)	4.0	4

Notes:
1. The results of the pure and mixed plots have been amalgamated. Sitka spruce in mixture will grow slightly faster than pure plots.
2. South Coastal Lodgepole pine has not been included because of its poor form and stability. However, it does have some benefit in providing rapid early shelter.

Forestry Commission trial at Langass, N. Uist. Lodgepole pine and Sitka spruce in mixture. Age 23 years.

LANGASS

On this more sheltered site, growth and form of both species are significantly better than at Marrival with exposure only a problem in the highest part of the plot where tatter rates are equivalent to the Marrival site (see Table 1). A timber crop has been produced which is likely to grow on to at least 13 m top height.

In general the trees are single stemmed and lightly branched in comparison with Marrival. However South Coastal lodgepole pine socketed and developed a pronounced lean at age five and began to blow over at age fifteen. Skeena origin lodgepole pine suffered the most severe foliage browning in the early years but have benefited from mutual shelter and are now growing vigorously.

Although growth of all species/origins was faster here than at Marrival regular foliar analysis indicated a need to apply N, P and K at intervals to maintain vigour. Applications similar to those at Marrival were applied.

The altitude range of 40 m between the top and bottom of the experiment does affect growth. Table 5 gives the heights and expected yield averaged over the whole site.

Table 5: Langass: Height and General Yield Class of Sitka spruce *(P. sitchensis)* and lodgepole pine *(P. contorta)* at 21 years of age.

Species	Height (m)	General Yield Class/ cubic metres/annum
Sitka spruce (Alaskan)	8.3	12
Sitka spruce (Queen Charlotte Islands)	9.4	14
Lodgepole pine (Skeena River)	7.3	8
Lodgepole pine (Alaskan)	7.5	8

Notes:
1. The results of the pure and mixed plots have been amalgamated. Sitka spruce in mixture will grow slightly faster than pure plots.
2. South Coastal Lodgepole pine has not been included because of its poor form and stability. However, it does have some benefit in providing rapid early shelter.

BERNERAY (HARRIS)

There is no natural tree growth on the machair and this experiment was designed to investigate which species of trees or shrubs were capable of forming a shelterwood to moderate the effect of severe winters on livestock.

A small experiment was planted in 1990 to test a variety of trees and shrubs with and without artificial shelter. Within the main experiment eight species of tree and eight species of shrub were planted in 25 plant plots. The experiment was divided into three blocks: one block was surrounded on two sides facing the prevailing wind with a 1 m high Paraweb fence; in the second block, individual trees and shrubs were planted inside 1 m high plastic shrub shelters; and the third block was unprotected. Other species were planted in single demonstration plots.

It is too early to draw firm conclusions, but Table 6 lists the main successes and failures over all treatments by year two. All species growing in the shrub shelters grew rapidly in the first season and soon filled their shelters. Without shelter, many species suffered very badly from the combined effects of wind and salt spray. Mutual shelter, therefore, will play an increasingly important role as the plants develop. Some damage is expected when the trees grow out of their shelters.

Table 6: Species of trees and shrubs planted on a machair site at Berneray (Harris). Successes and failures after the second year are indicated.

TREES Planted in 1990		SHRUBS Planted in 1990	
Crateagus oxycantha	Success	*Escallonia rubra*	Success
Pinus contorta (North coastal)	Success	*Griselinia littoralis*	Failure
Pinus mugo	Success	*Hebe franciscana*	Surviving
Pinus nigra var nigra	Surviving	*Hebe franciscana var variegata*	Surviving
Pinus pinaster	Success	*Hebe salicifolia*	Failure
Pinus radiata	Surviving	*Hippophae rhamnoides*	Surviving
Populus tremula	Surviving	*Lonicera ledebourii*	Success
Salix caprea	Surviving	*Olearia haastii*	Surviving
Sorbus aria	Success	*Olearia solandri*	Success
Sorbus intermedia	Success	*Phormium tenax*	Success
Planted in 1992		*Rosa rugosa*	Success
Acer pseudoplatanus	Surviving	*Salix daphnoides*	Surviving
Betula pubescens	Surviving	*Tamarix pentandra*	Failure
Corylus avellana	Surviving	*Ulex europaeus*	Success
Fraxinus excelsior	Surviving	**Planted in 1991**	
Ilex aquifolium	Surviving	*Atriplex canescens*	Surviving
Prunus spinosa	Surviving	*Atriplex halimus*	Failure
Sorbus aucuparia	Surviving	*Sarothamnus scoparius*	Surviving

Discussion

The results achieved by testing many different species on a number of sites show clearly that trees will grow in the Western Isles, and that woodlands can be created and achieve quite respectable growth rates.

The degree of exposure to wind and salt will decide, to a certain extent, the type of woodland which can be established. Tatter flags provide a very important way of correctly choosing sites for planting. A new tatter flag network, designed to last at least three years, was established in the Western Isles by the Forestry Authority Research Division in 1992. This covers a range of site characteristics, particularly north to south and east to west transects of the islands, including areas where shelter effects from existing shelterbelts can be shown. These sites will have excellent demonstration value, provide information for future planting schemes and help to refine data on relative exposure levels.

Now that public expectations and perspectives of tree planting are changing, it is appropriate to consider what are the most appropriate objectives for tree planting and what constraints must be met. Commercial plantations of pine and spruce have their place and could in time supply much of the islands' requirements for timber (croft lands have quite considerable quantities of fencing per acre). The correct choice of provenance is important and only lodgepole pine of Alaskan origin and Sitka spruce of Alaskan or Queen Charlotte Islands origin should be used on the more exposed peats and peaty gley soils. On more sheltered sites lodgepole pine of Skeena River origin can be used. The threat of damage by the Pine Beauty moth places a serious constraint on the widespread use of lodgepole pine as a commercial species and its main use appears to be confined to either a pioneer or nurse role. Pure Sitka spruce will require expensive fertiliser applications on nitrogen deficient organic soils. Therefore, it is recommended that both species should be planted in an intimate 3:3 mixture. The pine will act as a nurse species which will avoid later applications of nitrogen but maintain the growth rate of the more productive Sitka spruce until canopy closure. The extent, however, to which the establishment of large areas of coniferous woodland producing, at best, average grade timber, can be justified so far away from the commercial markets, remains questionable.

Environmental considerations also weigh against large scale planting. The almost complete absence of trees in the Isles leads to a very open and distinctive landscape. The fields and grasslands of the machair form an ecosystem unique in the British Isles. Any tree planting could be considered visually obtrusive and out of character. The majority of tree species used to date are not native to Britain, let alone the Western Isles. Planting might therefore be considered to be of little ecological benefit although providing new habitats for, for example, birds. Careful landscaping of tree planting schemes will be very important and it may be difficult to achieve a wholly satisfactory result.

Planting for shelter and amenity is easier to justify but environmental benefits should also be sought and there should be a presumption in favour of native species wherever possible. Although a great range of species has been used in the various trials, several native species remain more or less untested, including ash, Sessile oak, hazel, juniper, Bird cherry, blackthorn, Dog rose. All are, or were historically, found on the island or adjacent areas of the mainland. Some of these are not likely to succeed in a pioneer situation in new plantings, but should now be planted in open spaces in other established woodlands and trial plots.

It appears that nurse crops of hardy species are essential for initial establishment. Although lodgepole pine will probably remain the most reliable nurse species on difficult sites (*i.e.* deep peats), hardy broadleaves such as sycamore and Swedish whitebeam may also have a role on better sites. Perhaps this is the time to experiment with selective felling at the relatively mature SAC trials at Clachan and Laxay and the Forestry Commission experiments at Langass and Marrival. The nurse species could be removed to increase the proportion of broadleaved trees and develop the amenity and woodland environment as a further demonstration of the possibilities.

Conclusions

a) Strong winds and salt spray are limiting factors for successful tree growth on the Western Isles. Even in the most exposed situations, however, mixed woodlands can be established which will provide both good shelter for livestock and additional wildlife habitats. In more sheltered areas it is feasible to grow both broadleaved and coniferous timber with a considerably greater commercial value. Tatter flags provide an important way of assessing exposure and assisting with the correct choice of sites for planting.

b) Grazing pressure is a problem and all new planting schemes should have adequate protection from sheep, deer and rabbits.

c) Sitka spruce and lodgepole pine of Alaskan origins can be relied upon to grow relatively quickly, provide shelter at an early age and produce adequate commercial timber. Alaskan lodgepole pine is also a very effective pioneer species particularly on the most exposed sites and more difficult soils (*i.e.* deep peats). Where the soil conditions are better, hardy sycamore and Swedish whitebeam can be used to nurse sensitive broadleaves to help create a more environmentally acceptable woodland.

d) There is scope for planting a wide range of other species, both native broadleaves and conifer, within the sheltered environment of the pioneer species. These could be planted in gaps within the wood. A more intimate mix of species could only be achieved at time of planting, as any disruption to the tree canopy at a later stage is likely to lead to premature windblow. Similarly, it would not be feasible to thin such plantations on a commercial basis.

e) As shelterbelts age and the effect of prolonged exposure take their toll on the first 4 to 5 rows, shelterbelts can become less effective near ground level. It is therefore very desirable to have one or two rows of shrubs planted on the windward edge. The shrub species listed in Table 3 can be used but consideration should also be given to relatively untried native species *e.g.* hawthorn, willow, blackthorn, juniper and Dog rose.

f) The blanket peats and the 'blacklands' provide the best opportunity for establishing trees on the islands. Planting on any scale on the machair is undesirable due to environmental considerations and is, in any case, beset with physical problems of soil and climate.

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Memories of Forestry on the Orkney Island of Hoy

by M T T Phillips

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In the seemingly far off days of 1954, a series of four pilot plots were established by the Forestry Commission Research Branch in the northern part of the Island of Hoy, in order to determine the possibility of larger scale forestry.

I was responsible for the establishment of the plots, mostly with local assistance, and this account is, in effect, a historical record, largely unconnected with the silvicultural aspect and its success or otherwise. The latter are in the annals of the Forestry Commission Research Branch.

In my case it all started in March 1954, when having barely entered my second week of married life and settling into a little tin roofed house on the banks of the River Oich in Fort Augustus, when there was a knock on the door and I was ordered to report for duty in Hoy the next day. Angus MacDonald (Angie) was the Head Research Forester in Fort Augustus at that time, and very shortly we were on the road by van to Thurso. With us to help me with the planting was a research worker (ganger) by the name of Iain Cameron, a man of whom I had the highest regard and respect. A hard worker and with a wonderful sense of humour who was well named and known as the *Gaireachan* (the laughing man). It was a long journey to Thurso, however in those days there was something of a short-cut to avoid Inverness, long before the Kessock Bridge was built, and this was by a very steep narrow road over Culnakirk to Beauly, then northwards.

The night spent in Thurso, the next day was a drive to Scrabster to catch the St Ola to Stromness, followed by another night before catching a small boat, the Orcadia, to Longhope and finally by local transport to Lyness, which at that time was still a navy base and where we were granted special accommodation. All in all, a long haul just to get there and not having done a days work. However that was to come, almost a month in full seven days a week and no time off!

We were joined at Thurso by John Zehetmayr who was responsible for the vast amount of prior arrangements before a spade could be put to use. However the day of work dawned, and we all packed into a small van owned by Jack Spence, owner of Bu Farm, in the north of Hoy, who carried out much of the preparatory work and ferried loads of plants from the small pier at Moaness to the various plots. Jack usually had his dogs along with him in the van, so there was little room to spare. One of his dogs had an "evil squint" and did not like the intruders - it was alright so long as you avoided eye contact, however, if you did, you were given a sharp 'bite' to remind you of your social position.

The four plots were placed in declining situations relative to the exposure. The first, and most severe exposure was at Fea, the second at Lodge, the third at White Glen and the fourth at Lyrawa being considered the most sheltered. The four plots together totalled 31 acres. Previous to all this the ground had been ploughed by Cuthbertson plough, the like of which had never been seen before in Hoy, and the navy had been involved in providing a special craft and crane to transport and offload the massive tractor and plough.

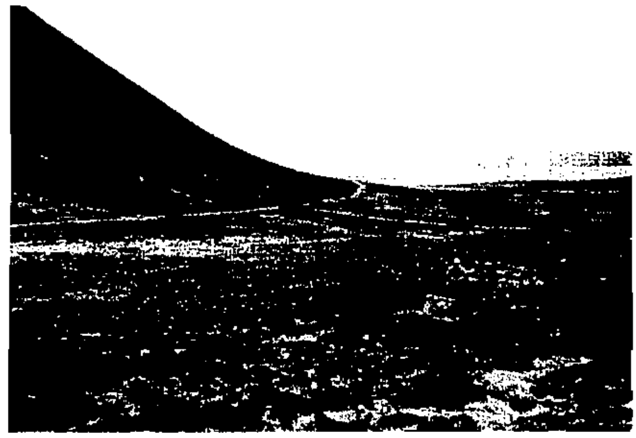
I had three men to help me with the planting, Iain Cameron, Jack Davidson and David Spence, latterly we stayed with the Davidsons at Garson, on the Bay of Quois, which was within walking distance of three of the plots. Plants arrived at intervals in large hessian mats, offloaded at Moaness, collected by Jack Spence and dispersed to the plots as required and then "scheughed-in" ready for planting.

At last the final plant was well and truly planted and all that was required was to reverse the long process of return to Fort Augustus, and home, to await the next of many orders over the years to report to duty to places far from the haunts of man, or beast even, come to that!

The plants used covered the usual range of species in current planting in north Scotland. Mountain Pine (EMP and DMP) in the surround, lodgepole pine from Lu Lu Island, in fact quite a mixture of origins, but mostly home collections of seed. This included Barnes Creek, Fraser River, Hat Creek, Alberta and of course Long Beach, lastly Hollis and Skagway, Alaska. The other main species were Japanese larch, Omorica spruce, Noble fir, Western hemlock, Sitka spruce and Scots pine. There were however a few broadleaves: whitebeam, willow and laburnum.

It is of interest that the Scots pine provenance used was Thetford, East England from the famous Breckland Hedges under 48/11A. This provenance is shown to have a similarity to Speyside, most likely Deeside by monoterpene analysis (Forrest, 1980; 1982).

The squad planting SPC in steps on furrows along the western side of the experiment. L-R: Miller - ganger Phillips - Ganger Ian Cameron from Fort Augustus.
Source: J W L Zehetmayr



General view 2 May 1963 of White Glen showing location of plot, looking north to Scapa Flow. Rock in foreground is the Dwarfie Stane.
Source: R. Lines

From October 1954 to 1956 there were further visits to inspect and beat-up the failed plants but it was in April 1955 that one Sunday afternoon I took a brief 'time off' (shouldn't have, of course), borrowed a bike and headed up the White Glen to visit Rackwick, on the extreme west coast This was an experience I will never forget, it was like moving back in time: tiny "black houses" thatched with heather as if growing out of the soil, set in a bay hemmed in by enormous cliffs, the whole defying description. It was very humbling, like reaching the end of the world and finding creation!

Here also are the tallest sheer cliffs in Britain, at 1100 ft, and then there was the Old Man of Hoy again, one of the most impressive sea stacks in the country, rising to 600 ft with the rough outline of a human form. It is of interest to record that just above Lyness there is a hill called "The Wee Fea" which in 1938 was hollowed-out to accommodate huge underground oil storage tanks for refueling the fleet during the war.

Back down White Glen I had time to see the "Dwarfie Stane" an enormous boulder which tradition tells of "Trolld, a dwarf, famous in the northern sagas". There are two sleeping compartments, one with a stone pillow, most likely and most plausible, originally a heathen alter, afterwards converted into a cell by some "holy anchorite of yore" (Anon, 1900). One can but only wonder at such things, whilst reading in the early sources of Scottish history. These islands were first inhabited by *the Picts.The Picts little exceeded pigmies in stature; they* did marvels in building walled towns, and lived in little underground houses. At that time the islands were not called Orchades, but Pictland. Then came Harold King of Norway and the most vigorous, Ronald who subdued the islands to themselves (Anon, AD 874).

The north end of the island of Hoy, where the plots were established had a population of only 37 in 1968, with some 10,000 acres of commons on the hills, now almost entirely unused, and except along the north shore which is bordered with a loamy soil and a rich verdure, the soil is composed of peat overlaying clay. (Miller and Luther Davies, 1968).

On the 3rd of September I paid my last homage to Rackwick, but the 12th of September 1956 was my last visit to Hoy, this time with George Stewart and Angie, at the end of which we were entertained to a huge meal at the Bu Farm. That was 42 years ago, I have never been back.

Since these early days, I understand that the White Glen Plot was partly burnt in 1984 and has now been taken over by the RSPB, and the 'foreign' plants removed (Anon, 1996).

Acknowledgements.
My thanks to the Forestry Commission for permission to peruse the old experiment files (which I had composed anyway) for various dates which had eluded my fragile memory.

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Anchorage of coniferous trees in relation to species, soil type, and rooting depth

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Abstract: A database was constructed of tree-anchorage measurements from almost 2000 trees from 12 conifer species that were mechanically overturned on 34 sites in the United Kingdom between 1960 and 2000. Anchorage was compared among species, soil groups (freely-draining mineral, gleyed mineral, peaty mineral, and deep peat) and root depth classes (shallow, <40 cm; medium, 40–80 cm; and deep, >80 cm) using regressions of critical turning moment against stem mass. Sitka spruce (*Picea sitchensis* (Bong.) Carr.) was used as a benchmark because it formed the largest part of the database and was the only species with all soil-group and depth-class combinations. Anchorage of Sitka spruce was strongest on peat and poorest on gleyed mineral soils. Deep rooting increased critical turning moments by 10%–15% compared with trees of equivalent mass with shallower roots. Significantly better anchorage than Sitka spruce was found for grand fir (*Abies grandis* (Dougl. ex D. Don) Lindl.), with various rooting depths on freely draining and gleyed mineral soils and for Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) on medium-depth mineral soil. Lodgepole pine (*Pinus contorta* Dougl. ex Loud.) had poorer anchorage than Sitka spruce over a range of soil groups and root depth classes. Norway spruce (*Picea abies* (L.) Karst.) on shallow gleyed mineral soil, and Corsican pine (*Pinus nigra* subsp. *laricio* (Poir.) Maire) on medium depth mineral soil, also had poorer anchorage. Other combinations had similar anchorage to the equivalent Sitka spruce. These results are discussed with respect to the development of forest wind-risk models.

Résumé : Une base de données a été construite à partir de mesures d'ancrage de près de 2000 arbres appartenant à douze espèces de conifères qui ont été déracinés mécaniquement sur trente-quatre sites au Royaume-Uni entre 1960 et 2000. L'ancrage a été comparé entre les espèces, les groupes de sol (sol minéral bien drainé, sol minéral gleyifié, sol minéral tourbeux, tourbe) et les classes de profondeur d'enracinement (< 40 cm « mince », 40–80 cm « moyen » et > 80 cm « profond ») en utilisant des régressions entre le moment critique en flexion et la masse de la tige. L'épinette de Sitka (*Picea sitchensis* (Bong.) Carr.) a été utilisée comme référence puisqu'elle constituait la majorité de la base de données et qu'elle était la seule espèce représentée dans toutes les combinaisons de groupes de sol et de classes de profondeur d'enracinement. Le meilleur ancrage de l'épinette de Sitka a été observé sur la tourbe alors que le moins bon a été observé sur les sols minéraux gleyifiés. Un enracinement profond a augmenté les moments critiques de 10 à 15 % en comparaison avec des arbres de masse semblable dotés d'un enracinement plus superficiel. Un ancrage significativement supérieur à celui de l'épinette de Sitka a été noté pour le sapin grandissime (*Abies grandis* (Dougl. ex D. Don) Lindl.), avec diverses profondeurs d'enracinement sur des sols bien drainés ou des sols minéraux gleyifiés, ainsi que pour le douglas de Menzies (*Pseudotsuga menziesii* (Mirb.) Franco) sur des sols minéraux d'épaisseur moyenne. Le pin tordu (*Pinus contorta* Dougl. ex Loud.) avait un moins bon ancrage que l'épinette de Sitka pour une gamme de groupes de sol et de classes de profondeur d'enracinement. L'épicéa commun (*Picea abies* (L.) Karst.) sur sol minéral mince gleyifié, de même que le pin laricio (*Pinus nigra* subsp. *laricio* (Poir.) Maire) sur sol minéral d'épaisseur moyenne, avaient aussi un moins bon ancrage. Les autres combinaisons avaient des ancrages comparables à celui de l'épinette de Sitka. Ces résultats sont discutés en lien avec le développement de modèles de prédiction du risque de dommages par le vent en forêt.

[Traduit par la Rédaction]

Introduction

Windthrow of trees is a major disturbance factor in forested areas of the world (Putz et al. 1983; Schaetzl et al. 1989; Ennos 1997). The gaps created by wind are important for forest structural dynamics and influence the diversity of tree species, structure, and age (Pontailler et al. 1997). In addition, overturning of trees accelerates the mixing of soil horizons and provides microsites with improved soil aeration and nutrition that favour tree regeneration (Beatty and Stone 1986; Schaetzl et al. 1990). However, windthrow reduces the profitability of forest stands managed for timber production through reduced economic value of windthrown timber (Savill 1983; Nieuwenhuis and Fitzpatrick 2002) and in-

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creased harvesting costs (Quine et al. 1995). In addition, stands in particularly windy regions are commonly harvested before their age of optimum economic return to reduce the risk of windthrow (Gardiner and Quine 2000). The British Isles are located in the track of most North Atlantic depressions and, as a result, have a windier climate than other parts of Europe (Troen and Peterson 1989). Within Britain, a large proportion of forest cover is located in the windiest parts of the country (Miller et al. 1987), and windthrow remains one of the most important problems that the forest industry must deal with.

To predict and reduce forest losses due to windthrow, it has long been recognised that data are required that describe the stability and anchorage of trees in relation to species, tree characteristics, site, soil, climate, and forest-management techniques. We define "stability" as the critical wind speed required to overturn a tree and "anchorage" as the resistance of the root system of the tree to uprooting. In 1960, A.I. Fraser and coworkers at the British Forestry Commission started investigations into factors that affect tree stability. They developed techniques for mechanically overturning trees and gathered information on soils, tree dimensions, rooting, and tree anchorage (Fraser 1962). Trees were pulled over on the range of soil types common to British forest plantations. Above- and below-ground tree dimensions, applied loads, and details of the pulling operation necessary for calculation of turning moment were recorded for each tree. Sampled trees were from a variety of conifer species, the majority being Sitka spruce (*Picea sitchensis* (Bong.) Carr.). In total, 1809 trees had been pulled by 1974, 969 of which were Sitka spruce. Sitka spruce was then, and remains, the most economically important tree species in Great Britain, presently accounting for around 29% of woodland tree cover and 49% of the conifer area (Forestry Commission 2004). The results of tree-pulling experiments conducted between 1960 and 1966 were described by Fraser (1967). Subsequent tree-pulling work up to 1974 was described in a series of brief progress reports (see Everard and Taylor 1969; Everard et al. 1970; Booth and Mayhead 1972; Pyatt and Booth 1973), but no overall analysis of the data set was published. Tree-anchorage investigations recommenced in the early 1980s when Blackburn (1986) examined the effects of tree spacing on anchorage. The relationships between architecture of tree root systems and the biomechanics of tree stability were investigated by Coutts (1983, 1986), and the stability of relatively mature trees was examined in relation to root architecture, rooting depth, and root–soil plate flexibility by Ray and Nicoll (1998).

A new impetus for gathering tree-anchorage data was provided in the 1990s by the development of a predictive model of windthrow for the British forestry industry: ForestGALES (Quine and Gardiner 1998). An anchorage module that would be a central component of this model was identified as a necessity. It was apparent that the existing tree-pulling data set would form a useful basis for this, but was inadequate in its current form. Most noticeably at that time, there were few data describing the anchorage of trees larger than 20 m height and 30 cm diameter (DBH) at breast height (DBH; 1.3 m) on most soils and few data for trees of any size on deep peat soils. Although only 45% of data were for species other than Sitka spruce, the decision was made to continue to concentrate on this species because of its commercial importance. A new programme of tree pulling was initiated that concentrated on anchorage of larger Sitka spruce trees on various soil types. Experiments conducted as part of this programme added another 129 trees to the data set. Data from tree-pulling experiments conducted in Britain between 1960 and 2000 have now been compiled into a database containing almost 2000 trees.[2] Tree-pulling sites were distributed throughout the forested regions of Britain (Fig. 1), most of which are in the windier parts of the country (Quine et al. 1995).

The anchorage of trees can be expressed as the critical (maximum) resistive turning moment at the base of the stem during overturning. Turning moment is defined simply as force × length of a lever arm. Fraser and Gardiner (1967) provided equations relating anchorage, expressed as critical turning moment, to stem mass, for trees on a variety of soil types, and a number of subsequent studies (e.g., Moore 2000; Meunier et al. 2002; Nicoll et al. 2005) have characterized anchorage using the same approach. Other authors have described relationships based on related stem characteristics, including stem volume and DBH (Fredericksen et al. 1993; Papesch et al. 1997). For example, Peltola et al. (2000) found significant correlations between maximum resistive turning moment and several aboveground characteristics of Scots pine (*Pinus sylvestris* L.), Norway spruce (*Picea abies* (L.) Karst.), and birch (*Betula* sp). Meunier et al. (2002) used linear regressions to compare critical turning moment with a variety of aboveground characteristics and found the best regression with stem mass. Therefore, regressions of maximum resistive turning moment against stem mass provide an effective means of making anchorage comparisons, for example, between trees of different species or between different soils.

In this paper, we describe a meta-analysis of the combined tree-pulling data set from tree-pulling experiments conducted in Britain between 1960 and 2000, to test the hypothesis that root anchorage of conifers varies between species and soil group, and increases with rooting depth. Our aim was to provide empirical models of the anchorage of a variety of conifer species in relation to tree size, soil group, and rooting depth, which could be used in the development of wind-risk decision-support systems for forest managers.

Methods

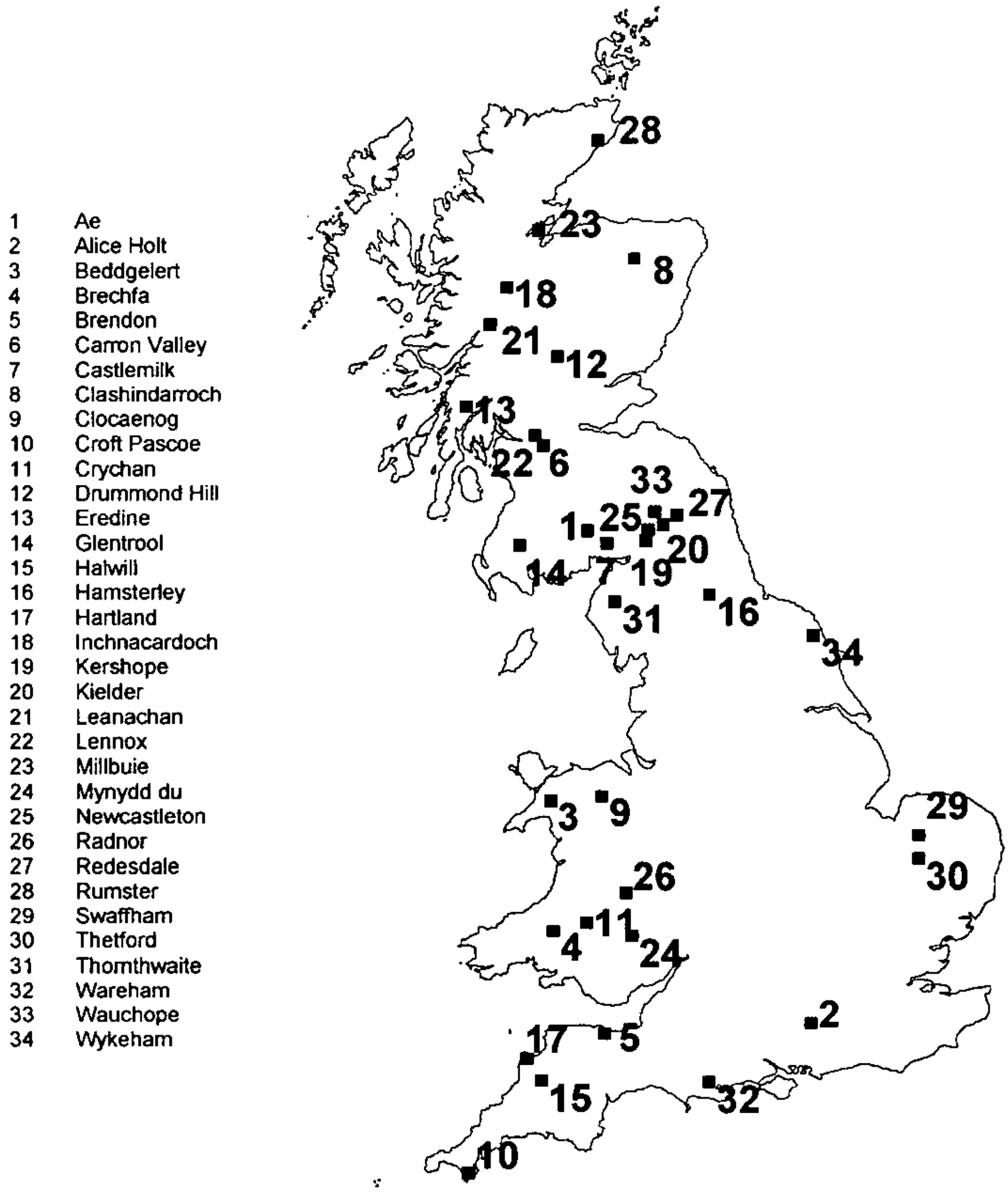
Tree-pulling methodologies

Original method

In the tree-pulling experiments that commenced in 1960, a sample of at least eight trees were selected at random for each soil type and silvicultural treatment examined. To overturn a tree, an almost horizontal force was applied at one-third of the tree height (Fraser and Gardiner 1967). This was achieved using a hand winch, a system of pulley blocks, and an adjustable pulley block spacer that raised a block to close to the pull height. Trees that obstructed the line of pull were removed before work started. As trees were pulled over, the

[2] The tree-pulling experiment database is available from the corresponding author.

Fig. 1. Location of tree-pulling experiment sites. Details of trees pulled on each site are given in Table 3.

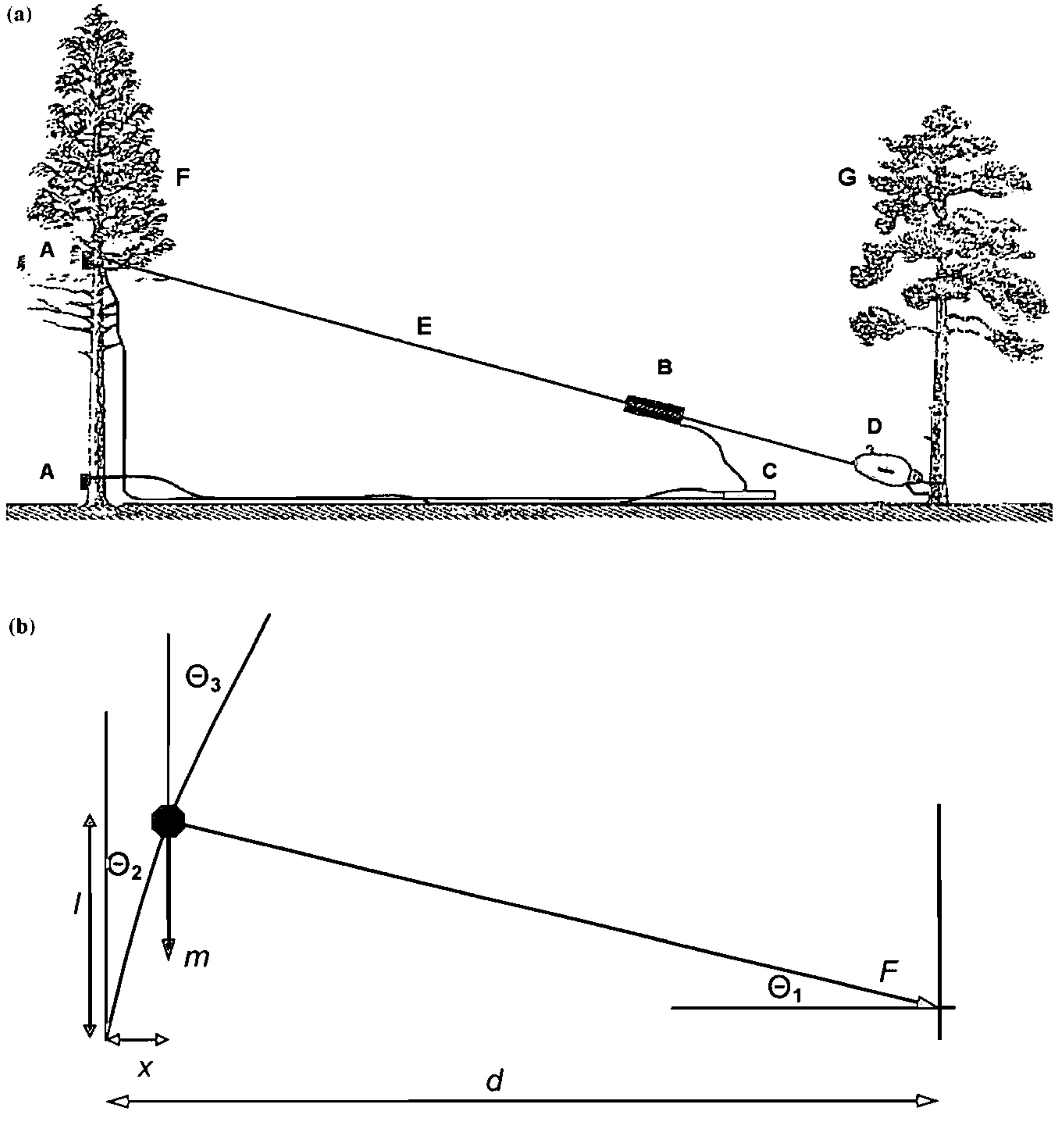


force applied was recorded by reading from the dial on a dynamometer for every degree of movement of the tree. Once the tree had been pulled over, tree dimensions were recorded, including, tree height, DBH, crown spread and depth, total root depth, and root–soil plate depth. The total mass of the stem, crown, and root plate were measured by hanging each component (in sections if necessary) from a weighing scale suspended beneath a tripod in the forest. Further details of the early tree-pulling sites and methodology are given by Fraser and Gardiner (1967). This methodology was used with only minor changes until the 1980s, and a modification where the top of the stem was removed before pulling was used by Ray and Nicoll (1998).

Current method

In tree-pulling experiments conducted from 1997 onwards, eight subdominant, eight codominant, and eight dominant trees were overturned, where possible, on each site. These trees were selected randomly from within diameter ranges based on quartile data from tariff plots. The direction of pull was as random as possible within the practical constraints of the tree-pulling operation. If trees were on a ploughed site, they were pulled in a direction perpendicular to the plough furrow. Neighbouring trees were felled to avoid obstruction of pull or crown interference. Digital bi-axial clinometers (Applied Geomechanics, Santa Cruz, California) were fixed to the stem near the base (1.3 m above soil level) and at one-half tree height (Fig. 2). A chainsaw-powered winch (Habegger, Thun, Switzerland) was attached to the anchor tree using a 2 m polyester webbing round-sling (safe working load 5 t), and a load-cell (0–5 t) was positioned between the anchor tree and the winch (Fig. 2*a*). The clinometers and load-cell were connected to a datalogger. The pulling cable was fixed to a polyester round-sling

Fig. 2. (*a*) Current tree-pulling method (A) inclinometers fixed at tree base and one-half tree height; (B) load cell; (C) datalogger; (D) powered winch attached by nylon sling to the anchor tree; (E) 9 mm winch cable between the winch and a nylon sling on the pull-tree at one-half tree height; (F) pull-tree; (G) anchor tree. (*b*) Measurements used in the calculation of critical turning moment: *m*, tree mass; *F*, force applied by the winch; *d*, distance between the anchor and pull-trees; *x*, horizontal displacement of the pull tree; *l*, the height of the centre of mass at time of maximum load; θ_1, angle of the winch cable relative to horizontal θ_2, angle of the tree base at time of maximum load; θ_3, angle of the tree above the attachment point at time of maximum load.



placed at half tree height on the pull-tree. Distance was recorded between the anchor tree and the pull-tree, and the angle (relative to horizontal) was recorded from the winch (or offset tree) to the attachment point on the pull-tree using a hand-held clinometer (Suunto, Vantaa, Finland). After taking a zero reading from the load-cell and both clinometers, the strain was taken up, and the tree was pulled slowly using the winch. The datalogger was programmed to record maximum load from the load-cell, and angles from both clinometers at the time of maximum load (Fig. 2*b*). Once the tree was on the ground, the crown width was measured, and instrument and cable attachment points were marked, as was

Table 1. Soil groupings used for tree anchorage comparisons.

Rootable depth (cm)	Freely draining mineral soils	Gleyed mineral soils	Peaty mineral soils	Deep peats
<40	A1	B1	C1	D1
40–80	A2	B2	C2	D2
>80	A3	B3	C3	D3

the position of the lowest live branch and the lowest complete live branch whorl. Live and dead branches were removed and weighed in bundles by hanging them from a balance under a 3 m high steel tripod erected in the forest. After branches were removed, the height of the cable attachment point, height of both clinometers, lowest live branch, lowest live branch whorl position, height to 7 cm stem diameter (timber height), and tree height were recorded. These measurements were comparable with those described in the original method.

Stem diameter was measured at 1 m intervals from the base to the top for calculation of stem volume as a series of truncated cones. A 1 m central section was cut from the stem, and diameters at each end were measured before weighing for estimation of stem green density and total stem mass. The accuracy of using this method on the 129 trees (6.5% of the data set) that were pulled using the current method was tested by comparing estimated stem mass with the weighed whole stem masses of ten, 15 m tall, 26-year-old, Sitka spruce trees (B.A. Gardiner, personal communication, 2006). On average, estimated stem mass was 1.02 × weighed stem mass (range 0.99–1.06).

Soil grouping

Because there were insufficient data to compare tree anchorage among all soil types and phases identified in British forestry (Pyatt 1982; Kennedy 2002), it was necessary to combine soils into groups with broadly similar physical properties: A, freely draining mineral soils; B, gleyed mineral soil; C, peaty mineral soils; and D, deep peat soils (Table 1). The soil groups from A to D have increasing moisture on the soil moisture regime scale devised for the ecological site classification (Pyatt et al. 2001). Freely draining mineral soils include brown earths, podzols, ironpan soils, calcareous soils, rankers, and skeletal soils. Gleyed mineral soils include groundwater and surface-water gleys as well as gleyed brown earths, gleyed podzol, and gleyed ironpans. Peaty mineral soils are peaty gley soils, peaty podzols, and peaty ironpans. Deep peats are defined as being >45 cm of organic matter and include Juncus (flushed basin) bogs, Molinia (flushed blanket) bogs, sphagnum (flat or raised) bogs, and unflushed blanket bogs (Kennedy 2002).

Root depth is known to have a large influence on tree anchorage (Blackwell et al. 1990); therefore, comparisons in this paper are based on a separation of soil groups into ranges of potential or actual rooting depths: shallow, <40 cm; medium, 40–80 cm; and deep, >80 cm (Table 1). We chose these as our rooting-depth ranges because they were broad enough to allow for variation across a site and to make prediction possible based on soil classification. Trees were assigned to a root-depth class based on actual measurements where they were available or by using default rooting depths for individual soil types provided by ecological site classification (D. Ray and B. Rayner, Forest Research, Northern Research Station, Roslin, Midlothian, Scotland, personal communication, 2002). Soil cultivation is also known to influence anchorage on some sites either by restricting root spread and reducing anchorage (Savill 1976) or by increasing root depth and improving anchorage (Ray and Nicoll 1998). Cultivation method and its influence on root architecture and depth vary considerably among soils and from site to site; for this reason, cultivation was not included as a variable in this analysis. However, the rooting depth used in this analysis will often reflect the effectiveness of cultivation on a particular site.

Standardization of data

Data from tree-pulling experiments conducted between 1960 and 2000 were compiled into a database that included dimensions and anchorage of 12 tree species (Table 2), aged between 15 and 56 years old. Because the experimental method had been modified over the years and parameters were measured in varying units, all data were checked against the original experimental records, and measurements were standardized to SI units. Written experimental and site records were explored to find soil type, tree dimensions, anchorage data, and other available information (Tables 2 and 3). Critical turning moments for all trees were recalculated at the stem base, as follows:

$$[1]\ M_{\text{critical}} = M_{\text{applied}} + M_{\text{mass}}$$

where M_{applied} (Newton metres) represents the maximum turning moment applied by the winch and M_{mass} (Newton metres) represents the turning moment resulting from the overhanging weight of the leaning tree at the time and angle of stem when the maximum load was reached. M_{mass} and M_{applied} were calculated from measurements shown in Fig. 2*b* using the following equations:

$$[2]\ M_{\text{mass}} = mx$$

$$[3]\ M_{\text{applied}} = F\cos\theta_1 \times l$$

where m is tree mass, F is the force applied by the winch, x is the horizontal displacement of the pull-tree, l is the height of the centre of mass at time of maximum load, and θ_1 is the angle of the winch cable relative to horizontal. The lengths x and l were derived using simple trigonometry. For the purposes of this calculation, the centre of mass of the tree was placed at one-half tree height (the pull height), and the stem was assumed to be a straight beam rotating around its base. For pre-1998 experiments where trees were pulled at one-third tree height, a single stem angle measurement was taken between the tree base and the pull height, and this measurement was taken to be the inclination of the beam between the stem base and the centre of mass. For experiments conducted from 1998 onwards, the inclination of the beam was

Table 2. Tree species, codes, height, and DBH of trees pulled in tree-anchorage studies in Britain between 1960 and 2000.

Species	Code	No. pulled	No. uprooted	No. snapped	Mean height (m)	Mean DBH (cm)
Corsican pine (*Pinus nigra* subsp. *laricio* (Poir.) Maire)	CP	88	83	5	13.4	21.9
Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco)	DF	40	40	0	16.0	22.8
European larch (*Larix decidua* Mill.)	EL	24	24	0	13.5	18.0
Grand fir (*Abies grandis* (Dougl. ex D. Don) Lindl.)	GF	40	37	3	17.5	22.1
Japanese larch (*Larix kaempfer* (Lindl.) Carr.)	JL	44	44	0	14.7	21.3
Lodgepole pine (*Pinus contorta* Dougl. ex Loud.)	LP	244	208	36	13.1	18.6
Noble fir (*Abies procera* Rehd.)	NF	16	16	0	13.8	20.3
Norway spruce (*Picea abies* (L.) Karst.)	NS	144	139	5	13.3	20.6
Scots pine (*Pinus sylvestris* L.)	SP	137	130	7	13.5	21.1
Sitka spruce (*Picea sitchensis* (Bong.) Carr.)	SS	1155	1045	110	14.6	21.0
Western hemlock (*Tsuga heterophylla* (Raf.) Sarg.)	WH	44	42	2	13.7	19.0
Western redcedar (*Thuja plicata* Donn ex D. Don)	RC	8	8	0	12.6	21.4

Note: Number of trees pulled is the sum of the number uprooted and the number snapped.

Table 3. Tree-pulling sites, species, tree height and DBH range, number of trees pulled, and pulling year.

Forest	Species pulled	Tree height range (m)	DBH range (cm)	No. of trees	Experiment years
Ae	NS	9.14–14.94	13.34–29.72	48	1963
	SS	10.97–18.90	10.80–41.91	152	1960, 1961, 1969
Alice Holt	CP	12.19–15.54	15.49–20.32	8	1968
	DF	11.89–14.63	16.26–20.32	8	1968
	GF	18.29–20.12	18.54–24.38	8	1968
	RC	11.89–13.72	18.54–22.61	8	1968
	WH	12.80–15.24	15.49–19.30	8	1968
Beddgelert	SS	10.66–20.42	16.97–29.10	48	1962
Brechfa	SS	13.10–22.00	10.60–26.50	20	1982
Brendon	CP	13.41–15.85	17.78–27.43	8	1966
	DF	16.46–19.51	21.84–29.21	8	1966
	LP	9.75–12.50	17.78–24.38	8	1966
	NS	14.63–16.46	17.02–23.37	8	1966
	SS	9.14–18.90	16.26–23.37	16	1966
Carron Valley	SS	8.53–13.41	12.95–22.61	44	1965
Castlemilk	SS	18.60–23.65	21.40–31.80	24	1998
Clashindaroch	EL	9.45–12.19	13.34–17.37	12	1962
	JL	10.36–12.19	13.34–17.37	12	1962
	LP	9.14–11.89	12.93–17.78	12	1962
	SP	8.84–10.67	12.93–14.96	7	1962
Clocaenog	NS	9.75–12.95	15.36–24.25	32	1963
	SP	10.66–11.88	19.40–22.63	2	1963
	SS	6.71–17.37	10.16–27.48	122	1962, 1963, 1968
Croft Pascoe	LP	5.60–8.70	8.00–13.00	31	1972
Crychan	SS	8.23–11.28	10.92–16.51	16	1968
Drummond Hill	EL	13.41–18.29	16.18–23.85	12	1962
	JL	15.54–18.29	18.19–25.07	11	1962
	LP	13.72–14.63	15.37–24.26	7	1962
	SP	11.89–12.50	17.79–22.63	5	1962
Eredine	SS	13.41–15.85	15.49–26.67	8	1969
	WH	13.41–16.15	17.02–24.89	8	1969
Glentrool	SS	24.00–30.08	28.50–55.50	22	1998
Halwill	GF	14.33–17.98	17.78–27.43	8	1968
	NS	12.19–22.50	18.54–31.00	16	1968, 1973
	SS	11.28–23.00	14.48–34.00	36	1965, 1968, 1973
	WH	12.50–14.02	17.78–25.91	8	1968
Hamsterley	LP	13.10–16.50	14.50–27.00	8	1972
	SS	12.60–15.30	13.50–25.00	16	1972

Table 3 (*concluded*).

Forest	Species pulled	Tree height range (m)	DBH range (cm)	No. of trees	Experiment years
Hartland	SS	13.72–16.46	16.26–31.52	32	1965
	WH	12.80–13.72	19.30–25.15	4	1965
Inchnacardoch	LP	10.50–21.60	11.43–40.50	92	1968, 1971
	SP	13.20–19.00	18.00–28.50	17	1971
	SS	9.50–15.20	14.00–24.00	28	1971
Kershope	SS	11.58–27.90	18.54–42.00	70	1966, 1993, 1994
Kielder	GF	12.50–18.29	15.75–27.18	16	1964, 1969
	LP	10.00–16.50	11.50–29.50	52	1969, 1971
	NF	9.80–14.50	15.00–24.50	8	1972
	NS	9.70–11.60	13.40–20.30	8	1969
	SS	9.00–17.00	10.00–35.50	196	1961, 1964, 1969, 1971–1974
Leanachan	SS	10.00–27.70	16.00–46.50	36	1998
Lennox	NS	10.36–13.72	14.48–25.40	8	1965
	SS	11.58–13.11	14.48–23.37	8	1965
Millbuie	LP	13.50–15.50	14.50–23.00	10	1974
	SP	11.00–13.50	15.50–26.00	10	1974
	SS	12.50–13.50	19.50–25.00	2	1974
Mynydd ddu	DF	15.85–20.12	24.38–32.26	8	1968
	GF	21.95–24.08	19.30–26.67	8	1968
	NF	14.33–15.24	17.78–25.91	8	1968
	NS	13.72–15.85	19.30–23.37	8	1968
	WH	16.46–19.20	18.54–26.67	8	1968
Newcastleton	NS	11.58–20.12	18.60–32.00	16	1964
	SS	10.06–24.69	14.48–35.56	72	1964
Radnor	SS	9.75–16.46	13.72–28.96	32	1963
Redesdale	SS	6.71–10.97	11.43–21.08	36	1964
Rumster	SS	20.21–27.30	24.50–40.10	15	1998
Swaffham	DF	11.13–18.29	12.12–32.33	16	1960
Thetford	SP	10.97–17.07	14.48–27.43	24	1966
Thornthwaite	SS	9.45–11.28	13.72–18.29	8	1968
	WH	8.23–9.75	12.45–14.48	8	1968
Wareham	CP	9.45–15.85	14.48–23.37	40	1969
Wauchope	SS	9.30–13.10	11.90–24.60	32	1998
Wykeham	CP	12.50–15.85	21.84–30.23	32	1968, 1970
	JL	13.41–16.76	21.08–35.56	21	1968–1970
	LP	14.02–16.15	19.30–27.43	24	1968, 1969
	SP	11.28–18.29	16.51–30.73	72	1968, 1970
	SS	10.36–17.07	14.99–27.94	64	1969, 1970

Note: See Fig. 1 for forest locations.

taken as being the mean of θ_2 and θ_3, the angles relative to vertical at the stem base and one-half tree height, respectively (Fig. 2*b*). Because bending of a tapered beam will increase with height, taking a mean of these two angles will introduce some error to the calculation of $M_{critical}$. However, Nicoll et al. (2005) found that a 20% change in stem deflection angle resulted in only a 2% change in the calculation of critical wind speed for tree overturning using the GALES model, and therefore, we found this method to be an acceptable simplification. The change in pulling height from one-third to one-half tree height was not expected to have any impact on calculated critical turning moment values as the difference in the effect of crown overhanging mass was accounted for in the calculation.

Statistical analysis

Data from trees that snapped during overturning (8.4% of the total data set) or for which visible root or stem rot was recorded (1.5% of the total data set) were excluded from the analysis. A series of mixed linear models were used to compare the effects of the soil and root depth factors, as well as tree species, stem mass, and all two-way interactions on critical turning moment. Fixed and random effects were modelled using residual maximum likelihood and included a function (the reciprocal of the variance) to down-weight trees with large stem mass to account for the greater variation in turning moments required to overturn such trees. Fixed effects were soil type, root depth and stem mass, and the random effect was forest within each soil – depth class combination.

Analyses for Sitka spruce were made using data from this single species, whereas differences in turning moments between Sitka spruce and the other tree species were examined by fitting a series of linear mixed models to the full data set

Table 4. Solution for fixed effects of stem mass × root depth and stem mass × soil type for Sitka spruce critical turning moment.

Effect	Soil type	Rooting depth (cm)	Estimate	SE
Stem mass × root depth	—	<40	167.48	8.19
Stem mass × root depth	—	40–80	167.83	6.97
Stem mass × root depth	—	>80	186.98	8.13
Stem mass × soil type	Free-draining mineral	—	−18.94	8.37
Stem mass × soil type	Gleyed mineral	—	−55.69	7.51
Stem mass × soil type	Peaty mineral	—	−39.85	8.78
Stem mass × soil type	Deep peats	—	0	

Note: To estimate the slope of the regression line (C_{reg}) for critical turning moment against stem mass for a particular soil type and root depth combination, the relevant stem mass × root depth estimate should be added to the stem mass × soil type estimate. As regression lines were fitted through zero, the critical turning moment is simply the slope estimate multiplied by stem mass.

and comparing parameter estimates for individual species. Rather than the usual R^2 statistic, estimated standard errors of the regression lines were calculated because they were considered to be more informative. Not only do they take into account the highly variable number of trees used to estimate the slope but also the variation between forests in which the trees were sampled.

Results

Anchorage of Sitka spruce

Sitka spruce was the only species with sufficient data to model the effects of all four soil groups (free-draining mineral, gleyed mineral, peaty mineral, and deep peats) at three rooting depths (<40 cm, 40–80 cm, >80 cm). Stem mass × soil group and stem mass × rootable depth were both significant factors ($p < 0.001$), and the best estimate of critical turning moment, containing only significant effects, is given by the model in Table 4. Stem mass was the single most important variable in determining the critical turning moment required to overturn a tree. The intercept term in the model was not significantly different from zero and was removed; therefore, all regression lines were forced to pass through the origin. On similar soils, trees with rootable depths >80 cm required 10%–15% more force to overturn them than trees with root depths less than 80 cm. For trees of similar mass, those growing on deep peats required the greatest force to overturn them. Trees growing on gleyed mineral soils were the most easily overturned, requiring only two-thirds of the turning moment of those growing on deep peats.

Although the interaction term stem mass × rootable depth × soil type was not included in the initial model above, it was considered for inclusion because it had a level of significance of $p = 0.06$. To provide regressions for use in windthrow risk models, critical turning moments were subsequently compared with stem mass for each soil-group, root-depth combination (Fig. 3, Table 5) using the fully parameterized model. On deep peat, Sitka spruce with shallow rooting depths had greater resistance to overturning than on all other soil types; with medium rooting depth, it had better anchorage than on gleyed mineral and peaty mineral soil; and with deep rooting depth, it had better anchorage than freely draining mineral and gleyed mineral soil (Table 5). On gleyed mineral soils, Sitka spruce had similar poor anchorage when rooting within shallow and medium depth ranges, but it was better anchored when deep rooted and had similar anchorage to deep-rooted trees on freely draining mineral soil. On peaty mineral soils, anchorage of Sitka spruce was similar within the shallow and medium rooting depth ranges and improved considerably when rooting depth was greater than 80 cm.

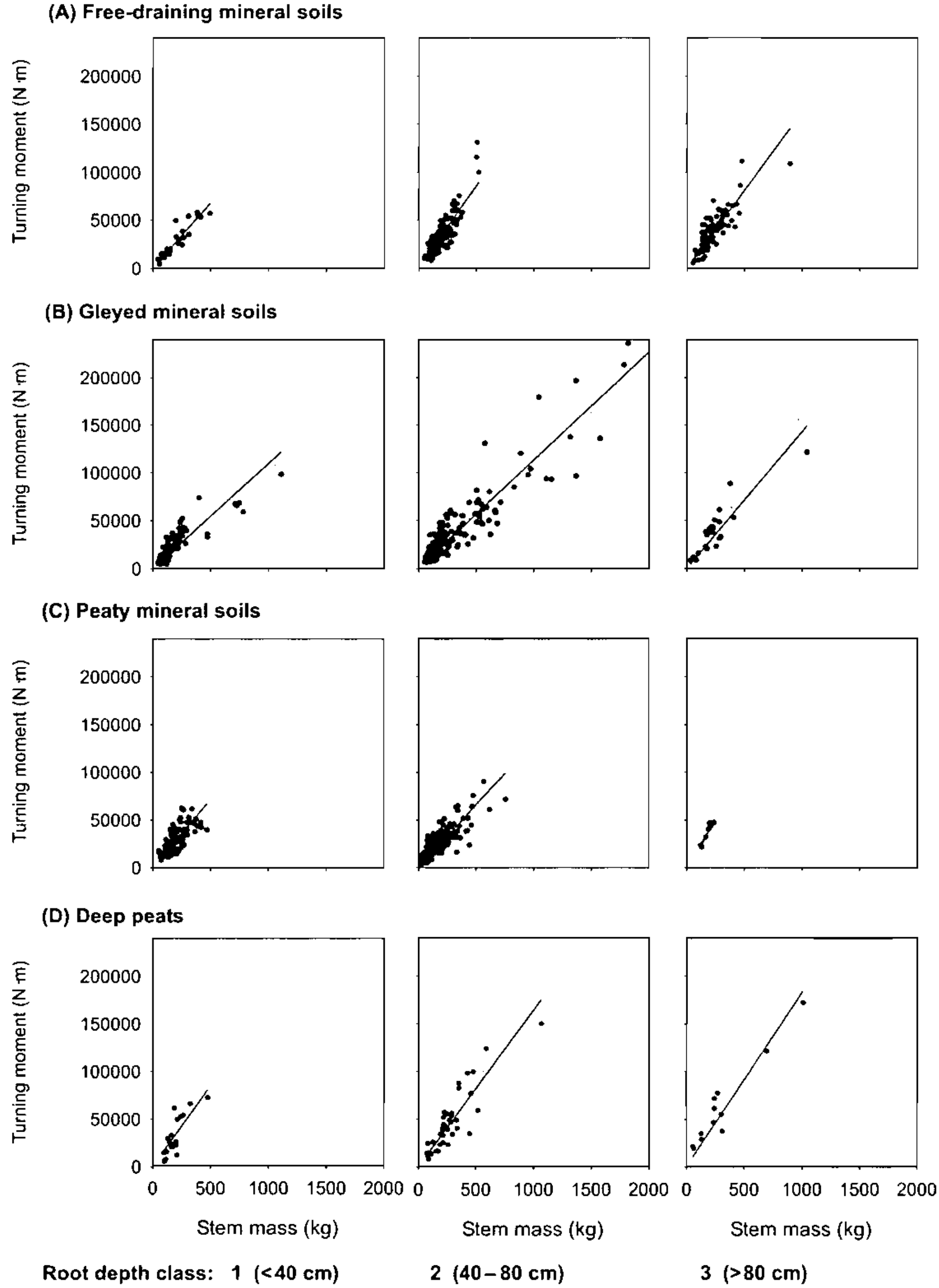
Anchorage of other species

There were considerably fewer data available for species other than Sitka spruce (Tables 2 and 3), and commonly, there was a poor spread of data between soil-group and depth combinations (Table 5). Therefore, data from each available species, soil-group, and root-depth combination were compared with data from Sitka spruce using regression analysis. Table 5 shows the estimates of slope coefficients for regression lines (C_{reg}) and p values that indicate the significance of similarities with equivalent lines for Sitka spruce. Medium rooting depth Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) and deep-rooted grand fir (*Abies grandis* (Dougl. ex D.Don) Lindl.) on freely draining mineral soils had significantly better anchorage (indicated by a larger C_{reg} value) than Sitka spruce (both $p < 0.001$). Shallow and medium root depth grand fir on gleyed mineral soils were also significantly better anchored than Sitka spruce ($p < 0.05$). Species, soil-group, and root-depth combinations that had significantly poorer anchorage than Sitka spruce on the same soil with the same rooting depth were medium root depth Corsican pine (*Pinus nigra* subsp. *laricio* (Poir.) Maire) on freely draining mineral soils ($p < 0.01$), shallow-rooted Norway spruce on gleyed mineral soils ($p < 0.001$); deep-rooted grand fir on peaty mineral soils ($p < 0.001$); medium-depth lodgepole pine (*Pinus contorta* Dougl. ex Loud.) on mineral soil ($p < 0.05$); and deep-rooted lodgepole pine on peaty mineral and deep peat soils ($p < 0.001$). For other combinations of species, soil group, and root depth, the comparison showed no significant difference, or there were no data (Table 5).

Discussion

Our study gives the first objective comparison of anchorage between a wide range of conifer species. Although care should be taken in interpreting these results in cases where there are few replicates or experiment sites, the analysis has revealed important yet complex differences among species and their interactions with site conditions. Of conifer species

Fig. 3. Relationship between critical turning moment and stem mass for each Sitka spruce soil and root depth grouping. The model fitted contains the stem.soil.root interaction terms and the dotted lines give the 95% confidence interval for this estimate.



commonly grown in the British Isles, grand fir was found to be the best anchored on deep, freely draining mineral soils and had significantly better anchorage than Sitka spruce. However, on peaty mineral soil, it had significantly poorer anchorage than Sitka spruce. Sitka spruce was particularly well anchored on deep peat soils and had significantly better anchorage than lodgepole pine, the only other species examined on deep peat soils. On shallow-rooted gleyed mineral soils, Sitka spruce had poor anchorage; although most other species behaved similarly, Norway spruce had significantly poorer anchorage. Therefore, anchorage comparisons among species are not simple and depend on soil physical properties and rooting depth.

In a tree-pulling experiment conducted on mineral soil in

Table 5. Soil group and rooting depth, coefficient of regression line (C_{reg}), number of samples (number of sites is given in parentheses), p value for the comparison with the equivalent regression for Sitka spruce, and standard error (SE), for each species.

		C_{reg}			No. of samples (sites)			P			SE		
Species	Soil group	<40 cm	40–80 cm	>80 cm	<40 cm	40–80 cm	>80 cm	<40 cm	40–80 cm	>80 cm	<40 cm	40–80 cm	>80 cm
CP	A	105.1	125.5*	131.0	1(1)	31(2)	24(3)	0.17	<0.01	0.10	24.8	10.3	12.7
	B		129.5			27(2)			0.39			21.9	
	C												
	D												
DF	A		197.9*	165.6		16(2)	15(2)		<0.001	0.39		10.1	11.9
	B	197.4	156.9		2(1)	6(1)		0.22	0.17		70.3	51.8	
	C												
	D												
EL	A		177.5	147.7		1(1)	23(2)		0.65	0.77		33.4	21.4
	B												
	C												
	D												
GF	A			212.9*			10(2)			<0.001			15.3
	B	166.0*	193.0*	173.1	8(2)	8(2)	3(1)	<0.05	<0.05	0.66	24.4	25.4	27.7
	C		135.2	128.5*		2(1)	6(1)		0.77	<0.001		31.9	9.0
	D												
JL	A	177.1	182.8	168.2	1(1)	12(1)	31(3)	0.29	0.19	0.35	30.9	14.7	13.6
	B												
	C												
	D												
LP	A	137.9	142.6*	140.1	6(4)	63(6)	25(6)	0.77	<0.05	0.33	12.8	7.3	12.8
	B		137.8	148.5		15(2)	5(2)		0.31	0.61		26.3	21.4
	C	94.1	119.0	123.2*	1(1)	12(1)	6(1)	0.72	0.78	<0.001	95.7	24.9	9.7
	D		141.3	132.2*		7(1)	19(2)		0.73	<0.001		42.9	15.6
NF	A			107.5			8(1)			0.07			24.7
	B												
	C	78.5	105.6	195.8	2(1)	5(1)	1(1)	0.34	0.48	0.78	51.9	28.1	20.9
	D												
NS	A	127.8	154.6	160.9	7(1)	22(2)	22(4)	0.67	0.72	0.63	32.7	19.2	12.4
	B	62.9*	114.2		24(3)	64(5)		<0.001	0.73		9.5	9.9	
	C												
	D												
RC	A												
	B		171.7	193.9		6(1)	2(1)		0.13	0.41		40.2	38.9
	C												
	D												
SP	A	124.1	146.4	141.3	5(3)	71(5)	40(5)	0.31	0.17	0.27	15.4	9.6	9.6
	B												
	C												
	D												
SS	A	142.4	162.0	154.0	31(8)	149(12)	101(13)	—	—	—	8.6	6.1	6.4
	B	111.0	110.6	160.2	109(12)		24(7)	—	—	—	6.4	3.7	8.9
	C	129.0	126.0	202.4	120(7)	191(14)	8(3)	—	—	—	8.6	6.6	9.5
	D	180.6	156.7	189.9	19(5)	137(8)	13(6)	—	—	—	20.2	10.4	11.8
						50(7)							
WH	A	109.9	141.2	168.7	5(2)	7(1)	8(1)	0.14	0.36	0.52	19.5	21.6	22.1
	B	126.0	152.2		12(2)	10(3)		0.70	0.13		36.6	27.2	
	C												
	D												

Note: Coefficients significantly different ($p < 0.05$) from Sitka spruce are indicated with an asterisk. Trees were excluded if they snapped during tree pulling or if root rot was recorded. Soil group codes are given in Table 1.

Table 6. Slopes of regression lines (C_{reg}) for critical turning moment against stem mass compared among species from tree-pulling studies described in the literature.

Species	Soil	Soil depth and consistency	Soil group and rooting depth[a]	C_{reg}	Reference
Balsam fir (*Abies balsamea* L.)	Podzol		A3	100.9	Achim et al. 2005
White spruce (*Picea glauca* (Moench) Voss)	Podzol		A3	100.9	Achim et al. 2005
Black spruce (*Picea mariana* (Mill.) BSP)	Podzol	Shallow, stony	A1	105.2	Elie and Ruel 2005
	Podzol	Deep, no stone	A3	108.9	
Jack pine (*Pinus banksiana* Lamb.)	Mineral	Deep, no stone	A3	130.9	Elie and Ruel 2005
Maritime pine (*Pinus pinaster* Ait.)	Podzol	Shallow, hard pan	A1	125.8	Cucchi et al. 2004
	Podzol	Deep, no hard pan	A3	168.8	
Radiata pine (*Pinus radiata* D. Don)	Orthic Pumice		A3	83.0	Moore 2000[b]
Douglas-fir	Orthic Pumice		A3	91.0	Moore and Gardiner 2001[b]

[a]Codes for the soil groups and rooting depths are given in Table 1.
[b]C_{reg} was calculated using regression of critical turning moment against stem volume and stem green density data.

Finland (Peltola et al. 2000). Scots pine was found to be better anchored than Norway spruce, whereas in our investigation these species had similar anchorage. The difference between these results may reflect deeper rooting depths of Scots pine compared with Norway spruce in the Finnish study, which is in agreement with our finding that anchorage of Norway spruce is comparatively poorer on sites with restricted rooting depth. However, regressions in the Finnish study are based on critical turning moment against tree height × DBH^2 rather than stem mass as used in our study. Results of tree-pulling studies where stem mass is the predicting variable and, therefore, can be more directly compared to our study are described in Table 6. In our study, Douglas-fir showed better anchorage than Sitka spruce for one soil group, i.e., medium-depth mineral soil. Similarly, in a study conducted in New Zealand, Douglas-fir grown on a mineral soil was better anchored than radiata pine (*Pinus radiata* D. Don) (Moore and Gardiner 2001). However, when the regression coefficient is compared between Douglas-fir in the United Kingdom and New Zealand tree-pulling experiments, this species appears to be considerably better anchored in the United Kingdom. Other conifer species are different from the species investigated in our study but, again, have lower C_{reg} values for equivalent soil group and root depth, except for maritime pine (*Pinus pinaster* Ait.), a tap-rooted species, on deep mineral soil (Table 6). Better anchorage of conifers in the present study may be expected because the British Isles experience higher average wind speeds than many other forested parts of the world (Troen and Peterson 1989), because our tree pulling sites were mostly in the windier parts of Britain, and because tree root anchorage is known to be strengthened in response to wind movement (Urban et al. 1994; Nicoll and Ray 1996; Stokes et al. 1997). Future work should quantify the variation in anchorage between sites that are sheltered from, and exposed to, a strong prevailing wind.

The finding that Sitka spruce has better resistance to overturning on deep peats than on other soils is perhaps surprising but reinforces some observations in the literature. Pyatt (1966) reported negligible windthrow of Sitka spruce on deep peats after a storm, despite 6% damage on surface-water gley and 2% damage on peaty gley. Rigg and Harrar (1931) reported that windthrow of conifers was rare on natural peat bogs, although it was common on adjacent mineral soils. One explanation for this phenomenon is that the extraction force for Sitka spruce roots has been found to be 9% greater in peat than in mineral soils (Anderson et al. 1989). An additional factor may be the tendency for conifer roots on peaty soils to develop eccentric "I-beam" cross-sectional shapes (Büsgen and Münch 1929). This behaviour is important to tree stability because a root with such a shape can have 300% of the flexural stiffness of a circular root with the same cross sectional area (Nicoll 2000). Roots that are held rigidly in mineral soils would be expected to have a smaller stimulus for adaptive development in response to wind (Nicoll and Ray 1996) than that experienced in more plastic peat soils. However, during a storm as the soil at the base of the root–soil plate starts to fracture, anchoring roots are pulled from the soil, and the stiffness of the lateral structural roots becomes particularly important (Coutts 1986). Therefore, if roots of a tree on deep peat flex more as the tree sways than roots of a tree on mineral soils, they will adapt better to the wind environment and be better prepared to resist bending in the strongest winds when they occur.

Conclusions

The analysis described here has provided linear relationships between critical turning moment and stem mass that can be used to predict tree anchorage within windthrow risk models. Despite our analysis being based on a large number of tree-pulling experiments conducted over a 40-year period and with almost 2000 data points, there are still a number of gaps in the database. Ideally, tree-pulling experiments would continue until each possible combination of species, soil grouping and rooting depth range had been investigated. However, the practical difficulties and high cost of tree-pulling experiments will limit work of this kind and it is likely that any similar work in the future will be small-scale studies to answer particular topical questions about tree anchorage. For example, as tree species diversity increases in importance in commercial forestry, a better understanding may be required of the anchorage of trees that are currently considered to be minority species. This could be achieved by the development of critical turning moment regressions based on tree-pulling experiments or through the development of improved mechanical models of tree anchorage. However, Sitka spruce is now well understood in terms of anchorage, and the anchorage of other species commonly appears to be similar on comparable soils. Therefore, it would be acceptable for wind risk models to use the relevant Sitka spruce regression lines for other conifer species until better data become available.

Acknowledgements

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The Principles of Using Woods for Shelter

INFORMATION NOTE

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SUMMARY

This Information Note describes the physical principles that determine the impact of woodlands on shelter provision. The importance of the woodland height, porosity, width, length, orientation and shape on the area and level of shelter are discussed. Three generic shelter wood types are identified ('windshield', 'windbreak' and 'hybrid') together with their most appropriate applications. The Note points to the crucial need to understand the reasons for creating shelter in order to determine the most effective shelter wood design and management.

INTRODUCTION

Throughout history humans have attempted to modify the climatic conditions affecting their crops and animals in order to increase productivity and comfort. In particular, trees have been planted in woods and belts to provide shelter and shade (Figure 1). Britain is one of the windiest countries in the world (Quine, 1995) so there is a long history of using trees for shelter in exposed parts of the British Isles. The agricultural improvers of the 18th and 19th centuries recognised the importance of shelterbelts in such a climate and we continue to benefit from their legacy (Mutch, 1997). Farmers still recognise the value of trees for shelter and the agricultural and forestry departments continue to encourage the establishment and management of farm woodlands for this objective (Forestry Commission, 2000). Recently there has been interest in encouraging the use of trees for the entrapment of air borne pollution (Forestry Commission, 1999) and to shelter urban areas to increase energy conservation (Patch, 1998).

Wind is the flow of air in response to atmospheric pressure differences and modifying this flow is the principal way in which shelter woods[1] are used to affect microclimatic conditions. Modifying the airflow not only affects wind speed but also **turbulence**[2] intensity, temperature, humidity and soil erosion. At the same time the shelter wood may affect the amount of sunlight falling on adjoining fields and heat loss due to radiation.

[1] The term 'shelter woods' is used in this Note to represent all woodlands that are valued for their shelter benefit. The term 'shelterbelt' is not used because it is usually identified with rectilinear plantations.
[2] Words in bold type are explained in Definitions (page 8).

Figure 1

Beech trees planted for shelter. Ayrshire, Scotland.

Shelter woods present a porous obstacle to approaching airflow creating an increase in pressure in front of the belt and a decrease behind. The high pressure slows the approaching flow down and forces it to be deflected upward (Figure 2a) in a region referred to as the **displacement zone** (Figure 2b). Above the top of the shelter wood the wind is accelerated and the increase in wind shear leads to an increased production of turbulence. Some of the approaching flow filters through the shelter wood with a reduced velocity (**bleed flow**) due to the drag provided by the trunks, branches and foliage. If the shelter wood is extremely dense then almost no air penetrates through the wood and a stagnant slow circulating **eddy** is formed behind the shelter wood (indicated by the **cavity zone** in Figure 2b). The more open the shelter wood the weaker this eddy becomes until it disappears completely and the **wake zone** begins immediately behind the shelter wood.

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Figure 2a The flow of wind over a shelter wood.

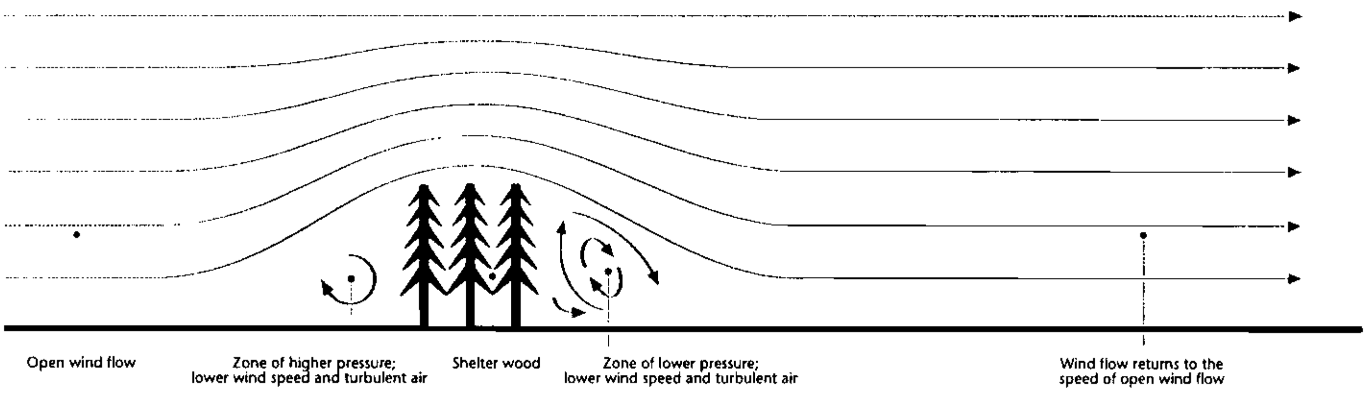
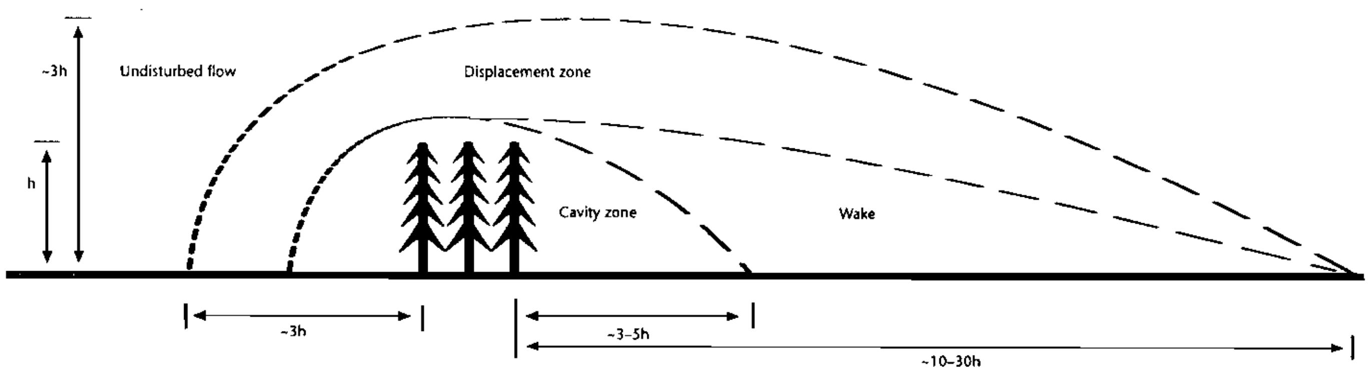


Figure 2b Wind flow zones created by the flow of wind over a shelter wood and their scale in relation to the height of the shelter wood.



The wake zone is the region in which fast moving air displaced above the shelter wood begins to mix with the slower moving air that has filtered through the shelter wood. Downstream of the shelter wood, within the wake zone, the wind speed gradually increases until it is the same as the wind speed upwind of the shelter wood. The wake zone is the main area where there are microclimatic benefits of shelter.

MICROCLIMATIC BENEFITS

A summary of the main microclimatic changes associated with shelter woods is given in Table 1.

The wind speed is reduced ahead of and behind the shelter. However, turbulence levels may be increased in the cavity zone, which can lead to increased **lodging** and abrasion damage to crops. Within the shelter wood itself the wind speed is generally reduced. However, if the wood has a very open understorey, squeezing of the flow between the canopy and the ground may increase the wind speed under the canopy.

The daytime temperature and humidity are generally increased in both the cavity and the wake zone. However, close to and within the shelter wood there may be shading from the sun, which will reduce the temperature. This may be a disadvantage if solar heating is important, but if crop scorching or sunburn to animals is a consideration it may be of benefit. Within the shelter wood the night-time temperature is raised because the canopy reduces **radiation transfer** to the atmosphere. However, the night-time temperature may be reduced in the cavity zone – if the belt is very dense – because it will restrict mixing of cold air near the ground with warmer air above. This could be important for animals sheltering behind or in dense belts on still clear nights.

Within the wake zone the reduced wind speed and turbulence leads to a reduction in the movement of gases to and from the ground. This means that moisture levels are higher and there is reduced water loss from the soil. Close to the shelter wood, within the cavity zone, this may lead to waterlogging if the soil is particularly wet, or increased plant growth if the soil is prone to drought. The reduced wind speeds can also lead to reduced soil erosion.

Table 1 Changes in microclimatic conditions in different areas adjacent to a shelter wood.

Area	Increased	Reduced
Displacement zone	• Wind speed above shelter wood • Turbulence	• Wind speed at ground level • Sunlight close to shelter wood
Inside shelter wood	• Wind speed (only for very open shelter wood) • Night-time temperature	• Wind speed (except for very open shelter woods) • Daytime temperature • Sunlight
Cavity zone	• Turbulence • Daytime temperature • Humidity • Lodging and abrasion • Waterlogging on wet soils	• Windspeed • Night-time temperature (on clear calm nights) • Sunlight close to shelter wood
Wake	• Daytime temperature • Humidity • Carbon dioxide	• Windspeed • Turbulence • Erosion • Water Loss

FACTORS CONTROLLING SHELTER WOOD PERFORMANCE

Height

The height of the shelter wood and the porosity are the most important factors controlling performance of a shelter wood. The area ahead of and behind the shelter wood over which it is effective is a direct function of shelter wood height as illustrated in Figures 3–5. The taller the shelter wood the larger the area of shelter.

Porosity

In simple terms, porosity (Definitions, page 8) is a measure of how open the shelter wood is and how easily the air can flow through it. The porosity of the shelter wood directly influences the intensity and area of shelter produced by the shelter wood. Porosity is affected by planting density, canopy distribution, species mix, shelter wood width and time of year.

Figure 3

The flow of wind across a dense shelter wood (0–40% porosity).

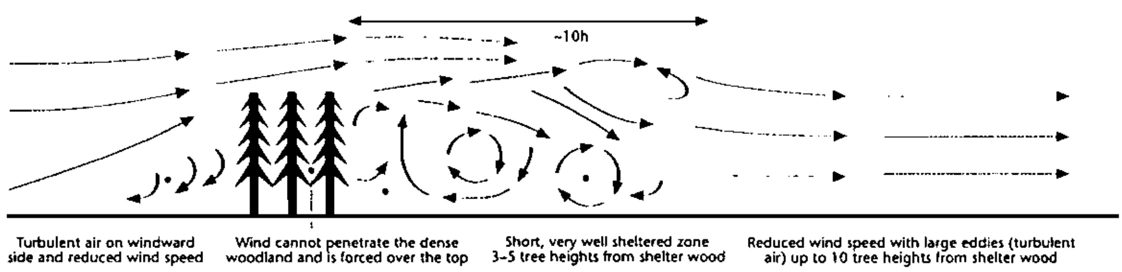


Figure 4

The flow of wind across a medium density shelter wood (40–60% porosity).

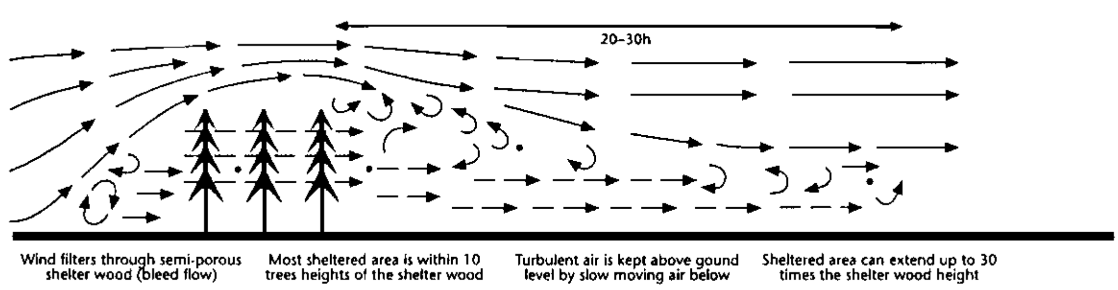
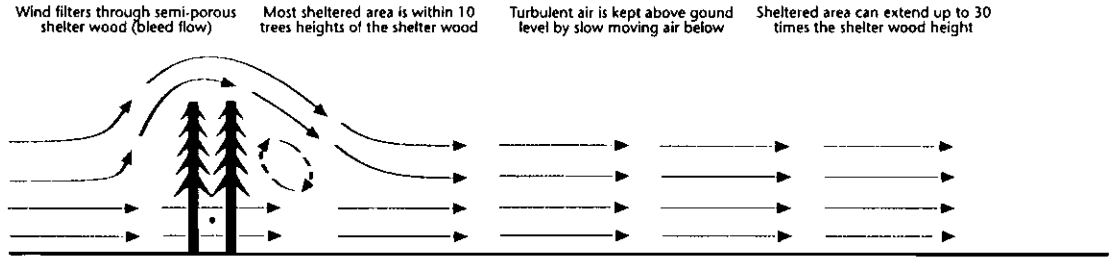


Figure 5

The flow of wind across an open shelter wood (60–100% porosity).



A dense shelter wood, or 'windshield' (Figures 3 and 6), will result from close spaced trees and shrubs, a large width of woodland or a combination of both factors. Shelter woods tend to have lower porosity when they are young and there are live branches down to the ground. The porosity tends to increase as the trees grow and the canopy lifts off the ground while, at the same time, self-thinning due to mortality will tend to lower the porosity as the shelter wood ages. The flow pattern across a dense shelter wood is illustrated in Figure 3. The majority of the air is forced over the trees by the high pressure ahead of the shelter wood. Because little air passes through the shelter wood, the flow separates and a cavity zone and a large drop in pressure is created behind the wood. This low pressure causes the high-speed wind above the shelter wood to return quickly to the surface giving a short region of shelter but with very reduced wind speeds.

A medium density shelter wood, or 'windbreak' (Figures 4 and 7) allows much more air to flow through the shelter wood. This reduces the chance of flow separation behind the wood so that the cavity zone may not exist and the wake zone begins immediately. The pressure changes across the shelter wood are also less severe than with the dense wood and, therefore, the return of the faster moving air towards the ground is more gradual. The result is the maximum area of shelter of any shelter wood but the intensity of the microclimatic changes are less dramatic. Figure 8 shows a 'hybrid' shelter wood with a medium density upper storey and dense lower storey. A broadleaved shelter wood such as this may have a high porosity in the winter but a much lower porosity in the summer (compare Figures 8a and 8b).

An open shelter wood (Figures 5 and 9) has a limited area of shelter and the reduction in wind speed downwind may be minimal. If the lower part of the shelter wood canopy is completely open, it is possible to increase the wind speeds within and just downwind of the wood compared with the open field values.

Figure 6

Dense shelter wood ('windshield').

Figure 7

Medium density shelter wood ('windbreak').

Figure 8

A medium density upper storey, dense lower storey shelter wood ('hybrid') in (a) winter and (b) summer.

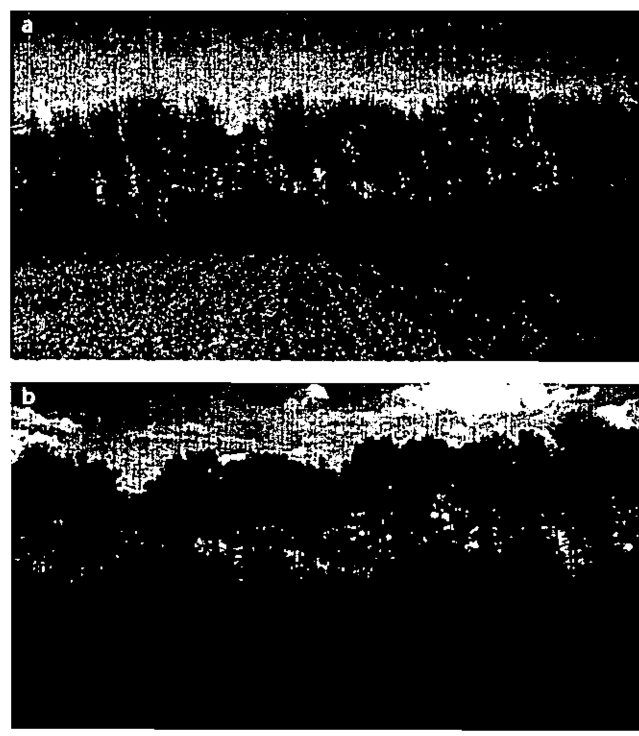
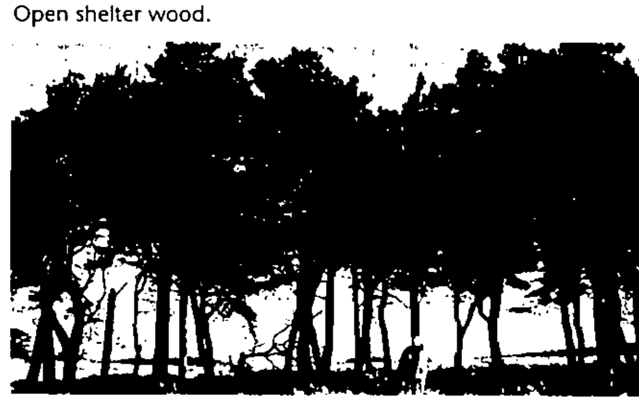


Figure 9

Open shelter wood.



Width

Width is generally not of such direct importance as height except in the way it affects porosity. A two-row shelter wood is as effective as a six-row shelter wood, provided they both have the same porosity, and it takes up less land. In extremely windy climates the leading rows of trees may be stunted in their growth and, therefore, a wider shelter wood will be necessary to obtain the required height.

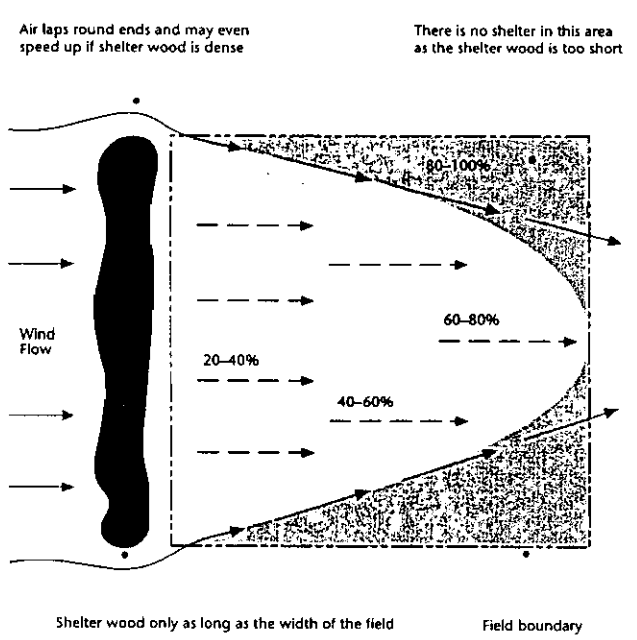
Very wide shelter woods (width >2 x tree heights) do not provide more shelter than a narrow belt because they behave very similarly to a dense shelter wood and wind speeds recover very quickly in their lee. Furthermore, the turbulence intensity over wide shelter woods is more developed and can lead to problems of lodging and plant abrasion.

Length

The shelter wood must be longer than the length of the area requiring shelter. This is due to the triangular shape of the sheltered zone (Figure 10). The air speeds up around the edge of the shelter wood resulting in higher wind speeds and turbulence levels in this area. Behind the shelter wood this high-speed turbulent air begins to encroach into the sheltered wake zone in an identical manner to the air that was displaced over the shelter wood.

Figure 10

The effect of shelter wood length on the area of land afforded shelter and the degree of shelter. The values shown (e.g. 20–40%) give the wind speeds expected for a particular area as a percentage of the open field value (unsheltered).



Orientation

The orientation of the shelter wood to the wind affects the area provided with shelter. The greatest area of protection is provided when the wind strikes the shelter at right angles but this is reduced when the wind strikes at a smaller angle (Figure 11). Therefore, the shelter wood is ideally located when it lies across the wind direction of particular concern. However, it is possible to construct shelter woods that provide protection from more than one direction (Figure 12).

Orientation also has an effect on porosity. The shelter wood is most porous to the wind when the wind strikes it at right angles. As the angle is reduced the porosity decreases because the effective width of the shelter wood is increased. The effect is more marked with wide shelter woods.

Figure 11

The effect of shelter wood orientation to the direction of wind flow on the area of land afforded shelter.

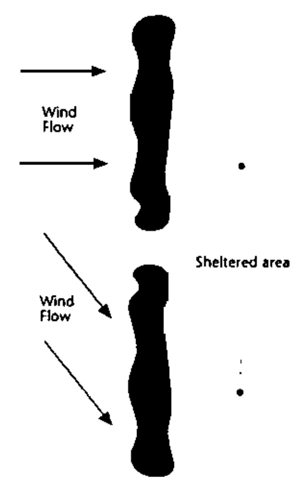
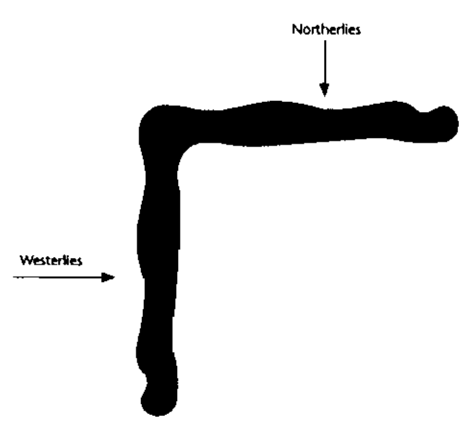


Figure 12

A shelter wood designed to be effective for two wind directions.

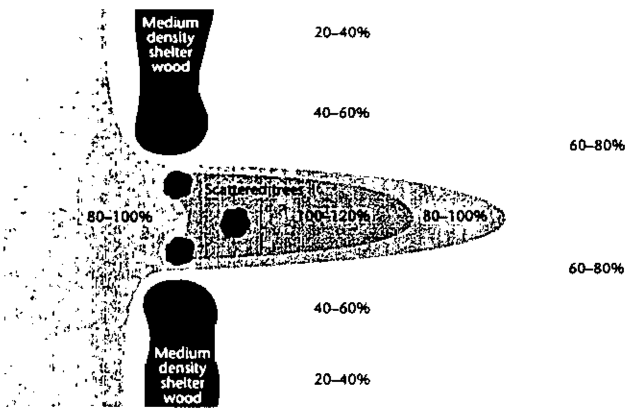


Openings

Any opening in a shelter wood has the same effect as the end of the shelter wood by increasing the wind speed and turbulence through the gap (Figure 13). The wind speeds within the opening may be significantly higher than the up-wind values. If an opening is required for access then it should be angled through the shelter wood or a 'dog-leg' included.

Figure 13

The effect of an opening in a shelter wood on wind speeds. The values shown give the wind speeds expected for a particular area as a percentage of the open field value (unsheltered).

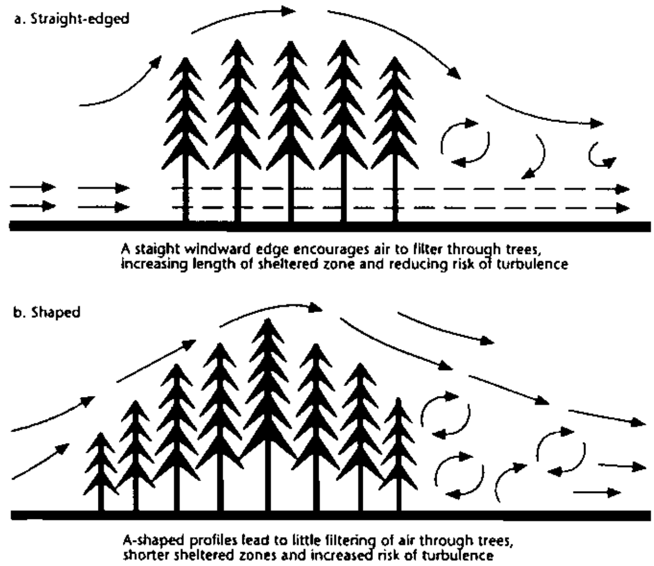


Shape

The ideal profile for a shelter wood is generally straight sided. This provides the maximum shelter for the minimum use of ground (Figure 14a). A profiled edge will tend to deflect more air over the shelter wood and allow less air to flow through the trees (Figure 14b). The result is to produce a sheltered area very similar to that achieved with a dense shelter wood.

Figure 14

The effect of the shape of a shelter wood profile on wind flow.



TYPES OF SHELTER WOOD

Differences in the porosity of the shelter wood produce different intensities and areas of shelter. By adjusting the porosity of the shelter wood and the vertical distribution of canopy elements different forms of shelter wood can be produced, which are appropriate to different shelter applications. Porosity can be increased by thinning, pruning and reducing shelter wood width. Porosity can be decreased by underplanting, increasing the width of the shelter wood or, for example, by the use of fencing, hedging and straw bales. In Table 2 the three basic types of shelter wood are set out with a description of the area and intensity of the shelter zone and their most appropriate applications.

Table 2 Descriptions of shelter wood types, their impact on wind speeds and their application.

Shelter wood type	Broad description of features (porosity/height/length)	Porosity profile	Length of wind speed reduction	Reduction of open wind speed	General application
Windshield (Figure 3 and 6)	• dense • as tall as necessary • as long as necessary	<40%	Up to 10 x height of the wood (max. shelter at 3–5 times the height)	up to 90%	• lambing/calving areas • feeding areas • farm buildings
Windbreak (Figure 4 and 7)	• medium density • as tall as possible • as long as necessary	40–60%	20–30 x height of the wood	20–70%	• crops • improved pasture
Hybrid (Figure 8 and 15)	• dense lower storey; medium density upper storey • as tall as possible • as long as necessary	<40% lower storey 40–60% upper storey	5 x height (approx) of the lower storey 20–30 x height of the upper storey	up to 90% 20–70%	• where a combination of applications suit both windbreak and windshield shelter wood types

SUMMARY

- The denser the shelter wood the greater the reduction in wind speed, the shorter the sheltered zone and the greater the turbulence in the lee.
- The taller the shelter wood the larger the area of shelter for any density of shelter wood.
- Porosity is more important than width – a narrow shelter wood with equal porosity to a wide shelter wood will be equally effective.
- The area of shelter behind a shelter wood is roughly triangular with the base set by the length of the shelter wood.
- Wind speeds are increased at the end of shelter woods and within any gaps or openings through the shelter wood.
- Shelter woods that are straight sided will be more effective than those with a tapered profile.
- Very wide shelter woods tend to have low porosity and provide a limited area of shelter.
- Dense (0–40% porosity) shelter woods create small but very sheltered zones appropriate for lambing, calving and feeding and the protection of buildings (Figures 3 and 6).
- Tall semi-permeable (40–60% porosity) shelter woods provide effective shelter to the largest area and are most appropriate for sheltering arable crops and grazing animals (Figures 4 and 7).
- Hybrid shelter woods with low porosity at their base and higher porosity at their top can provide a dual shelter function with a relatively wide area of shelter and an intense area of shelter close to the shelter wood (Figures 7 and 10).
- Very open (> 60% porosity) shelter woods are of little value and can actually increase wind speeds locally.
- Understanding the reasons for creating shelter will determine the most effective shelter wood design and management.

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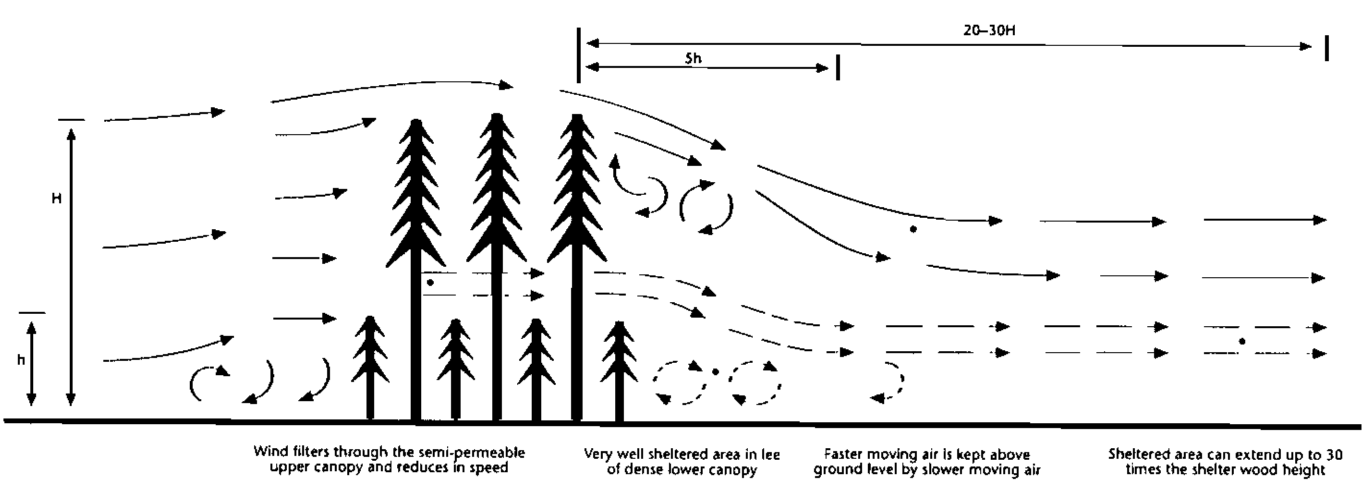
Figure 15 The flow of wind across a 'hybrid' shelter wood (Upper storey 40–60% porosity, lower storey < 40% porosity).



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Further information

This Information Note on The Principles of Using Woods for Shelter will be supported by additional information about the role of woods for shelter. Topics will include:

- Designing shelter plantings
- Farm woodland shelter assessment
- Protecting grazing livestock
- Protecting newly born lambs and calves
- Protecting crops and grassland

For more information, visit: www.forestry.gov.uk/shelter

Definitions

Bleed flow
The flow which filters through the shelter wood.

Cavity zone
A region of recirculating very low velocity air behind a shelter wood. Exists when the porosity is low and is absent when the porosity is above 40%.

Displacement zone
The area ahead of and above the shelter wood in which the flow is displaced upwards.

Eddy
A circular motion in the airflow.

Lodging
Wind damage to crops either by uprooting or by stem/stalk breakage. Exacerbated by turbulence.

Porosity
A measure of the ease with which air may move through a shelter wood. Optical porosity is a rough guide to the aerodynamic porosity and is the ratio of sky visible through the shelter wood to the area occupied by the shelter wood. An optical porosity of 0% represents a very impermeable shelter wood which cannot be seen through, a porosity of 90% would represent an extremely open shelter wood.

Radiation transfer
The radiative exchange of energy with another body or the atmosphere. During the day radiation transfer from the sun heats up the ground, plant canopies and animals. During the night radiation transfer to the sky cools the ground, canopies and animals. The cooling is most rapid when the sky is clear.

Shear
Any change of wind velocity with a change of position. Strong vertical shear exists over a shelter wood and strong horizontal shear exists at the end of shelter woods. Shear produces turbulence.

Turbulence
Random motions in the air. Turbulence encourages the exchange of gases between the atmosphere and plants, and heat between the atmosphere and animals and plants. High turbulence can lead to lodging and abrasion.

Wake zone
The main area of shelter behind a shelter wood. This is the region in which faster moving air displaced above the trees begins to mix back towards the ground.

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By Appointment to Her Majesty The Queen
Woodland Tree and Shrub Nurserymen

INFORMATION MEMORANDUM

AUGUST 2005

ALBA TREES PLC

COMPANY AIM

The aim of the company is to develop a leading horticultural business by growing and selling high quality cell-grown plants and associated products to the UK and European market, thus providing a profitable return to its stakeholders.

Contact

Tel: 01620 825058 Email: sales@albatrees.co.uk Fax:01620 825316

www.albatrees.co.uk

S:\salesdept\prospectus

ALBA TREES PLC – HISTORY

The company was formed in March 1988 by raising £1.75m of share capital from over 600 investors throughout the UK.

The rationale was to develop a major new container cell-grown tree nursery with a production capacity of 7 million trees to meet the anticipated demand for British native trees. The principles of cell-grown production were well proven in Canada and Scandinavia, though almost unknown in the UK where traditional planting was with bare-rooted stock (grown in open fields and lifted when dormant with as little soil as possible on the roots).

Up to the late eighties UK forestry had been led by individuals seeking business tax relief by investing in planting commercial conifer species with the aim of timber production. This came to a sudden end following the budget of April 1988 which removed the tax advantage. A revised Woodland Grant Scheme was introduced, which encouraged the planting of native species, including Broadleaves and Caledonian Pine. The new nursery was designed specifically to meet this demand for which traditional UK nurseries were not well-equipped.

A 20-acre site was bought and developed with the most modern plastic greenhouses, automatic irrigation, borehole, lagoon, closed water drainage system, large work-shed, despatch area and offices.

Container growing consists of sowing seed or transplanting seedlings into a plastic multicavity tray (cells) filled with a growing medium. Germination/establishment takes place in controlled environmental conditions followed by a hardening off period in the open.

Alba utilises specifically designed containers for improved root development, monitoring of root growth and ease of extraction for selection and planting.

Trees and shrubs for non-forestry reasons have increased in importance. This market includes the supply of landscape projects ranging from new builds in industrial and amenity projects to landscaping of new roads.

To facilitate the different plant specifications for this market Alba has increased its range of container sizes. The forestry market utilises small capacity containers ranging from 100cc to 250cc whereas the landscape industry requires larger cells ranging from 175cc to 1.8 litre capacities.

The advantages of cell-grown trees for the planter are numerous, including:

- All-year-round planting
- Improved establishment rate
- Improved early growth
- Wider range of native species and seed sources.

Since inception the results from the nursery have been exceptional. From 1988 to date, Alba Trees has sold 72 million trees and shrubs and the field performance of cell-grown seedling trees is well-proven. It is noteworthy that this success has been won against the background of a severe recession in the UK forestry sector.

The experience the company has gained covers not only the establishment of a new nursery, but also the development of systems and techniques specifically for container growing of trees and shrubs including:

- Seed collection and germination treatments
- Cultural techniques for intensive cell production
- Compost (medium) composition and filling
- Pallet handling and air pruning systems
- Irrigation systems, including water extraction and collection
- Fertiliser and chemical treatments, pest control
- Grading and despatch techniques
- Plant handling and packaging
- Computerised stock control and traceability of seed origins

Many of these developments have been innovative in the U.K., but have now been followed by other growers, including the Forestry Commission and nurserymen abroad. They have involved the large scale production of broadleaf (hardwood) trees and shrubs, as compared to earlier production of conifers in other countries. Results with broadleaves have been most successful both in the nursery and in their rapid establishment in the field. The Company has worked closely with the Forestry Commission Research Stations, especially at Roslin, Edinburgh but also with Edinburgh University, and the Edinburgh Tropical Forestry Unit. There are regular contacts with overseas visitors and students.

Major overseas consultancy projects undertaken have included:

1992 –1995
European community funded project for re-afforesting in Baltic countries. Main work was in Latvia in co-operation with timber harvesting company Latvijas Finieris and Latvian State Forestry department. Established two nurseries producing selected Betula pendula.

1993 – 1995
Consulting with Portuguese Forestry Company (Silvocentro) to develop a nursery to produce 2 million trees per year. Main species Quercus suber, pinus pinaster, pinus pinea and eucalyptus.

1995 – 2001
Development of a new container nursery in Czech republic for Lesoskolky s.r.o., the largest forest nursery in the Czech republic. For the last 6 years we have developed 3 nursery sites for them which together grow 5 million container trees. Species include Quercus, Fagus, Fraxinus and the conifer species of Pinus, Picea and Abies.

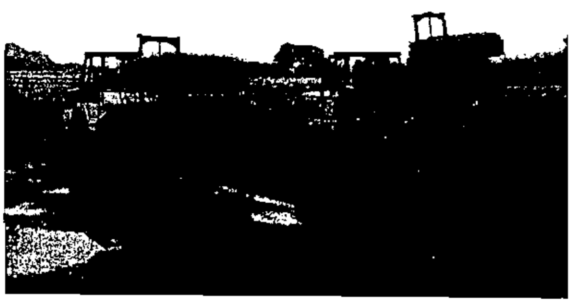
1996 – 1999
3 million tree nursery developed for the State Forestry of Ireland (Coillte Teoranta). The main output of the nursery is vegetative propagation of Picea sitchensis.

2002 – Present
Assisting the Georgian Forest Sector Development Centre and State Forest Department to design and develop a framework for the successful implementation of afforestation and reforestation programmes. This includes operating procedures/practises, guidelines, technical specifications for tendering procedures including the programming of related seed allocation and nursery production activities.

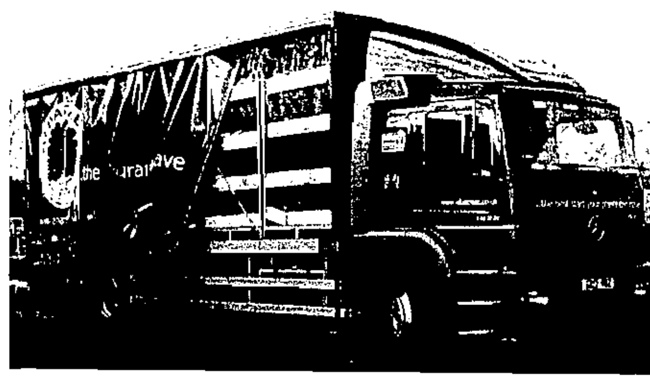
2002 – Present
Consulting with a major hi-tech Chinese company Zhengguang Group to develop a nursery capable of producing plants to halt the spread of desert in the high plateau grass lands of the Roergai County in the Northern part of the Sichuan Province.

Alba Trees plc is now the leading nursery in its field in both the UK and Europe. It is both successful and profitable and continues to expand both in size and in the development of new technology. As a young company it recognises the need to keep ahead of its competitors by actively researching new ideas and skills. Based on sound horticultural and forestry practice, and with a trained and enthusiastic staff Alba aims to maintain its position in the forefront of plant supply.

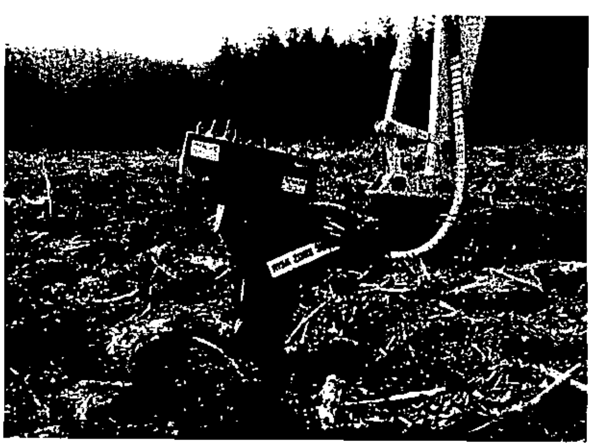
Rodney Shearer being presented the Royal Warrant by Provost O'Brien, James Hepburne Scott looks on



Stock Movement



Delivery Vehicle



Brackĕ Planter

A more comprehensive pictorial nursery tour is available on Alba's web site at www.albatrees.com

Milestones in Development of Alba Trees

Nov 87	Conceived idea for UK's first major forest container tree nursery.
Apr 88	Raised £1.5 million pounds from investors throughout the UK.
May 88	Began development of a green field site in East Lothian into a modern container nursery.
Jan 90	First major production programme began.
Nov 90	Sold first million trees.
Mar 91	First large Caledonian Pine forest supplied with 2 million trees.
Nov 92	First exhibited at trade fairs in Europe.
Dec 92	10 million trees sales target achieved.
Sep 93	First major export order to mainland Europe.
Feb 94	Alba Trees Nursery Developments formed to provide overseas nursery development consultancy.
May 96	25 million tree sales target achieved 10,000th Customer supplied.
May 97	Introduced advanced stock control system to verify traceability of stock.
Feb 00	50 million tree sales target achieved
Jan 01	Awarded Royal Warrant by HM The Queen.
Nov 01	Awarded East Lothian Business of the Year Award
Jan 02	Became UK agents for the Swedish Bräcke planting machines.
Jan 03	60 million trees sold to date.
April 03	Increase product range to include Wildflowers, Reeds and Native Trees in larger containers.
Jun 03	Increase species range to include vegetative propagation of genetically improved Sitka Spruce.
Aug 03	6 Bräcke Planting machines in operation.
Oct 04	Royal Warrant re-awarded until 2009.
Mar 05	72 million plants sold to date, making Alba one of the UK's largest suppliers to the forestry, amenity and horticulture markets.

MARKET SECTOR ANALYSIS

New forestry planting (private sector)
From an annual level of 25,000 hectares in the late 1980's planting reduced sharply to 15,000 hectares in the mid 1990's following the removal of tax relief.
The new century has seen a further decline to approximately 12,000 hectares as grant support is re-directed from afforestation to re-forestation work.
It is hoped that CAP reform will release land and grant funding from agriculture to other sustainable productive land uses including woodland creation. The emphasis remains on planting of native species and increasingly of local provenance plants, an area in which Alba Trees leads the market.
The company, through its contribution to the Forestry and Timber Association, is pressing the case for an accelerated programme of afforestation for enhanced carbon sequestration and to produce wood fuel for the future.

Forestry re-stocking (private sector and FC)
Licenses are required to fell timber and legally oblige the owner to replant the land felled. Since 1994 a constant area of 14-15,000 hectares has required re-planting with approximately 37 million trees. Future timber output is expected to double in the next 10 years and with it the demand for trees for re-stocking. Traditionally planting is by hand involving large teams of labour. Shortages of such labour and associated management supervisory time are now becoming limiting factors. Alba Trees is currently in the forefront of mechanical planting and has secured a UK dealership for a machine to prepare ground and plant cell-grown trees.
After the removal of the existing forest, young trees planted are attacked by the devastating forestry pest, pine weevil. Alba have pioneered 3 new techniques to protect young trees from this insect:

- Injecting systemic insecticide granules by the planting machine into the planting hole.
- Mechanical, semi-automated application of contact insecticide to base of trees on the nursery.
- Application of plastic net sheath to tree from base of root to growing point to exclude insects (patent applied for).

With mechanical planting and insect control Alba is now experiencing strong growth in demand for cell-grown trees from this sector.

New Native Woodlands
This area of new planting continues to receive strong support from bodies such as The Woodland Trust, Scottish Forest Alliance, Borders Forest Trust etc. Alba's seed collection expertise and unique traceability system gives confidence to such organisations with particularly stringent local provenance requirements.

Land reclamation
Large areas of "damaged land", landfill sites, coal mines etc, are now being reclaimed, often with new woodland creation. Alba enjoys a good share of this market on account of the ability of cell-grown trees to establish in the poor soil conditions frequently encountered.

Export
The continuing strength of sterling makes export a particularly challenging activity. However we have continued to develop a strong network of European and Irish customers and contacts which is now bringing increasing levels of new business.

E-business
The Alba website www.albatrees.com.uk is regarded as one of the best in the nursery trade It is easy to navigate with 50 pages of information and a live connection to a current availability list.
A special "Mail-Pack" for despatch of our plants and a "back office" administration system to exploit the e-business sector has been developed. Thus Alba now supplies the trees for the Woodland Trust Native Tree Shop and their schools packs and corporate promotions.

New markets

Alba Trees has recently introduced a range of new products designed to exploit new market sectors. These include:

- Native trees in 2-litre containers for the landscape market
- Reeds for constructed wetlands for water treatment and flood relief
- Oil-bearing aromatic plants for heath-care markets
- Wild-flowers for landscape and garden planting
- Trees grown in peat-free medium

In common with most other industries forestry has a cyclical nature. During 2000 and 2001 all European Nurseries experienced a down-turn in their fortunes. However at Alba Trees we recognise that the re-stocking of the great forests planted during the boom years of the 60's and 70's presents the company with a major opportunity. Our ability to innovate and adapt to changing market circumstances is one of our greatest strengths and a programme of change to exploit this increasing market is already well in progress.

Alba Trees is broadly-based and supplies markets outwith traditional forestry. But we remain fully committed to the rural and urban landscape sectors and to the major restoration and expansion of Britain's native woodlands.

The entrepreneurial spirit which founded the company is very much alive and we look to the future with confidence.

BOARD OF DIRECTORS
Personal Profiles

Peter Church - Chairman

Aged 60 - Married with 4 children. Peter Church lives at Kelso in the Borders and is a businessman and farmer. His family company is Ronaash Ltd., manufacturer of Rootrainers, the leading container for growing forestry trees. He holds a diploma in Rural Estate Management and originally conceived the plan for the company with Bill Thomson in 1987. He has been a Director since its inception and was Managing Director for 12 years and deputy chairman for 2 years.. He became Chairman in May 2003.

Rodney Shearer, NDH, RHS, IOD - Managing Director

Age 48 - Married with 3 children, he lives in Haddington. Rodney was one of the founding Directors of Alba Trees, and held the post of Production Director since the Company's inception in March 1988 until 2000, when he was promoted to Managing Director. He holds NDH Hort. (with Distinction) and RHS qualification, and since joining Alba he has obtained the IOD Diploma in Company Direction. A horticulturist to trade with 30 years experience, he is now the leading expert in Europe in the production of container grown trees and shrubs.

James Hepburne Scott, BSc (Hons) - Sales Director

Age 57 - Married with 3 children and lives at Lauder in the Borders. James comes from a hill-farming background in the Scottish Borders and has an extensive knowledge of agriculture and forestry throughout the UK. He joined the Company from the Agricultural Mortgage Corporation Plc, which finances agriculture, horticulture and forestry, where he was Regional Manager for Scotland. He is Chairman of Forestry & Timber Association for Scotland and a member of the National Farmers Union. He joined Alba in 1993 as a Non-executive Director and in 1996 became Sales Director.

Barry Sutton – Development Director

Barry joined Alba in 1989 and joined to board in 2005. His background as a forester ensures the sales team is able to appreciate the challenges faced by woodland managers. He has been responsible for establishing the network of Bracke planting contractors and is widely consulted in Europe for his knowledge of this technique. He has developed unique software used for production planning, stock control and sales order processing to assist in the management of a complex mix of crops and product specifications.

William Thomson - Non-Executive Director

Age 57 - Married with 4 children. Bill Thomson lives in Edinburgh and is well respected in the Scottish business community. His directorships include Forth and Celtic Tankers plc, Tibbett & Britten Group and a member of the Trinity House Lighthouse Board. Along with Peter Church he conceived the original plan for the company, and has been a Director since its inception. His wide business experience and entrepreneurial skills make him a valuable member of the Board.

George Heggie, F.C.A. - Non-Executive Director

Age 57 - Married with 2 children. George lives in Surrey and is an Accountant by profession. He is the Managing Director of Private Investors Monitoring Services Ltd of London and has been a Non-executive Director and Company Secretary of Alba since its inception in 1988,. He represents the interests of the Shareholders.

KEY PERSONNEL

Anne White – Accounts Administrator

Anne joined Alba in February 1989 and has developed from part time bookkeeper to accounts administrator and has been involved in the transformation from manual to computerised accounts. Her role has greatly expanded and along with the daily management of accounts she is also responsible for company insurance's and assists in budget forecasting.

Anne's length of service makes her the company's longest serving employee

Jackie Watson – Office Sales Executive

Jackie joined the company in 1992. She comes from a farming background. The company enjoys a reputation for speedy response to quotes and sales queries. This is in no small part down to the hard work of Jackie who has become a familiar voice to many of our customers in her role as Office Sales Executive.

Kevin Shearer – Transport / Despatch Supervisor

Since joining the company in 1995 as a Nursery Worker he has been Alba's representative for Overseas Development and has worked in nurseries in Canada and the Czech Republic. Since attending the Forestry School at Inverness he has now progressed to Supervisor for Transport and Despatch and is responsible for scheduling all deliveries and ensuring that the orders are despatched on time. Kevin is normally the last point of contact with customers to arrange the safe and efficient delivery of goods.

Margaret Allan – Sales Administrator

Margaret joined us in 1997. She comes from a farming background and has become a familiar voice to many customers over the past few years. Toghether with Jackie she helps to put together our annual show and exhibition programme

Derek Stewart – Nursery Supervisor

Derek joined Alba in 2001 as a Nursery Chargehand. He has 15 years' of experience in horticulture coming to Alba from a nursery in the north of Scotland. In 2002 Derek took over as the Nursery Supervisor and has taken over the responsibility for the day to day management of the largest cell-growing nursery in the UK. This requires good teamwork and dedication. Derek is responsible for maintaining a strong team who man the nursery 7 days a week and successfully manage a complex mix of crops.

ForestGALES

A PC-based wind risk model
for British Forests

User's Guide

Version 2.0 June 2004

Barry Gardiner, Juan Suárez,
Alexis Achim, Sophie Hale
and Bruce Nicoll

Forestry Commission

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Welcome to ForestGALES

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For details of latest updates and on-line version of this manual access

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1

Why use ForestGALES?

Wind damage to forest stands results in both direct costs (additional cost of harvesting) and indirect costs (loss of amenity, danger). Threat of wind damage has restricted silviculture and led to the use of truncated rotations with precautionary felling in anticipation of windthrow.

Forest managers therefore require guidance on the timing and magnitude of wind damage. A number of risk-minimising strategies can be applied (see Quine *et al.*, 1995) but these may be costly and so are best carried out only where the risk is high. The strategies can involve operations within individual stands (typically 1–20 ha), or the layout of stands at the forest scale (areas up to 50 000 ha). A sound choice between techniques which may influence the risk of damage such as type of cultivation, thinning, sequence of felling, is most likely where prediction of their effects is possible. Research into both prevention and prediction of damage has been carried out for nearly 30 years and this past work has been drawn together to provide ForestGALES as a tool to guide forest managers.

The degree of constraint posed by strong winds in Britain

Wind damage is a serious problem in forests planted on exposed sites in Britain and western Europe. It is believed to cost the countries of the EU more than €15 million per year, and in extreme cases substantially more. Five 'catastrophic' storms have affected British forests in the 50 years since 1945, emphasising the frequency and scale of the problem – these include the storms of 1998 in south Scotland, 1990 in south-west England and south Wales, 1987 in the south-east of England, 1968 in the central belt of Scotland, and 1953 in north-east Scotland. In each case over 1 million cubic metres of timber was damaged, and up to five times the normal annual cut for the affected region required harvesting. In 1999, storms Lothar and Martin damaged more than 190 million cubic meters of timber in continental Europe. Lesser storms also cause some wind damage in most years, and their combined effect is a serious constraint in upland forests. Windthrow has been the main form of damage, but wind snap can be locally important when trees are particularly well anchored or the crowns are loaded with wet snow.

Historical context – previous predictive windthrow model

Until recently choices of windthrow-minimising strategies were guided by the windthrow hazard classification ((WHC): Miller, 1985) which provided a method to zone forest areas of 500 ha or more by adding scores for windiness and soil together to estimate a hazard class. Each class was associated with a critical and a terminal height (see Table 1.1) which respectively indicated the heights at which damage was expected to start and to reach a level necessitating clearance. The WHC provided a successful basis for comparing sites and guiding decisions on thinning, but did not predict the timing or amount of damage with acceptable accuracy (Quine and Bell, 1998). It was based on subjective weighting of the influence of strength of wind and inadequacy of rooting on the timing of wind damage. While this synthesised understanding in the 1970s it could not be readily updated to incorporate new knowledge.

Research since the WHC was devised has improved understanding of root anchorage (Coutts, 1983; Coutts, 1986), turbulence (Gardiner *et al.*, 1997), adaptive growth (Nicoll and Ray, 1996), and wind climate (Suárez *et al.*, 1999). While it was possible to incorporate such advances in qualitative advice (Quine *et al.*, 1995) a new system was needed to treat wind risk quantitatively.

Table 1.1

Critical and Terminal heights for each of the six classes defined by the Wind Hazard Classification.

WHC	Critical height (m)			Terminal height (m)		
class	Non-thin	Selective	Line thin	Non-thin	Selective	Line thin
1	Unconstrained by windthrow			Unconstrained by windthrow		
2	25.0	22.0	21.0	31.0	28.0	28.0
3	22.0	19.0	17.0	27.0	25.0	23.5
4	19.0	16.0	14.0	24.0	21.5	18.5
5	16.0	13.0	12.0	19.5	17.5	15.5
6	13.0	10.0	9.0	15.5	13.5	11.5

What does ForestGALES calculate?

ForestGALES calculates the probability of *average trees* being damaged within a stand. Damage to the average tree will by implication mean that the stand as a whole will be substantially damaged.

How does ForestGALES compare to the WHC?

ForestGALES estimates the chance (or probability) of windthrow or stem breakage, rather than stating a precise height at which damage will occur as in the WHC. Probabilistic predictions are more realistic than precise heights since the occurrence of damaging winds varies from year to year, which has a powerful influence on the occurrence and spread of damage.

The risk of damage is extremely dependent on the windiness of the site. In the WHC the measure of windiness is much coarser than is used in ForestGALES. This allows ForestGALES to discriminate several levels of risk for trees in similar WHC classes.

For example, a crown thinned stand of YC 12 Sitka spruce planted on a deep ploughed gley soil, with average drainage, where the DAMS score is 14, will have a critical height of 19.0 m and a terminal height of 21.5 m. The standard Forestry Commission yield models (Edwards and Christie, 1981) indicate that the trees will reach 21.4 m top height at age 51 when the return period for damage will be 7 years. On the other hand if the DAMS score is 10, then the site will still have a WHC class of 4, yet the return period for damage to a 51-year-old stand has increased to 200 years.

What is new in ForestGALES 2.0

ForestGALES 2.0 represents a complete rewrite of the ForestGALES software. The new software is a much more efficient and robust code, which is easier to understand and to document. Furthermore, it allows much easier integration with other modelling tools. The main part of ForestGALES (the part that does the actual calculations) has been constructed as a stand-alone dynamic link library (DLL). This means that all the functionality of ForestGALES is available from any other programme. The creation of a DLL has made it much easier for ForestGALES to be integrated with GIS software such as ArcView. Currently trials are under way in a forest district on the use of ForestGALES within ArcView. Following these trials a general release of a ForestGALES add-on to ArcView will be made available.

Wind Climate

The most important change to the calculation of risk is the change to the wind climate calculator. The calculation of the probability of a particular wind speed occurring at a site is based on the DAMS score. Additional analysis of wind climate data from Forest Research wind monitoring areas has suggested that the wind climate calculator was pessimistic. The differences are most pronounced at low DAMS scores but even at a DAMS value of 15 the new regression has the effect of reducing the DAMS score by 2 to an effective score of 13.

This is the only change in the calculation of risk. Critical wind speeds remain identical to ForestGALES 1.3 but the probability of these wind speeds occurring is reduced.

Appearance

The appearance of ForestGALES has been improved to provide a more consistent view and to provide for easier operation.

Defaults

There is now a Defaults button (Alt + D) that can be used to store the current values as the default. Therefore, if the current soil is a brown earth and the Defaults button is pressed then brown earth becomes the default soil used in ForestGALES. This is particularly useful if one is consistently working with a particular combination of species, cultivation and soil types.

Multiple Stands (Batch) Mode

The Batch operations have been substantially improved. Entering data in Multiple Stands Mode now uses the same forms as for Single Stand data entry and there are three versions of Multiple Stands Mode matching the three methods of calculating risk (Predictions using field measurements, Predictions using yield models, Predictions through time). Unlike the previous version of ForestGALES it is now possible to use the yield models to enter data or to calculate risk through time when in Multiple Stands Mode. In all cases input data and results can be stored in files for later use.

Export

There are improved export facilities in ForestGALES 2.0 allowing results to be sent to Word® as a Doc or Rtf file in the Single Stand mode and to Excel® in Multiple Stands Mode for display, storage and printing.

2

System requirements

ForestGALES will run on IBM compatible personal computers that have a minimum of:

- Microsoft Windows operating system
- Pentium 133 megahertz (MHz) or higher processor
- 32 Mb of RAM
- CD-ROM drive
- 20 Mb of hard disk space if DAMS scores left on CD (520 Mb for full installation)
- Super VGA (800 x 600) display or higher-resolution monitor with 256 colours

Recommended: Microsoft Excel/Word 97® or above to use data export facilities

Installing ForestGALES

To install ForestGALES:

1. **Place the ForestGALES CD in the CD drive.**
2. **The program will automatically install.**

If automatic installation does not occur, then:

3. **Press the Start button.**
4. **Press Run.**
5. **Type D:\Setup.exe into the dialog box, which will appear (replace the letter D with whatever drive letter corresponds to your CD-ROM drive).**
6. **Left click on OK.**

By default the program will then be installed into the directory **C:\Program Files\Forest Research\ForestGALES_ver2** on the drive, although it may be placed elsewhere if required. The installation program will automatically place all the files where they are needed, and add an option to run ForestGALES 2.0 from the Programs bar.

Uninstalling ForestGALES

To uninstall the program:

1. Press **Start.**
2. Choose **Settings.**
3. Choose **Control Panel.**
4. Choose **Add/Remove Programs** then select **ForestGALES 2.0** from the list of programs.
5. Left click on **Add/Remove.**

This will remove all the components and data files of ForestGALES 2.0, with the exception of files created while using the program. Exceptions include saved/exported data files and new yield models.

Running the model for the first time

Start the program from the Windows **Start**. After the initial welcome screen you will be presented with the main menu window as shown in Figure 2.1. Choose **Mode, Single stand, Prediction using field measurements** and a new query form will appear as shown in Figure 2.2.

Set:

- Species to 'Sitka spruce'
- Cultivation to 'notched planting'
- Drainage to 'Average'
- Soil to 'Peaty Gley'
- Current spacing to 2.6 m
- Top Height to 18 m
- DBH to 19 cm
- DAMS score of 15

Press the **Run** button and the Return Period, Wind Damage Risk Status and Critical Wind Speeds for overturning and breakage will appear in the previously empty boxes at the bottom of the form. Return periods will be 200 years for both overturning and breakage. Change the top height to 19 m using the up arrow next to the top height edit box and press the **Run** button again. The return periods will change to 53 years for breakage but remain 200 years for overturning. **You are running ForestGALES!**

The various options available for the model are explained in later sections of this manual.

Figure 2.1 The ForestGALES main menu.

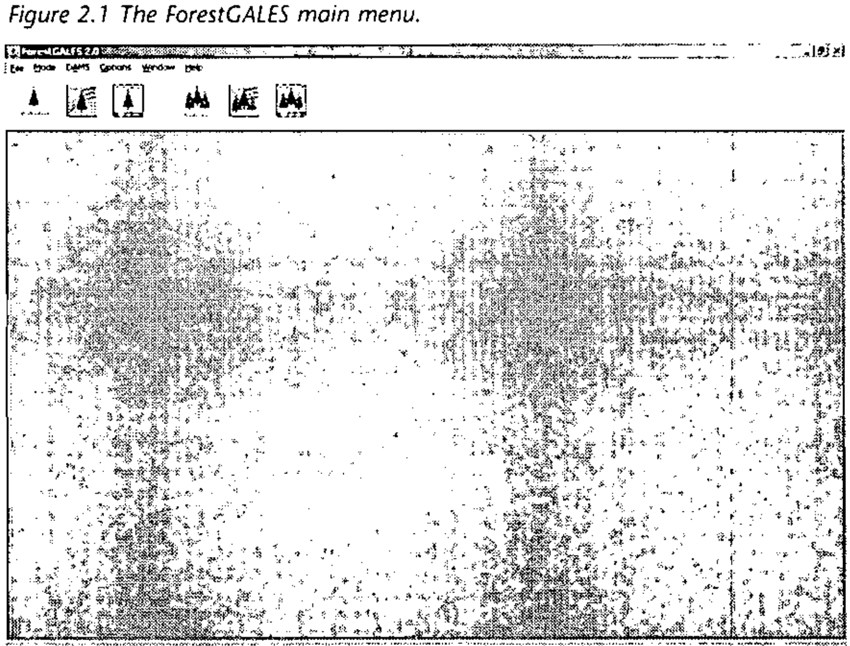
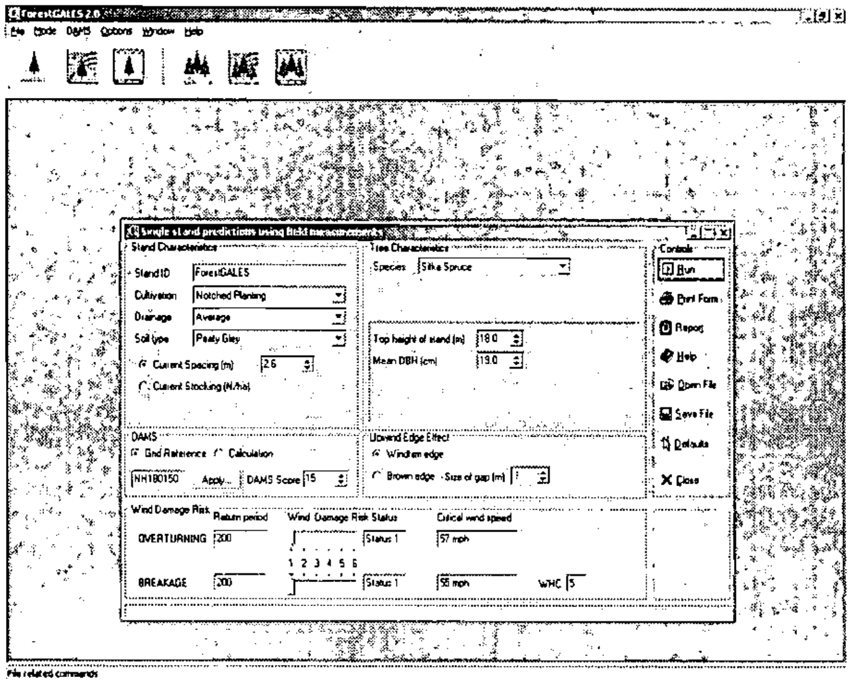


Figure 2.2 Query form for Single stand predictions using field measurements.



3

How does the model work?

The model uses data relating to individual trees to estimate the risk of damage to stands of trees by answering three questions:

1. *What force would be needed to uproot or break the tree?*
2. *What wind speed would create the force required to damage the tree (i.e. what is the threshold or critical wind speed)?*
3. *What is the probability of the threshold wind speed being exceeded?*

What force would be needed to uproot or break the tree?

The model calculates the strength of the stem and the resistance of the tree to overturning independently.

Stem strength is based on theoretical work regarding tree stems as structures, and a knowledge of the wood strength and stiffness of different tree species.

Resistance to overturning is based on an extensive database of tree pulling experiments that relate tree characteristics to the load required to pull a tree over. These experiments have been conducted on a range of soil and cultivation types for many species. However in some circumstances no data are available, so assumptions have been made to allow data to be extrapolated. When this happens, a warning message box will appear and the results should be used with caution. The effect of drainage intensity is included in the calculation based on the average change in force needed to pull over trees on well or poorly drained soils in comparison to soils with 'average' drainage.

What wind speed would create the force required to damage the tree?

In ForestGALES the wind loading on trees is calculated from the drag the forest exerts on the flow above the canopy. The drag is a function of the wind speed and the aerodynamic roughness of the canopy which is dependent on the crown size and the area of ground occupied by each tree.

Crown size is modelled using regressions based on the height and diameter of the tree.

From a knowledge of the average wind loading on each tree and the resistance to breakage and overturning, the wind speed that would just cause the tree to overturn or break is calculated. This includes calculating the extra force due to the overhanging weight of the crown and stem as the tree bends.

What is the probability of a damaging wind speed occurring?

Having calculated the wind speed required to damage the tree, the probability of such a wind speed is estimated.

The average windiness of the site is measured using the DAMS system, which is based on location, elevation and exposure. However, average winds are unlikely to damage the tree, and the risk of extreme winds that are sufficiently strong to cause damage must be derived from DAMS using a Weibull distribution.

This distribution is extremely sensitive, and small changes in the wind speed required to cause damage can be associated with large changes in the probability of damage occurring.

Having calculated the probability of damage, this is converted to a return period for a damaging wind speed occurring. This is the average interval between storms that are associated with damaging winds.

Wind Damage Risk Status provides a rough estimate of risk, ranging from Status 1 (return period for damaging winds more than 100 years) to Status 6 (return period less than 10 years).

Running ForestGALES

4

There are several ways to start the program.

The easiest is to press **Start**, followed by **Programs, ForestGALES 2.0, ForestGALES**. When this is done, the program will start and the main menu (Figure 2.1) will load onto the screen.

ForestGALES has been designed as a complete Windows application. Menus are easily accessible with the mouse in the top part of the main window, or they can be accessed using pop-up windows, shortcut keys or speed buttons.

Operating modes

ForestGALES can be used interactively in two operating modes:

Single stand mode	- calculates the risk for one particular stand.
Multiple stand mode	- calculates the risk for a number of stands one after another (batch mode).

There are three ways of making predictions within these modes:

Predictions using field measurements	- calculates the risk of damage at a single point in time from stand characteristics defined by the user.
Predictions using yield models	- calculates the risk of damage at a single point in time from stand characteristics contained in yield models.
Predictions through time	- calculates the risk of damage over a typical rotation from stand characteristics contained in yield models.

Selecting a mode and opening a query form

Having started the program, to select a particular mode, left click on **Mode** at the top of the main menu.

A menu will appear. Left click on the mode that you want, and the menu will disappear, and a form will appear automatically.

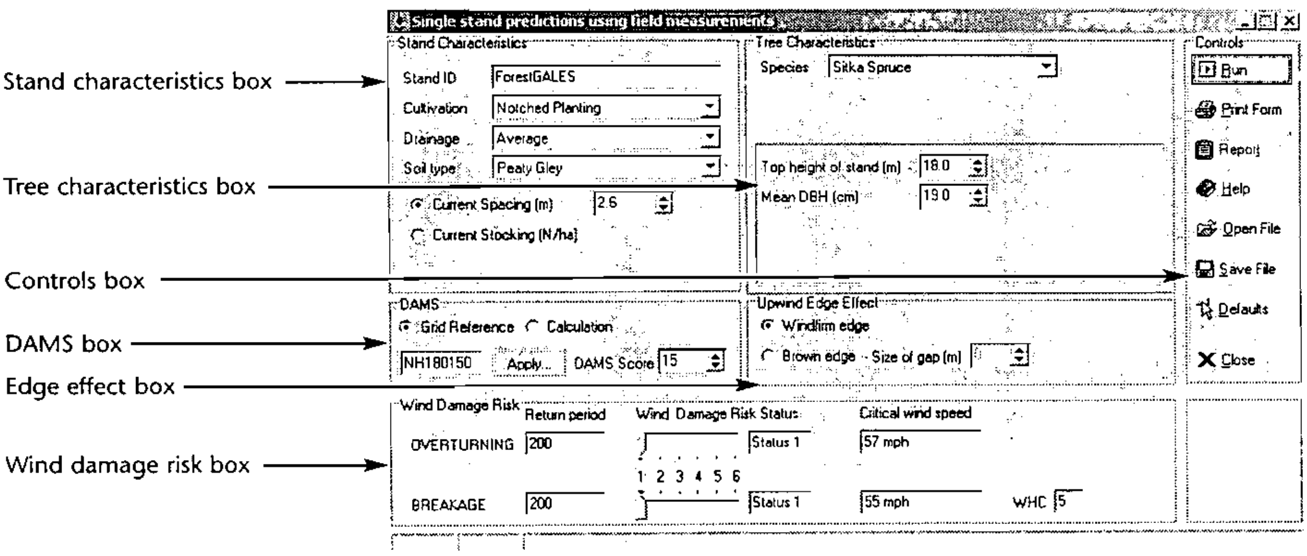
Alternatively, a new form can be created using the shortcut buttons at the top of the main window. The meaning of each shortcut button is indicated by a hint message that appears when the mouse is positioned over the button.

It is possible to have several copies of a query form open at the same time. This may be useful if you wish to compare alternative scenarios.

ForestGALES query forms

ForestGALES collects data from and writes results to query forms. The exact layout of the form depends on the mode (single stand, multiple stands) in which the model is being used and the type of prediction being made (using field measurements, using yield models, through time). Figure 4.1 shows the layout of the form for *Single stand predictions using field measurements.*

Figure 4.1. Query form for Single stand predictions using field measurements. The parts of this form are:



Stand characteristics box – describes the soil, spacing, cultivation, drainage, and (where appropriate) planting year.

Tree characteristics box – describes the size of the trees within the stand being modelled.

Upwind edge effect box – states whether a new brown edge is present, and, if so, the size of the gap created.

DAMS box – describes how windy the site is. DAMS can be entered directly, calculated exactly, extracted from a pre-calculated data file for a particular location or estimated roughly. The layout of the box depends on which selection is chosen.

Controls box – allows the user to run the model, save inputs, load a saved file, print results, close the form and obtain help.

Wind damage risk box – indicates the risk of uprooting or stem breakage occurring, and the estimated return period.

The query forms for other modes are described in later sections of this manual.

Navigating ForestGALES

Using the mouse to make selections

As the mouse is moved over the query form, any of the components can be selected by clicking the left mouse button. If text boxes (such as Stand ID), up/down boxes (such as spacing) or menu boxes (such as species) are selected, then changes can be made to the box by either typing in text (for the text and up/down boxes) or by selecting the arrow buttons at the right edge of the box (for menus and up/down boxes).

When one of these boxes is selected then pressing **F1** will result in Help being displayed to describe the use of the box.

If the mouse is moved over one of the buttons then the appearance of the button will change. Clicking the left hand mouse button will cause the button on the form to be pressed. This can be used to Run the model, Print the form, etc.

Using the Tab key

Pressing Tab causes the 'focus' to move through each of the controls in turn. The appearance of focus depends on the type of control. For text boxes, up/down boxes and menus the focus is indicated by the background becoming blue. For the buttons, focus is indicated by a thin black border and a black dashed box around the caption (and picture, if present) on the button.

When a control has focus, pressing **F1** will result in help being displayed that relates to the control.

A control which has focus can also be edited, changed or activated as follows:

Text boxes (e.g. Stand ID)	Edit using the keyboard;
Up/down boxes (e.g. spacing)	Edit using the keyboard;
Menu boxes (e.g. species)	Edit using the **up** & **down** keys;
Radio buttons (e.g. windfirm/brown edge)	Select using the **up** & **down** keys;
Buttons (e.g. Calculate DAMS or RUN)	Use the **Enter** key to press the button.

Using shortcuts

Shortcuts allow a combination of the ALT key plus a letter to be used to select an option.

The **Alt + key** shortcuts in the main menu are:

Alt + F	Open File menu
Alt + M	Open Mode menu
Alt + A	Open DAMS menu
Alt + O	Open Options menu
Alt + W	Open Window menu
Alt + H	Open Help menu

Within ForestGALES, the shortcut for a particular button is indicated by an underlined letter in the button caption.

Getting help

Help can be obtained either by clicking on a **Help** button, selecting **Help** from the main menu, or by pressing **F1**.

Pressing **Help** starts the help system – this allows the user to search for a particular topic or keyword.

Pressing **F1** will display help relating to the component that has focus (usually the last item where you clicked the mouse). These help pages are therefore 'context sensitive'.

5

Introduction

This is the standard type of prediction. It allows the user to calculate the risk of damage based on the stand's mensurational characteristics at a **single** point in time.

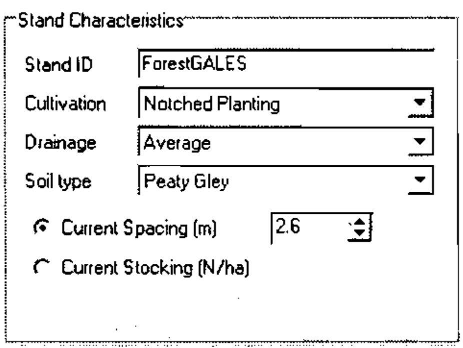
The user enters data that describe the site, the tree crop and whether or not a new edge is present.

In individual stand predictions, pressing **RUN** will then calculate the probabilities of damage occurring based on the selected options. Making predictions for multiple stands is explained in Chapter 8.

The stand characteristics box

The stand characteristics box (Figure 5.1) allows you to describe the stand for which you wish to calculate the risk of damage. The options are described below.

Figure 5.1 The Stand characteristics box.



Options – Stand ID

An identification for the stand. Note: names longer than 25 characters will not print correctly if a report is produced.

Options – Cultivation

The cultivation type of the stand. The options are grouped into three main categories, which are shown in Table 5.1.

Table 5.1

Cultivation methods available within ForestGALES, indicating the pooling of options used by the model. (Notched planting means no cultivation.)

Mounding	Shallow ploughing	Deep ploughing
Notched planting	Shallow ploughing <45cm	Deep ploughing >45cm
Turf planting	Scarifying	Disc trenching
Moling		Alternate single/double
Mound planting		Contour ploughing
Complete ploughing		

Options – Drainage

This describes how well drained the site is. Poor drainage (due to blocked drains), for example, results in increased risk of uprooting. The options are:

Average – site is 'typical'

Poor drainage – site is much wetter than you would expect

Good drainage – site is much drier than you would expect

Options – Soil type

This describes the main soil type in the stand. The most important factor is whether the soil is a peat, a gley, or a freely draining soil. The options are shown in Table 5.2.

Table 5.2

Soil types available within ForestGALES, indicating the pooling of options used by the model. 'Other' soils are currently treated like gleys.

Free draining	Peats	Gleys	Other
Brown earth	Juncus (Flushed basin) bogs	Ground-water gley soils	Rankers and skeletal soils
Podzols	Molina (Flushed blanket) bogs	Peaty gley soils	Littoral soils
Ironpan soils	Sphagnum (flat raised) bogs	Surface-water gley soils	Man-made soils
Calcareous soils	Unflushed blanket bogs		
	Eroded bogs		

Options – Current spacing

The average spacing between trees *at the time of risk assessment.* It must be between 0.6 and 10 metres.

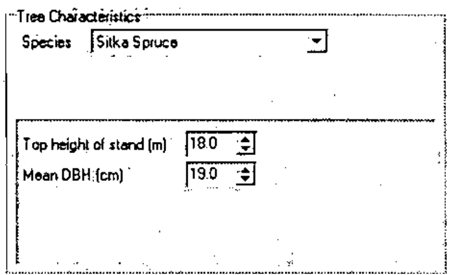
Options – Current stocking

The number of trees per hectare *at the time of risk assessment.* The user has the choice between this option and the previous one.

The tree characteristics box

The characteristics of the average tree of the stand are entered in the *Tree characteristics box* (Figure 5.2).

Figure 5.2 The Tree characteristics box.



The options that can be selected from the Tree characteristics box are:

Options – Species

The main species in the stand. Options are:

Scots pine	Douglas fir
Corsican pine	Noble fir
Lodgepole pine	Grand fir
European larch	Sitka spruce
Japanese larch	Norway spruce
Hybrid larch	Western hemlock

Options – Top height

Top height (in metres) of the stand being assessed. This must be between 5 and 75 m.

Options – DBH

Mean diameter (in cm) of the stand being assessed. This must be between 5 and 50 cm.

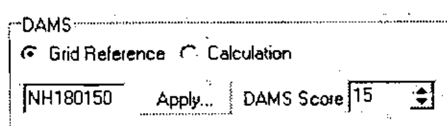
The DAMS box

DAMS is a measure of site windiness. The greater the value, the windier the site. Only values between 5 and 32 (the range of values found in Britain) will be accepted by the model. If the DAMS score for the site is known then it can be entered directly. If it is not known then it can be estimated, looked up or calculated by the program. The DAMS box is displayed in Figure 5.3.

Grid References method

In the DAMS box, the user can select **Grid Reference** and then enter the grid reference of the site; the DAMS score, if available, will be displayed. The DAMS scores are supplied on a separate CD-ROM, and this must be installed in the CD drive if the data are to be accessed.

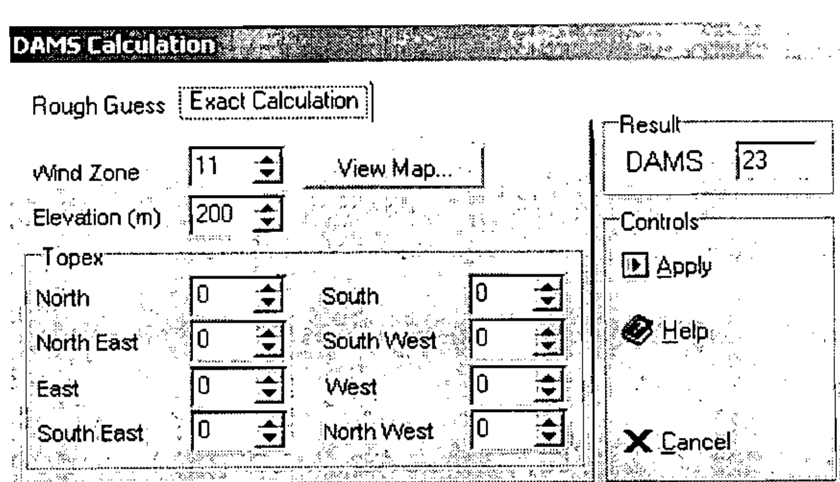
Figure 5.3 The DAMS box.



Exact Calculation method

In the DAMS box, select **Calculation** then click the **Apply...** button. The calculation box will appear. Selecting the **Exact Calculation** box (Figure 5.4) will give the opportunity to calculate the exact DAMS score. The Wind Zone for the location can be found using the map that is displayed when **View Map** is pressed. Elevation is entered together with the Topex values for each of eight compass directions (TOPEX is the angle to the horizon in whole degrees in the particular compass direction, with values less than zero being entered as zero). The resulting DAMS score can be copied to the main form by pressing **Apply**, or discarded by pressing **Cancel**.

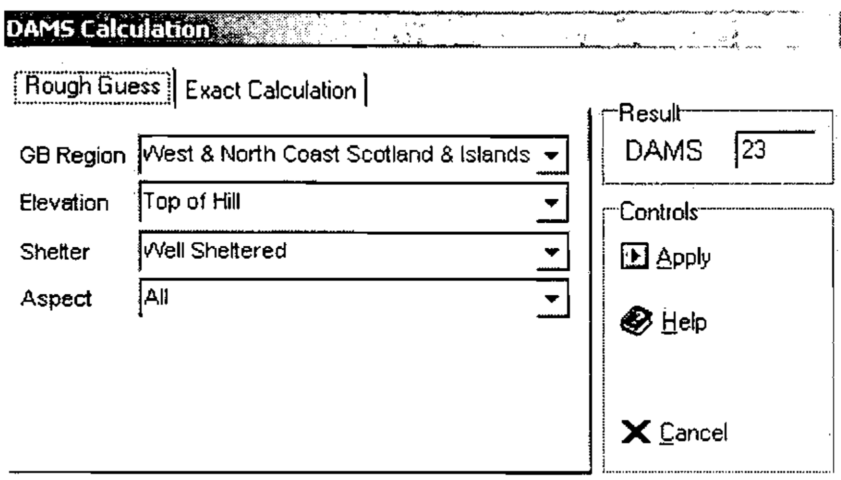
Figure 5.4 The Exact Calculation box.



Rough guess method

In the DAMS box, select **Calculation** then click the **Apply...** button. The calculation box will appear. Selecting the **Rough Guess** box (Figure 5.5) will give the opportunity to estimate the DAMS score. Select the options that best describe the site based on region within GB, elevation, shelter and aspect. Press **Apply** to copy the resulting DAMS score to the query form, or **Cancel** to close the window without copying the value across. This method is particularly useful for making general comparisons between sites.

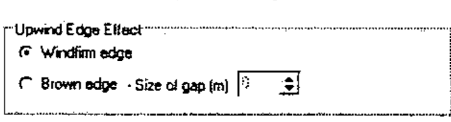
Figure 5.5 The Rough Guess box.



The upwind edge effect box

The *Upwind Edge Effect* box (Figure 5.6) is used to describe whether a new non-wind-firm edge has been created adjacent to the stand being modelled. Brown edges (i.e. edges that were originally not at the stand edge) are often a place where wind damage starts. If a new edge has been created then the **Brown Edge** button should be pressed. The size of the gap can then be altered. The default value is 0 m. The effect of a gap increases with gap width until the size equals 10 x mean tree height, after which the effect remains at a maximum.

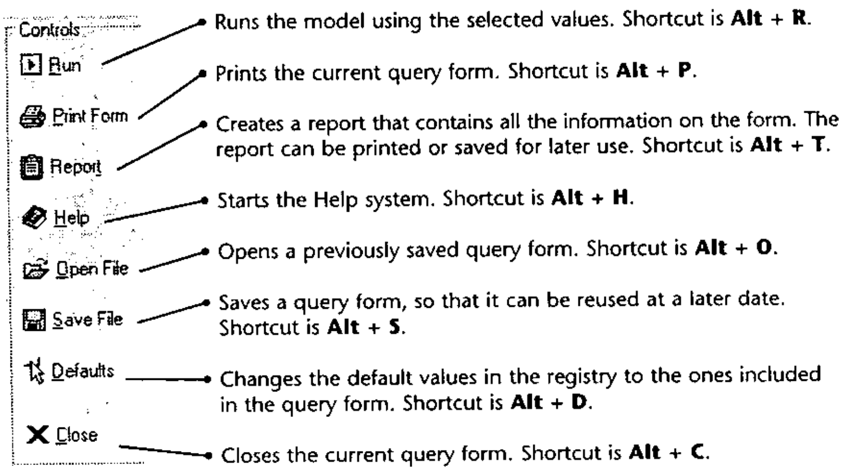
Figure 5.6 The Upwind Edge Effect box.



The controls box

The *Controls* box (Figure 5.7) allows the user to control ForestGALES. The options are described below.

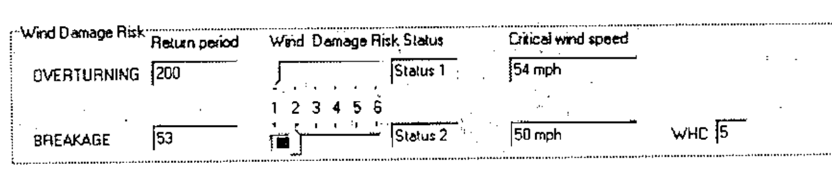
Figure 5.7 The Controls box.



The wind damage risk box

Model outputs are displayed in this box (Figure 5.8).

Figure 5.8 The Wind Damage Risk box.



Critical wind speed

The critical wind speeds (i.e. the lowest wind speeds that will cause overturning or breakage) are presented. By default these are presented in mph. Wind speed units can be changed in the **Options** menu.

Return period

The *average length* in years between wind speeds exceeding the critical wind speed occurring at the site. This is the *average* interval between gales that will damage the site. The statistical nature of the wind climate means that strong winds with long return periods (i.e. 50 years) may occur within a few years of each other. The occurrence of a damaging storm does not alter the risk of further damage in subsequent years.

Wind damage risk status

A measure of the risk of damage either by overturning or stem breakage. Six classes of wind damage risk status exist. These are listed in Table 5.3.

Table 5.3

Wind risk status and associated return periods.

	Return period
1	>100 years
2	100–50 years
3	50–33 years
4	33–20 years
5	20–10 years
6	<10 years

Unlike the Windthrow Hazard Class (WHC) classes, the risk status of a site will change over time. If the risk status for stem breakage is greater than for overturning, then stem breakage is likely to be the predominant form of damage, whereas if the risk status is greater for overturning than for breakage then uprooting is likely to be the predominant form of damage.

Windthrow Hazard Classification (WHC)

The WHC class for the site, based on the 'traditional' system (Miller, 1985) using the DAMS score and soil type. This is provided to allow comparisons to be made between the old and new system.

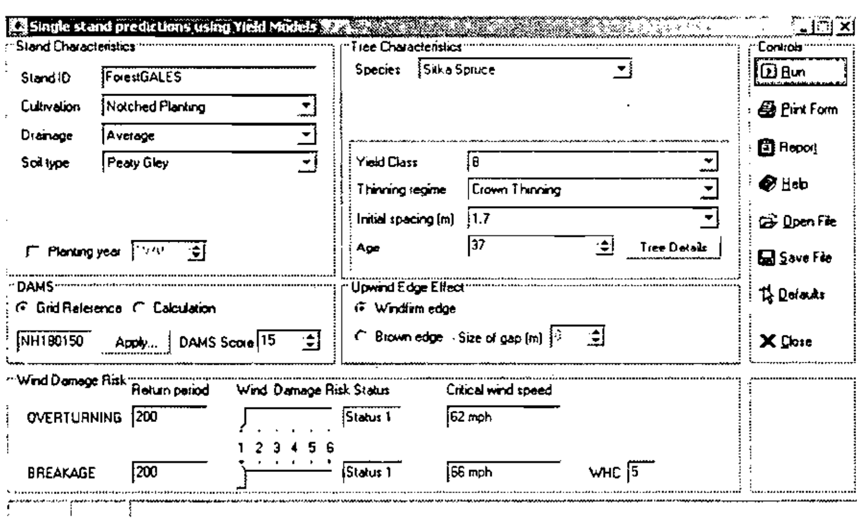
Introduction

6

This type of prediction allows the user to calculate the risk of damage at a single point in time based on stand characteristics defined in yield models. It is particularly useful when the mensurational characteristics of a stand are not known or when wanting predictions made at a single point in the future. Figure 6.1 shows the *Predictions using yield models* query form for single stands. Making predictions for multiple stands is explained in Chapter 8.

A selection of yield tables is distributed with ForestGALES, and is stored in the directory **yldmdls**. To select a yield model, choose the species, then select the yield class, thinning regime and initial stocking that apply. Only the yield models which are available can be selected from the program. It is, however, possible to create new yield models which can be used as input for ForestGALES. This is described on page 6.3.

Figure 6.1 The query form for Single stand predictions using yield models.



Stand characteristics box

As for *Predictions using field measurements*, the *Stand characteristics* box contains the **Stand ID, Cultivation, Drainage** and **Soil type** options (see page 5.1). The current stocking cannot be specified as this is taken from the yield tables.

Options – Planting year

A planting year can be specified. This will automatically adjust the stand age to present in the *Tree characteristics* box. If you want to make a prediction into the future adjust the age of the stand (see below) instead of specifying a planting year.

Tree characteristics box

When predictions are made using yield models, the *Tree characteristics* box shows the same **Species** option as found in the *Predictions using field measurements* (see page 5.3). However, the other options are different:

Options – Yield class

The thinning model regimes displayed will depend on the yield models available (Edwards and Christie, 1981).

Options – Thinning regime

- Intermediate thinning with no delay
- Intermediate thinning with five year delay
- Intermediate thinning with ten year delay
- Line thinning
- Line thinning with five year delay
- Line thinning with ten year delay
- Crown thinning
- No thinning

Options – Initial spacing

The initial spacing (in metres, based on square planting) should be selected. The range varies from 0.9–3.0 m depending on yield models available.

Options – Age

The age of the crop to be modelled. The valid range varies between yield models. Ages between published values are calculated using linear interpolation between the nearest younger and nearest older published value. By default if the date of planting has been entered then the age of the stand will be calculated. This will give the risk now. It is possible however to change the date, allowing the risk to be calculated at some other time.

The 'Tree Details' button

If this button is pressed then the height, diameter, current spacing and volume of the trees will be displayed. This is designed to provide information about the type of stand being modelled.

Other boxes

The **DAMS** box, the **Controls** box, the **Upwind edge effect** box and the **Wind damage risk** box are identical to those described on pages 5.4 to 5.7.

User-defined yield models

New yield models can be constructed for use within ForestGALES using a word processor, or spreadsheet program.

Overview

Currently ForestGALES doesn't contain a user-defined yield model helper. Yield models must therefore be created using a word processor or Excel®. The general layout of the yield model file is described below. An Excel® template is included with ForestGALES in directory **yldmodls\userdefined** and is called **yieldmodel.xls**.

The format of the model is illustrated in Table 6.1 and is:

Line one: a header to describe what is in each field
Line two onwards: fields separated by a single space to define

- Age (years)
- Top Height (m)
- Stocking density (stems ha^{-1})
- DBH (cm)
- Basal area (m^3 ha^{-1})
- Mean tree volume (m^3/tree)
- Volume per hectare (m^3 ha^{-1})

In each case data refer to the main crop after thinning. This is the format of the Forestry Commission Yield Models.

Table 6.1

Layout of a yield model for use in ForestGALES.

Age (years)	Top height (m)	Trees/ha	Mean DBH (cm)	Basal area (m^2/ha)	Mean tree volume (m^3)	Volume (m^3/ha)
20	7.4	2781	11	26	0.03	71
25	9.2	2300	13	32	0.06	90
30	10.9	1900	15	38	0.10	120

Naming user-defined yield models

The file should be saved as a text file with a file extension of **.yld**.
If ForestGALES is to recognise the model then it must be named in a specific way. This consists of an 8 character name.

1. The first two characters indicate species; these are shown in Table 6.2.

2. The second two characters refer to the yield class (02–30).

3. The third two characters refer to thinning regime, and are shown in Table 6.2.

4. The final two characters refer to initial spacing in metres x 10. Therefore 0.9 m spacing becomes 09, and 2.1 m spacing becomes 21.

Table 6.2

Species and thinning codes for naming user-defined yield models.

Species code	Species	Thinning code	Thinning regime
SS	Sitka spruce	IZ	Intermediate thinning no delay
NS	Norway spruce	IF	Intermediate thinning five years delay
SP	Scots pine	IT	Intermediate thinning ten years delay
LP	Lodgepole pine	LZ	line thinning no delay
CP	Corsican pine	LF	line thinning five years delay
EL	European larch	LT	line thinning ten years delay
JL	Japanese larch	CZ	crown thinning
HL	Hybrid larch	NO	non-thinning
DF	Douglas fir	T1	user-defined thinning regime
GF	Grand fir	T2	user-defined thinning regime
NF	Noble fir	T3	user-defined thinning regime
WH	Western hemlock		

A user-defined model for yield class 18 Sitka spruce for a non-standard thinning regime planted initially at 2.0 m spacing would therefore be saved as **SS18T120.yld.**

The file should be saved in the directory **yldmdls\XX** where **XX** is the two letter species code indicated in Table 6.2.

If a new model is created with an identical name to a model that already exists, then the old model will be lost.

Using Excel® to create user-defined yield models

1. Open the file **yieldmodel.xls** in Excel®. It is in the directory **\yldmdls\userdefined** wherever you have installed ForestGALES.

2. Type data for the yield model into the template.

3. Extra lines can be added as necessary. If the template contains more lines than are needed, then remember to delete the extra lines.

4. Press **File, Save As.**

5. Choose the option **Formatted Text(Space delimited)(*.prn).**

6. The file must be saved in the directory **XX**, where **XX** is the two character species code indicated in Table 6.2.

7. Type the filename according to the format described on page 6.3 to 6.4.

*Note: The filename must be enclosed in quotes (e.g. "**SS20IZ20.yld**"), otherwise the file extension **.prn** will be added resulting in a filename called something like **SS20IZ20.yld.prn***

8. Press **Save**.

The new model will be accessible within ForestGALES when a new *Predictions using yield models* query form is opened.

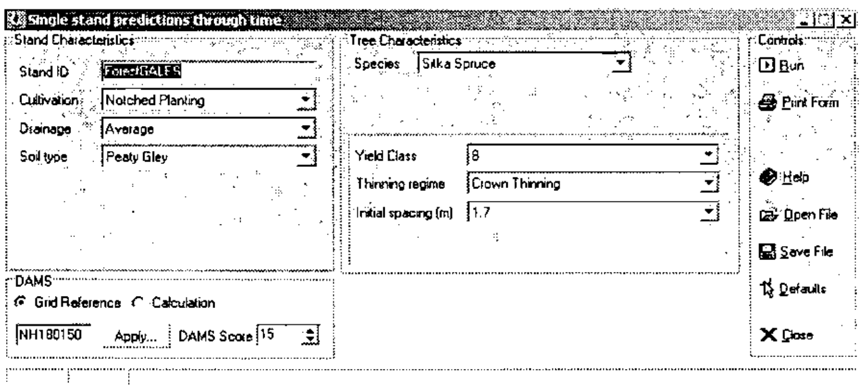
7

Introduction

This type of prediction allows the user to calculate the risk of damage to a stand over part or all of its rotation, rather than at just a single age.

Figure 7.1 shows the *Predictions through time* query form for single stands. Making predictions for multiple stands is explained in Chapter 8. The main difference between predictions through time and predictions at a single point in time is that the results are displayed on a separate form when the model is run. Also, there is no option for modelling the effect of a new edge.

Figure 7.1 The query form for single stand predictions through time.



Stand characteristics box

This is identical to the Stand characteristics box in Predictions using yield models (see page 6.1) except that year of planting is not available, since Predictions through time calculates risk over the whole rotation, not at just a single age.

Tree characteristics box

This is identical to the Tree characteristics box described on page 6.2 except that age is not available.

The DAMS box

This is identical to the DAMS box described on page 5.4.

The controls box

This is identical to the Control box described on page 5.6, except that a report cannot be created.

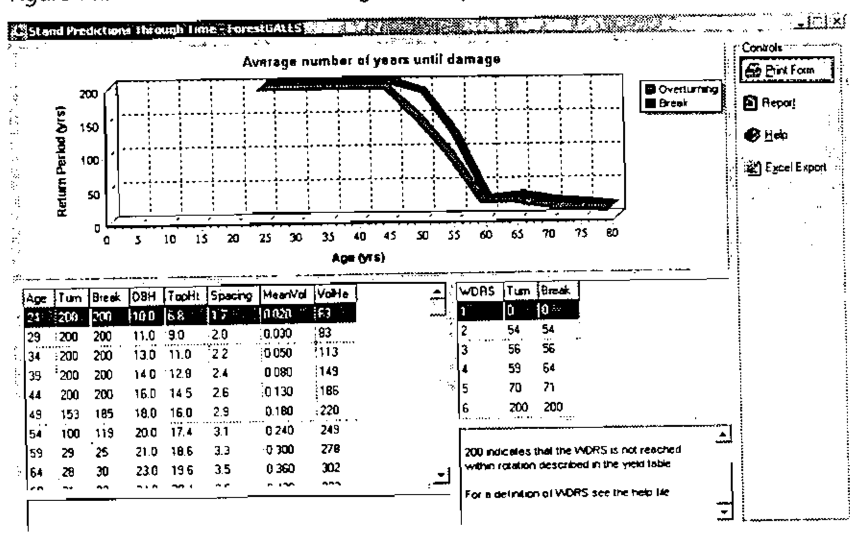
User-defined yield tables

New yield tables can be constructed using the method described on page 6.3.

Viewing the results

Figure 7.2 shows a typical results form. The form has four areas: a graphics window, two tabular windows and a controls box. These are described below.

Figure 7.2 The Results form for single stand predictions through time.



The graphics window

The graphics window indicates the return period in years for damaging storms at intervals throughout the rotation. Typically as the trees grow older and taller the risk of wind damage increases and the return period therefore decreases.

The graph contains two lines. The red line indicates the risk of overturning, and the blue line indicates the risk of stem breakage. The data relate to average trees (i.e. with mean diameter and height) based on the yield tables.

Details of the graph can be investigated as follows:

Zooming into the graph:

- Place the mouse cursor at the top left hand corner of the area you wish to zoom in to.
- Hold down the left mouse button.
- With the mouse button held down, move the mouse to the lower right hand corner of the area you wish to zoom in to.
- Release the mouse button.
- The display will then change to the selected area.

Note: there is a minimum area which can be selected, and if a smaller area is selected then no zooming will occur.

Scrolling around the graph:

- Place the mouse cursor somewhere on the graph.
- Hold down the right mouse button.
- With the right button held down, move the mouse.
- The graph will move as you do this.

Resetting the graph:

- Place the mouse cursor on the graph.
- Hold down the left hand mouse button.
- With the left button held down move the mouse to the left and upwards.
- The display will then revert to the original state.

Note: there is a minimum area which can be selected, and if a smaller area is selected, then the graph will not reset.

Displaying new results:

The effect of changing the yield model used can be observed directly in the graphics window. Go to the query form, change any parameter, press the Run button and the graphics display will change. This allows the user to easily observe the effect of changing the thinning model or soil type or species, for example.

The tabular data windows

The table window on the left hand side indicates how return period changes with age, and provides details on height, diameter, spacing and volume of the crop with age. The date when the crop enters each Wind Damage Risk Status (WDRS) is displayed in the table window on the right hand side. Data can be exported as described on page below.

The results form controls box

The controls that can be used on the results form are:

Print Form	Prints the current query form. Shortcut is **Alt** + **P**.
Report	Creates a report that contains all the information on the form. The report can be printed or saved for later use. Shortcut is **Alt** + **T**.
Help	Starts the Help system. Shortcut is **Alt** + **H**.
Excel® Export	Allows the user to export the tabular results to Excel®. Shortcut is **Alt** + **X**.

Introduction

8

ForestGALES has been designed to allow batch files of data (Multiple stands) to be processed, in addition to assessing the risk to stands one at a time. This allows data for a whole forest, property or coupe to be stored and calculated together.

In this mode, data are read in from one file, and output to a different file. This can be very helpful if a large number of stands need to be assessed at a single time. Those stands would not necessarily have to be linked to each other as the calculations are made independently. The *Multiple stands mode* can be used with each type of prediction.

The interface of ForestGALES in *Multiple stands mode* is different from that used for individual stands, and contains input and output areas as well as the control panel. Figures 8.1–8.3 show the interface for each type of prediction.

Figure 8.1 The query form for Multiple stand predictions using field measurements.

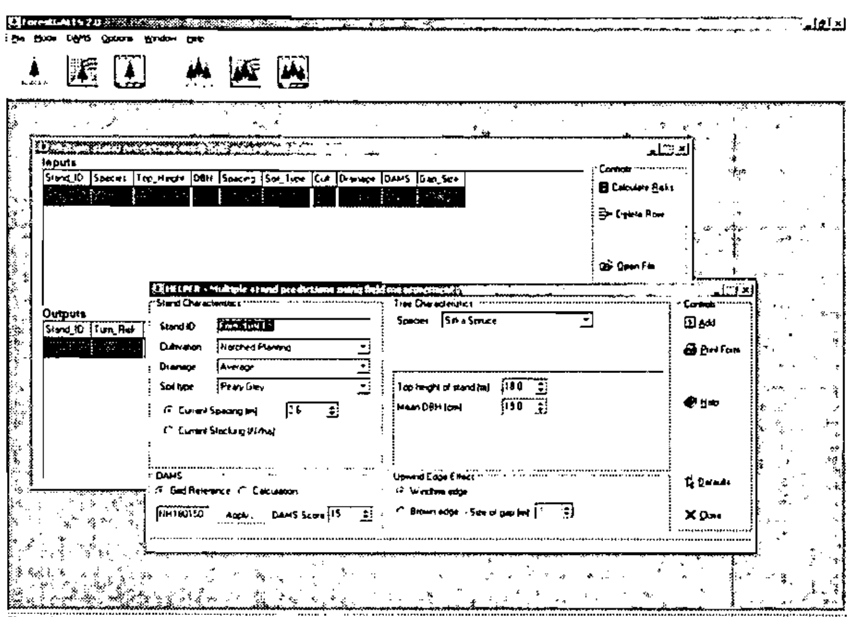


Figure 8.2 The query form for Multiple stand predictions using yield models.

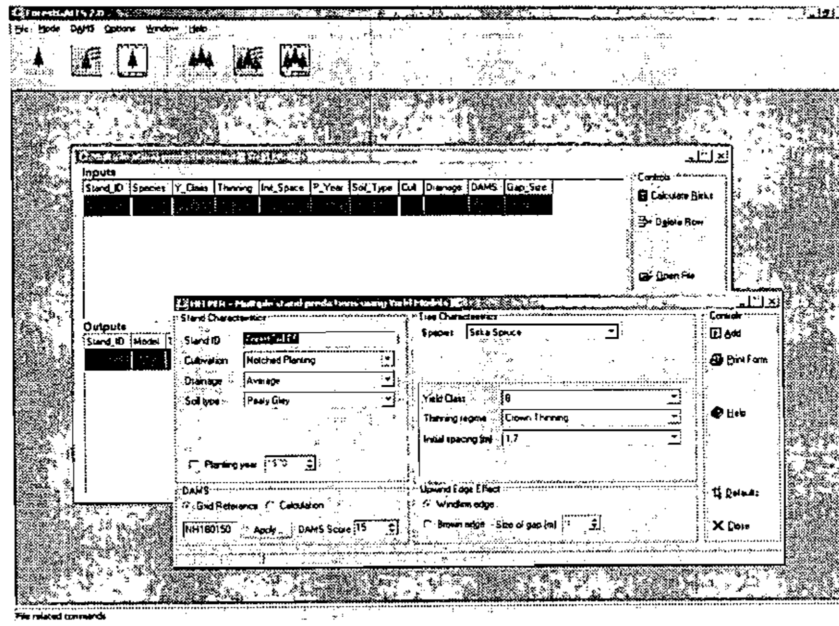
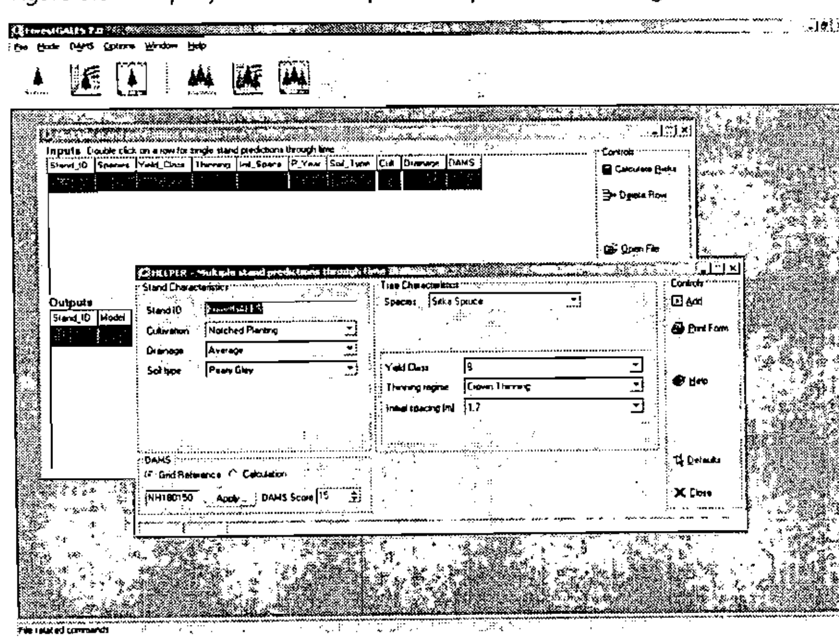


Figure 8.3 The query form for Multiple stand predictions through time.



Input files can be created using the *Multiple stands helper* window that appears in front of the query form when working in the *Multiple stands mode* (see Figure 8.1–8.3). The input files can also be created from a spreadsheet. However, since special codes are needed for some parameters, the use of the *Multiple stands helper* application is recommended.

The multiple stands helper

The multiple stands helper allows the user to select inputs from menus, and these are then written to the input area of the query form. This is useful because ForestGALES uses coded values to describe the species, site and cultivation rather than descriptions, and these values may be difficult to remember. For each prediction type, the options are identical* to those described for the corresponding query form in the *Single stand* prediction mode (See Sections 5, 6 and 7).

*Note: Clicking on **Close** causes both the helper and the Multiple stands query form to be closed. Unless you want to discard the inputs, click on **Calculate Risk** before closing the helper.*

*There is a slight difference when making predictions for multiple stands using yield models. The year at which you wish to calculate the risk has to be specified on the query form rather than in the helper.

The controls box

The controls in the *Multiple stands helper* are:

Add	Adds the selected values to the input area of the query form. Shortcut is **Alt + A**.
Print Form	Prints the current query form. Shortcut is **Alt + P**.
Help	Starts the Help system. Shortcut is **Alt + H**.
Defaults	Changes the default values in the registry to the ones included in the query form. Shortcut is **Alt + D**.
Close	Closes both the helper and the query form. Shortcut is **Alt + C**.

The multiple stands query form

The characteristics of the stand are entered in the **input area.** All data relating to a single stand are displayed on the same line. After running the program, the results of the model are displayed in the **output area.** If the data have been saved then the filename will be displayed at the top of the output area. The outputs vary slightly depending on the mode you are running in (see Table 8.1).

Table 8.1

Modes available for multiple stand predictions.

MODE	OUTPUTS
Predictions Using Field Measurements	Return Period for Overturning, Wind Damage Risk Status for Overturning, Return Period for Breakage, Wind Damage Risk Status for Breakage.
Predictions Using Yield Models	Model Used, Current Top Height (m), Current DBH (m), Current Spacing (m), Return Period for Overturning, Wind Damage Risk Status for Overturning, Return Period for Breakage, Wind Damage Risk Status for Breakage.
Predictions Through Time*	Model Used, Age to reach WDRS 4 for overturning, Age to reach WDRS 5 for overturning, Age to reach WDRS 6 for overturning, Age to reach WDRS 4 for breakage, Age to reach WDRS 5 for breakage, Age to reach WDRS 6 for breakage.

**Double clicking on any of the input lines in this mode will open the graphics display window as for a single stand. In this way it is possible to observe differences between the risk for all the stands entered as inputs.*

The controls box

The controls in the *Multiple stands* query form are:

Calculate Risks Runs the model using the selected values. Shortcut is **Alt + R**.

Delete Row Deletes a row of data from the input area. Shortcut is **Alt + E**.

Open File Opens a previously saved query form. Shortcut is **Alt + O**.

Save Inputs Saves the input file for later use. Shortcut is **Alt + N**.

Save Outputs Save the output file so that it can be exported to another application. Shortcut is **Alt + U**.

Help Starts the Help system. Shortcut is **Alt + H**.

Excel® Export Allows the user to export the tabular results to Excel®. Shortcut is **Alt + X**.

Year of calculation

When you are in the *Predictions Using Yield Models mode* then the option is provided to modify the Year of Calculation in the bottom right corner. The default is the current year but any year in the past or future (up to 2100) can be chosen. If the age is less than the minimum in the yield table the model defaults to the minimum age. If the age is beyond the maximum age in the yield tables the model defaults to the maximum age.

Single stand predictions using field measurements – getting started

1. Start **ForestGALES**.

2. Left click on **Mode**

   ⇨ The Mode dialog box will open.

3. Choose **Single stand, Predictions using field measurements**

   ⇨ A new query form will open. This form has a range of pre-selected options. However, no value will be present in the Wind Damage Risk box.

   For the purpose of this exercise, make sure the default options are set to the following values: ***Cultivation*** *Notched planting,* ***Drainage*** *Average,* ***Soil type*** *Peaty Gley,* ***Current spacing*** *2.6 m,* ***Species*** *Sitka spruce,* ***Top height of stand*** *18 m,* ***Mean DBH*** *19 cm,* ***DAMS Score*** *15.* ***Windfirm edge.***

4. Left click on **Run**

   ⇨ Values of 200 years will appear in the Wind Damage Risk box for the return period for both overturning and breaking.

5. Left click on the up button to the right of the **Mean DBH** box

   ⇨ The DBH will increase by 0.1 cm per 'click'.

6. Keep changing the DBH in this way until a value of 25 cm appears in the box.

7. Change **Top height** until it reads 21 m.

8. Change **Current Spacing** until it reads 3.8 m.

9. Left click on **Run**

   ⇨ The values in the Wind Damage Risk boxes will change to 12 years for **Return period for overturning** and 13 years for **Return period for breakage.**

This indicates that the risk of damage changes rapidly with changes in DBH, height and spacing. Other parameters can be changed in a similar way.

Single stand predictions using field measurements – the effect of a new edge

This example shows how creating new edges affects the risk of damage.

1. Start ForestGALES and open a query form for Single stands predictions using field measurements in the same way as the previous example.

2. Using the pre-selected options, left click on **Run**

   ➧ This will give the return periods for damage for the default parameters, and no new edge.

3. Left click on the **Brown Edge** button

   ➧ A black dot will appear on the button, and the value for size of upwind gap will become black. Change the **Size of gap** to 400 m.

4. Using the pre-selected values left click on **Run**

   ➧ The values in the Probabilities boxes will change and should become 4 years for **Return period for overturning** and 3 years for **Return period for breakage**.

This indicates that the risk of damage is much greater if a new edge is present, than if no new edge is present. The Gap size box will also have changed to 167 m. This is 10 x the mean tree height. Gap widths greater than this have no additional effect on stability.

5. Now try changing the size of the gap to 5 m and left click on **Run**

   ➧ The values in the Probabilities boxes will change and should become 14 years for **Return period for overturning** and 8 years for **Return period for breakage**.

Again, try changing other options to see what happens.

Single stand predictions using yield models

This example shows how to use yield models to provide input data for the model.

1. Left click on **Mode**

   ➧ The Mode dialog box will open

2. Choose **Single stand, Predictions using yield models**

   ➧ A new query form will open. This form has a range of pre-selected options. However, no value will be present in the Wind Damage Risk box.

   *For the purpose of this exercise, make sure the default options are set to the following values: **Cultivation** Notched planting, **Drainage** Average, **Soil type** Peaty Gley, **Species** Sitka spruce, **Yield class** 8, **Thinning regime** Crown Thinning, **Initial spacing** 1.7 m, **Age** 37, **DAMS Score** 15. **Windfirm edge.***

3. Left click on **Run**

➧ This will give the probabilities of damage for a stand of YC 8 Sitka spruce, planted at 1.7 m spacing with a crown thinning regime at an age of 37. The values in the Probabilities boxes will change and should become 200 years for **Return period for overturning** and 200 years for **Return period for breakage.**

The size and spacing of the modelled trees can be viewed using the **Tree Details** button.

4. Now change the age to 55 and left click on **Run**

➧ The values in the Probabilities boxes will change and should become 75 years for **Return period for overturning** and 81 years for **Return period for breakage.**

This indicates that the risk is increasing with stand age.

5. Now left click on the **down arrow** to the right of Thinning regime

➧ A menu of thinning options will appear as you move the mouse over the options, they are highlighted in turn.

6. Left click on **Intermediate with no delay**

7. Left click on **Run**

➧ The values in the Probabilities boxes will change and should become 200 years for the **Return period for overturning** and 200 years for the **Return period for breakage.**

Again, try changing other options to see what happens.

DAMS example

This example demonstrates the use of DAMS as an input for the model.

1. Start **ForestGALES** and open a query form for Single stands predictions using yield models in the same way as the previous example.

2. Leave the options as they were in the previous example and left click on **Run**

➧ This will give the probabilities of damage for a typical tree in a stand of YC 8 Sitka spruce, planted at 1.7 m spacing with a crown thinning regime at an age of 37. The values in the Probabilities boxes will change and should become 200 years for **Return period for overturning** and 200 years for **Return period for breakage.**

3. Within the **DAMS** box, use the up and down arrows to select 19 as the value of DAMS score. The higher the DAMS score the windier the site.

4. Leave the options as they are and left click on **Run**

   The return periods should change to 21 years for the **Return period for overturning** and 57 years for **Return period for breakage**.

It should be apparent that relatively small changes in DAMS result in large changes in calculated risk.

Again, try changing other options to see what happens.

DAMS – rough guess example

This example demonstrates using a rough estimate of DAMS as an input for the model.

1. Start **ForestGALES** and open a query form for Single stands predictions using yield models.

2. Within the DAMS box select the **Calculation** button then click **Apply...**

   A new form will appear.

3. Left click on the **Rough Guess** tab

   New options will appear.

4. Select **GB Region** Scottish & English Borders, **Elevation** Mid-Slope, **Shelter** Exposed, **Aspect** West.

   18 will appear in the DAMS box Pressing **Apply** would copy this value to the query form.

5. In the **GB Region** box, select Central Wales

   17 will appear in the DAMS box.

Again, try changing other options to see what happens.

DAMS – grid reference example

This example demonstrates how to obtain the DAMS score for a specific grid reference.

1. Start **ForestGALES** and open a query form for Single stands predictions using yield models.

2. Within the DAMS box click the **Grid Reference** button. Press **Apply...**

   15 will appear in the DAMS box. This is the value of DAMS for NH180150. If ForestGALES cannot find the DAMS data it will ask you to locate it. The **Find Files** option in the Windows start-up menu may

be useful for this.

3. Type NY659932 in the Grid Reference box

4. Left click **Apply**

   ▷ 17 will appear in the DAMS box.

Again, try changing other options to see what happens.

DAMS – calculate DAMS example

This example demonstrates how to obtain the DAMS score for a location based on ground measurements.

1. Start **ForestGALES** and open a query form for Single stands predictions using yield models

2. Within the DAMS box select the **Calculation** button then left click **Apply...**

   ▷ A new form will appear.

3. Left click on the **Exact Calculation** tab

   ▷ New options will appear. By default, 23 will appear in the DAMS box. This would relate to a hill top site at 200 m elevation in the west of Scotland. Pressing **Apply** would copy this value to the query form.

4. To change the location left click on **View Map**

   ▷ This will cause a new window to appear.

5. Left click in the dark blue area in central Scotland (North West of the Tay estuary).

6. Press **OK**

   ▷ The windzone value 3 should be placed into the **Windzone** box and 15 will appear in the DAMS box.

7. Select **100** in the Elevation box

   ▷ 13 will appear in the DAMS box.

8. Enter **Topex** scores as shown in Table 9.1.

Table 9.1

Example Topex values.

North	0	South	5
North-east	3	South-west	2
East	5	West	0
South-east	10	North-west	0

11. Left click **Calculate**

➪ 10 will appear in the DAMS box.

Again, try changing other options to see what happens.

Anchorage	The complex of mechanisms by which the root system and soil resist the wind forces on the stem and crown.
Brown edge	An edge of a stand that was created by felling part or all of the adjacent crop, rather than being a crop boundary since the time of planting.
Centre of pressure	The average position in the crown of the tree where the total force of the wind can be said to act.
Coherent gusts	Organised rotational motions in the air (= Vortices).
Critical wind speed	Threshold hourly wind speed above which the average tree of a stand is expected to be overturned or snapped.
Critical height	The top height of the stand at which damage was expected to start within the WHC system.
Cultivation	The method of preparing the soil prior to tree establishment. This may have been done by many means such as ploughing, mounding or producing turves.
Damping	The processes by which oscillations are reduced in size and tend to stop. Damping includes canopy clashing, canopy drag through the air, and frictional movement of stem fibres.
DAMS score	Detailed Aspect Method of Scoring – a system for scoring windiness derived from tatter flags and using representation of location and terrain to calculate a score (Quine and White 1993).
DBH	Diameter of a tree at 1.3 m above ground level.
Dominance	The 'social' status of a tree within a crop. Five categories are usually defined – dominant (trees with a crown entirely within the canopy), codominant (trees with much of their crown in the canopy), subdominant (trees with their crowns generally below the canopy), suppressed (trees with small crowns entirely beneath the canopy, which are gradually dying from lack of light) and dead.
Drag area	The surface area of the tree (canopy and stem) presented to the wind. Drag area is reduced as wind speed increases, due to streamlining of the tree.
Drag force	The force on the tree caused by the pressure exerted by the wind on the crown (= wind loading).
Drainage	A description of site wetness; poor refers to a wet site where rooting is severely restricted by a shallow watertable – due to local topography or failure of/lack of installed

drainage system; good refers to better than average site – due to topography (e.g. shedding slope) or good quality intensive drainage network.

Frequency of oscillation	The number of sway cycles of the tree per second.
Fulcrum	The position on the lee-side of the tree where the root system pivots when the tree is bent by the wind (= hinge).
Gust	A rapid increase in wind speed over a short period of time (seconds rather than minutes).
Hinge	See Fulcrum.
Leeward	The side of the tree facing away from the wind.
Lever	The distance between the point of action of a force and the fulcrum.
Modulus of elasticity	A measure of stiffness. Modulus of elasticity is the load that theoretically would be required to make a material double (or halve) in length were it to behave perfectly elastically. In practice timber generally stops behaving elastically when its length changes by 1% and breaks when the change exceeds 2%.
Modulus of rupture	The force per unit area that is required to break a material when a bending load is applied.
Moment	Force multiplied by distance (= torque).
Overturning moment	The force on the tree multiplied by the distance from where the force acts (the centre of pressure) to the fulcrum, plus the additional moment due to the weight of the over-hanging crown.
Risk (for a tree)	The probability in a particular year of the critical wind speed being exceeded (see Vulnerability).
Risk status	A measurement of the probability of the critical wind speed being exceeded in a particular year, grouped into six categories. Status 1: return period >100 years; Status 2: return period 50–100 years; Status 3: return period 33–50 years; Status 4: return period 20–33 years; Status 5: return period 10–20 years; Status 6: return period <10 years.
Root architecture	The appearance and structure of the root system, particularly the number and arrangement in three dimensions of the thickest roots.

Spacing – Current	The average spacing between trees at the time of risk assessment.
Spacing – Initial	The average spacing between trees at the time of planting.
Stocking	The number of trees per hectare at the time of risk assessment.
Terminal height	The top height of a stand at which wind damage was expected to reach a level necessitating clearance.
Thinning	The removal of a proportion of the tree crop for silvicultural or economic reasons. ForestGALES can extract data from yield models categorised according to thinning regime and initial spacing. The regimes used in the yield models are non-thinning (no trees actively removed, though some may die naturally), intermediate thinning (removal of trees from throughout the crop, with the smaller trees being preferentially removed), line thinning (removal of trees in straight lines) and crown thinning (removal of trees that are competing with the crowns of the highest quality trees). Models have also been produced for delayed thinnings.
Top height	The average height of the 100 trees of largest diameter per hectare, usually measured as the average height of the largest diameter trees in a sample of 0.01ha plots.
Topex	A measure of exposure based on the sum of the angles to the horizon in eight compass directions.
Turbulence	The random variations in wind speed and direction.
Vortices	See Coherent gusts.
Vulnerability (of a tree)	The threshold wind speed required to blow over a particular tree on a particular site.
WHC	See Windthrow Hazard Classification.
Wind loading	See Drag force.
Windthrow hazard classification	A method to zone forest areas of 500ha or more by adding scores for windiness and soil together to estimate a hazard class. Each class was associated with a critical height and a terminal height.
Windward	The side of the tree facing towards the wind.
Wind zone	A range of windiness categories for the whole of Britain. The higher the wind zone the windier the climate on average. Windzone boundaries are defined in Quine and White (1993).

Yield class A commonly used expression of growth rate – defined as the mean maximum annual increment that could be achieved by the stand (units – $m^3\ ha^{-1}\ yr^{-1}$).

11

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